

IAEA-TECDOC-322

SURFICIAL URANIUM DEPOSITS

**REPORT OF THE WORKING GROUP ON URANIUM GEOLOGY
ORGANIZED BY THE
INTERNATIONAL ATOMIC ENERGY AGENCY**



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FOREWORD

The great surge of interest 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 developed by government and industry programmes is not widely available, and in many cases has not been systematically coordinated, organized and prepared for publication. With the current cut-back in uranium exploration and research, there is a real danger that much of the knowledge gained will be lost and, with the anticipated resurgence of interest in the future, will again have to be developed, with a consequent loss of time, money and effort. In an attempt to gather the most important information on the types of uranium deposits, a series of reports are 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, gathers and exchanges information on key issues of uranium geology and coordinates 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 Strata Bound Uranium Deposits	— John Ferguson
Surficial Deposits	— Dennis Toens

The success of the projects has been heavily dependent on the dedication and efforts of the project leaders and their organizations. Without the active participation and contribution of world experts on the types of deposits involved, this volume would not have reached fruition. 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.

Special thanks are extended to Dr. Dennis Toens for guiding the work of this project, to Dr. Brian Hambleton-Jones for compiling and editing the papers and to the Nuclear Development Corporation and its staff for their work on preparing this report on Surficial Uranium Deposits.

John A. Patterson
Scientific Secretary

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INTRODUCTION

P.D. TOENS

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In order to achieve the objectives as set out in the Foreword, this project was formally constituted in June 1981, and consisted of a group of scientists from ten countries, all with acknowledged expertise in the field of surficial uranium deposits. This volume is the collective effort of the members of the group, and their associates, all of whom have given of their time on a purely voluntary basis. This has been done with the full cooperation of the authorities in the participating countries which, in some cases, also bore the travelling expenses to attend meetings. A comprehensive list of participants and co-workers is given at the end of this volume.

The group has had to contend with many problems, such as the reluctance of some countries to actively participate and the confidentiality of company-related information. A volume of this nature has therefore perforce many self-evident shortcomings and can by no means be regarded as all-embracing. At its best, it can be regarded as representing the state of the art as at the end of 1983.

The discovery of surficial uranium ore deposits, in particular Yeelirrie, during the early seventies highlighted the importance of surface phenomena, other than the weathering of primary uranium ore deposits, in concentrating uranium. Factors such as epeirogenesis and climatic stability are extremely important in the preservation of these deposits and in particular those that are Upper Tertiary to Recent in age. However, it is possible that certain surficial deposits could have been preserved under a protective sedimentary or volcanic cover.

Although unanimity has not been reached, it would seem that deposits usually termed uraniferous calcretes, dolocretes or gypcretes cannot, in the strict sense of the term, be described as such, since in numerous cases the CaCO_3 content is less than 5 or 10 %. Although the terms calcrete and gypcrete have become entrenched in the literature in less than a decade, it would, in the view of some authors, seem unwise to perpetuate this partial misnomer. Toens and Hambleton-Jones [1] proposed the term valley-fill, amongst others, to describe these deposits. Their proposed terminology has been fully accepted by some authors, accepted with reservations by certain contributors, and rejected by others. The terminology remains, therefore, in a state of flux and it is hoped that the conclusions drawn by the reader will assist in clarifying the problems pertaining to nomenclature in subsequent discussions.

The uranium deposits which are now generally termed calcrete or valley-fill, or valley-calcrete, have a number of factors in common, the most important of which is that the uranium mineralization is almost invariably in the form of carnotite. Furthermore, the mineralization occurring in sediments of fluvial or lacustrine origin are associated with variable amounts of replacement epigenetic calcite, dolomite, gypsum, or strontianite. Uranium also occurs as carnotite in pedogenic occurrences in some localities, but is of lesser importance. In most cases it is evident that the material hosting the uranium mineralization has been derived from a source not far distant from the deposit. The origin of the vanadium, without which carnotite cannot form, is not always self-evident, but it appears to have been derived from mafic rocks or minerals in the vicinity of the deposit. Most deposits also present clear evidence that the uranium mineralization, carbonates and gypsum were precipitated interstitially in the surficial material. Some deposits are still forming at the present.

Although uneconomic uraniferous bog-type occurrences, which formed under reducing conditions, have been known for some time in Europe, notably Scandinavia and the United Kingdom [2], they have not received much attention to date and their economic significance has only recently been recognised. Uranium, in association with diatomaceous peaty material occurring in drainages and in pans of Recent age, has been recognized in South Africa, where at least one of these deposits could prove viable under improved market conditions. Extensive deposits of uranium associated with organic material have been located in western Canada and the northwestern USA and are described in this volume for the first time [3]. Some of the North American deposits could, in all probability, be viable in a number of localities. It is noteworthy that, due to the young age of the uranium, marked disequilibrium occurs so that radioactivity is extremely low.

The surficial deposits are often of limited extent and are located in remote areas. Metallurgical problems and the low grade of the potential ore add to the difficulties of exploiting these deposits. On the other hand, mining can usually be undertaken by relatively cheap opencast methods, particularly as the ore is often rippable.

Collectively, these deposits constitute about 10 to 15 % of global resources, which could be recovered at a cost of less than \$80 per kg U. Therefore, provided certain metallurgical problems can be solved, it would appear that these deposits will ultimately make an important contribution to the resource inventory. Due to their mode of formation, many of the surficial deposits are likely to occur in remote desert regions and their exploitation could eventually assist in opening up areas which would normally have remained undeveloped. It is hoped that this volume will bring the potential importance of these deposits to the attention of geologists and scientific administrators, especially in the developing countries, and so stimulate further research in this connection.

REFERENCES

- [1] TOENS, P.D., HAMBLETON-JONES, B.B., Definition and classification of surficial uranium deposits, this Volume.
- [2] WILSON, M.R., Uranium enrichment in European peat bogs, this Volume.
- [3] CULBERT, R.R., BOYLE, D.R., LEVINSON, A.A., Surficial uranium deposits in Canada, this Volume.

DEFINITION AND CLASSIFICATION OF SURFICIAL URANIUM DEPOSITS

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ABSTRACT

DEFINITION AND CLASSIFICATION OF SURFICIAL URANIUM DEPOSITS

Uraniferous surficial deposits may be broadly defined as uraniferous sediments or soils, usually of Tertiary to Recent age, that have not been subjected to deep burial and may or may not have been cemented to some degree. Evaluation of the available literature shows that confusion has arisen as to the use of the term "calcrete" when describing fluvial sediments that have been calcified to a greater or lesser degree. It is felt that a useful purpose would be served by proposing a classification system which may go some way towards a redefinition of the applicable terminology.

Unfortunately the terms "calcrete" or "valley calcrete" have been used to define Tertiary to Recent sediments ranging from boulder beds to silts which, in some Namibian examples, contain between 5 and 50 % CaCO_3 and as much as 90 % total carbonate in some Australian surficial uranium deposits. It is proposed that the detrital material constituting the sediments be prefixed with the terms calcareous, dolomitic, gypsiferous, halitiferous or ferruginous (e.g. calcareous grit) rather than the terms calcrete, dolocrete, gypcrete, and ferricrete, all of which have genetic connotations. The latter group of terms are preferably used for the pedogenic uranium deposits only. This will have the effect of placing these deposits in categories of their own and not confusing the issue with the overprint of pedogenic calcrete or duricrustal deposits which may or may not be present. This view is not shared by some authorities notably Butt and Carlisle (see this volume).

1. INTRODUCTION

Subsequent to the discovery of the Yeelirrie deposit in Australia in 1972 "calcrete" uranium deposits are continuing to receive attention. Numerous similar uranium deposits have been located in various parts of the world and a number of potential areas remain to be investigated. The uranium deposits located to date vary considerably in size and there seems little doubt that some of the larger ones will make a significant contribution to the uranium resource inventory of certain countries.

Evaluation of the available literature shows that some confusion has arisen as to the use of the term "calcrete" when describing fluvial sediments which have been calcified to a greater or lesser degree. In spite of the fact that the term calcrete is so well entrenched in the literature a useful purpose could be served by proposing a classification system which may go some way towards a redefinition of the applicable terminology. It is however realized that a classification based on a genetic concept may not always be valid or acceptable.

2. DEFINITIONS AND TERMINOLOGY

Uraniferous surficial deposits may be broadly defined as uraniferous sediments or soils, usually of Tertiary to Recent age, which have not been subjected to deep burial and may or may not have been cemented to some degree. It is recognised that there are many cementing minerals, these include (in approximate order of importance), calcite, gypsum, dolomite, ferric oxide, strontianite, and halite.

In terms of Lampugh's [1] original definition, calcrete was defined as a pedogenic deposit in which the main constituents are carbonates. This definition would in the same sense apply to the terms dolocrete, gypcrete, and ferricrete (or laterite). It is therefore unfortunate that the terms "calcrete" or "valley calcrete" of Carlisle et al [2] have been used to define Tertiary to Recent sediments ranging from boulder beds to silts which, in some Namibian examples, contain between 5 and 50 % CaCO_3 , and as much as 90 % total carbonate in Yeelirrie in Australia [3] where they could quite legitimately be described as calcretes.

A proposed system of classification of surficial uranium deposits is illustrated in Table 1. The secondary classifications are to be found in Tables 2 to 4. From this classification three main groupings, namely, **Fluvial**, **Lacustrine/Playa** and **Pedogenic** are recognised and that the terms calcrete, dolocrete, ferricrete, and gypcrete should in the opinion of the authors preferably be used for pedogenic uranium deposits only.

It will also be noticed that the economically important calcareous and gypsiferous material referred to by Carlisle et al [2] as valley calcretes and Hambleton-Jones [4] simply as calcretes are termed valley-fill sediments in Table 2. They could be prefixed by the terms calcareous, dolomitic, gypsiferous or ferruginous rather than the terms calcrete or dolocrete etc which have a genetic connotation.

This classification is not entirely definitive for within a surficial deposit there may well be two or more types in juxtaposition separated by a transitional zone. A problem also occurs regarding the process of pedogenesis and the question arises as at what stage a fluvial or lacustrine sediment can be referred to as a calcrete? These

Table 1
Classification of Surficial Uranium Deposits

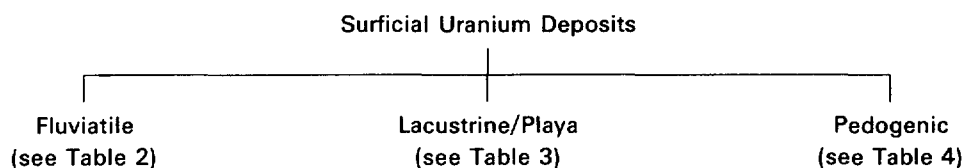


Table 2
Classification of Uraniferous Fluvatile Deposits

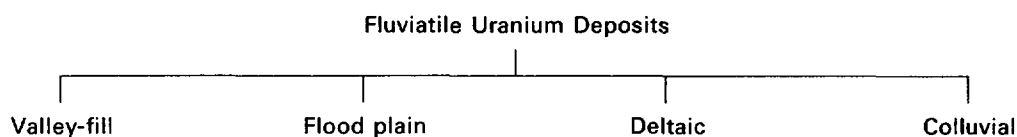


Table 3
Classification of Uraniferous Lacustrine/Playa Deposits

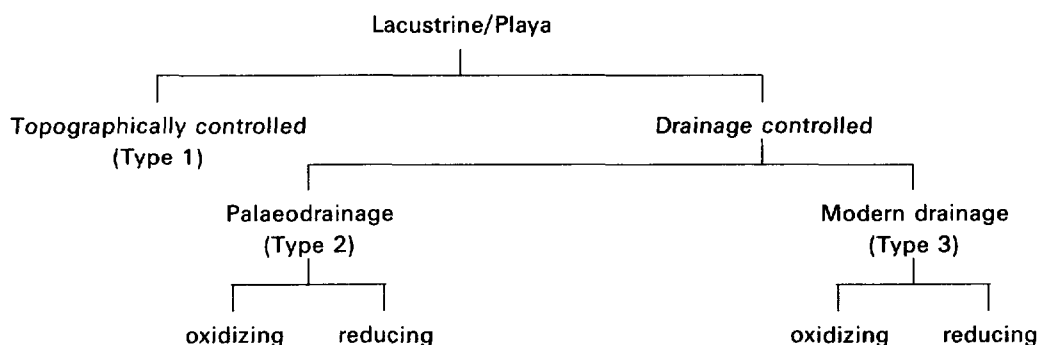
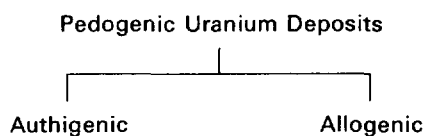


Table 4
Classification of Uraniferous Pedogenic Deposits



problem areas may tend to cloud the absolute meaning of the suggested terminology but are regarded as sufficiently objective in terms of some known field relationships.

A brief outline of the concepts and proposed nomenclature and a description of the essential features of each type is presented below and diagrammatically in Figure 1.

3. TYPES OF SURFICIAL URANIUM DEPOSITS

3.1 Fluvatile

Uraniferous fluvatile sediments of Tertiary to Recent age host uranium deposits which occur in valley-fill, flood plain and deltaic environments from which the nomenclature is derived (Table 2). As indicated by the terminology the valley-fill sediments occur in areas of steeper gradient while the flood plain or deltaic sediments form under lower energy regime conditions. The gradation from one type to the next is naturally transitional and ill-defined. It should be noted that the term fluvatile is used very loosely and it is recognised that much of the sediment may contain aeolian, alluvial, colluvial, lacustrine, and evaporitic components deposited as the result of periodic flow, ponding and sheetwash (C.R.M. Butt, personal communication).

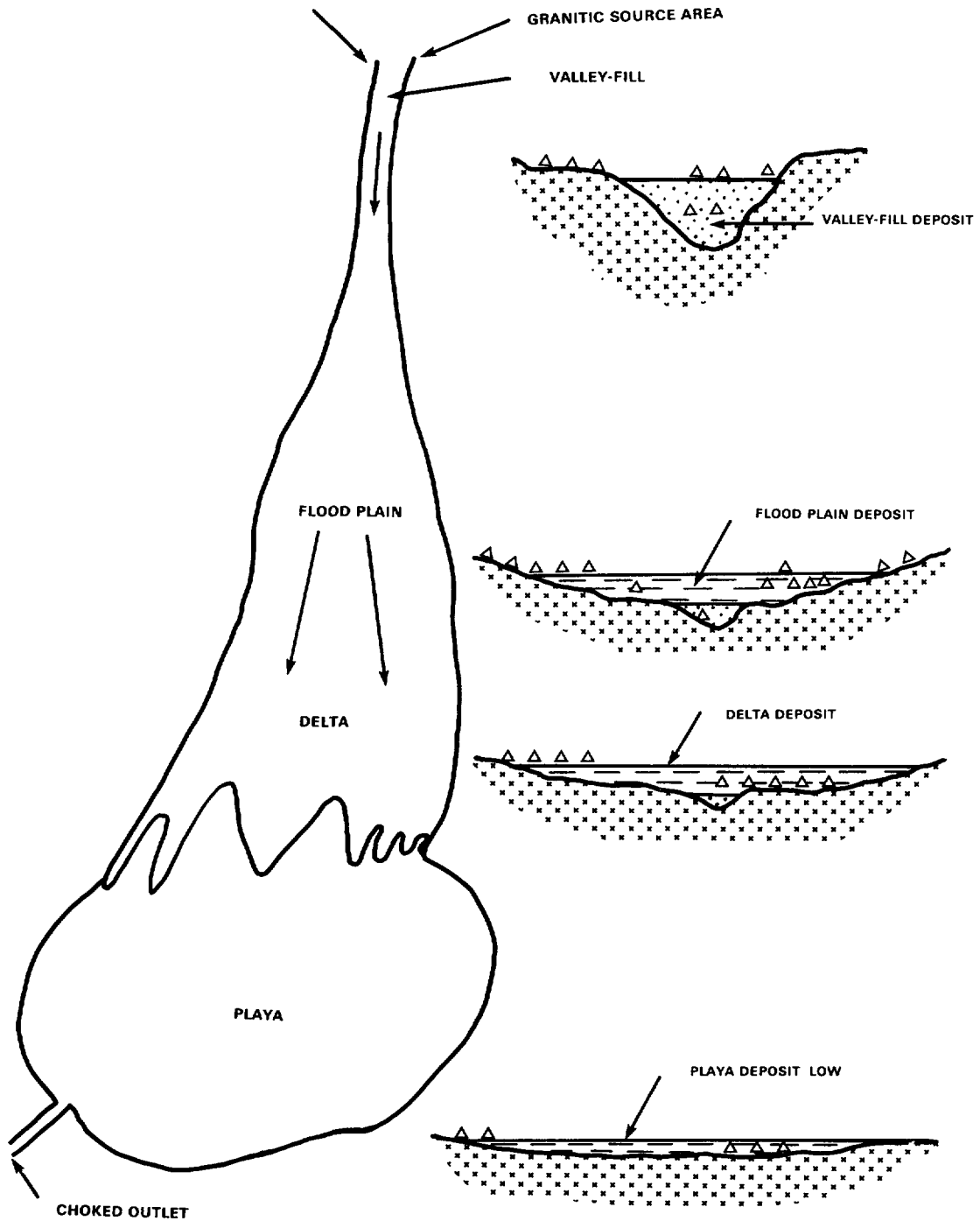


Figure 1
Schematic presentation of the location of valley-fill, flood plain, deltaic and playa deposits within a drainage system. Intercolated pedogenic deposits (Δ) representing period of quiescence are dispersed throughout the successions.

Valley-Fill

Uraniferous valley-fill deposits have the greatest economic potential of all the surficial uranium deposits so far discovered and a great number of which have been reported on [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17]. They are known to occur in Australia, Namibia, South Africa, Mauritania, Somalia, and China. The most noteworthy occurrences are the Langer Heinrich, Trekkopje, Tubas, and Aussinanis in Namibia; Yeelirrie Centipede, and Lake Way in Australia, and Kamasoas and Henkries in the northwestern Cape of South Africa.

Uranium occurs usually as carnotite and is an important accessory mineral of the epigenetic portion of the sediment occurring as coatings, vugg-fills, concretions, and veins.

In the Namib Desert of Namibia, the fluvial sediments are typically breccia conglomerate, conglomerate, gravel, grit, sand, silt and clay and are all of a general arkosic composition with some being reworked aeolian sand. Deposition of these sediments frequently took place under flash-flood conditions in high energy regimes. The upper sedimentary layers, irrespective of their texture, have been cemented epigenetically by calcite, gypsum, dolomite and, to a much lesser degree, strontianite. Lower down in the sequence the carbonate or gypsum contents decrease.

Uraniferous deposits in the northwestern Cape of South Africa occur in a mixture of both reddish to brown fluvial and reworked aeolian sediments being sandy in texture. Gypsum and to a lesser extent calcite constitute the cement. In the Australian deposits, the main uranium zone is porous and friable in texture and may contain as little as 10 % fine-grained detrital or aeolian material. Calcite, with subordinate dolomite, is the main constituent. In the Salar Grande in northern Chile, the detrital gravels have been cemented with halite which has become blue due to the radiation damage from the associated uranium mineralization. This occurrence may in part have a deltaic component [18]

The drainage patterns of the type areas are generally internal in that very little or no water reaches major rivers or the ocean as it tends to disappear rapidly within the alluvium. Tilting, loss of erosional power and deposition at barriers has tended to choke the valleys. For example, in Namibia, the Tumas River water can travel many tens of kilometres before gradually disappearing into the sand. In Western Australia, flow is sub-surface, the valley calcretes being prolific aquifers, and many drainages terminate in playas.

Flood Plain

Uraniferous flood plain deposits are essentially sheet-like, and may either overlie or occur downstream of valley-fill uranium deposits. Their composition is essentially the same as that of valley-fill type but as the name implies, they may have considerable lateral extent but may vary in thickness. Much of the material may be derived from the reworking of valley-fill sediments.

Deltaic

Uraniferous deltaic deposits form where the flood plain or valley-fill sediments enter a lacustrine or playa environment. The composition of the sediment is essentially the same as that of the flood plain type. It is, however, finer grained and more argillaceous and often contains interbedded lacustrine chemical precipitates. The carnotite mineralization in the Salar Grande, of northern Chile [18] and the Napperby deposit of central Australia [27] are typical of this environment [18]. Valley calcretes in Western Australia commonly broaden into extensive platforms or form "chemical deltas" where they enter playas. The deltas represent a facies change in the evaporites, which here consist dominantly of dolomite, with minor sepiolite and accessory argonite. Parts of the North Lake Way [13] and Centipede [16] deposits are in these environments.

3.2 Lacustrine/Playa

Uraniferous playa deposits have been located in South Africa [19], Australia [15, 17], and Chile [18]. No deposits of this type are known to contain sufficient mineralization to constitute a viable proposition under current market conditions. It is nevertheless important to categorise these deposits for future reference.

The term "playa" is herein used to refer to those flat and generally barren portions of arid basins of usually internal drainage that periodically flood and accumulate detrital and/or evaporitic sediments. Other terms that have been used to describe these dry or ephemeral lakes include: salina or salar (Chile and Spanish speaking lands), sabkha (Arabia, North Africa); ga (Jordan); pans (southern Africa); takyr (USSR) and kavir (Iran) [20].

It has been estimated that there are about 50 000 playas on the earth, the vast majority being small, having an area of a few square kilometres or less. Only about 1 000 have areas greater than 100 km² [20]. Playas may form either under oxidizing or reducing conditions.

Classification of Playas

Three main types of playas which may contain uranium in some localities have been recognized. Two of the types can be subdivided further into reducing and oxidizing varieties. The classification is shown in Table 3.

- Type 1 Circular topographically controlled playas with fairly steep sides having floors well below the regional elevation
- Type 2 Elongated playas coinciding with palaeo- or choked-drainage channels in which the conditions can either be oxidizing or reducing
- Type 3 Floor playas are large and irregular in size and are usually not significantly depressed below the surrounding country. They are related to Type 2 as they form part of a modern drainage superimposed on an older one.

Playa sediments are mostly fine grained (clays and silts), commonly rich in calcite, gypsum, and halite, with associated hypersaline water

An interesting variation is the occurrence of highly reducing conditions in certain playas having marsh and bog sediments and could conveniently be referred to as cienages. Such deposits occur in Canada, USA, Europe, Scandinavia, South Africa, and Chile [18, 21, 22, 23, 24, 25, 26]. Typically the sediments are composed of peaty material with some containing diatomaceous earth. The reduced organo-complexed uranium and certain oxidized minerals found in them frequently have a high degree of disequilibrium. Many of the Australian lakes have reducing conditions at depth while some have peats or lignites 20 or 30 m below surface. South of about 30° (the Menzies Line) reducing conditions occur at or close to surface. However, no uranium deposits have yet been found in these reduced environments (C.R.M. Butt, personal communication).

3.3 Pedogenic

Soil development in desert environments is usually thin but may well have developed from deeply weathered rocks. It may have formed in-situ from weathered basement or derived from transported material. The assemblage of terms having the "crete" suffix – such as calcrete, gypcrete, dolocrete, ferricrete, halicrete (or salcrete) etc should in the opinion of the authors be reserved for material of pedogenic origin. These rock types have formed in-situ from various host materials such as weathered bedrock, fluvial (or alluvial), colluvial, and aeolian sediment.

Uranium has been found to occur in these deposits but at current prices none are considered viable.

Based on the origin of the host material pedogenic uranium deposits can be classified in the following way as shown in Table 4.

Authigenic pedogenic uranium deposits occur in a weathered or decomposed zone over underlying basement rocks. This decomposed material is entirely of in-situ origin which may have been cemented by one or other mineral and associated uranium. Allogenic pedogenic uranium deposits occur in soils developed from transported material of fluvial or aeolian origin.

The terms calcrete and gypcrete uranium deposits although widely used it is suggested that strictly speaking they should be considered as applicable only to these rock types and for a lack of a better term are referred to as duricrustal uranium deposits. It is accepted that these views are not shared by some contributors to this volume.

4. CONCLUSIONS

In order to obtain a measure of clarity in the nomenclature the use of the terms calcrete, gypcrete, dolocrete, and ferricrete should be discontinued when referring to valley-fill and lacustrine/playa deposits. This will have the effect of placing these deposits in categories of their own and not confusing the issue with the over-print of pedogenic calcrete or duricrustal deposits which may or may not be present. It will also hopefully eliminate the tendency of referring to a sediment which may contain as little as 5 or 10 % CaCO₃ as a calcrete and thereby making it easier for workers outside southern Africa and Australia to classify new surficial uranium deposits.

It is also abundantly clear that at the time of formation of the valley-fill and allied uranium deposits, the climate must in fact have been wetter than it is now. The present-day dry climate has militated against flushing out the carnotite and the preservation of these deposits is therefore entirely due to the current climate conditions. The appreciation of these factors should therefore be borne in mind when selecting potential areas suitable for the preservation of uraniumiferous valley-fill deposits. Some deposits are still forming today, for example in Australian deposits such as Centipede and North Lake Way where precipitation is continuing (C.R.M. Butt, personal communication).

The organic-rich bog-type uraniumiferous deposits are a newer variety of surficial deposit which may still be forming today.

REFERENCES

- [1] LAMPLUGH, G W., Calcrete, Geol. Mag 9 (1902) 575–583.
- [2] CARLISLE, D, MERIFIELD, P.M., ORME, A.R., KOHL, M.S, KOLKER, O, The distribution of calcretes and gypcretes in southwestern United States and their uranium favorability based on a study of deposits in Western Australia and South West Africa (Namibia), US Dept. of Energy, Open File Report GJBX-29(78) (1978) 274.
- [3] WESTERN MINING CORP LTD (EXPLORATION DIVISION), A general account of the Yeelirrie uranium deposit, Privately published and distributed to 25th Int. Geol. Cong. tours, Sydney, Australia (1975) 14
- [4] HAMBLETON-JONES, B B., The geology and geochemistry of some epigenetic uranium deposits near the Swakop River, South West Africa, Thesis (D Sc). (Unpubl.) Univ. of Pretoria (1976) 306.
- [5] MANN, A.W, Chemical ore genesis models for the precipitation of carnotite in calcrete, Aust. CSIRO Div Mineral Report No. FP 7 (1974) 18.

- [6] MANN, A.W., DEUTSCHER, R.L., Genesis principles for the precipitation of carnotite in calcrete drainages in Western Australia, *Econ. Geol.* 73 (1978) 1724–1737.
- [7] MANN, A.W., DEUTSCHER, R.L., Hydrogeochemistry of a calcrete-containing aquifer near Lake Way, Western Australia, *J. Hydrol.* 38 (1978) 357–377.
- [8] BUTT, C.R.M., HORWITZ, R.C., MANN, A.W., Uranium occurrences in calcrete and associated sediments in Western Australia, *Aust. CSIRO Div. Mineral Report No. FP 16* (1977) 67.
- [9] PREMOLI, C., Formation of, and prospecting for, uraniferous calcretes, *Australian Mining* (1976) 13–16.
- [10] LANGFORD, F.F., A supergene origin for vein-type uranium ores in the light of the Western Australian calcrete-carnotite deposits, *Econ. Geol.* 69 (1974) 516–526.
- [11] BUTT, C.R.M., MANN, A.W., HORWITZ, R.C., Regional setting, distribution and genesis of surficial uranium deposits in calcretes and associated sediments in Western Australia, this Volume.
- [12] CAMERON, E., The Yeelirrie calcrete uranium deposit, Western Australia, this Volume.
- [13] FRENCH, R.R., ALLEN, J.H., Lake Way uranium deposit, Wiluna, Western Australia, this Volume.
- [14] GAMBLE, D.S., Lake Raeside uranium deposit, this Volume.
- [15] CAVANEY, R.J., Lake Maitland uranium deposit, this Volume.
- [16] CRABB, D., DUDLEY, R., MANN, A.W., Hinkler Well-Centipede uranium deposits, this Volume.
- [17] HEATH, A.G., DEUTSCHER, R.L., BUTT, C.R.M., Lake Austin uranium deposit, Western Australia, this Volume.
- [18] PEREZ, L.E., Depositos superficiales de uranio en el norte de Chile, this Volume.
- [19] RICHARDS, D.J., Preliminary report on pan mineralization from airborne radioactive surveys, NW Cape Province, *S. Afr. Geol. Surv. GH-2113* (1975) 8.
- [20] NEAL, J.T. (Ed), *Playas and Dried Lakes Occurrence and Development*, Benchmark Papers in Geology/20. Dowden, Hutchinson & Ross, Pennsylvania (1975) 411.
- [21] CULBERT, R.R., BOYLE, D.R., LEVINSON, A.A., Surficial uranium deposits in Canada, this Volume.
- [22] OTTON, J.K., Surficial uranium deposits in the United States of America, this Volume.
- [23] WILSON, M.R., Uranium enrichment in European peat bogs, this Volume.
- [24] HAMBLETON-JONES, B.B., Surficial uranium deposits in South Africa, this Volume.
- [25] LEVIN, M., Uranium occurrences in the Gordonia and Kuruman Districts, *S. Afr. Atomic Energy Board, PER-37* (1978) 24.
- [26] CARLISLE, D., Possible variations on the calcrete-gypcrete uranium model, US Dept. of Energy, Open File Report GJBX-53(80) (1980) 38.

PROCESSUS DE MINÉRALISATION URANIFÈRE DES CALCRETES: UNE HYPOTHÈSE NON PÉDOLOGIQUE

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ABSTRACT – RESUME

A NON-PEDOLOGICAL HYPOTHESIS FOR THE PROCESSES OF URANIUM MINERALIZATION IN CALCRETE

The non-pedological hypothesis presented for the origin of the uraniferous calcrete deposits in Western Australia is based on the premise that alluvial and calcareous lacustrine sediments were initially formed during earlier wet periods, evidence for which has been found in the fossil records. These were followed by subsequent epigenetic alteration accompanied by the precipitation of uranium mineralization during drier semi-arid periods. Typical examples of the processes involved were found in the Yeelirrie uranium deposit. During the latter semi-arid period, the limited surface flow which consisted of periodic flash flood conditions probably contributed marginally to the recharge of the groundwater, and consequently, semi-stagnant groundwater conditions evolved, particularly where the hydraulic gradient was extremely small, for example, for the Yeelirrie channel it is approximately 0.001. In addition, ponding of water behind a natural barrier caused the groundwater to evolve along the following geochemical sequence: mild alkalinity, weak oxidizing conditions, and oversaturation in dissolved elements. These hydrological and hydrogeochemical conditions induced the epigenetic alteration of the palustral/lacustrine limestone, bringing about dolomite neogenesis and the precipitation of carnotite. The limited downstream recharge of the groundwater table in the Yeelirrie channel introduced slightly oxidizing conditions causing the development of a geochemical barrier where dissolved V^{4+} was oxidized to V^{5+} . This process provided the mechanism for the precipitation of carnotite, whereby V^{5+} reacted with already available uranium and potassium in solution. At that period partial dolomitization of the calcitic host rock occurred with the simultaneous development of swelling structures and the formation of sepiotite. Subsequently, during a period of greater aridity, the diagenetic-epigenetic dolomitization process stopped. This was followed by a period of silicification whereby opaline silica was precipitated within the sediments and partly covered the carnotite protecting it from further significant leaching. The source of the uranium in the calcretes and the groundwater of the Yeelirrie channel is considered to be the weathered outcrops of the breakaways along its margins. The genetic hypothesis proposed in this paper, although somewhat different from those described previously and elsewhere in this volume, could be applied to the other uranium-bearing calcretes in Mauritania, Namibia, and Somalia.

PROCESSUS DE MINÉRALISATION URANIFÈRE DES CALCRETES: UNE HYPOTHÈSE NON PÉDOLOGIQUE

En Australie Occidentale, les inféro-flux des chenaux de drainage sont les principaux agents de la genèse des calcretes et de leurs transformations diagénétiques. Dans le cas du gisement de Yeelirrie (46 000 tonnes d' U_3O_8 estimées), les balancements du toit de la nappe lors de l'alternance des saisons sèches et humides d'un climat semi-aride conduit à l'épigénèse des alluvions et au dépôt d'un clacaire palustre. L'aridification du climat amène à l'aval du calcrete, juste en arrière d'une structure barrage, les conditions hydrologiques et hydrogéochimiques nécessaires à sa diagénèse: dolomitisation, précipitation de la carnotite. . . La source de l'uranium des calcretes est à rechercher dans des pré-concentrations uranifères, à la base des altérations du bouclier Yilgarn, dont seule une anomalie radioactive est le témoin actuel. L'uranium rejoint les eaux des nappes de chenaux de drainage après son lessivage par les eaux météoriques percolantes. Les grandes lignes du processus génétique ainsi que les contrôles paléoclimatologiques et paléomorphologiques de la minéralisation mis en évidence à Yeelirrie sont vérifiés pour les concentrations uranifères de type calcrete en Mauritanie, Namibie et Somalie.

1. INTRODUCTION

Cette contribution propose une hypothèse génétique pour la formation des gîtes uranifères de type calcrete. Par de nombreux points elle diffère de celle développée, en particulier, par les auteurs australiens et qui est énoncée dans cet ouvrage au chapitre Australie et dans la bibliographie correspondante [1,2,3,4,5,6,7,8,9,10]. Le gîte uranifère de Yeelirrie et les autres occurrences uranifères dans un contexte semblable (Australie Occidentale, Mauritanie, Namibie, Somalie) ne résultent pas uniquement de la mise en place d'un calcrete et de sa minéralisation uranifère. L'histoire 'ante chenal' de l'uranium en relation avec la morphologie de plate-forme stable du bouclier et avec l'évolution climatique joue un rôle important. C'est l'ensemble de cette évolution qui va aboutir à la formation de gîtes uranifères de type calcrete.

2. L'EXEMPLE DE L'AUSTRALIE OCCIDENTALE

2.1 L'altération du Bouclier Yilgarn

Le bouclier Yilgarn est une vieille surface pénéplanée, entaillée par des chenaux de drainage qui limitent des escarpements ou breakaways. Ces derniers constituent de véritables coupes naturelles qui permettent l'étude des altérations successives du socle archéen. Trois phases consécutives sont mises en évidence :

La première correspond à une arénisation du socle archéen. Elle se traduit par l'installation d'un profil kaolinitique. Cette altération est caractéristique sur roche mère acide (granite, gneiss) des vieilles plate-formes usées, horizontales ou faiblement inclinées, sous climat tropical [11].

La seconde voit s'installer sur ce profil un silcrete. Le titane sous forme d'anatase de néoformation est associé à la silicification.

La troisième coiffe les deux précédentes et peut également les raviner. C'est une formation rougeâtre qui présente certaines caractéristiques de l'horizon B d'accumulation d'un sol.

Dans la région de Yeelirrie (Nord-Ouest de l'Yilgarn), le granite peu altéré est constitué de feldspaths, quartz, kaolinite et un peu d'illite. Avec l'augmentation de l'altération les feldspaths disparaissent et la kaolinite devient prépondérante. Le quartz reste en proportion importante, l'illite se rencontre toujours en faibles quantités. Au sommet l'arène est silicifiée. La silicification se présente sous la forme de microquartz remplaçant progressivement la kaolinite. Le silcrete sous-jacent est presque exclusivement quartzueux. Illite et kaolinite peuvent y être présents en faible quantité. L'anatase accompagne les premiers phénomènes de silicification. Dans la formation rouge, le quartz détritique est prépondérant, la kaolinite réapparaît tandis que l'anatase disparaît. La kaolinite est de type pédologique.

La composition chimique des altérites reflète l'évolution minéralogique. Même peu altéré, le granite a déjà perdu une grande partie de ses éléments alcalins et alcalino-terreux. Cette évolution se poursuit dans la partie arénisée et non silicifiée du profil avec un départ partiel de la silice et une augmentation de l'alumine. Le rapport $\text{SiO}_2/\text{Al}_2\text{O}_3$ décroît pour atteindre 2,63 à la base de l'arène silicifiée. L'arène serait à rapprocher des sols "d'argiles ferralitiques" de Duchaufour [11]. Le rapport $\text{SiO}_2/\text{Al}_2\text{O}_3$ est certes supérieur à 2 qui est la limite du domaine ferralitique selon les normes de la classification française des sols [12], mais la silicification ultérieure masque l'évolution de ce rapport vers le sommet du profil. L'arénisation correspond donc aux sols "d'argiles ferralitiques" développés sur vieux socle à relief usé et à drainage médiocre sous climat équatorial.

Les teneurs en uranium sont relativement élevées dans les roches non altérées du bouclier Yilgarn (5 à 10 ppm avec un écart de 2 à 80 ppm sans concentration effectivement exprimée [2]). Dans l'arène granitique et la formation rouge, les teneurs en uranium sont faibles. Elles peuvent être plus élevées dans les niveaux silicifiés. Pourtant une anomalie radioactive existe à la base des profils (150 à 300 chocs SPP2, atteignant 650 chocs SPP2 sur les fissures). Elle est probablement due à l'activité de ^{214}Bi et ^{214}Pb éléments de filiation de ^{226}Ra issu de ^{230}Th selon le schéma proposé par Hambleton-Jones [13]. La possibilité de fixation de l'uranium sur les kaolinites existe soit sous forme de microcristallisations soit par adsorption [14,15,16].

Une telle anomalie radimétrique peut être l'empreinte d'une concentration uranifère pédologique provenant du lessivage du socle lors de la première phase d'altération, préconcentration d'abord protégée (silcrete) puis remobilisée à son tour lors de l'évolution morphologique et climatique du bouclier Yilgarn. La protection va toutefois devenir inopérante lors des phases les plus récentes. L'érosion conduit à la formation des paysages actuels de l'Yilgarn avec le creusement des chenaux de drainage, leur comblement par des alluvions et l'établissement des breakaways. La morphologie actuelle est créée, rompant ainsi l'équilibre géochimique antérieur.

La mobilisation de l'uranium par des eaux oxydantes et lessivantes devient possible. L'aridification du climat va être le catalyseur de cette remise en mouvement et de la genèse des formations carbonatées d'origine palustre. Cette évolution, sur l'Yilgarn est aussi bien spatiale que temporelle et traduit dans la région le passage d'une climatologie chaude et humide à un climat aride. Les prémices de ce changement commencent entre 17 et 10 millions d'années tandis que l'installation d'un climat aride avec des caractéristiques voisines de celles de la climatologie actuelle se produit vers 2,5 millions d'années [17].

2.2 Hydrogéochimie du Chenal de Yeelirrie

Le chenal de Yeelirrie comme les autres chenaux de la région ne présente pas actuellement de circulation des eaux en surface, sauf exceptionnellement après de très fortes pluies, l'essentiel de la circulation se fait en nappes alluvionnaires peu profondes. L'origine des éléments dissous présents dans ces nappes sub-superficielles est à rechercher dans le lessivage des profils d'altération du bouclier Yilgarn. Dans cette région à pluviométrie faible, à évaporation importante et où l'écoulement des nappes est lent (gradient hydraulique inférieur à 0,001), les eaux subsistent en quelques kilomètres un cycle hydrologique complet, une maturation intense [18]. Il s'ensuit une augmentation importante de la salinité à l'approche et dans le calcrete pour atteindre 20 g/l au sein de la minéralisation [1]. Au cours de cette maturation, il n'y a pas de changement de chimisme des eaux mais uniquement croissance de leur charge. Celle-ci n'est pas uniforme entre tous les ions majeurs, les quatre ions principaux (Cl^- , Na^+ , Mg^{++} , SO_4^{--}) se concentrent d'une façon plus importante que les trois ions "secondaires" (Ca^{++} , K^+ ,

HCO_3^-) aussi se produit-il un enrichissement relatif des eaux vis à vis de ces quatre ions principaux [19] Hormis les ions majeurs, de nombreux éléments traces participent à ce processus d'augmentation de la salinité Ainsi augmentent d'amont en aval et de l'extérieur vers le centre du chenal

la silice (de 48 à 106 ppm) qui a toutefois des teneurs plus basses à l'intérieur des calcretes (70 ppm environ) ce qui ne peut être dissocié des processus de silicification et de meulièrement.

le zinc dont les teneurs dans les eaux du chenal varient de 35 ppb à 2 200 ppb se concentre vers le centre du chenal à proximité du calcrete (Figure 1)

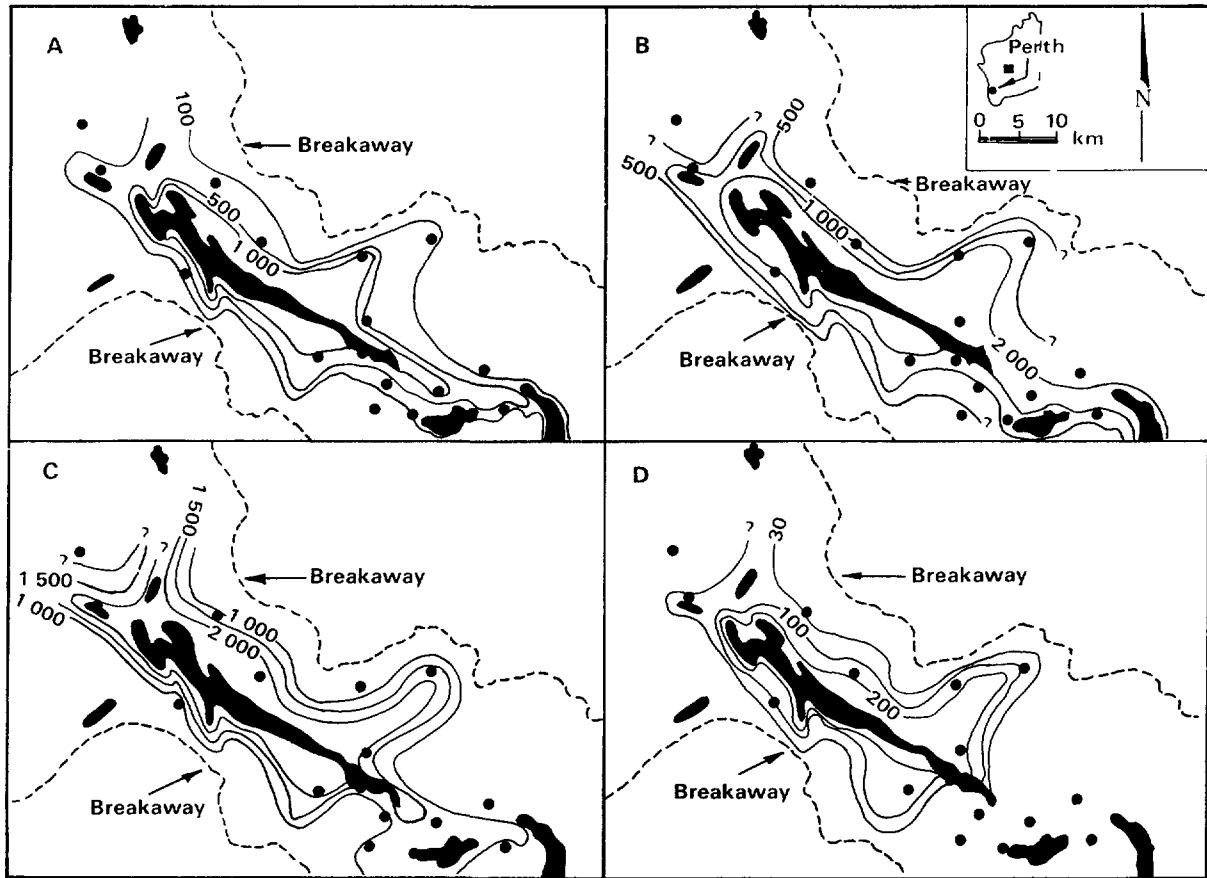


Figure 1

Cartes des isoteneurs en zinc (A), strontium (B), fluor (C) et uranium (D) des eaux du chenal de Yeelirrie (les teneurs sont exprimées en ppb)

Contour maps of zinc (A), strontium (B), fluorine (C) and uranium (D) of the Yeelirrie channel waters (values in ppb) The black areas indicate the distribution of the calcrete in the channel

il en est de même du strontium (310 à 3 400 ppb) et du fluor (350 à 2 350 ppb) (Figure 1)

l'uranium présente dans les eaux du chenal de Yeelirrie des teneurs élevées La teneur maximale mesurée est 375 ppb (Figure 1) Les teneurs en uranium supérieures à 30 ppb se localisent en amont de la structure barrage de Yeelirrie Il y a jusqu'à la Homestead concentration de cet élément dans les eaux vers le centre du chenal

À l'amont de la structure verrou, au niveau du calcrete, la nappe présente une maturation poussée La présence du verrou (remontée du socle?) contribue à ralentir l'écoulement phréatique et provoque l'installation d'une nappe sursaturée en sels dissous. Les eaux du calcrete et donc de cette nappe sursaturée en amont du verrou sont moins oxydantes que les eaux du chenal en bordure du calcrete Cette nappe peu oxydante va pouvoir mettre en solution le vanadium (IV) des préconcentrations vanadifères des alluvions En amont de la structure barrage, au contact de cette nappe et des eaux plus oxydantes arrivant dans le calcrete, va se produire un front d'oxydo-réduction qui induit le passage de l'état vanadium (IV) à vanadium (V) Parallèlement à l'oxydation et à l'apport du vanadium, les autres éléments nécessaires à la néoformation de la carnotite et à la dolomitisation K^+ , U^{6+} et Mg^{++} vont se concentrer par évapo-transpiration dans les eaux jusqu'au calcrete Par ailleurs, la pression partielle en CO_2 est minimale au niveau du gîte augmentant d'autant le champ de stabilité de la carnotite La dolomitisation partielle qui se produit provoque la diminution de l'activité de l'ion CO_3^{--} induisant ainsi la décomplexation des ions uranyles carbonates Toutes les conditions sont ainsi réunies pour la dolomitisation et l'installation de la minéralisation uranifère



Figure 2

Electron micrograph of an Ascomycete spore du Gelasinopora type de Yeelirrie. La longueur de la photo est presque 25 μm .

Electron micrograph of an Ascomycete spore of the Gelasinopora type from Yeelirrie. Length of picture is approximately 25 μm .

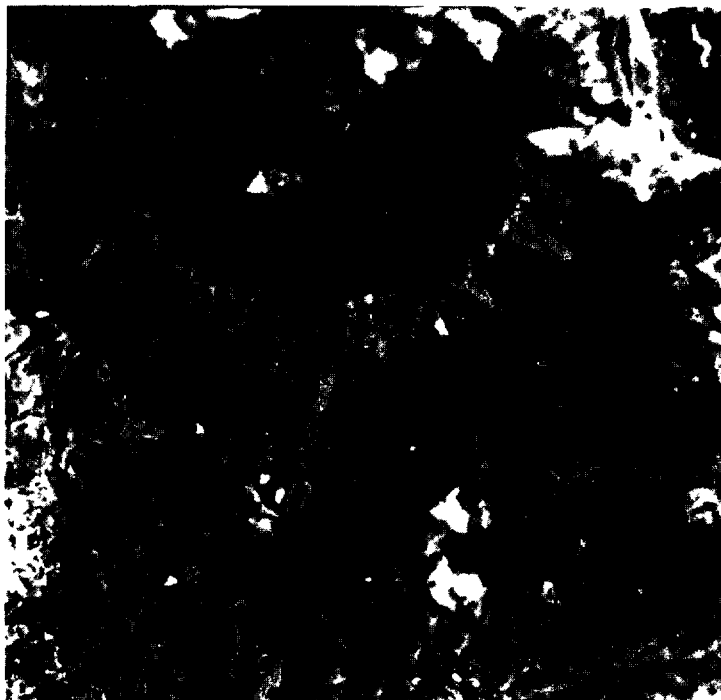


Figure 3

Electron micrograph d'une Ascomycete spore du Spherale type du Xylariaceae de Yeelirrie. La longueur de la photo est presque 1 000 μm .

Electron micrograph of an Ascomycete spore of the Spherale type of the Xylariaceae from Yeelirrie. Length of picture is approximately 1 000 μm .

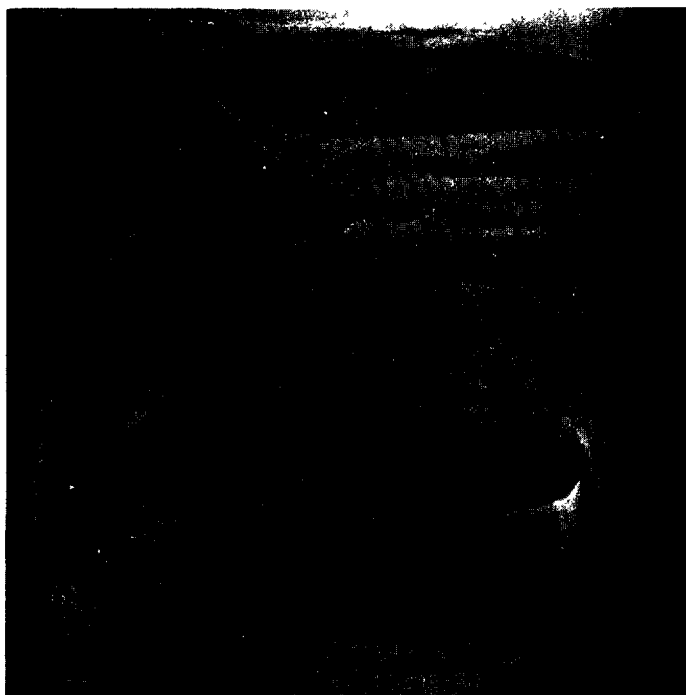


Figure 4

Electron micrograph d'une fissure contenant des sépiolite "colonnes". La longueur de la photo est presque 100 µm.

Electron micrograph of a fissure containing sepiolite "pillars". Length of picture is approximately 100 µm.

2.3 Histoire du Calcrete de Yeelirrie

L'étude à différents niveaux et à l'aide de différentes techniques analytiques du calcrete de Yeelirrie associée aux données de la littérature permettent de préciser les conditions de sa formation ainsi que le processus de mise en place de la minéralisation uranifère.

Il apparaît qu'avant 25 000 ans le climat était plus humide qu'actuellement. Le niveau des lacs et plus généralement celui des nappes phréatiques était plus élevé. Lors des saisons de pluies, les dépressions étaient inondées. La remontée du niveau des nappes et/ou les apports latéraux concourent à ce processus de mise en eau des bas-fonds avec dépôt calcite et simultanément prolifération de flore fongique dont les restes peuvent localement être les constituants essentiels de la roche [19,20]. Il semble que durant la saison humide le ruissellement transporte des matériaux d'origine organique (bois morts. . .). Pendant la saison humide et le début de la saison sèche, les champignons vont se développer sur ce substrat. Parallèlement, la précipitation chimique des carbonates commence. Puis avec l'augmentation de la sécheresse il se produit conjointement une diminution de l'activité mycologique (baisse du taux d'humidité, disparition progressive des supports organiques) et une augmentation de la néogénèse de la calcite avec accessoirement minéralisation et donc fossilisation d'une partie des organes fongiques (Figures 2 et 3). En même temps, la pédogénèse s'installe sur ces sédiments en voie d'assèchement. Une telle évolution tend à faire du calcrete de Yeelirrie une formation sédimentaire palustre. Elle est en contradiction avec l'hypothèse développée en particulier par Mann et Horwitz [8] qui considèrent les phénomènes de type pédologique et sédimentaire visibles macroscopiquement comme des remaniements superficiels actuels.

Il va y avoir ensuite progressivement (entre 25 000 et 18 000 ans) mise hors d'eau des carbonates ainsi déposés et installation d'une pédogénèse de type sol peu évolué non climatique d'apport alluvial hydromorphe hypercalcimorphe à fissurations courbes [21]. A ce stade sont associés : un phénomène de dolomitisation et la néogénèse de sépiolite. La sépiolite est le minéral argileux prépondérant dans le calcrete dolomitisé. C'est un minéral fréquent des milieux continentaux [22,23,24,25,26,27,28,29]. Localement se développent des structures de gonflement (swelling structures) avec augmentation de volume et brèchification des intercalations argileuses du calcrete palustre. A l'extérieur des structures gonflantes, les sépiolites sont sous forme de cutanes de vide, de nodules ou de masses filamenteuses entre les cristaux de carbonates. A proximité des structures gonflantes les sépiolites apparaissent perpendiculairement aux parois des vides, elles ont un aspect de piliers (observations au microscope optique (Figure 4)). L'examen au M.E.B. confirme l'importance de ce phénomène. Les cavités, le plus souvent des fissures, ont une configuration de galeries dont les parois sont reliées par des piliers dont l'aspect rappelle celui d'un matériau plastique après étirement. Aucune orientation préférentielle n'est observée dans la disposition spatiale des fissures et des piliers. De plus, la roche des structures gonflantes est très fracturée, les éléments ont de nombreuses faces lisses et luisantes. L'observation au M.E.B. des faces fait apparaître un enduit de fibres de sépiolite de petites tailles sans orientation préférentielle dans le plan.

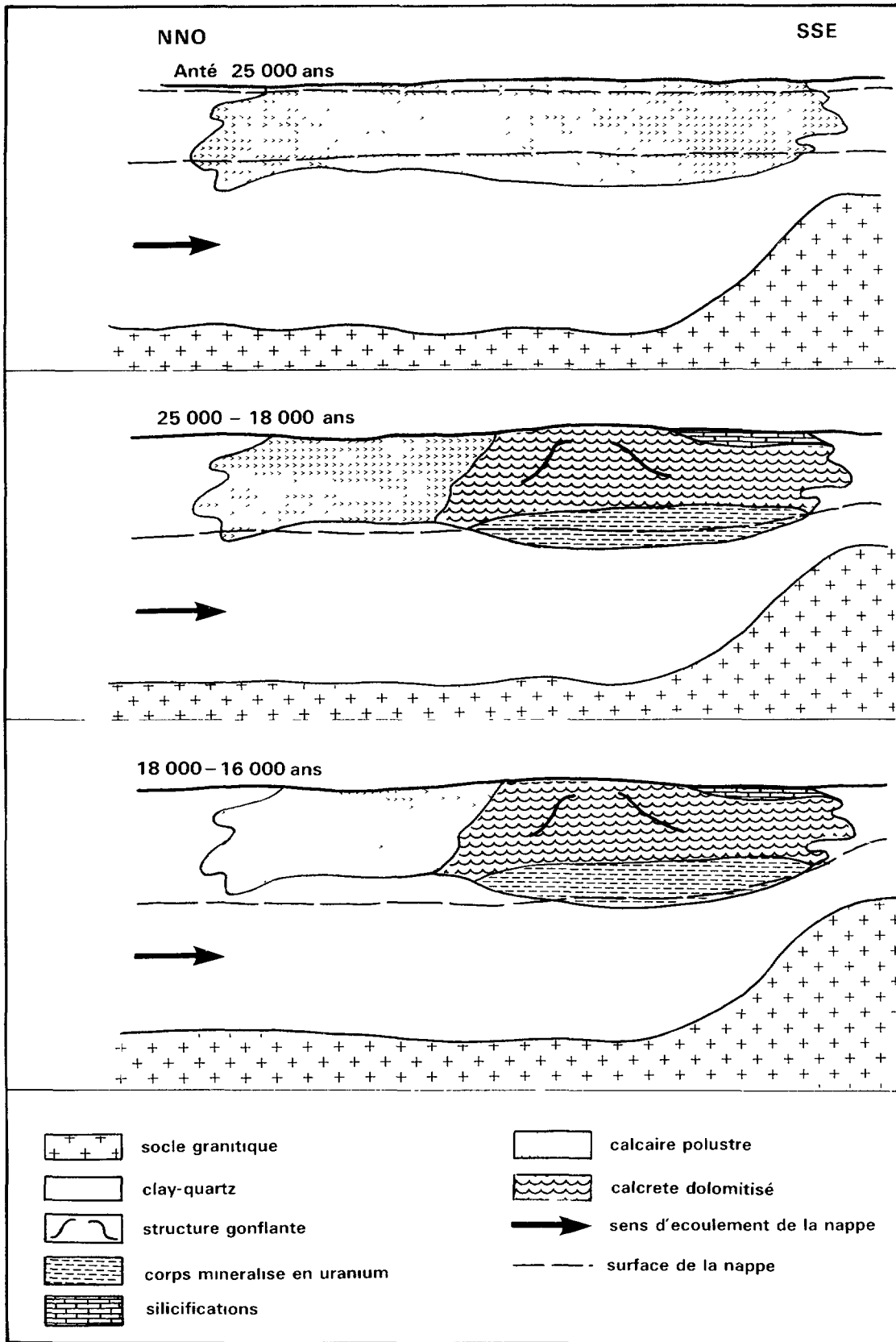


Figure 5

Coupes schématiques longitudinales du calcrete uranifère de Yeelirrie lors des principales phases de sa mise en place.

Schematic longitudinal section of the Yeelirrie uraniferous calcrete during the main stages of its formation.

Quel peut être le processus de formation de ces structures gonflantes? Lors de la dolomitisation du calcaire palustre originel il y a simultanément néogénèse et précipitation de sépiolite. Le calcrete est constitué d'un mélange de calcite et de dolomite, la calcite est pure ou légèrement magnésienne. Dans les structures gonflantes elle est pure. A l'échelle du calcrete, la dolomitisation est soit partielle soit totale. Dans les zones où elle est partielle, le mélange de carbonates est constitué de dolomite et de calcite magnésienne. Là où elle est totale, il y a simultanément précipitation des ions Ca^{++} libérés et le mélange est constitué de calcite stoechiométrique et de dolomite [19].

Le remplacement d'un cristal de calcite par un cristal de dolomite provoque une diminution de volume comprise entre 12 et 14 % [30,31,32], c'est à dire une augmentation de la porosité d'autant et la libération de la moitié des ions Ca^{++} présents dans la calcite originelle. La reprécipitation de ces ions sous forme de calcite produit alors une augmentation de volume. A partir d'un volume V initial, le volume de dolomite formée est égal à $0,86 V$ auquel s'ajoute $0,5 V$, volume de la calcite reprécipitée à partir de la totalité du Ca^{++} libéré. Dans ce volume égal à $1,36 V$, la calcite représente environ 37 % du mélange, la dolomite 63 %. Ces deux pourcentages correspondent à ceux trouvés à Yeelirrie dans les faciès poudreux et porcelanés.

Par contre, dans les structures gonflantes les analyses montrent l'existence d'un mélange à 70 % de calcite non magnésienne. Les structures gonflantes apparaissent comme des sites privilégiés dans lesquels outre le phénomène de reprécipitation sur place des ions Ca^{++} libérés se produisent des apports et des précipitations de Ca^{++} libérés dans d'autres zones. Le calcul de l'augmentation de volume liée à un mélange à 70 % de calcite pure fait apparaître un volume final de $2,86 V$ soit une augmentation de 186 % par rapport au volume initial.

Les structures gonflantes sont donc des sites privilégiés où les phénomènes de dolomitisation et de calcitisation dans un sédiment déjà induré provoquent des phénomènes de compaction et d'extension qui se traduisent par la disposition particulière des sépiolites en "piliers" et par une porosité élevée.

Dans la partie sommitale des calcretes, la présence de phénomènes de silicifications marque une aridification maximale entre 18 000 et 16 000 ans (Figure 5).

Enfin entre cette dernière phase et le présent, il y a stabilisation des conditions climatiques dans l'aride avec certaines fluctuations et conjointment dépôts de cutanes argileuses et carbonatées [19].

La mise en place et l'évolution du calcrete de Yeelirrie apparaît donc comme un phénomène polyphasé marqué par l'influence des variations climatiques et des changements de niveaux phréatiques connexes sur un matériel calcaire palustre originel.

3. DONNEES MORPHOLOGIQUES ET GEOCHIMIQUES SUR LES CALCRETES URANIFERES D'AUTRES REGIONS

Dans le cas de Yeelirrie, la minéralisation uranifère est le résultat de la succession de deux grands événements climatiques. Un climat aride succédant à un climat de type chaud et humide. Le climat aride permet la formation du calcrete et la mise en place définitive de la concentration uranifère, le climat chaud et humide permet quant à lui la libération de l'uranium lessivable.

Dans le cas des gisements africains étudiés en Mauritanie, en Namibie et en Somalie, le second événement climatique est celui qui est le moins bien connu actuellement.

En Namibie (région de la Rivière Tumas) et en Somalie (Province de Mudugh, région de Dusa Mareb – El Bur) (Figure 6), les dépôts carbonatés sont liés à des chenaux de drainage et sont en de nombreux points semblables à ceux de l'Ouest australien. Par contre en Mauritanie septentrionale (région de Aln Ben Tili) (Figure 6), les minéralisations sont en relation avec des cémentations carbonatées épigénétiques de formations détritiques : les hamadas. Mais le point essentiel commun aux occurrences africaines et australiennes est la filiation directe qui existe entre elles et les nappes phréatiques circulant en leur sein. Les eaux sont salines, chlorurées sodiques, légèrement alcalines et elles ont en général des teneurs élevées en uranium. La maturité de ces eaux est le fruit d'un mûrissement rapide sous un climat aride qui est encore un trait spécifique de la géographie physique de ces différentes régions.

Si en Mauritanie et en Somalie, la chronologie événementielle fine de la mise en place des minéralisations ne permet pas de la mettre en relation avec des oscillations climatiques, par contre en Namibie Wilkinson [33] a pu l'établir dans les sédiments de la rivière Tumas. Il propose la succession suivante : à une période d'humidification avec des précipitations de l'ordre de 250 à 400 mm/an succède une première phase de gypsification et le dépôt concomitant de la carnotite en relation avec une période d'aridification. Le creusement des vallées avec la mise en terrasses des calcretes et une deuxième phase de gypsification seraient liés à une période aride avec de violents orages sans nécessairement des précipitations annuelles importantes. Une telle concordance entre une climatologie fine et une chronologie événementielle rappelle celle mise en évidence à Yeelirrie. Elle souligne le rapport étroit entre la mise en place définitive d'un calcrete uranifère et les oscillations à l'intérieur d'un climat de type aride. Ainsi, même si les périodes de dépôts sont différentes : Holocène en Australie Occidentale, Quaternaire en Mauritanie pour le sommet des hamadas [25], fin Tertiaire pour la première génération de calcrete en Namibie [4,5] et Miocène à Quaternaire en Somalie [34], il semblerait que chaque phase du processus génétique soit en relation avec une oscillation à l'intérieur d'une climatologie de type aride.

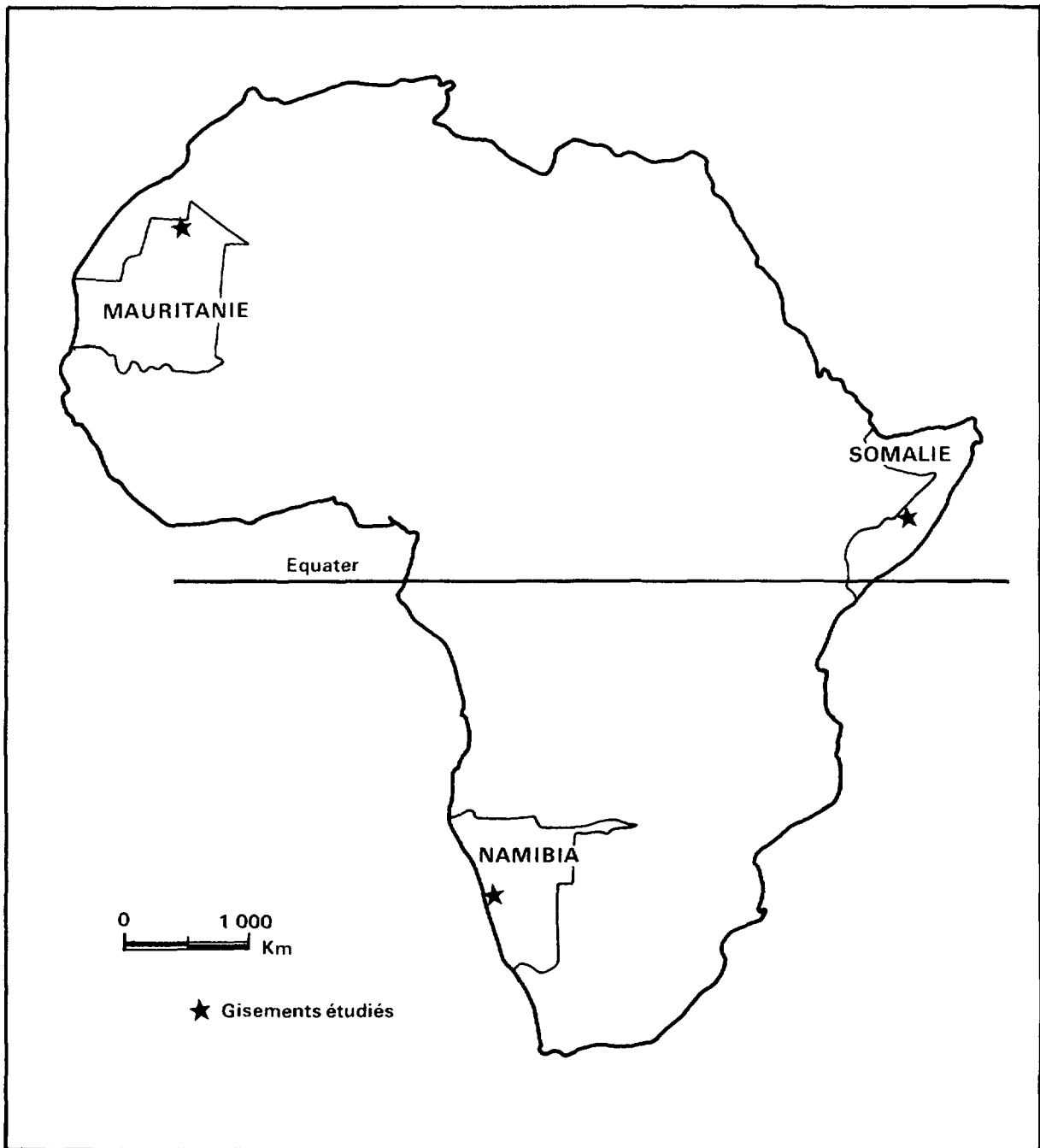


Figure 6
Localisation des gîtes uranifères de type calcrete étudiés en Afrique.
Localities of the calcrete uranium deposits described in Africa.

L'origine de l'uranium et son "histoire géochronologique" avant son arrivée dans les eaux des nappes et son piégeage sous un climat vraisemblablement chaud et aride sont les deux problèmes sur lesquels existe peu d'études et de documentations. Toutefois, il paraît acquis qu'en Mauritanie le socle stable (Dorsale Reguibat) légèrement anormalique est la source de l'uranium par l'intermédiaire d'un puissant manteau d'altération [25,20]. En Namibie la source de l'uranium est proche, il s'agit du socle altéré et légèrement anormalique du Damara Belt [4,33]. En Somalie par contre la source est inconnue et trois possibilités sont envisageables :

- .le socle éthiopien
- .des roches volcaniques
- .des remobilisations hydrothermales le long de failles Nord-Sud [34,35,36,37]. Cette imprécision est liée en partie au développement des calcretes non pas sur un socle cristallin stable mais sur une puissante couverture sédimentaire [34,35,36,37]. Dans ces trois pays, les altérites mises en évidence et/ou la présence de galets ferrugineux ou de galets à cutanes ferriargileuses dans les sédiments hôtes des calcretes semblent indiquer

l'existence de processus d'altérations continentaux proches de ceux qui se sont développés sur le bouclier Yilgarn en Australie Occidentale. Il n'est pas impossible de penser à une libération de l'uranium lessivable de ses sites originels sous climat chaud et humide et à son stockage. Puis par lessivage lors d'une rupture d'équilibre géochimique en liaison avec un changement climatique (aridification) à son arrivée dans la nappe phréatique.

4. CONCLUSION

Ainsi, il existe de grandes similitudes mais également des différences notables entre ces différentes minéralisations et leur processus de dépôt, de la source de l'uranium à son piégeage dans les calcretes? Mais tous ces gisements (Australie Occidentale, Mauritanie, Namibie, Somalie) ont semble-t-il comme points communs les grands contrôles paléoclimatologiques et paléomorphologiques qui les régissent. Contrôles paléoclimatologiques aussi bien dans la succession et le passage d'un climat chaud et humide à un climat aride que dans les oscillations climatiques à l'intérieur de cette dernière climatologie. Conditions climatiques qui vont d'une part permettre la libération de l'uranium lessivable de ses sites originels et son stockage, puis lors d'un changement climatique au lessivage de l'uranium et à son arrivée dans les eaux des nappes phréatiques, d'autre part permettre la mise en place des conditions hydrogéochimiques qui vont amener la précipitation de la carnotite. Contrôles paléomorphologiques qui sont moins bien définis en Afrique par manque d'information mais qui existent probablement. Contrôles aussi bien à l'échelle régionale (socle stable Australie Occidentale, Mauritanie, Namibie) qu'à l'échelle locale (structures verrous Australie Occidentale, Mauritanie, Namibie).

Contrôles paléoclimatologiques, paléomorphologiques et hydrogéochimiques qui deviennent des guides de prospection pour la recherche de gîtes uranifères de type calcrete. Guides d'autant plus importants que les gîtes d'uranium de type calcrete se caractérisent par des anomalies radiométriques faibles.

REFERENCES

- [1] WESTERN MINING CORPORATION LIMITED, A general account of the Yeelirrie uranium deposit, Prepared by the staff of Exploration Division (1975)
- [2] BUTT, C R M, HORWITZ, R C, MANN, A W, Uranium occurrences in calcrete and associated sediments, CSIRO, Miner Res Lab, Div Min, Report FP 16 (1977).
- [3] RYAN, G R, Uranium in Australia, In Jones, M D., (Ed) Geology, mining and extractive proceedings of uranium, Inst Min Met (1977) 24-42.
- [4] CARLISLE, D, MERIFIELD, P M, ORME, A R, KOHL, M S, KOLKER, O, The distribution of calcretes and gypcretes in southwestern United States and their uranium favourability based on a study of deposits in Western Australia and Namibia, US Dept of Energy Report GJBX-29(78) (1978) 274
- [5] CARLISLE, D, Possible variations on the calcrete-gypcrete uranium model, US Dept Energy, GJBX-53(80) (1980) 38
- [6] MANN, A W, DEUTSCHER R L, Hydrochemistry of a calcrete-containing aquifer near Lake Way, Western Australia, J Hydrol (1978) 357-377
- [7] MANN A W, DEUTSCHER R L, Genesis principles for the precipitation of carnotite in calcrete drainages in Western Australia Econ Geol (1978) 1 724-1 737
- [8] MANN, A W, HORWITZ, R C, Groundwater calcrete deposits in Australia some observations from Western Australia J Geol Soc Australia (1979) 293-303
- [9] DEUTSCHER, R L MANN, A W, BUTT, C R M, Model for calcrete uranium mineralization, J Geochem Explor (1980) 158-161
- [10] HEATH, A G, DEUTSCHER, R L, BUTT, C R M, Lake Austin uranium prospect, Murchinson Region, Western Australia, J Geochem Explor (1980) 347-349
- [11] DUCHAUFOUR, P, Processus de formation des sols Biochimie et géochimie, CRDP, Etud Rech, Nancy (1972)
- [12] COMMISSION DE PEDOLOGIE ET DE CARTOGRAPHIE DES SOLS, Classification des sols, Lab Péd -Géol, ENSA Grignon (1967)
- [13] HAMBLETON-JONES, B B, Theory and practice of geochemical prospecting for uranium, Miner Sci Engng, 10 3 (1978) 182-197
- [14] ROGERS, J J W, ADAMS, J A S, Uranium, In Wedepohl K H, (Ed) Handbook of Geochemistry, 2, Springer Verlag, Berlin (1969)
- [15] EULRY, M, VARGAS, J M, Les altérations ante-liasiques des Cévennes méridionales Leur rôle dans la métallogenèse des concentrations uranifères, Thèse 3^e cycle, INPL, ENSG, Nancy (1979)

- [16] MOKADDEM, M., Le bassin de Tin-Serrine et ses minéralisations uranifères (Hoggar, Algérie), Thèse 3^e cycle, Orsay (1980).
- [17] BOWLER, J.M., Aridity in Australia : age, origins and expression in aeolian landforms and sediments, *Earth Sci. Rev.* (1976) 279–310.
- [18] DALL'AGLIO, M., GRAGNANI, R., LOCARDI, E., Geochemical factors controlling the formation of the secondary minerals of uranium, In : *Formation of Uranium Ore Deposits*, IAEA, Vienna (1974) 33–48.
- [19] BRIOT, P., Géologie et géochimie des gisements d'uranium liés aux milieux pré-évaporitiques intra-continentaux : les calcretes uranifères, Thèse d'Etat, UPMC, Paris (1983).
- [20] BRIOT, P., LAROCHE, S., LOCQUIN, M., Rôle de champignons dans la genèse de certaines croûtes carbonatées. L'exemple des calcretes de l'Australie Occidentale et du calcrete uranifère de Yeelirrie, *Congr. Soc. Sav.*, Grenoble (1983).
- [21] BRIOT, P., Phénomènes de concentration de l'uranium dans les environnements évaporitiques intra-continentaux : les calcretes de l'Yilgarn australien. Essai de comparaison avec les calcretes de Mauritanie et de Namibie, Thèse 3^e cycle, Univ. Orsay (1978).
- [22] MILLOT, G., La géologie des argiles, Masson, Paris (1964).
- [23] VANDEN HEUVEL, R.C., The occurrence of sepiolite and attapulgite in the calcareous zone of a soil near Las Crices, New Mexico, *Clays and Clay Miner.* (1964) 193–207.
- [24] GOUDIE, A.S., On the definition of calcrete deposits, *Z. Geomorph.* (1972) 464–468.
- [25] BRAUN, R., Etude des hamadas de la dorsale Reguibat. Région de Aïn Ben Tili (Rép. Isl. Maur.), Rapport DEA, Univ. Marseille (1974).
- [26] REEVES, C.C., Caliche, Estacado Books (1976).
- [27] POST, J.L., Sepiolite deposits of the Las Vegas, Nevada Area, *Clays and Clay Miner.* (1978) 58–64
- [28] WATTS, N.L., Quaternary pedogenic calcretes from the Kalahari (southern Africa) : mineralogy, genesis and diagenesis, *Sediment.* (1980) 661–686.
- [29] HUTTON, J.T., DIXON, J.C., The chemistry and mineralogy of some South Australian calcretes and associated soft carbonates and their dolomitization, *Geol. Soc. Australia* (1981) 31–39.
- [30] LARSEN, G., CHILINGAR, G.V., *Diagenesis in sediments*, Elsevier, Amsterdam (1967).
- [31] BEALES, F.W., Diagenesis in pelleted limestones, In : Pray L.C., Murray R.C. (Ed.) *Dolomitization and Limestone Diagenesis*, **13** (1965) 49–70.
- [32] SCHMIDT, V., Facies, diagenesis and related reservoir properties in the gigas beds (upper Jurassic) northwestern Germany, In : Pray L.C., Murray, R.C. (Ed.) *Dolomitization and Limestone Diagenesis*, **13** (1965) 124–168.
- [33] WILKINSON, J., Preliminary report on aspects of the geomorphology of the lower Tumas River basin, South West Africa, Rapport inédit, Johannesburg (1975).
- [34] BARBIER, J., BAUBRON, J.C., BOSCH, B., BRIOT, P., JACOB, C., Données préliminaires sur les isotopes du soufre dans les calcretes uranifères : un cas dans la Province de Mudugh (Somalie), *C. R. Acad. Sci. Paris, D*, 290 (1980) 1 047–1 050.
- [35] CAMERON, J., The occurrence and mode of formation of the Mudugh uranium deposits in Somalia, Report IAEA, Vienna (1973).
- [36] CAMERON, J., The Alro Ghelle radioactive mineral occurrence in the Bur region of the Republic of Somalia : a brief summary of the principal features, In : *Uranium Exploration Geology*, IAEA, Vienna (1970) 169–175.
- [37] INT. URAN RES. PROJ., Rapport inédit, IAEA, Vienna (1976).

SURFICIAL URANIUM OCCURRENCES IN RELATION TO CLIMATE AND PHYSICAL SETTING

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ABSTRACT

SURFICIAL URANIUM OCCURRENCES IN RELATION TO CLIMATE AND PHYSICAL SETTING

Important surficial chemogenic uranium deposits develop within 1) calcretes, 2) simple evaporative environments and 3) bogs or similar organic environments ("young" uranium). Calcrete occurrences are the largest, most novel and most dependent upon extreme aridity and geomorphic stability. Economic calcrete deposits are nonpedogenic, resulting from near-surface groundwater transport and lateral concentration of uranium, vanadium, potassium, calcium, and magnesium rather than from ordinary soil-forming processes. Their genesis is essentially observable in Western Australia where carnotite-bearing nonpedogenic calcrete is currently forming under a unique aridic soil moisture regime and where major deposits have formed under similar climates during the last few thousand years. Rainfall is less than 250mm annually, only 1/12 to 1/20 of potential evaporation and concentrated almost entirely in episodic late summer storms. Outside this region, under less arid conditions, only pedogenic calcretes form and they do not contain economic uranium. In southern Africa, calcrete and gypcrete uranium deposits, although Late Tertiary (?) to Quaternary in age, are also nonpedogenic and appear to have formed under similar climatic constraints with local variations in geomorphology and calcrete morphology.

1. INTRODUCTION

This paper addresses regional controls which affect the world distribution of surficial chemogenic uranium deposits, with the emphasis on uraniferous and nonuraniferous calcrete. The major controlling factors are 1) climate, 2) geomorphology, including physiographic and climatic stability, and 3) provenance, i.e., the weathering terrane from which uranium and associated substances are derived. These apply to large areas: if climate, geomorphological development and provenance of a region are favourable for uraniferous calcrete deposits, for example, such occurrences are likely to be found in a wide range of valley, deltaic and lacustrine settings. The particular conditions likely to result in the ore are, of course, different for each of the major surficial uranium environments:

1. **The calcrete environment** (including dolocrete and gypcrete) is characterized by groundwater transport and shallow subsurface precipitation of uranium, vanadium and potassium in association with authigenic carbonate (sulphate) in an oxidizing and chemically complex regime. The ore mineral is carnotite. Introduced carbonate cement ranges from sparse to dominant and reworking of both ore and gangue minerals may be extensive. Economically, this environment may be the most productive of surficial chemogenic occurrences.
2. **Simple evaporative environments** are characteristic of open basins of accumulation or playas, less commonly springs, in arid regions and varied geomorphic settings. They are chemically diverse and yield hexavalent uranium minerals, often transient, along with other evaporative minerals. The mineralization is part of the original sediment rather than an introduced filling or replacement as in calcretes. Under some circumstances the concentrated brines themselves are of economic interest and by-product or co-product production from these may be more important than from the evaporite minerals.
3. **"Young" uranium environments; bogs, marshes, muskegs, swamps, and organic-rich playas.** These are predominantly organically controlled environments. Climate, elevation, physiography and provenance range widely [1,2]. Uranium concentration involves incompletely understood mechanisms of transport, adsorption, chelation, cation exchange, mineral precipitation and perhaps biological uptake. The chemical environment is most commonly, but not necessarily, reducing. Uranium concentrations are characteristically "young", i.e., strongly deficient in gamma-ray producing daughter products and are often mobile. Deposits tend to be small but commonly occur in groups. Of these categories, the calcrete uranium environment is probably the most novel and the most uniquely constrained, especially in the need for long-term stability of both climate and physiography. The remainder of this chapter is focused, therefore, on calcrete uranium.

2. URANIUM BEARING AND NON-URANIUM-BEARING CALCRETES

Calcretes (calcrete, dolocrete and gypcrete) consist of soil, alluvium, soft sediment or weathered bedrock variably cemented and replaced by authigenic carbonate or sulphate. They tend to evolve with time. In relatively early stages, the carbonate or sulphate occur as powdery, nodular or honeycomb-like masses. With maturity, laminar, hardpan, and massive calcretes may develop, the most advanced of which may resemble ordinary limestone [3,4,5]. The point at which incompletely calcified soil, sand, gravel or other regolith becomes calcrete is not clearly defined, nor is it critical here, since ore grade carnotite can occur in very weakly calcified or in highly indurated (or gypsiferous) varieties and in subjacent materials. Calcite and dolomite are by far the most common

A Genetic Classification of Calcretes and Their Uranium Favorability

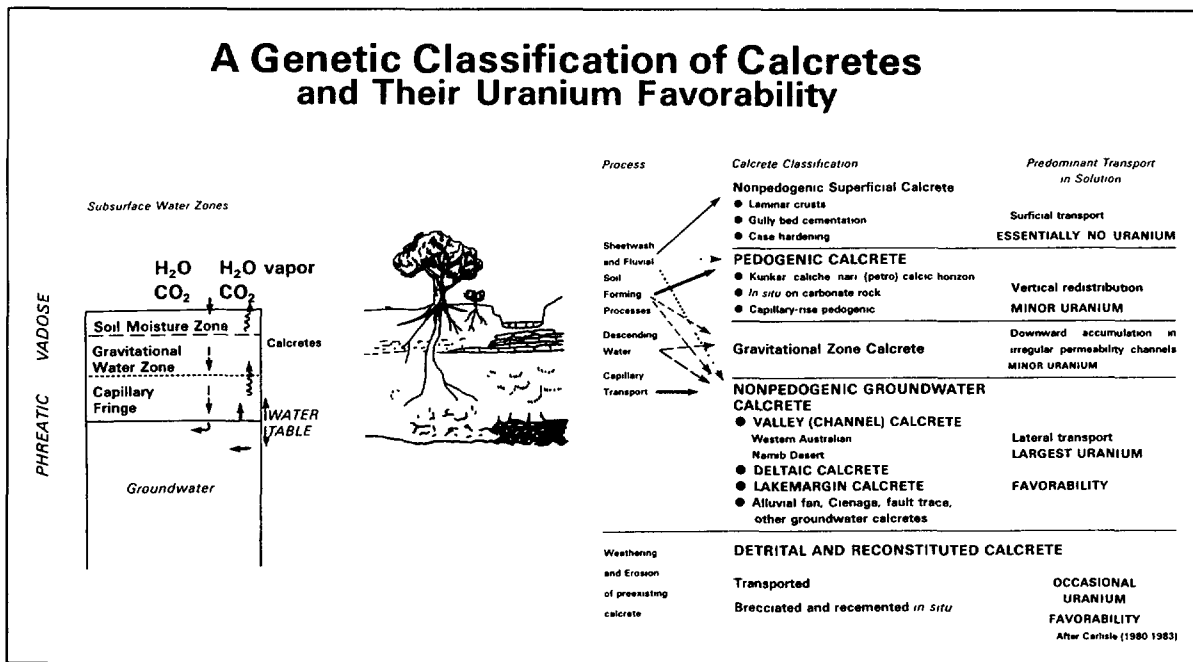


Figure 1

A genetic classification of calcretes and their uranium favourability based upon relations to subsurface water, depositional process and geomorphic setting. A given calcrete may result from multiple processes as suggested by the arrows but not all varieties form conjointly or under similar conditions [22]. (Reproduced by permission of the Geological Society of London.)

cementing materials. Gypsum is subordinate to absent except under special conditions such as on the margins of or downwind from salinas or as on the Namib Desert, where marine mists provide sulphate. Calcretes may be eroded and the transported fragments reconstituted into detrital calcrete.

The role of climate and other regional controls of calcrete uranium mineralization is tied to physical, chemical, and genetic differences between two major categories of calcrete (Figures 1 and 2). In calcrete uranium exploration, a critical distinction must be made between these:

1. Pedogenic calcrete, i.e., soil caliche, kunkar, crote calcaire, nari or caprock, which is generated in the soil moisture zone by ordinary soil-forming processes and is not favourable for uranium mineralization and,
2. Nonpedogenic = groundwater calcrete [4,6,7], i.e., "valley calcrete" or simply "calcrete" in earlier Australian terminology [8,9] is generated mainly near the water table from groundwater moving along extremely low gradients and which, under favourable circumstances, may contain recoverable uranium.

2.1 Distinguishing Characteristics

Pedogenic calcrete, then, is simply a calcic soil horizon or, if indurated, a "petrocalcic" horizon. It is typically only a few centimetres to a metre or two thick, and laterally extensive. Other things being equal, the thickness and maturity of a pedogenic calcrete are a function of the age and stability of the surface beneath which it forms. The calcrete in turn tends to reinforce the surface. Almost invariably, pedogenic calcretes display some sort of "calcrete soil profile" consisting, for example, of calcified soil perhaps overlain by a completely cemented (plugged) or hardpan horizon, and possibly by laminated or solution-brecciated calcrete or by more soil. Multiple or stacked pedogenic calcretes are common. The calcium, magnesium, carbonate, and trace elements are derived from adjacent soil or from the air and are merely redistributed vertically within the profile. Only if soils are unexpectedly rich in uranium or enriched from the air, from below, or by deep residual concentration, are pedogenic calcretes likely to reach ore grade. Though small-scale examples are known, the favourability of pedogenic calcretes as uranium ore, is very low to negligible [10].

Nonpedogenic groundwater calcretes, on the other hand, result from lateral transport of soluble ions toward favourable sites of deposition, making it possible for ores to develop by concentration of uranium from a large source area into a relatively compact calcrete body. The calcrete-free drainage catchment above the ore zone at Yeelirrie for example, is 3 000 km², which is 20 times the area occupied by calcrete and 1 000 times the area underlain by ore. Because water tables fluctuate and because flowing groundwater brings a continuing supply of constituents, such calcretes can be much thicker than a single pedogenic calcrete. In arid regions of low relief, concentrations of calcium, magnesium, uranium, vanadium, and potassium are increased down drainage by evaporation, but not that of dissolved CO₂. As groundwaters converge, typically along the axes of stable near-surface trunk drainages, or where they encounter bedrock constrictions, lower gradients, less permeable clays or

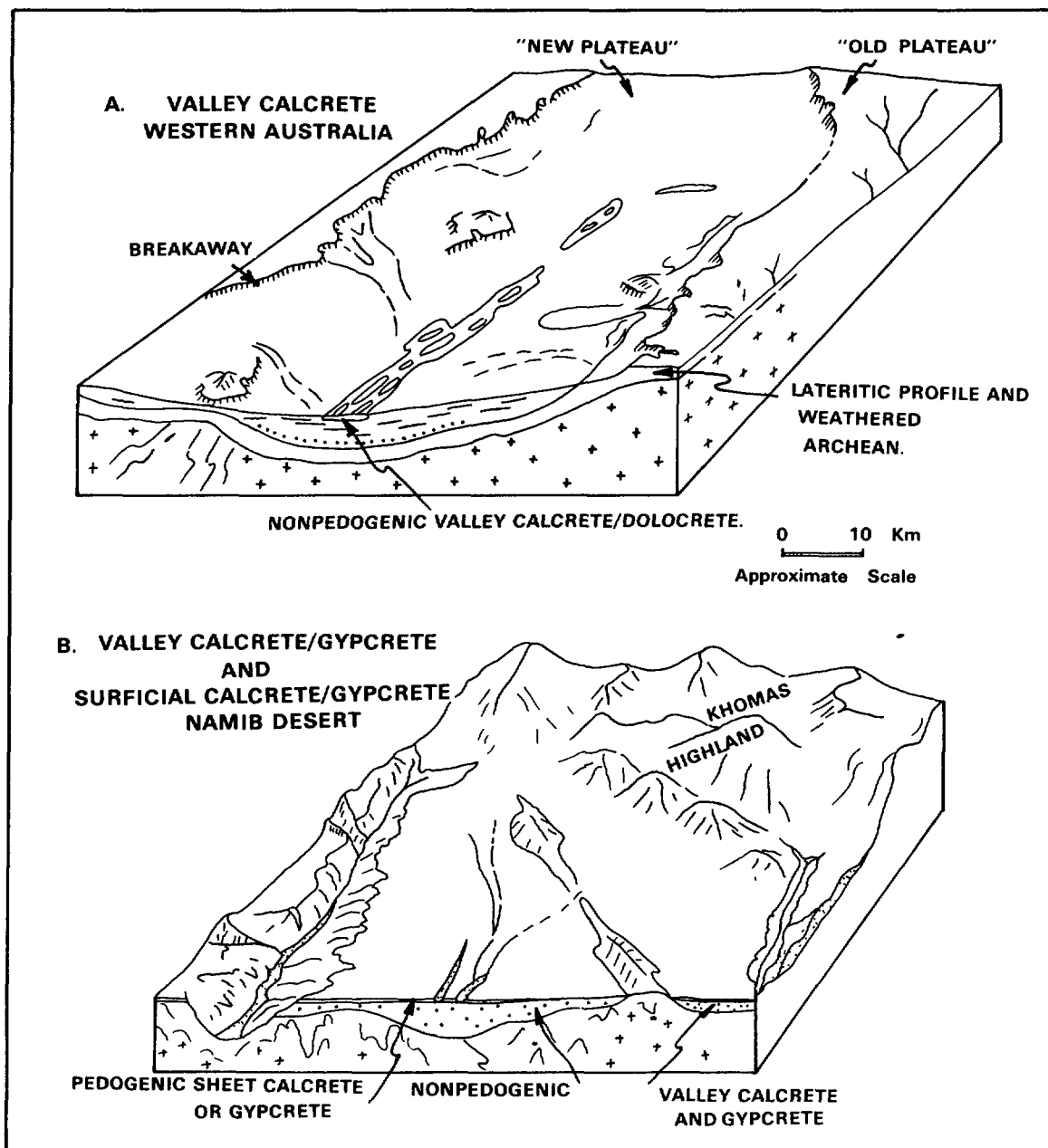


Figure 2

Valley calcrete morphology. a) valley calcrete, Western Australia. (b) valley calcrete/gypcrete and surficial calcrete/gypcrete, Namib Desert [22]. (Reproduced by permission of the Geological Society of London.)

dense hypersaline waters on the edge of evaporative basins, water tables tend to rise toward the surface, loss of CO_2 and H_2O is accelerated, and authigenic carbonate precipitates within the regolith. Carnotite may precipitate with it.

Groundwater calcretes are diagnostically free of any pedogenic soil profile or vertical sequence of pedogenic calcrete horizons unless modified by later pedogenic processes. They tend simply to preserve the original sedimentary structures and textures of the host materials or to develop new structures related to groundwater flow. Groundwater calcretes which develop within the phreatic zone or in relatively unweathered sands or gravels tend to contain clean sparry carbonate as opposed to the clayey, impure, and amorphous mixtures characteristic of pedogenic calcrete. Even in a clay-rich host, they do not contain a distinct horizon of clay accumulation. Groundwater calcrete generated in swampy or lake margin environments may develop primary sedimentary – not pedogenic – layering, however, and may contain organic structures perhaps of algal, bacterial or macrobiotic origin. This latter variety is in essence a transition toward fresh-water limestone.

On a large scale, groundwater calcretes may develop systematic changes in morphology and composition along their length, reflecting lateral flow in an evaporative regime. Thus in Western Australia, calcretes are part of an orderly sequence from silicified non-calcareous soils on the flanks of the valleys, to siliceous calcrete

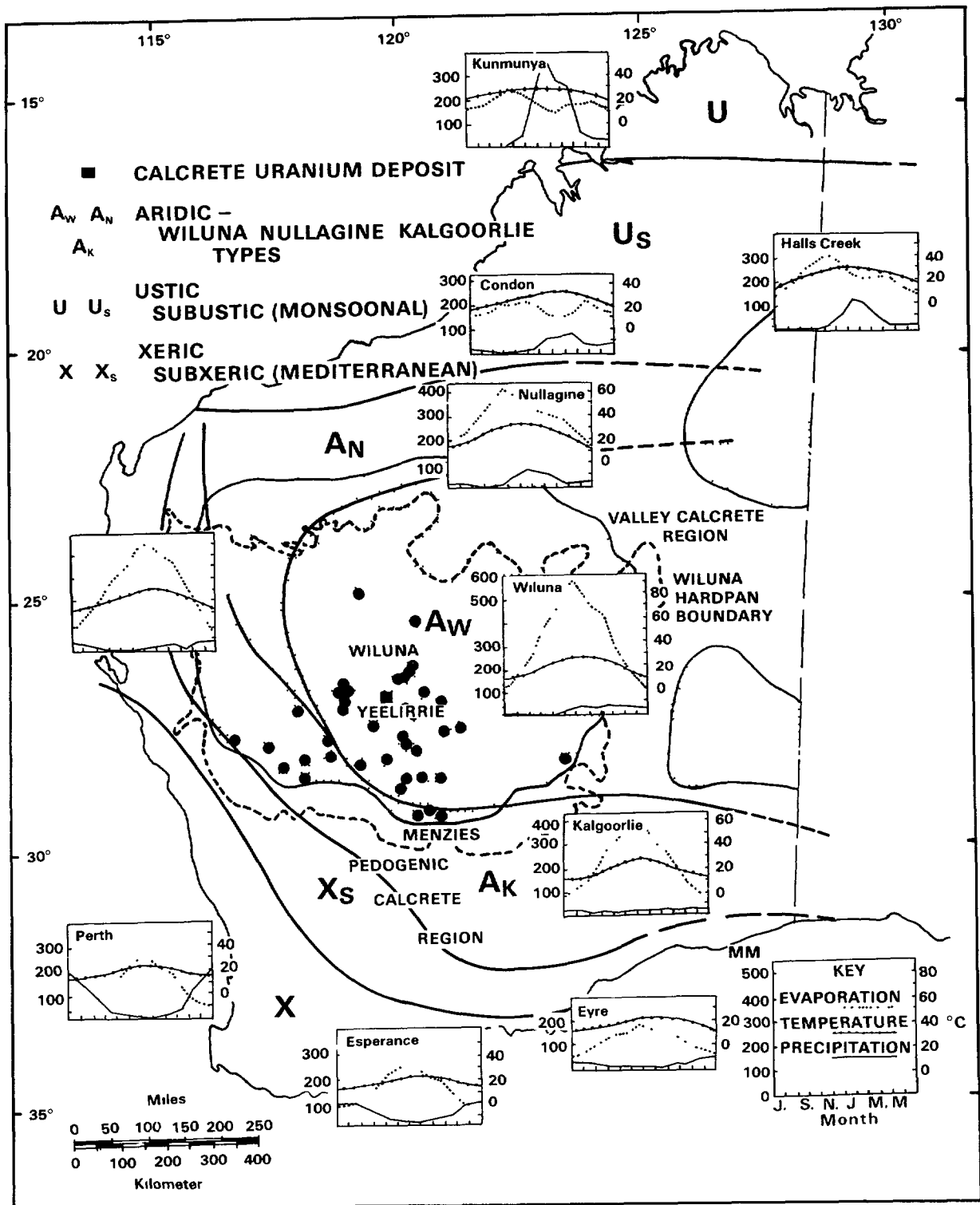


Figure 3

Valley calcrete, Wiluna Hardpan and soil moisture regimes of Western Australia inferred from climadiagrams. Nonpedogenic valley, deltaic and lake-margin calcrites, siliceous Wiluna Hardpan and Mulga-dominant plant community all fall within the tropical cyclone belt and predominantly within a specific aridic regime (A_w) characterized by erratic late summer storms. Boundaries of valley calcrete region and Wiluna Hardpan largely after Sanders [9] and Bettenay and Churchward [23] respectively. Climadiagrams assembled from data supplied by Australian Bureau of Meteorology [22]. (Reproduced by permission of the Geological Society of London.)

increasingly magnesian in the main channels, to lake-margin gypsum and finally the salt pan itself. The calcrete portion, up to hundreds of kilometres in length, several kilometres in width and tens of metres thick (Figure 2) commonly contains domal structures ("mounds") apparently developed around rising groundwater plumes. Valley calcrete usually terminates in a calcrete delta or lake-margin calcrete, and at Lake Matland [11], uraniferous groundwater calcrete appears to have formed within the main body of the playa itself.

Nevertheless, differentiating between groundwater and pedogenic calcretes at the local scale is not easy, and hand specimens of the two varieties may appear physically and chemically identical. Moreover, upper surfaces of exposed groundwater calcretes are usually modified by pedogenic processes including solution-brecciation and recementation. Groundwater calcretes may be overlain by younger pedogenic calcretes or, if the water table is very shallow, carbonate deposition from the capillary fringe or the phreatic zone may overlap pedogenic deposition in the soil moisture zone. On alluvial fans, pedogenesis may combine with lateral transport, producing hybrid calcretes. However, as discussed next, uraniferous groundwater calcretes tend to develop optimally under conditions which are much less favourable for pedogenic calcretes and vice versa.

3. THE UNIQUE DISTRIBUTION OF URANIFEROUS CALCRETE IN AUSTRALIA

On geological evidence [6] and by inference from isotopic studies [7, 12, 13, 14, 15] the well-exposed uraniferous calcretes of Western Australia are less than 700 000, perhaps less than 25 000 years in age. Some are forming and some are being reconstituted today. Their genesis is in essence directly observable.

With few exceptions, none of which have been shown to be economic, all of the important uranium occurrences are in nonpedogenic valley, deltaic and lacustrine calcrete and dolocrete in the most arid parts of Western Australia (Figure 3), the Northern Territory, and South Australia. They are inland from the active coastal streams of the Indian Ocean, south of the monsoonal rain belt and entirely north of the "Menzies Line", a curving boundary approximately along latitude 30 °S. Over sixty significant prospect areas have been found, all within an area of one-quarter million km² in the northern part of the Archaean Yilgarn Block. The main region of valley calcrete extends as far again to the north above proterozoic granitic, metavolcanic and metasedimentary rocks and even above Palaeozoic and Cretaceous sedimentary rocks but contains few prospects outside the Yilgarn Block. Yilgarn granites with uranium contents of from less than 2 to 25 ppm are apparently the main uranium source rock [16]. By contrast, Yilgarn source rocks are found and much the same geological and geomorphic history pertains to the area south of latitude 30 °S. But here there are only pedogenic calcretes and no significant uranium mineralization.

The uranium-bearing calcretes occupy minor portion of alluviated valleys on the "new plateau," which is a Cenozoic surface of extremely low relief within a pre-Tertiary deeply laterized surface of the "old plateau" (Figure 2) [17]. Drainage gradients range from roughly 1.5 % near the headwaters to as little as 0.02 % in the vicinity of, for example, the Yeelirrie orebody. The thickest and widest calcrete bodies tend to occur where bedrock morphology or some other feature has caused a decrease in gradient and where the groundwater table approaches the surface. They are entirely within the uppermost portion of the valley-fill, at Yeelirrie roughly the upper one-fifth. As suggested above, therefore, they postdate considerably the onset of arid alluviation some 2.5 Ma ago and perhaps may correspond with the major period of aridity beginning 25 000 years ago [18].

4. CLIMATE AND SOIL MOISTURE REGIME IN RELATION TO CALCRETE URANIUM MINERALIZATION IN AUSTRALIA

The contrast between regions with uraniferous nonpedogenic calcrete and those with nonuraniferous pedogenic calcrete is clearly reflected in the Soil Map of Australia. North of latitude 30 °S and over an area almost precisely congruent with that of the valley calcretes, the dominant soils within the new plateau, exclusive of the calcretes themselves, are noncalcareous earthy loams with a red-brown siliceous hardpan (see Wiluna Hardpan below and Figure 3, not to be confused with silcrete on the old plateau). None of these soils occur in the semi-arid region south of latitude 30 °S. Instead, one finds great areas of alkaline and calcareous red earths and grey-brown calcareous earths, many with visible pedogenic calcrete.

An almost exactly correlative and equally striking difference is shown by the dominance of the Mulga tree (*Acacia aneura*) in the plant communities of the north and of the Mallees, eucalyptus trees with a multi-stemmed growth habit, in the south. The Mallees are characteristic of drier areas with winter rainfall. Mulgas favour the more arid summer storm belt. These and other contrasts between climate and consequent soil moisture regimes north and south of latitude 30 °S are summarized in Table 1. Main climatic factors which influence soil moisture regimes and calcrete genesis are shown on Figures 4 and 5.

1. **Inferred Xeric (X, Xs)** – Characteristic of a Mediterranean climate where winters are moist and cool and summers are warm and dry. The moisture coming in winter when potential evaporation is at a minimum, is particularly effective for leaching.
2. **Inferred Aridic (Ak, Aw, An)** – Characteristic of an arid climate, less commonly semi-arid. The soils are hot and dry on average or never moist for long periods. Potential evaporation and temperature are usually high during rainy periods. Calcretes in general form predominantly in aridic regimes.

Table 1
Contrasts Between Uraniferous and Nonuraniferous Calcrete Regions,
Western Australia [6,22] (Reproduced by permission of the
Geological Society of London)

VALLEY CALCRETE REGION	GENERALLY SOUTH OF VALLEY CALCRETE
ANNUAL RAINFALL (P_a): 170–250 mm. Highly variable, episodic late summer thunderstorms sporadic tropical cyclones.	200–500+ mm. Predominantly winter rainfall from anti-cyclonic frontal rains or indefinite rain season.
ANNUAL POTENTIAL EVAPORATION (E_a): 3 300–4 200 mm	3 300 mm
RATIO E_a/P_a : 12–20	6–16
WATER BALANCE E_a-P_a : 3 000 mm	3 000 mm
TEMPERATURE; MEAN ANNUAL 19 °C	19 °C
SOIL MOISTURE REGIME: Strongly aridic and distinctive Moderate to severe drought incidence.	Aridic to Xeric. Moderate to low drought incidence.
SOILS: Acidic to earthy loams with siliceous Wiluna Hardpan. Calcareous on or near calcrete.	Alkaline calcareous earths common. Neutral, alkaline, to acidic in humid southwest.
VEGETATION: Mulga (<i>Acacia aneura</i>) dominant.	Mallee habit of eucalyptus dominant.
GROUNDWATER: Potable high on drainages, saline downdrainage	Extensively saline and nonpotable in wells or bores.

3. Inferred Ustic (U, Us) – In this case, characteristic of the monsoonal areas of the north where rainfall reaches a decided peak in the summer and is accompanied by a decline in evapotranspiration.

All of the major calcrete uranium occurrences are in region Aw, the subdivision characterized not only by the most extreme water deficiency but also by brief, intense, highly variable storms which occur during the summer and autumn while soil temperatures and evaporation rates are near their highest. It lies directly in the belt of highly erratic tropical storms and unlike the aridic Kalgoorlie region (Ak), it lacks year-round precipitation and frontal rains which would cause the soil moisture zone to become saturated for long periods. The boundary between Aw and Ak closely approximates latitude 30 °S

One more striking coincidence between the aridic region Aw and the region of uraniferous calcrete is the distribution of the siliceous Wiluna Hardpan (Figure 3). Wiluna Hardpan is an authigenic deposit consisting of soil, colluvium, and alluvium up to 15 m thick, variably cemented and replaced by opaline or chalcedonic silica. Part of the orderly but less conspicuous sequence mentioned earlier is just as characteristic of the valley calcrete region as in the calcrete itself and essentially contemporaneous with it. It is found universally beneath alluvial and sand plains of the new plateau down to valley axes where it may alternate with or give way to calcrete. Soils above the hardpan are porous earthy loams which are freely permeable and well drained. They are nonsaline, acidic, and low in organic matter and in base exchange capacity. In addition to the distribution shown on Figure 3, hardpan is also known to occur near the Western Australia – South Australia border in that area of nonpedogenic calcrete.

The writer suggests that siliceous hardpan, valley calcrete, and carnotite mineralization are related genetically to climate, including analogous climates of the last 25 000 years or more in Western Australia

North of latitude 30 °S, rain from the sporadic mid-summer and late-summer storms falls almost invariably on hot, dry surfaces. A large part of it evaporates directly or runs off initially as sheet flood. The bulk infiltrates deeply enough into open-textured earthy loams above the hardpan to be more or less protected from evaporation and loss of CO₂. The permeability of hardpan is apparently sufficient when wet to facilitate downward movement of the water, and the fact that soil temperatures decrease with depth in summer, results in downward transport of soil water vapour as well. In essence, a relatively small fraction of the storm rain remains in the soil moisture zone, where it is subject almost immediately to evapotranspiration. The soil does not remain wet for any long period, and there is very little opportunity for precipitation of pedogenic carbonate by CO₂ loss prior to evaporative

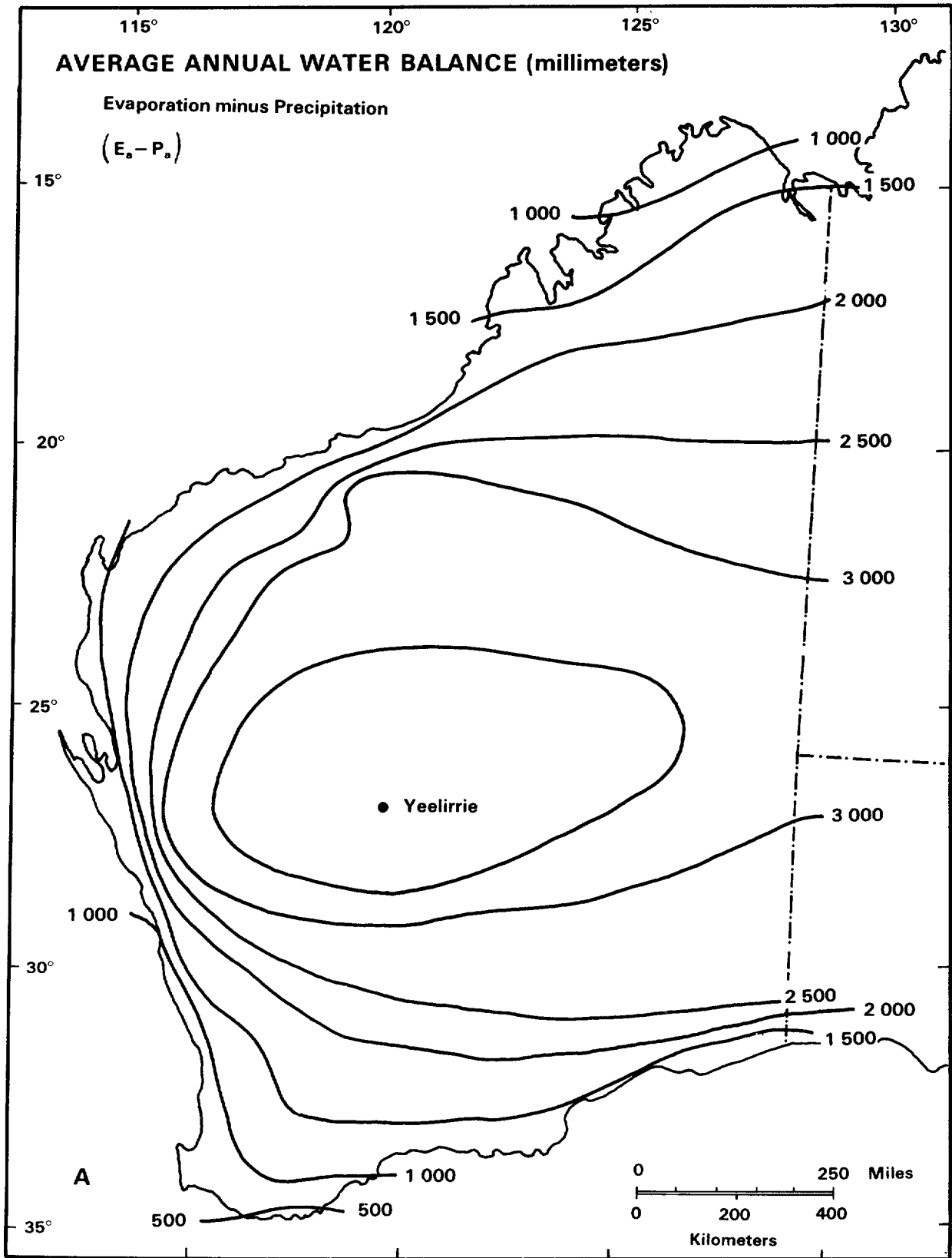


Figure 4
 Average annual water balance (evaporation minus precipitation, millimeters) for Western Australia [6].

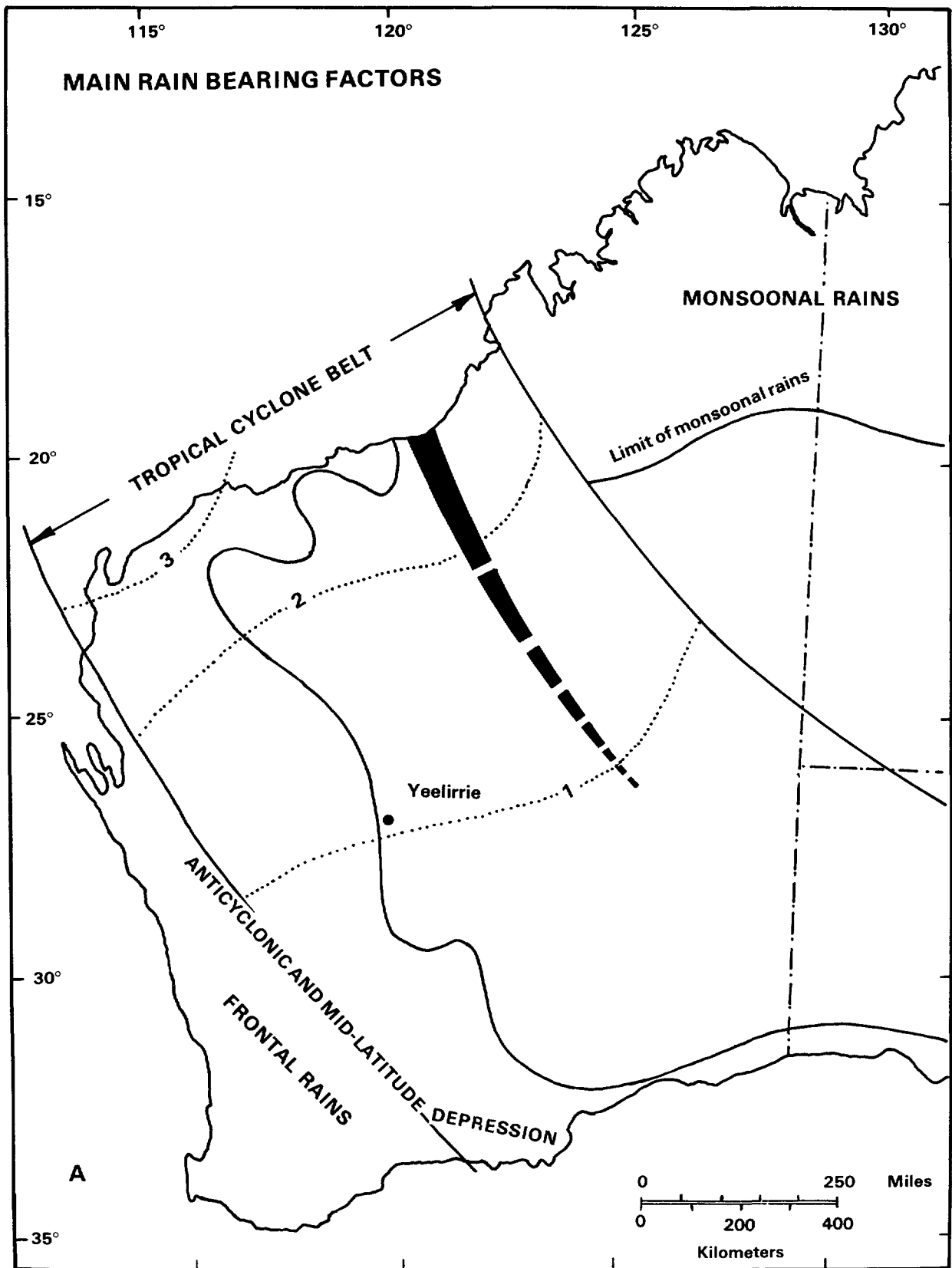


Figure 5
 Main rain factors for Western Australia. Monsoonal influence decreases to south and west. Frontal rains decreases southeasterly; thin broken wedge is axis of greatest frequency in March, isopleths show mean 10 year frequency in March [6].

precipitation of silica. Soil pH remains neutral to acid. The very minor amount of carbonate which is precipitated is dissolved away in the next storm, but the silica is not. Evaporative concentration of salines is minimal; the soils are nonsaline and nonalkaline. By the same token, there is very little tendency for carnotite to precipitate in soil horizons under such a soil moisture regime. The highly soluble uranyl ion in sulphate, phosphate, hydroxyl, neutral carbonate or, if pH rises, dicarbonate or tricarbonate complexes, is free to migrate with groundwater toward the calcreted valley axis.

South of the Menzies Line, quite to the contrary, moderate to large fractions of the rainfall occur during the winter, when evaporation rates and temperatures are comparatively low but adequate, nevertheless, to cause a buildup of calcium within the soil. Rains tend to be persistent, and the soil is wet or actually at field capacity over long periods. Even between rains, since surface temperatures are no higher than sub-soil temperatures, there is no tendency for water vapour to migrate downward, but rather upward in the direction of increasing soil moisture tension and decreasing P_{CO_2} . As a consequence, pedogenic calcium carbonate tends to precipitate directly in the soil. As it precipitates, soil moisture pH increases towards a theoretical maximum value of 9.9 for a de-aerated solution in contact with calcite. This in turn enhances the solubility of silica. With time, evapotranspiration becomes increasingly important and salinities rise, but silica saturation is not necessarily reached. With strong decication and appropriate amounts of vanadium, potassium, and uranium in the soil, minor amounts of carnotite may accumulate in the carbonate environment which will be sparsely disseminated and noneconomic.

5. CALCRETE AND GYPCRETE URANIUM MINERALIZATION IN SOUTHERN AFRICA IN RELATION TO SOURCE TERRANE GEOMORPHOLOGY AND CLIMATE

Three calcrete-gypcrete uranium areas have been extensively explored in southern Africa: 1) the Namib Desert in Namibia, 2) a region centered on Upington in South Africa and, 3) a small area near Beaufort West. All have arid to very arid climates very comparable to Western Australia, although in the Namib Desert this is complicated by marine mist.

In the Namib Desert, carnotite-bearing groundwater calcrete and lesser gypcrete occur within palaeochannels on the mid-Tertiary African Surface from the Atlantic coast to the foot of the Great Escarpment 100 km inland (Figure 2b). The calcretes, and probably the uranium mineralization as well, predate Quaternary gorge cutting.

The orebody at Langer Heinrich, in fact, is exposed only because of headward erosion of the rejuvenated Gawib River. Most occurrences are not thus exposed and the mineralization itself has developed on extremely broad low-gradient surfaces that remained stable for large portions of the Late Tertiary. A significant geomorphic difference from Western Australia is the Great Escarpment, rising steeply to the Khomas Highland immediately east of the calcreted Namib platform. The calcretes differ from Australian calcretes, in their Late Tertiary age, the abundance of coarse detrital fragments, the fact that carbonate is predominantly sparry calcite but with some dolomite [24] the presence of abundant gypsum in the upper parts of occurrences within 60 km of the Atlantic, and in the superposition of unmineralized pedogenic sheet calcrete and gypcrete. In the Langer Heinrich orebody, carnotite occurs in gravelly, sandy and silty facies and is not uncommonly richest where calcification is least.

Gypcrete, with the same kind of aggregate as the calcite, occurs directly above groundwater calcrete within the belt of habitual fog from the Atlantic Ocean. Thicknesses up to 25 m have been drilled in palaeochannels on the Tumas River where a potential orebody occurs beneath Holocene surficial gypcrete. The sulphate is derived largely from marine mist [19]. The uranium is probably derived in part at least from uraniferous calcrete updrainage and is reconcentrated as carnotite in a sparsely gypcreted sand facies adjacent to a palaeo-water table [10]. A ubiquitous overlying layer of surficial gypcrete or, inland from the fog limit, surficial calcrete, covers almost the entire Namib Desert. Carnotite is found only very rarely in this superficial gypcrete or calcrete, a consequence mainly of capillary rise from subjacent mineralization.

In spite of the differences and much greater difficulty in delineating valley calcretes and gypcreted in Namibia, numerous examples support the conclusions that lateral transport of uranium in groundwater is essential to ore deposition and that bedrock barriers or constrictions which narrow the channel of subsurface flow, and thus force the water closer to the evaporative surface, greatly favour formation of uraniferous calcretes. Source rocks are not hard to find: Proterozoic migmatites, pegmatites, alaskites, and granites abound, many appreciably anomalous in uranium. The unusually uraniferous alaskitic pegmatites and migmatic granites of the central metamorphic zone of the Damara Belt (e.g. Rossing, Valencia) are not directly updrainage from any well-known calcrete occurrences, however, and may not be uniquely significant as source rocks. As in Australia, vanadium is probably sufficiently abundant in the granitic source terrane to permit carnotite deposition, but certain of the schists in the Damara Belt are enriched in vanadium [19]. Within a given drainage, the ratio of catchment or source terrane to mineralized calcrete is of the same general order of magnitude as in Western Australia. Salt lakes are absent.

Do the climatic parameters separating uraniferous groundwater calcrete from non-uraniferous pedogenic calcrete in Western Australia apply in southern Africa? Is summer-only episodic rainfall and extreme aridity essential for calcrete uranium? If one compares the distribution of calcretes in southern Africa as recorded by Netterberg [20] with present-day climates and inferred soil moisture regimes [10] two points become clear:

1. The overall distribution of calcretes in general, but predominantly the pedogenic type, coincides with present-day aridic and subaridic soil moisture regimes.
2. Although the best developed pedogenic calcretes, including great stretches of "Kalahari Limestone", are in an area with a present climate almost identical with the valley calcrete region of Western Australia, they are in fact of Tertiary to Pleistocene age, recording a wetter climate than that of today. With rare exceptions attributable only to especially favourable circumstances, pedogenic calcretes are not forming in that climatic region today. Instead, throughout the Uppington region, for example, nonpedogenic calcretes of Pleistocene (?) to Holocene age are found in shallow valleys eroded into the older calcrete. In some of these, in constricted parts of the valleys, there are subeconomic concentrations of carnotite.

Although these nonpedogenic calcretes consist very largely of eroded and recemented fragments of older pedogenic calcrete, the climatic parameters for pedogenesis vs. nonpedogenesis would seem to apply.

The situation in the Namib Desert is complicated by the sulphate-bearing fogs which occur during three quarters of the year, and which at places account for about two-thirds of the total precipitation. Gypsum is at present crystallizing on the moist surfaces. Climates during the Late Tertiary, however, when uraniferous groundwater calcretes were being formed, were apparently arid to extremely arid and even then probably characterized by summer rains and dry winters [21]. In spite of a favourable climate, calcrete would not form and still does not form on the escarpment and the highlands because of the relief and rejuvenation. Instead, the groundwaters migrating into alluviated valleys on the gently sloping Namib platform retained abundant carbonate and have progressively calcified almost the entire valley-fill. Locally, carnotite has been precipitated apparently in essentially the same way as in Western Australia. Presumably, this process may have continued even as pedogenic calcrete may have been accumulating on the overlying desert surface, though this is by no means clear at this time. Reworking and the evaporative succession characteristic of Western Australia are apparently operative on the Namib Desert but distorted by topography and marine mist.

REFERENCES

- [1] CULBERT, R.R., BOYLE, D.R., LEVINSON, A.A., Surficial uranium deposits in Canada, this Volume.
- [2] OTTON, J.K., Surficial uranium deposits in the United States of America, this Volume.
- [3] GILE, L.H., PETERSON, F.F., GROSSMAN, R.B., Morphological and genetic sequences of carbonate accumulation in desert soils, *Soil Sci.*, **101** (1966) 347-360.
- [4] NETTERBERG, F., The interpretation of some basic calcrete types, *S.Afr. Archaeol. Bull.*, **24** (1969) 117-122.
- [5] GOUDIE, A., *Duricrusts in tropical and subtropical landscapes*, Oxford, Clarendon Press (1973) 174.
- [6] CARLISLE, D., MERIFIELD, P.M., ORME, A.R., KOHL, M.S., KOLKER, O., The distribution of calcretes and gypcrettes in southwestern United States and their uranium favourability based on a study of deposits in Western Australia and South West Africa (Namibia), US Dept. of Energy, Open-File Rpt. GJBX-29(78) (1978) 274.
- [7] MANN, A.W., HORWITZ, R.C., Groundwater calcrete deposits in Australia. Some observations from Western Australia, *J. Geol. Soc. Australia*, **26** (1979) 293-303.
- [8] SOFOULIS, J., The occurrence and hydrological significance of calcrete deposits in Western Australia, *Western Australia Geol. Surv. Ann. Report* (1963) 38-42.
- [9] SANDERS, C.C., Hydrology of a calcrete deposit on Paroo Station, Wiluna, and surrounding areas, *Western Australia Geol. Surv. Ann. Report* (1973) 15-26.
- [10] CARLISLE, D., Possible variations on the calcrete-gypcrete uranium model, US Dept. Energy, Open-file Report, GJBX 53(80), (1980) 38.
- [11] CAVANEY, R.J., Lake Maitland uranium deposit, this Volume.
- [12] LIVELY, R.S., HARMON, R.S., LEVINSON, A.A., BLAND, C.J., Disequilibrium in the uranium series in samples from Yeelirrie, Western Australia, *J. Geochem. Expl.* **12** (1979) 57-65.
- [13] DICKSON, B.L., FISHER, N.I., Radiometric disequilibrium analysis of the carnotite uranium deposit at Yeelirrie, Western Australia, *Proc. Aust. Inst. Min. Metall.*, No. 273 (1980) 13-19.
- [14] AIREY, P.L., ROMAN, D., Uranium series disequilibria in the sedimentary uranium deposit at Yeelirrie, Western Australia, *J. Geol. Soc. Aust.*, **28** (1981) 357-363.
- [15] DICKSON, B.L., Uranium series disequilibrium in the carnotite deposits of Western Australia, this Volume.
- [16] MANN, A.W., DEUTSCHER, R.L., Genesis principles for the precipitation of carnotite in calcrete drainages in Western Australia, *Econ. Geol.* **73** (1978) 1724-1737.

- [17] BUTT, C.R.M., MANN, A.W., HORWITZ, R.C., Regional setting, distribution and genesis of surficial uranium deposits in calcretes and associated sediments in Australia, this Volume.
- [18] BOWLER, J.N., Aridity in Australia. Age, origins and expression in aeolian landforms and sediments, *Earth Sci. Rev.* **12** (1976) 279–310.
- [19] HAMBLETON-JONES, B.B., The geology and geochemistry of some epigenetic uranium deposits near the Swakop River, South West Africa, University of Pretoria, D.Sc. Thesis Unpubl. (1976) 306.
- [20] NETTERBERG, F., Calcrete in road construction, *Nat. Inst. for Road Research, S. Afr., CSIR Bull.* **10**, Report 286 (1971) 73.
- [21] KORN H., MARTIN, H., The Pleistocene in South West Africa, In: Clark, J.D., (Ed.), *Proc. Third Pan-African Cong. On Prehistory*, London (1975).
- [22] CARLISLE, D., Concentration of uranium and vanadium in calcretes and gypcretes, In: Wilson, R.C.L., (Ed.), *Residual deposits: surface related weathering processes and materials*. Geol. Soc. London (1983) 258.
- [23] BETTENEY, E., CHURCHWARD, H.M., Morphology and stratigraphic relationships of the Wiluna Hardpan in arid Western Australia, *J. Geol. Soc. Aust.* **21** (1974) 73–80.
- [24] HAMBLETON-JONES, B.B., Surficial uranium deposits in Namibia, this Volume.

PETROLOGY, MINERALOGY AND GEOCHEMISTRY OF SURFICIAL URANIUM DEPOSITS

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ABSTRACT

PETROLOGY, MINERALOGY AND GEOCHEMISTRY OF SURFICIAL URANIUM DEPOSITS

A comprehensive understanding of the petrology, mineralogy, and geochemistry of surficial uranium ore deposits is important for developing prospecting and evaluation strategies. Carnotite is the main uranium mineral and is found in those deposits that have the greatest potential uranium resources. The following uranium-bearing minerals have been reported to occur in surficial deposits: carnotite, tyuyamunite, soddyite, weeksite, haiweeite, uranophane, betauranophane, metaankoleite, torbernite, autunite, phosphuranylite, schroeckingerite, Pb-V-U hydroxide (unnamed mineral), uraninite, and organourano complexes. The interrelationships between some of the minerals of the host rocks (especially the clays) are not well understood.

1. INTRODUCTION

A knowledge of the petrology, mineralogy and geochemistry of surficial uranium deposits is important in understanding their genesis, which in turn is essential to developing prospecting strategies. From the literature it appears that only a limited amount of information is available on paragenetic studies as well as the relationships between certain mineral assemblages, but on some deposits, such as Yeelirrie [1], more data is available.

A brief petrographic outline of the main types of surficial uranium deposits will be given, but for those deposits which are uneconomic, they will be referred to in the mineralogical section only because of their importance in recognizing potential uranium resources. This will be followed by a section giving a tentative mineralogical characterization of surficial uranium deposits.

2. PETROGRAPHY OF SURFICIAL URANIUM DEPOSITS

2.1 Calcrete or Valley-Fill and Lacustrine/Playa Deposits

The main petrographic characteristics of some surficial uranium deposits are given in Table 1 and a synthesis of the essential mineralogical compositions of mineralized calcretes from selected occurrences in Australia, Namibia, and Somalia is given in Table 2. It is clear that there are important mineralogical variations, especially between calcite, magnesium calcite, and dolomite on the one hand, and the nature and proportion of clay minerals on the other hand. It also appears that lithological controls are not as important as other factors such as porosity, geomorphology or geochemistry for controlling the distribution of the uranium mineralization. In general, calcretes are transitional downwards into alluvial clay-quartz units overlying lateritic profiles.

Carnotite is the main uranium mineral in calcrete deposits and can be distributed in one or more of the following ways:

- Isolated discontinuous sheets or lenses.
- Fine-grained disseminated material in calcrete nodules, in the more calcareous clays as fine crystallites (some tenths of microns in size).
- In fissures in calcite and dolomite.
- Coatings along cracks, bedding, and slippage planes on clays.
- Patches on clays.
- In interstices between sand grains.
- Narrow steeply dipping stringers in sands and calcareous material.
- Films on the walls of voids as euhedral to anhedral crystals.

2.2 Organic-Rich Deposits

Uranium concentrations have been discovered in peat, bogs, muskegs, marshes, beaver meadows, and organic sediments in small lakes and ponds in closed basins especially in glaciated terranes. Enrichments in uranium up to 3 000 ppm are known. Generally, no uranium minerals are found, but direct relationship with organic matter suggests possible formation of urano-organic complexes.

2.3 Evaporite Deposits

Kovalev [2] has described the formation of evaporitic uranium deposits by direct evaporation of surficial waters, with schroeckingerite as the main uranium mineral formed.

Table 1
Main Petrographic Host Rock Features of Mineralized Surficial Uranium Deposits Considered in this Handbook

Yeelirrie (Australia)	A valley-fill calcrete characterized by an intense dolomitization and development of sepiolite.
Lake Austin (Australia)	Calcrete (calcite and dolomite) with chalcedony in silicified zones overlying red-brown clays and/or weathered bedrock. A cover of sand or alluvium is locally present. Mineralization in sandy clays, carbonate-rich with a kaolinite/smectite matrix.
Lake Way (Australia)	Mainly in carbonated reworked fluvial-clastics, also in valley-fill calcrete and in the younger chemical delta carbonates.
Lake Raeside (Australia)	Red or brown calcareous clays and clayey grits.
Lake Maitland (Australia)	Essentially a discontinuous calcrete, rich in dolomite but mineralization also occurs in sand, pale and sandy clays and brown silts.
Hinkler Well (Australia)	An elongate valley calcrete consisting of calcite and chalcedony with dolomite, gypsum, and sepiolite. In chemical delta, dolomite and sepiolite are more important and aragonite is present.
Tubas (Namibia)	Fluviatile sediments constituted of poorly consolidated sand, sometimes gritty to pebbly bedded sand and gravel, presence of a gypcrete capping.
Langer Heinrich (Namibia)	Conglomerates, gravel, grit, and clay sediments deposited under flash-flood conditions in deep palaeochannels.
Brulkolk (South Africa)	Gypsiferous red sand and gravel with calcareous nodules or clay-rich alluvium with grit bands or beds and clay with calcareous nodules.
Abikwaskolk (South Africa)	Gypsiferous sand, silt, and shales.
Mudugh (Somalia)	Calcrete, marls, clays, and bentonite.
Kannikwa (South Africa)	Organic-rich diatomaceous earth between an upper calcified alluvial gravel and aeolian sand overlying gravel, sand, and clay lenses.
NE Washington E Idaho (USA)	Organic-rich uranium host sediments (plant debris, peat, marls, sand clay, and gravel, possibly air-fall or reworked air-fall ash.
Lost Creek (USA)	Subhorizontal tabular bodies of schroeckingerite in Eocene sandstone and siltstone and Quaternary sand and gravel.

2.4 Anomalies in Weathered Granites

In weathered granites, minor uranium enrichments in the form of uranium silicates and phosphates have been reported [3, 4] but the Slagintweit uranium deposit in Argentina is being mined [28].

2.5 Superficially Altered Sedimentary Phosphorites

In sedimentary phosphorites, enrichments of uranium between 50 to 400 ppm are known to occur. Fission track data have shown that the enrichments occurred during diagenesis [5]. Uranium is distributed homogeneously in apatite but U(IV) and U(VI) are present in variable proportions [6, 7]. For outcropping phosphorites, oxidation is enhanced and most of the uranium could be in the U(VI) state [8]. In superficially altered zones, uranium could be adsorbed onto apatite or occur as U(VI) minerals (torbernite, autunite, carnotite, tyuyamunite) in the form of coatings along cracks and small fissures. Aluminous phosphates such as crandallite, are generally richer in uranium than is apatite. The formation of pitchblende by deep weathering of phosphorites with subsequent reduction has been described by Glagolev [9].

3. URANIUM DISTRIBUTION IN SURFICIAL DEPOSITS

Detailed studies on the uranium distribution and especially on uranium-bearing minerals in surficial deposits are relatively few and are quite often of a very general nature. The studies have been based on macroscopic and microscopic observations and X-ray data but chemical analyses of these minerals are generally lacking. These problems are highlighted when one considers the fact that solid solutions could exist, for instance in the francevillite $[\text{Ba}(\text{VO}_4)(\text{UO}_2)_2 \cdot 6\text{H}_2\text{O}]$ and tyuyamunite $[\text{Ca}(\text{VO}_4)_2(\text{UO}_2)_2 \cdot 8\text{H}_2\text{O}]$ series in the St Pierre du Cantal deposit in France [10]. There is an absence of trace element data in U(VI) minerals, which is unfortunate because

Table 2
General Petrographic and Mineralogical Data on Uraniferous Calcretes

	Australia						Namibia			Somalia	GENERAL OBSERVATIONS
	Yeelirrie	Lake Austin	Lake Way	Lake Raeside	Lake Maitland	Hinkler Well	Tubas	Lake Heinrich	Tumas River	Mirigh	
Calcite	++	++	(+)	++		++	++			++	Calcite could be slightly magnesian Development of dolomite at the expense of calcite has been proven in Yeelirrie
Dolomite	++	++	++		++	++	++				
Gypsum		++	+	++	++	++	++	++	++		Quartz is often detrital
Quartz		+	++	++	++			++	++	++	
Chalcedony	++	++				++					Generally late in the mineralization process, could preserve carnotite from dissolution
Sepiolite	++					++				++	
Attapulgite		++								++	Important clays for understanding genesis of of the deposit, could be overlooked if no study of the clay fraction is undertaken
Smectite		(++)	++		++				++		
Smectite		++									Zonalities in clay distribution are general but few studies have made clear distinction between those which are really associated with the mineralization process and those which are contemporaneous with the formation and evolution of the calcrete
Illite		(+)	+						++		
Illite		(+)	+						++		
Kaolinite	++	+	++	++	++						
Halite		+	(+)	+					+		Detectable in the calcrete of the chemical delta
Aragonite			(+)			++					
Goethite		+	+								
Hematite							++	++			
Fluorite		+								+	F and Sr are often anomalous in these deposits
Celestite	+							+	+		
Feldspar		+	+	+					+		Always detrital

it is possible to distinguish between hexavalent minerals resulting from the oxidation of a previous U(IV) oxide and a hexavalent uranium mineral resulting from direct precipitation from solution. For example, in the Bois Noirs deposit [11], torbernite is especially rich in some elements such as copper, arsenic, and bismuth which are abundant in the primary sulphide minerals as chalcopyrite, lollingite and bismuthinite. In many descriptions, paragenetic relationships are, in general, lacking with the exception of a few cases such as Yeelirrie which has been thoroughly studied. It was pointed out by Carlisle et al [12] that the epigenetic nature of carnotite does not prove that carnotite and calcite are contemporaneous, as the mineralization has probably passed through one or more stages of dissolution and recrystallization.

Before proceeding with the description of the major uranium-bearing minerals in surficial deposits, some observations are presented concerning the nature of the association between uranium and other minerals, viz 1) association with organic matter, 2) adsorption on clays, 3) adsorption on Fe-Ti oxyhydroxides, and 4) adsorption or co-precipitation with silica.

- 1 In some surficial deposits and particularly in bogs and peats, the mineralogical expression of uranium is unknown, even for uranium concentrations up to 2 000 ppm. For the Canadian occurrences, uranium is loosely bonded to organic matter and clays but the type of bonding is totally unknown [13]. Relationships of uranium with organic matter are complex and several processes have been involved to explain this association. Organometallic compounds have been discovered in uranium deposits or showings [14, 15]. Recently, Nakashima et al [16] have demonstrated that fixation of uranyl species by lignite and subsequent reduction to uraninite can be brought about by an increase in temperature, but the initial fixation process takes place from oxidizing conditions before final reduction.
2. Investigations of the adsorption of uranyl species by clays have been conducted in recent years [17, 18]. The process seems effective and increases with the sequence kaolinite-illite-montmorillonite and the amount of uranium adsorbed is dependent upon the pH of the solution [18]

3. Adsorption of uranium on Fe-oxyhydroxides has been investigated by Michel [19] and Michel et al [20]. In the Saint Pierre du Cantal deposit in France there is a good correlation between iron and uranium as determined from chemical analyses. Michel [19] pointed out that this correlation is manifested by a bonding between phosphate ions and goethite particles in addition to adsorption by particles which have a high specific adsorption surface area defined by the zero point of charge (ZPC) [21]. The adsorption of uranium in lateritic profiles has also been described [20, 21]. In the Vosges area, accumulations of uranium occur in placic horizons of hydromorphic soils rich in lepidocrocite with the uranium probably adsorbed onto amorphous surfaces, and enrichment factors due to adsorption can be up to one hundred times greater than substitution in crystalline lattices [22].
4. Butt et al [23] suggested that some uranium could have been adsorbed or co-precipitated by silica in caprocks over the upper terrace calcretes in the Gascoyne Valley and in silica-rich pans at Nangarrong and Narloo in Australia. This silica is highly fluorescent.

The four uraniferous environments described above vary considerably in their economic viability, but are important from the point of view of target selection and prospecting methods. In surficial uranium deposits, the greater part of uranium is associated with U(VI) minerals and especially carnotite in the majority of cases, but U(IV) minerals are less abundant and occur in organic-rich environments. Among the most common uranium hexavalent minerals present in surficial deposits are the vanadates, silicates, and phosphates and those minerals mentioned in this volume are briefly described in the following sections.

3.1 Uranyl Vanadates

Carnotite [$K_2(VO_4)_2(VO_2)_2 \cdot 3H_2O$] is monoclinic and is the most frequently occurring U(VI) mineral in valley-fill and lacustrine/playa deposits. Mann and Deutscher [24] have noted that carnotite could vary in colour from bright canary yellow to a dark olive green. They interpret this variation to be the result of reduction of vanadium (V) to vanadium (IV). Carnotite is an epigenetic mineral and generally appears as fillings in voids and coatings on fracture surfaces. In the Langer Heinrich deposit in Namibia, carnotite has grown at the expense of calcite [12] and a second generation of calcite filling is covered with carnotite. In Yeelirrie, microcrystalline quartz coatings protect carnotite from subsequent dissolution [12] and the latest Raman microprobe data have shown that this is often the case. Some dissolution has, however, taken place as indicated by the occurrence of significant disequilibrium [24, 25].

Tyuyamunite [$Ca(UO_2)_2(VO_4)_2 \cdot 5-8H_2O$] is orthorhombic and is sometimes present in certain deposits, for example in the Yamarna occurrence in Australia [26]. Scarcity of tyuyamunite is explained as the result of its higher solubility than carnotite in mineralizing waters. Metatyuyamunite, in association with carnotite, is known in calcretes in Tanzania [27] and in surficial deposits in Argentina [28]. Accumulations of tyuyamunite in caves of karst terranes have been described in the Bighorn and Pryor Mountains of Montana and Wyoming [29, 30].

3.2 Uranyl Silicates

Soddyite [$(UO_2)_2(SiO_4) \cdot 5H_2O$] has been observed in the Welwitschia uranium occurrence in Namibia [31].

Weeksite [$K_2(UO_2)_2(Si_2O_5)_3 \cdot 4H_2O$] occurs in Tanzania in the Kusalalo River prospect in association with calcite, silica (opal-like material), detrital feldspar, and minor iron and manganese hydroxides [27]. It occurs as small yellow-greenish flakes which coat cavities in massive silica or as irregular bands replacing the fine-grained calcitic groundmass. Weeksite is also known in Afghanistan [32] in association with gypsum and calcite in polymictic Neogene sandstones and in the USSR [33] in carbonate concretions in Quaternary clays underlying gypsiferous clays.

Haiweeite [$Ca(UO_2)_2(Si_2O_5)_3 \cdot 5H_2O$], also called *ranquillite*, is very rare and has only been reported from an occurrence in the USSR in association with weeksite [33].

Uranophane [$Ca(UO_2)_2 Si_2O_7 \cdot 6H_2O$] is sometimes present as a minor uranium-bearing mineral in surficial deposits. **Beta-uranophane** is present in association with carnotite in Lake Hombolo in Tanzania [27].

3.3 Uranyl Phosphates

Metaankoleite [$K_2(UO_2)_2(PO_4)_2 \cdot 6H_2O$] or a related uranyl phosphate occurs in a playa near Menzies in Australia [23]. This mineral can be distinguished from carnotite by a brighter yellow colour and is highly fluorescent.

Torbernite [$Cu(UO_2)_2(PO_4)_2 \cdot 8-12H_2O$] and **autunite** [$Ca(UO_2)_2(PO_4)_2 \cdot 10-12H_2O$] have not been described in valley-fill and lacustrine/playa deposits, but they are major phases in altered phosphatic rocks such as in the Bakouma deposit [34]. They are late in the paragenesis, often geodic or fissural in occurrence and result from remobilisation of uranium from the primary apatite. Secondary crandallite can also occur. Sodian potassian hydroxonian meta-autunite occurs in the Boomerang Lake occurrence in Australia as disseminations in saline muds [35]. Its formula is $[Na_{0.56}K_{0.29}(H_3O)_{0.16}]UO_2 \cdot PO_4 \cdot 3.25H_2O$, and appears as bright greenish yellow micaceous crystallites.

Phosphuranylite [$Ca(UO_2)_3(PO_4)_2(OH)_2 \cdot 6H_2O$] is present in minor amounts in association with apatite in weathered metasediments, granite, and dolerite in the Mile 72 pedogenic uranium deposit in Namibia [4]. These minerals formed in situ and are alteration products of uraninite, betafite, monazite, and apatite. A similar

occurrence, in association with wecksite, has been reported from weathered granitoids in the Gascoyne Province of Australia [23].

3.4 Other uranium (VI) minerals

Schroekingerite $[\text{NaCa}_3(\text{UO}_2)\text{SO}_4(\text{CO}_3)_3\text{F}\cdot 10\text{H}_2\text{O}]$ is highly soluble and frequently occurs in association with gypsum and other members of the tri-carbonate-dioxyuranium (VI) group minerals. In the USSR, it occurs with uranophane, autunite, torbernite, and kasolite [2] and also occurs in Wyoming [30, 37]. An **unnamed Pb-V-U hydroxide** is present at various levels within the calcrete layer in the Mokobaesi No.1 prospect in Botswana [38] and is associated with manganese or carbon. It occurs as bright canary yellow aggregates in the calcrete matrix or as coatings on calcrete nodules.

3.5 Uranium (IV) minerals

Uraninite has been reported to be present in organic-rich diatomaceous earth and peat from some localities in South Africa [4], but chemical or X-ray data are lacking. Traces of reduced uranium occurring below carnotite mineralization is found in Lake Dundas [3]. Uraninite, associated with quartz, gypsum, halite, and an autunite phase, is present in muds from Boomerang Lake in Australia [35]. Electron diffraction data indicate that the uraninite has a cubic fluorite type cell, $[a = 5.46 \text{ \AA}]$.

The model presented by this geological situation is important from the point of view that potentially larger reduced uranium deposits could underlie oxidized surficial uranium concentrations.

4. A PROPOSED CLASSIFICATION OF URANIUM-BEARING MINERALS OCCURRING IN SURFICIAL URANIUM DEPOSITS

Table 3 is a summary of the proposed classification of uranium-bearing minerals occurring in surficial uranium deposits. Langmuir [40] has stressed that as autunite and uranophane are at least one hundred times more soluble than carnotite and tyuyamunite, they will be present only in vanadium-deficient environments. The fact that the solubilities of carnotite and tyuyamunite are very low in the pH range 5-8.5 explains the predominance of vanadate minerals in calcrete deposits.

Experimental thermodynamic data have shown that schroekingerite and gypsum are commonly associated, which explains the former's occurrence in evaporative environments [41].

5. ASSOCIATED MINERALS AND GEOCHEMICAL ANOMALIES

Several minerals are often associated with uranium-bearing minerals in valley-fill and lacustrine/playa deposits. Amongst the most common accessory minerals are celestite, fluorite, and barite. Celestite (SrSO_4) is often present as it has been observed in Yeelirrie [42], Mauritania [43], Somalia [44], and calcrete horizons in Texas [30]. Its distribution is largely erratic and confined to specific parts of the deposit. This is reflected geochemically by very high strontium contents up to 6 % [12, 30]. Fluorite (CaF_2) has been observed in the Lake Austin prospect [43] and in Somalia [44]. Barite (BaSO_4) is thought to occur in the Yeelirrie deposit [24].

Molybdenum is sometimes present in supergene chemical precipitates [36]. In young uranium deposits [13, 30] molybdenum anomalies are systematic but their mineralogical associations are unknown at present. Some selenium anomalies are also possible. In recent bogs, marshes, and closed basin environments, there are positive correlations between uranium and copper, selenium, rare earths, arsenic, vanadium, and molybdenum, all of which show local enrichments [36].

Studies of clay minerals would be of great benefit for the understanding of and prospecting for surficial uranium deposits, but there are too little data to fully assess their potential use. For example, there are no maps and only a few profiles representing their distribution. Moreover, it seems that some clays are unimportant with respect to the distribution of uranium. In the case of Yeelirrie, a profile published by Western Mining Corp. [42] indicates that montmorillonite is important, whereas more recent studies have shown that sepiolite is a major clay mineral [1].

In valley-fill and lacustrine/playa deposits it appears that in mineralized samples, sepiolite is often present but occasionally attapulgite occurs. In the Mudugh deposit in Somalia, Barbier et al [44] have estimated that between 5 and 20 % of mineralized samples contain attapulgite and sepiolite. This is also the case of the Hammadas from Mauritania. In the Ain Ben Tili area [45] the clay mineral associations change within the sedimentary profile and from the bottom to the top are as follows: in the basal conglomerate, montmorillonite + illite; in the mid section, montmorillonite + attapulgite; and in the top calcareous cap, montmorillonite decreases and sepiolite appears. The association of sepiolite and attapulgite is in fact very common in all the calcrete deposits of the world [46]. Smectite has been found in several deposits (Table 1). Briot [43] described an interlayered illite/smectite clay and suggested that smectite resulted from the transformation of illite. Smectite and illite are also present in the Tumas River deposit of Namibia [43]. Kaolinite and illite are also often present in uranium occurrences, but their relationships to mineralized zones are not clear in some cases but in others they are the only clays present.

Table 3
A Proposed Classification of Uranium-Bearing Minerals
in Surficial Uranium Deposits

TYPE OF ENVIRONMENT	MAIN URANIUM SITES	OTHER MINERALS DESCRIBED	REMARKS
Anomalies in weathered granites in arid environments	Phosphuranylite Weeksite		Essentially silicates, phosphates, and vanadates
Valley-fill and lacustrine/playa deposits	Carnotite (Tyuyamunite)	Soddyite Metaankoleite (?) Pb.V.U hydroxide	Vanadates are essential
Silica cap rocks and pans	U-associated with silica (adsorption or coprecipitation)	Weeksite Uranophane	Same type of association in altered pre-existing U(IV) deposit in Chihuahua [39]
Superficially altered phosphorites	Carnotite Tyuyamunite Autunite Torbernite Crandallite U-adsorption on apatite		Essentially phosphate minerals, but vanadates are common
Organic-rich deposits (Peats and bogs)	Adsorption, Organo-metallic complexes, Uranium oxide, Generally uranium content increases as shown by the arrow		
Evaporites	Schroekingerite Uranophane	Autunite Torbernite Kasolite	Schroekingerite is unstable and easily leachable
Laterites	Adsorption on Fe-oxyhydroxides	Resistate minerals, e.g. zircon and monazite	

A short distance away from the deposits other clay mineral assemblages may exist, and Briot [43] noted that along the margins of Yeelirrie, the clay is composed of chlorites with traces of illite and talc.

In altered phosphorites, the clay mineral assemblage can be quite unique. For example, in the Bakouma uranium phosphate deposit in the Central African Republic, illite, kaolinite, montmorillonite, and chlorite are present. In the reduced zones, however, illite predominates whereas in the oxidized (possibly leached) zones, kaolinite is the major clay mineral.

6. CONCLUSION

Economically, carnotite is the most important uranium mineral in surficial uranium deposits. This is because of its very low solubility. The other uranium minerals in the surficial environments occur largely in uneconomic occurrences. Unfortunately, there is insufficient data available on the interactions between uranium in solution and host rock minerals (in particular clays) in order to fully understand the paragenesis of the ores.

REFERENCES

- [1] BRIOT, P., FUCHS, Y., *Processus de minéralisation uranifère des calcrétés: une hypothèse non-pédologique*, this Volume.
- [2] KOVALEV, A.A., *Les occurrences uranifères par évaporation dans les régions arides*, *Vestrik. Akad. Nauk.*, **3**, 204 (1962) 23–34.
- [3] BUTT, C.R.M., MANN, A.W., HORWITZ, R.C., *Regional setting, distribution and genesis of surficial uranium deposits in calcretes and associated sediments in Western Australia*, this Volume.
- [4] HAMBLETON-JONES, B.B., *Surficial uranium deposits in South Africa*, this Volume.
- [5] AVITAL, Y., STARINSKY, A., KOLODNY, Y., *Uranium geochemistry and fission-track mapping of phosphorites, Zefa Field, Israel*, *Econ. Geol.* **78** (1983) 121–131.
- [6] KOLODNY, Y., KAPLAN, I.R., *Uranium isotopes in seafloor phosphorites*, *Geochim. et Cosmochim. Acta*, **34** (1970) 3–24.
- [7] BURNETT, W.C., VEEH, H.H., *Uranium series disequilibrium studies in phosphorite nodules from the west coast to South America*, *Geochim. et Cosmochim. Acta*, **41** (1977) 755–764.
- [8] BURNETT, W.C., GOMBERG, D.N., *Uranium oxidation and probable subaerial weathering of phosphatized limestone from the Pourtales terrace*, *Sedimentology*, **24** (1977) 291–302.
- [9] GLAGOLEV, N.A., *Development features of a supergene zone on a uranium-phosphorous deposit*, *Inter. Geol. Rev.* **22**, 9 (1980) 1070–1076.
- [10] CARRE, J.L., *Les minéralisations uranifères des dépôts oligocènes de Saint Pierre (Cantal, France) dans leur cadre géologique régional et local*. Thèse INP Nancy, unpubl. (1979).
- [11] CUNEY, M., *Geologic environment, mineralogy and fluid inclusions of the Bois Noirs Limouzat vein, Forez, France*, *Econ. Geol.* **73** (1978) 1567–1610.
- [12] CARLISLE, D., MERIFIELD, P.M., ORME, R.R., KOHL, M.S., KOLKER, O., *The distribution of calcretes and gypcretes in southwestern United States and their uranium favourability based on a study of deposits in Western Australia and South West Africa (Namibia)*, *US Dept. of Energy, Open-File Report GJBX-29(78)* (1978) 274.
- [13] CULBERT, R.R., BOYLE, D.R., LEVINSON, A.A., *Surficial uranium deposits in Canada*, this Volume.
- [14] BACH, A., *Evolution dans les conditions d’affleurement de shales uranifères à matière organique (Bassin Permien de l’Aumance France)*, Thèse I.N.P. Nancy, unpubl. (1980) 100.
- [15] ROUZAUD, J.N., *Etude structurale de matières carbonées associées à des minéralisations uranifères*, Thèse Orléans, unpubl. (1979) 109.
- [16] NAKASHIMA, S., DISNAR, J.R., PERRUCHOT, A., *Etude expérimentale des mécanismes de concentration de l’uranium par une matière organique sédimentaire dans des conditions de diagenèse croissante, premiers résultats*, *C.R. Acad. Sc. Paris t. 296, Série II*, 1425–1428.
- [17] BOROVEC, K., *The adsorption of uranyl species by fine clay*, *Chem. Geol.* **32** (1981) 45–58.
- [18] GIBLIN, A.M., *The role of clay adsorption in genesis of uranium ores*, In: *Uranium in the Pine Creek Geosyncline*, IAEA Vienna (1980) 521-529.
- [19] MICHEL, D., *Modalités des liaisons fer-uranium: le cas des concentrations ferrifères de Saint Pierre du Cantal (Cantal, France)*, *C.R. Acad. Sc. Paris, t. 293 Série II* (1981) 209–214.
- [20] MICHEL, D., N’GANZI, C., SAMAMA, J.C., *L’adsorption: implications sur la prospection géochimique de l’uranium en milieu tropical*, In: *Symposium on Geochemical Prospecting*, IAEA, Vienna (1982), in press.
- [21] SAMAMA, J.C., *Uranium in lateritic terranes*, this Volume.
- [22] GUENIOT, B., GUILLET, B., SOUCHIER, B., *Fixations de l’uranium sur les surfaces d’oxyhydroxydes de fer (lepidocrocite) des horizons placiques de sols hydromorphes: exemple des stagnoglays des Vosges cristallines*, *C.R. Acad. Sc. Paris, t. 295, II* (1982) 31–36.
- [23] BUTT, C.R.M., HORWITZ, R.C., MANN, A.W., *Uranium occurrences in calcrete and associated sediments in Western Australia*, *Australia, CSIRO, Division of Mineralogy Report No. FP 16* (1977) 67.
- [24] MANN, A.W., DEUTSCHER, R.L. *Genesis principles for the precipitation of carnotite in calcrete drainages in Western Australia*, *Econ. Geol.* **73**, 8 (1978) 1724–1737.
- [25] HAMBLETON-JONES, B.B., ANDERSEN, N.J.B., *Natural and induced disequilibrium in surficial uranium deposits*, this Volume.

- [26] RYAN, G.R., Uranium in Australia, In: *Geology, Mining and Extractive Processing of Uranium* (1977).
- [27] BIANCONI, F., BORSHOFF, J., Surficial uranium deposits in the United Republic of Tanzania, this Volume.
- [28] RODRIGO, F., OLSEN, H., BELLUCO, A.E., Surficial uranium deposits in Argentina, this Volume.
- [29] BELL, K.G., Uranium in carbonate rocks, *US Geol. Surv. Prof. Paper 474-A* (1963) 29.
- [30] OTTON, J.K., Surficial uranium deposits in the United States of America, this Volume.
- [31] HAMBLETON-JONES, B.B., The geology and geochemistry of calcrete-gypcrete uranium deposits in duricrusts, of the Namib desert, South West Africa, *Econ. Geol.* **73** 8 (1978) 1407–1408.
- [32] YEREMENKO, G.K., ILNENOV, Y.S., AZINI, N.A., Finds of weeksite-group minerals in Afghanistan, *Doklady Akademii Nauk SSR* **273**, 5 (1977) 1191–1193.
- [33] CHERNIKOV, A.A., SIDORENKO, G.A., VALUYEVA, A.A., New data on uranyl minerals in the ursilite-weeksite group, *Int. Geol. Rev.* **20**, 11 (1978) 1347–1356.
- [34] MIAUTON, J.D., Bakouma-Genèse et gîtologie d'un gisement néoformé continental phosphato uranifère, Thèse INP Nancy (1980) 160.
- [35] BUTT, C.R.M., GRAHAM, J., Sodan potassian hydroxonian meta-autunite, first occurrence of an intermediate member of a predicted solid solution series, *Amer. Mineral.* **66** (1981) 1068–1072.
- [36] BOYLE, R.W., Geochemical prospecting for thorium and uranium deposits, *Developments in Economic Geology*, **16** (1982) 498.
- [37] SHERIDAN, D.M., MAXWELL, C.H., COLLIER, J.T., Geology of the Lost Creek schroeckingerite deposits, Sweetwater County, Wyoming, *US Geol. Surv. Bull.* **1087-J** (1961) 391–478.
- [38] MORTIMER, C., Surficial uranium deposits in Botswana, this Volume.
- [39] ANIEL, B., Les gisements d'uranium associés au volcanisme acide tertiaire de la Sierra de Peña Blanca (Chihuahua, Mexique), *Géol. Géochim. Uranium, Mém. Nancy*, **2** (1983) 291.
- [40] LANGMUIR, D., Uranium solution mineral equilibria at low temperatures with applications to sedimentary ore deposits, *Geochim. et Cosmochim. Acta*, **42** (1978) 547–569.
- [41] O'BRIEN, T.J., WILLIAMS, P.A., The aqueous chemistry of uranium minerals – Part 4, Schroeckingerite, grimselite, and related alkali uranyl carbonates, *Mineral. Mag.* **47** (1981) 69–73.
- [42] WESTERN MINING CORP., A general account of the Yeelirrie uranium deposits. Privately published and distributed to 25th Intern. Geol. Cong. tours, Sydney, Australia (1975) 14.
- [43] BRIOT, P., Phénomènes de concentration de l'uranium dans les environnements évaporitiques intercontinentaux: les calcrètes de l'Ylgarn Australien. Essai de comparaison avec les calcrètes de Mauritanie et de Namibie, Thèse Orsay (1978) 167.
- [44] BARBIER, J., BAUBRON, J.C., BOSCH, B., BRIOT, P., JACOB, C., Données préliminaires sur les isotopes du soufre dans les calcrètes uranifères, un exemple dans la Province de Mudugh (Somalie), *C.R. Acad. Sci. (Paris)*, **D**, 290 (1980) 1047–1050.
- [45] BRAUN, R., Etude des hamadas de la dorsale Reguibat Région d'Ain Ben Tili (Rep. Mauritanie) Rapport DEA Faculté St Jérôme-Marseille (1974) 67.
- [46] GOUDIE, A., The chemistry of world calcrete deposits, *J. Geol.* **80** (1972) 449–463.

THE GENESIS OF SURFICIAL URANIUM DEPOSITS

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ABSTRACT

THE GENESIS OF SURFICIAL URANIUM DEPOSITS

Surficial uranium deposits can form in such diverse environments as calcareous-dolomitic-gypsiferous fluvial and aeolian valley sediments in hot arid and semi-arid regions, oxidizing and reducing alkaline and saline playas, highly organic and/or clay-rich wetland areas, calcareous regoliths in arid terranes, laterites, lake sediments, and highly fractured zones in igneous and metamorphic basement complexes. Formation of ore is governed by the interrelationships between source of ore-forming elements, mechanisms of migration, environment of deposition, climate, preservation, tectonic history and structural framework. The principal factors controlling mobilization of ore-forming elements from source to site of deposition are the availability of elements in source rocks, presence of complexing agents, climate, nature of source rock regolith and structure of source rock terrane. The major processes governing precipitation of uranium in the surficial environment are reduction mechanisms, sorption processes, dissociation of uranyl complexes, change in redox states of ore-forming constituents, evaporation of surface and groundwaters, change in partial pressure of dissolved carbon dioxide, changes in pH, colloidal precipitation, and mixing of two or more surface and groundwaters. One or a number of these processes may be actively involved in ore formation.

1. INTRODUCTION

The discovery of Yeelirrie (Western Australia) and a number of other similar surficial uranium deposits in the early 1970's awakened many exploration geologists to the fact that economic concentrations of uranium, remote from primary mineralization, can form in oxidizing environments within a relatively short period of time. Considering the number of intensive periods of uranium exploration since the early 1950's, it is somewhat remarkable that practically all uranium deposits classed as surficial have only recently been discovered, an obvious indication of how much more research on uranium ore genesis is still required.

The present work is a "state of the art" explanation of processes giving rise to anomalous accumulations of uranium in the surficial environment. The surficial environment is considered here only in the context of continental chemical weathering. Placer and other physical accumulations of uranium-bearing minerals are not considered, the emphasis being on chemogenic concentrations of the element.

Surficial uranium deposits occur in a variety of environmental settings within all recognizable climatic zones. They may occur in:

1. calcareous-dolomitic-gypsiferous fluvial or aeolian valley sediments in hot arid and semi-arid environments (calcrete-gypcrete carnotite deposits);
2. certain oxidizing and reducing (cienagas, anoxic lakes) alkaline and saline playas (also called salars, pans, sabkhas, takyrs, gas, kavirs);
3. highly organic and/or clay-rich wetland environments such as peat bogs, flood plains, swamps, dambos, marshes, and cienagas;
4. calcareous regoliths in arid and semi-arid regions;
5. halite-cemented fluvial sediments in arid terranes;
6. lateritic (ferralitic) environments;
7. organic-rich diatomaceous earth deposits;
8. lake bottom sediments; and
9. highly fractured zones in igneous and metamorphic basement complexes (both sulphide and nonsulphide-bearing).

In essence, they can occur in practically any type of surficial environment provided: (a) there is an adequate source of ore-forming elements; (b) the climate is conducive to uranium mobilization and precipitation; (c) host sediment compositions promote precipitation of the element, and (d) the host sediments, basins and fracture zones in which ore may form are in (1) a zone of lateral groundwater movement or discharge (as opposed to recharge), (2) a zone characterized by a fluctuating groundwater table, or (3) a region having internal drainage.

Detailed descriptions of the various types of surficial uranium deposits can be found in the papers of this volume. The reader should familiarize himself with their general characteristics since limitations of space dictate that these can only be referred to briefly in this article.

A successful genetic interpretation of the formation of surficial uranium deposits is dependent on a sound understanding of the interrelationships between the source of ore-forming elements, mechanisms of migration, environment of deposition, climate, preservation, tectonic history and structural framework. Unfortunately, many of these factors are poorly understood. It is, however, under these headings that the following genetic description is structured, since it provides an opportunity to indicate within each of the various important sections where research is required.

2. SOURCE OF ORE-FORMING ELEMENTS

Examination by the reader of authors' comments in this volume and elsewhere in the literature on the source of ore-forming elements (mainly uranium) to form surficial uranium deposits emphasizes the fact that this subject is generally treated in a cursory manner. Many descriptions simply state that the deposit is located on or adjacent to rocks with high radioactivity or high uranium content. But what percentage of this uranium is or has been labile? Reported total uranium values for source rock areas vary from as low as 2 ppm to as high as 50 ppm [1, 2, 3]. Clearly total uranium contents of source rocks cannot be a viable parameter to incorporate in a genetic model. A more appropriate approach might be the recognition of mass uranium loss under given climatic conditions [4, 5] or the recognition of "fertile" groundwaters within a source terrane which are capable of forming a deposit under a particular set of environmental and geological conditions [3, 6]. Very little research has been carried out relating rock composition, structure, tectonic history, hydrology and groundwater chemistry of source rock areas to the formation of surficial uranium deposits (see [3] for a description of this approach to basal-type uranium deposits). Rigid guidelines cannot be set since, if all other conditions of formation are optimal, a source with low fertile characteristics may be adequate. General guidelines, however, should be possible with more detailed research. At present, the only general statement that can be made concerning source rocks and the occurrence of surficial uranium deposits is that, with few exceptions [19], these deposits occur on or immediately adjacent to igneous or metamorphic massifs composed of one or a number of granite, monzonite, and alaskite bodies with lesser amounts of granodiorite, gneiss, metasediments and greenstone. These massifs, varying in age from Archaean (e.g. Yilgarn Block, Australia) to late Mesozoic (e.g. North American Cordillera batholiths), have generally undergone one or more periods of uplift prior to ore deposition making them more susceptible to groundwater leaching.

3. PHYSICAL CONTROLS ON ORE FORMATION

Morphology plays a dominant role in the localization of surficial accumulations of uranium. Three main types of morphology are conducive to the formation of surficial uranium deposits, namely (a) closed or partially closed basins into which surface and groundwaters are discharged after traversing a source area (e.g. playas, alkaline lakes, deltas, bogs, swamps); (b) linear depressions characterized by lateral groundwater movement (e.g. recent and ancient fluvial drainage systems), and (c) zones within source rock areas characterized by vertical groundwater movement and water table fluctuations (e.g. fault, fracture and stockwork zones).

Recognition of these environments is generally not difficult, but the localization of uranium mineralization within them is often controlled by local morphological features. For deposits occurring in linear depressions, mineralization may accumulate in areas where the valley is constricted or where the basement topography shows a prominent rise [2, 7, 8, 9, 10]. These are areas where laterally moving ore-forming groundwaters will stagnate or be ponded long enough for uranium to precipitate, the causal processes for which are discussed in a later section.

For basin environments, the absence of outflow channels is generally a prerequisite for ore formation, especially in arid and semi-arid environments. This, however, does not apply to organic-rich basins since a relatively constant filtering of groundwaters through the organic phases is required for optimal uranium concentration.

Stratigraphy is a further physical feature controlling the emplacement of ore. Clay-rich horizons, which generally form aquicludes to groundwater, may act as physicochemical barriers promoting the precipitation of uranium, or if more than one horizon is present, may channel the groundwaters into areas favourable to precipitation of ore (e.g. deltaic deposits, bog-sediment interfaces, marl-sand-organic sequences). Permeability and porosity also play a major role in ore formation with uranium mineralization precipitating in porous horizons such as the calcareous-dolomitic-gypsiferous valley and deltaic sediments of arid regions.

4. CLIMATE

Examination of the environments of formation of the many types of deposits described in the following papers should serve to emphasize to the reader that climate does not determine whether a deposit will form, but rather what type of deposit will form. Uraniferous ore-forming surface and groundwaters occur in all climatic zones. What is most important, therefore, in relating genesis to exploration, is the recognition of favourable environments of ore formation in a given climatic zone. Thus, in arid hot desert environments, calcareous, dolomitic or gypsiferous sediments and certain closed alkaline and saline basins have proved to be the most favourable environments for economic concentrations of uranium. In cold-temperate climates, the presence of large concentrations of organic matter within a potential ore-bearing environment is almost mandatory for the occurrence of significant uranium accumulations. Between the two climatic extremes mentioned above, there are many inorganic-organic environments in which surficial uranium deposits may occur, some of which are described in the papers of this volume.

In some cases, regional climatic variations, or anomalous weather conditions within a given climatic zone, may have a determining effect on the localization of surficial uranium deposits. For example, over the Yilgarn Block of Western Australia, which hosts the Yeelirrie and other similar deposits, it has been noted that surficial uranium deposits are found only north of what is known as the Menzies Line [10]. South of this line rainfall exceeds

225 mm falling mainly in winter, and the mean temperature is less than 10 °C. North of this line the rainfall is less than 225 mm, falling mainly in the summer, evaporation is greater than 2 500 mm, and the mean temperature exceeds 19 °C. In the Namib Desert region of Namibia, the dense fogs rolling in from the Atlantic Ocean are responsible for bringing in seawater sulphate from which gypsum precipitates in the surficial sediments. When coincident with the shallow emergence of uranium- and vanadium-bearing groundwaters, this climate-related process may be responsible for localization of orebodies such as occur at Tubas, Namibia [9].

It would appear from research carried out to date that, relative to climate, the economic potential for surficial uranium deposits decreases in the order hot arid, semi-arid, cold-temperate, temperate, tropical. This is also the order of increasing precipitation and dilution of uranium in the hydrosphere.

5. MOBILIZATION OF ORE-FORMING ELEMENTS

Formation of surficial uranium deposits requires mobilization of ore-forming elements from their source(s). The principal elements that must be mobilized to form surficial deposits are uranium (all deposits), vanadium (carnotite deposits in hot arid and semi-arid terranes), and phosphorus (certain uranyl-phosphate deposits in structural zones of intrusive bodies). It is generally considered that major cations, such as calcium and potassium, which form constituents of the uranyl minerals of these deposits, are always present in sufficient quantities in the environment of deposition. They, therefore, have a minimal dictatorial role in the formation of orebodies, although they may determine to some extent which types of minerals are formed.

The major factors which affect levels of concentration and mobilization of ore-forming elements from source to site of deposition are: (a) availability of elements in source rocks, (b) presence of complexing agents, (c) climate, (d) nature of source-rock regolith, and (e) structure of source-rock terrane.

5.1 Availability of Elements

Most of the surficial uranium deposits found to date are associated with intermediate to felsic intrusive rocks, or with their metamorphic equivalents. During formation of these bodies uranium may enter early resistate minerals such as zircon; more generally, however, because of the large ionic radii of uranous and uranyl oxides, the element is prevented from entering the rock-forming minerals and instead concentrates, probably in the uranous oxide form, in small "nucleated sites" along grain boundaries and small microfractures. The element is, therefore, especially susceptible to mobilization under oxidizing chemical weathering conditions. A number of researchers [4, 5, 11] have shown that felsic intrusive rocks may lose a considerable percentage (up to 80 %) of their uranium during weathering, depending on climatic conditions and the length of the period of weathering. In addition, groundwaters draining granitic terranes with associated surficial deposits often display anomalous uranium concentrations [1, 3, 6, 12]. Excepting the results presented by Culbert et al [6] for the Okanangan area of British Columbia, Canada, there are no published data on the labile content or percentage losses of uranium due to weathering of source rocks associated with surficial uranium deposits.

Information on the mobility of vanadium is meagre, except that it is known that the element must be mobile to some degree for carnotite deposits to form. Vanadium, to form carnotite, is often considered to come from the weathering of mafic minerals such as hornblende, pyroxene and biotite [1]. High concentrations of the element can also be found in magnetite, ilmenite, and hematite [14], ferruginous concretions in lateritic regolith can contain high concentrations of vanadium (up to 3 000 ppm). Clearly more research is required on the supergene geochemistry of this element.

Phosphorus is almost entirely derived from the weathering of apatite in igneous rocks. Groundwaters draining source rocks associated with both uranous (ningyoite) and uranyl (autunite, saleeite) phosphate mineralization have been found to contain adequate concentrations of phosphate for the formation of these minerals [3].

5.2 Complexing Agents

In natural waters, uranium, as U^{6+} or UO_2^{2+} , may form carbonate, phosphate, sulphate, silicate, fluoride, chloride, hydroxide and humate complexes [15]. Formation of these complexes are pH dependent, and consequently only important in specific environments. For example, below pH 5.0, the sulphate and fluoride complexes are stable and are important during the weathering of sulphide deposits such as those at Bondon, France [16]. Between pH 4.5 and 7.5, phosphate complexes are stable and may be important in the formation of such deposits as Daybreak, Washington State, USA [17]; Los Gigantes, Argentina [18] and Sila, Italy [13]. Above pH 7.0, the di- and tricarbonat complexes of uranium predominate and are most important in the formation of distal surficial uranium deposits such as Yeelirrie, Australia [1, 2] and Langer Heinrich, Namibia [2, 9].

Regarding surficial uranium deposits, complexation of uranyl cation plays two important roles. Firstly, it greatly accelerates the dissolution of uranium minerals in the source rocks, thus increasing the amount of uranium available for concentration at the site of deposition. Secondly, uranium complexed during leaching of source rocks is less likely to be affected by sorption processes and mild redox changes along its route from source to site of deposition.

5.3 Climate

The rate and type of weathering of source rocks and thus the mobility of the ore-forming elements are greatly affected by climate. In hot arid environments, the movement of ore-forming elements from source to site of deposition is slow due to a low, sporadic rate of precipitation, but these conditions coupled with a high rate of evaporation are also optimal for the precipitation of minerals such as carnotite, calcite, dolomite and gypsum. In contrast, tropical regions experience a heavy, steady rate of precipitation, and the mobility of elements may be so great that precipitation of uranium cannot occur even in the most favourable environments because of high dilution rates and constant, heavy surface and groundwater flushing.

5.4 Source Rock Regolith

Mobility of the ore-forming elements may be seriously impaired if weathering conditions promote fixation in the regolith overlying source rocks. This fixation usually takes place by clay and iron-manganese oxyhydroxide components. In most environments accumulation of uranium in the source regolith does not occur, and there is in fact a significant elemental loss [4, 5]. In hot arid environments, however, the absence of pedogenic calcretes in the source terrain is considered to be a necessary condition for the formation of carnotite mineralization in valley and deltaic sediments [2]. To a great extent this condition has been verified by a distinct absence of this feature in mineralized areas and the accumulation of uranium in the regoliths of certain source regions where pedogenic calcretes do occur [9, 19, 20]. Samama [40] has also shown that the mobility of uranium may be severely suppressed in source regions characterized by laterites.

5.5 Structure of Source Rock Terrane

Optimum structural conditions for the leaching and mobilization of ore-forming elements from a source-rock terrane are met by an intrusive or metamorphic massif having a high density of open fault and fracture systems with a high degree of interconnection and a rock fabric loosened by repeated intrusive activity and/or regional uplift. On a smaller scale, uraniferous surficial sediments may be located over or adjacent to individual fault zones which act as major aquifers and often have associated uraniferous waters with long residence times [6].

6. ENVIRONMENTS AND PROCESSES OF PRECIPITATION

The various processes leading to precipitation of uranium in the supergene zone and the surficial environments in which each process is significant are summarized and discussed below under the following headings:

1. Reduction mechanisms.
2. Sorption processes.
3. Dissociation of uranyl complexes.
4. Change in redox states of ore-forming constituents.
5. Evaporation of surface and groundwaters.
6. Change in partial pressure of dissolved carbon dioxide.
7. Precipitation due to changes in pH.
8. Colloidal precipitation.
9. Mixing of two or more surface or groundwaters.

6.1 Reduction Mechanisms

Most known surficial uranium deposits occur in zones of oxidation, but there are a number of surficial reducing environments which are capable of concentrating the element, the most notable being wetland areas (peat bogs, swamps, cienagas, flood plains, etc.), closed anoxic lake and playa basins, and sulphide orebodies. The processes by which the uranyl ionic species are reduced to uranous forms may be one or a combination of (a) direct reduction by organic matter, (b) anaerobic bacterial activity, (c) reduction by gases such as H_2S and H_2 , and (d) redox processes accompanying near-surface oxidation of sulphides. Most of the uranium precipitated in organic bodies, such as peat bogs and swamps, results from cation exchange processes discussed in the following section, but direct reduction by certain organic forms may also be important in some environments [21].

Anaerobic bacteria, especially the sulphate-reducing species, are powerful reducing agents for uranium. Although probably a contributing factor in most organic-reducing environments, bacterial reduction is the dominant precipitating mechanism in closed anoxic alkaline and saline lakes (e.g. the Purple Lake deposit, Canada, described by Culbert et al. [6], some cienaga deposits, and certain reducing playa lakes having a black ooze layer immediately below the surface. In organic environments, both the decay of organic matter and anaerobic bacterial activity produce gases such as H_2S and H_2 that are potentially strong reducing agents capable of precipitating uranium. When primary uranium is present, or when uraniferous groundwaters are introduced into the oxidation-reduction environment of a near-surface sulphide orebody, considerable enrichment of uranium may occur in the zone of reduction, an excellent example being the Bondon deposit in France [16].

6.2 Sorption Processes

Due to their large ionic radii and high-charge density, respectively, both the uranyl (UO_2^{2+}) and uranous (U^{4+}) ions are adsorbed onto various organic materials [22, 23, 24], clays [25, 26], zeolites [25], phosphate minerals [25],

and hydrous oxide precipitates of elements such as iron, manganese, silicon, aluminium, and titanium [15, 25, 27]. In most cases, adsorption is physical and is accomplished by processes of simple ion exchange but, in organic regimes, chemisorption may be a precursor step in the formation of more stable organic-uranium complexes. Decaying organic material in peat bogs, swamps and flood plains may contain 1 000 to 5 000 ppm uranium [6, 12, 28] and occasionally as much as 3 % uranium [28]. Such bodies often receive uranium from one or more groundwater sources and may concentrate the element in one or more horizons; often, however, the element is erratically distributed. The ability of organic material to concentrate uranium is dependent largely on the pH of the environment, the degree of humification, and the uranium and total dissolved salt content of the inflowing surface and groundwaters. Depending on the type and composition of organic matter, the optimum pH for adsorption of uranium is between 4 and 7 [22]. At equilibrium conditions, the amount of uranyl ion adsorbed by organic matter is proportional to the uranium content of the interstitial waters [22]. In the vicinity of the uraniferous Masugnsbyn bog in Sweden, surface and groundwaters contain between 4 and 140 ppb uranium [28]. Spring waters entering the uraniferous bog deposits at Kasmere Lake, Manitoba, Canada contain up to 50 ppb uranium whereas interstitial waters in these bogs contain up to 400 ppb of the element [12]. These findings may be compared to those of Halbach et al. [11] who found that, despite the fact that the weathered zones of the Brockan granite (West Germany) showed uranium losses of up to 80 % (from 14 ppm to 2 ppm) the high rainfall in the area (1 500 mm/yr) resulted in very dilute solutions (0.1 to 0.6 ppb uranium) and very little concentration of uranium (3 to 4 ppm) in the associated bogs. Enrichment factors, represented by the ratio of uranium in the organic matter to its concentration in associated waters, may vary from 10 000 to 50 000:1 [22, 24]. The ability of organic environments to extract large quantities of uranium from natural waters has been demonstrated by Bowes et al. [29] for a bog deposit on the Sierra Nevada Batholith of California. The uranium contents of spring waters entering this bog were reduced by a factor of ten after flowing through the bog. Generally, the ability of organic matter to concentrate uranium increases with increasing humification, although all of the other above-mentioned factors will affect this relationship. For the uraniferous peat bogs at Kasmere Lake in Canada, Coker and Dilabio [12] found a good relationship between uranium content and degree of humification, concentrations of up to 5 000 ppm occurring in the most humified bottom layers of the bogs. For the Masugnsbyn bog in Sweden, the relationship between uranium content and degree of humification is less clear, indicating that other factors have a stronger influence on concentration processes [28]. In extremely alkaline environments, where most of the uranium in surface and groundwaters is strongly complexed by di- and tricarboxylate ions, the ability of organic materials to concentrate uranium is severely hampered. In such environments, highly reducing conditions (e.g. some cienagas) may be required to obtain significant concentrations.

The ability of clay minerals to adsorb uranium from natural waters is well established [25, 26], the conditions being optimum between pH values of 5 to 7 [26]. Few, if any, significant uranium accumulations occur in pure clay deposits. In most cases, uraniferous clays are associated with organic deposits [6], lake sediments [6], playa sediments [13] or halite deposits [30], in all of which uranium is also present in a variety of other forms.

Uranium may be adsorbed from solution during the precipitation of iron, manganese, silicon, aluminium and titanium hydrous oxides of which iron oxyhydroxides seem to be the most significant accumulators. The uraniferous ochre deposits in Botswana [19] would appear to be the first significant deposit described where uranium-iron coprecipitation predominates. The sorption characteristics of iron oxyhydroxides for uranium have been studied by a number of researchers [15, 27, 40].

6.3 Dissociation of Uranyl Complexes

Complexing of uranium by such ions as carbonate, sulphate and phosphate greatly aids in transporting large amounts of the element to potential sites of deposition. Destabilization of these complexes liberates sufficient amounts of uranium to form orebodies in some places. The breakdown of uranyl complexes may be accomplished by reduction mechanisms, pH changes, or a change in partial pressure of gases such as CO₂ (carbonate decomplexing). All of these mechanisms are discussed in following sections. The dissociation of uranyl carbonate complexes is considered to be important in the formation of calcrete and gypcrete carnotite deposits [1, 2].

The dissociation of uranyl sulphate complexes is important to the formation of uranium mineralization in oxidizing sulphide environments.

6.4 Change in Redox States of Ore-Forming Constituents

Redox changes are considered by Mann and Deutscher [1] to be dominant mechanisms in the formation of carnotite calcrete-gypcrete deposits. Considerably greater concentrations of vanadium can be carried in solution to a site of deposition if it is in the four-valent state, as VO(OH)⁺ or HV₂O₅⁻, rather than the five-valent state required for carnotite formation. The model has U⁶⁺ and V⁴⁺ moving to the site of deposition in slightly oxidizing to mildly reducing, neutral to acidic groundwaters, where upwelling causes oxidation of V⁴⁺ to V⁵⁺ and carnotite is precipitated. Convincing field evidence is presented in the form of Eh-pH measurements in drill holes around the North Lake Way prospect that shows a shallow redox boundary corresponding to the calculated boundary for V⁴⁺ and V⁵⁺.

6.5 Evaporation of Surface and Groundwaters

The behaviour of uranium during evaporation in arid and semi-arid regions has been examined by a number of researchers [31, 32, 33, 34]. In the absence of precipitating agents such as vanadium and phosphorus, evaporation is not a particularly good mechanism for concentrating uranium in the surficial environment [31, 32, 34]. During evaporation, uranium is concentrated in the final bitter residues of alkaline and saline lakes [31, 32, 33, 34] and only precipitates during the final stages of desiccation. Playa deposits are susceptible to wind ablation and flushing during periods of heavy rainfall [32, 35], and uranium accumulations are, therefore, merely transitory. Uranium will accumulate in reducing (black oozes) and clay-rich horizons in these environments, and even then only in relatively low concentrations, due probably to the presence of complexing ions in the associated waters. Evaporation of upwelling groundwaters in calcrete-gypcrete drainage channels may be partially responsible for the localization of carnotite deposits due to increased activity of K^+ , V^{5+} and U^{6+} above the solubility product of carnotite [1, 36]. Evaporation discharge involving capillary rise or evaporative pumping of groundwaters above the groundwater table may be responsible for the formation of autunite deposits in structural zones of granitic bodies, e.g. Los Gigantes, Argentina [18] and Daybreak, USA [17], as well as accumulations of uranium in pedogenic calcretes, e.g. Mile 72, Namibia [9] and Mokobaesi, Botswana [19].

6.6 Change in Partial Pressure of Carbon Dioxide

Due to strong uranium-carbonate complexation, concentrations in groundwater of uranium, vanadium, potassium, and bicarbonate leached from source rocks may exceed the limits of the solubility of carnotite at a given pH. If these waters become deep-seated, they will also have a greater carbon dioxide content due to increased confining pressures. Such conditions will promote higher bicarbonate concentrations and greater uranium complexation. When these waters re-enter the near-surface environment, the hydrostatic pressure will decrease, carbon dioxide will exsolve from solution, calcium carbonate will precipitate, uranium will be decomplexed and carnotite will precipitate. Such a process has been considered as a possible mechanism for the formation of calcrete-gypcrete carnotite deposits [36]. A similar process (without vanadium) has been used to explain the formation of uraniferous travertine deposits [37].

6.7 Precipitation Due to pH Changes

The solubilities of many uranyl minerals, especially carnotite and uranyl phosphates (*see* Figure 1 of Hambleton-Jones [38] for solubility of carnotite vs pH), and the stabilities of all uranyl complexes are pH dependent [15, 36]. It follows, therefore, that when uraniferous surface or groundwaters enter a potential ore-forming environment and undergo a significant pH change, uranium mineralization may form. The formation of ore as the result of pH changes can be accomplished by such processes as: (a) mixing of two or more surface or groundwaters, to form a variety of uranium minerals; (b) loss of carbon dioxide by rising uraniferous groundwaters to form carnotite [36] and uraniferous travertines [37]; (c) oxidation of sulphide bodies to form a host of uranyl and uranous silicate, phosphate, arsenate and sulphate minerals, and (d) reaction with soluble acids in organic (humic, fulvic), clay-rich environments where the pH may change into a range (i.e. 4 to 7) favourable for adsorption.

6.8 Colloidal Precipitation

Very little is known about the role of colloid formation in the precipitation of uranium mineralization and, with the exception of changes in pH, very little is known of the processes involved. Undoubtedly, one or more of dehydration, deflocculation, peptization or polymerization are responsible for colloid formation. During the weathering of sulphide deposits, uranyl solutions may react with colloidal or gelatinous silicates, phosphates, arsenates, molybdates, vanadates, selenites and tellurites to form a variety of mineral types. Reaction of uranyl solutions with silica gels may lead to significant accumulations of minerals such as uranophane, coffinite and soddyite (e.g. Welwitchia occurrence, Namibia [9]).

6.9 Mixing of Two or More Surface or Groundwaters

Although a number of ore-forming scenarios involving mixing of surface or groundwaters of different compositions can be invoked for the formation of surficial uranium deposits, such processes have been difficult to verify under natural conditions. Mixing of separate uranium- and vanadium-bearing groundwater systems has been proposed by Mann [1, 36] to be a possible contributing mechanism for formation of calcrete-gypcrete carnotite deposits. There is little doubt that surface and groundwaters do mix in the hydrosphere and, therefore, may be a dominant factor in ore formation within a variety of environments.

7. TECTONICS

The tectonic history and structural framework of a region play an important role in the formation of surficial uranium deposits. Tectonic processes, such as uplift and/or extensional tectonism, prepare the source rock area for both surface and groundwater leaching of ore-forming elements. Because the formation of a surficial uranium deposit requires a stable hydrological regime, a distinct period of tectonic quiescence is also required. For some deposits, the period of ore formation may be as short as 5 000 to 10 000 years [6, 28], whereas for others, such as the uraniferous calcrete-gypcrete deposits, a much longer period of tectonic stability may be required [9].

8. PRESERVATION

Surficial uranium deposits are formed under specific hydrogeochemical and climatic conditions and, as such, are susceptible to destruction due to changes in the original ore-forming conditions. Tectonic activity and climatic changes are the principle causes of destruction. Pleistocene uplift of parts of southern Africa has led to erosion of many of the uraniumiferous calcrete-gypcrete deposits [39]. Drastic changes in climate, or even sporadic climatic conditions, such as the periods of heavy rainfall and flooding in Western Australia [35], will greatly affect the stability of deposits. The existence of ancient surficial uranium deposits in their original form is unlikely, since very few geological processes would allow their preservation, although they may be remobilized to form other types of deposits. In older geological terranes, such transformed deposits should be located along unconformities.

9. CONCLUSION

Until recently, geologists have always considered the processes leading to surficial accumulations of uranium as interfering factors in mineral exploration for primary ores. In the last five to ten years, it has become apparent that such processes may yield relatively large economic, or potentially economic, uranium deposits. Knowledge of the mechanisms and environments of formation for this class of deposit is, however, meagre and much more research is required to determine the full potential of the supergene zone for uranium ores.

REFERENCES

- [1] MANN, A.W., DEUTSCHER, R.L., Genesis principles for the precipitation of carnotite in calcrete drainages in Western Australia, *Econ. Geol.* **73** (1978) 1724–1737.
- [2] CARLISLE, D., MERIFIELD P.M., ORME, A.R., KOHL, M.S., KOLKER, O., The distributions of calcretes and gypcretes in southwestern United States and their uranium favourability, US Dept. Energy, Bendix Field Engineering Corp. and Regents University California Report GJBX-29 (78) (1978) 274.
- [3] BOYLE, D.R., The formation of basal-type uranium deposits in south central British Columbia, *Econ. Geol.* **77** (1982) 1176–1209.
- [4] STUCKLESS, J.S., NKOMO, I.T., Uranium-lead isotope systematics in uraniumiferous alkali-rich granites from the Granite Mountains, Wyoming; Implications for uranium source rocks, *Econ. Geol.* **73** (1978) 427–441.
- [5] MOREIRA-NORDEMANN, L.M., Use of $^{234}\text{U}/^{238}\text{U}$ disequilibrium in measuring chemical weathering rates of rocks, *Geochim. Cosmochim. Acta* **44** (1980) 103–108.
- [6] CULBERT, R.R., BOYLE, D.R., LEVINSON, A.A., Surficial uranium deposits in Canada, this Volume.
- [7] BRIOT, P.B., FUCHS, Y., Processus de minéralisation uranifères des calcretes: Une hypothèse non pédologique, this Volume.
- [8] HAMBLETON-JONES, B.B., Surficial uranium deposits in South Africa, this Volume.
- [9] HAMBLETON-JONES, B.B., Surficial uranium deposits in Namibia, this Volume.
- [10] BUTT, C.R.M., MANN, A.W., HORWITZ, R.C., Regional setting, distribution and genesis of surficial uranium deposits in calcretes and associated sediments in Australia, this Volume.
- [11] HALBACH, P., BORSTEL, D.V., GUNDERMANN, K.D., The uptake of uranium by organic substances in a peat bog environment on a granitic bedrock, *Chem. Geol.* **29** (1980) 117–138.
- [12] COKER, W.B., DiLABIO, R.N.W., Initial geochemical results and exploration significance of two uraniumiferous peat bogs, Kasmere Lake, Manitoba, *Geol. Surv. of Canada Paper* 79-18 (1979) 199–206.
- [13] DALL'AGLIO, M., GRAGNANI, R., LOCARDI, E., Geochemical factors controlling the formation of the secondary minerals of uranium, in *Formation of Uranium Ore Deposits*, IAEA, Athens (1974) 33–40.
- [14] EVANS, H.I.JR., LANDERGRAN, S., Vanadium, In: *Handbook of Geochemistry*, Vol. 2 (Wedepohl, Ed), Springer Verlag (1970).
- [15] LANGMUIR, D., Uranium solution-mineral equilibria at low temperatures with applications to sedimentary ore deposits, *Geochim. Cosmochim. Acta*, **42** (1978) 547–569.
- [16] EULRY, M., VARGAS, J.M., Le rôle des altérations anté-Liasiques dans la métallogenèse de la périsphère du Mont Lozère (France). Cas de L'Uranium, in *Paleosurfaces and their Metallogensis*, Mem. BRGM 104 (1980) 15–175.
- [17] LEO, G.W., Autunite from Mt. Spokane, Washington, *Am. Min.* **45** (1960) 99–128.
- [18] RODRIGO, F., OLSEN, H., BELLUCO, A.E., Surficial uranium deposits in Argentina, this Volume.
- [19] MORTIMER, C., Surficial uranium deposits in Botswana, this Volume.

- [20] BIANCONI, F., BORSHOFF, J., Surficial uranium deposits in the United Republic of Tanzania, this Volume.
- [21] ANDREYEV, P.F., CHUMACHENKO, A.P., Reduction of uranium by natural organic substances, *Geochem. Int.* **1** (1964) 3–7.
- [22] SZALAY, A., Cation exchange properties of humic acids and their importance in the geochemical enrichment of UO_2^{++} and other cations, *Geochim. Cosmochim. Acta* **28** (1964) 1605–1614.
- [23] MANSKAIA, S.M. DROZDOVA, T.V., EMELIANOVA, M.P., Binding of uranium by humic acids and by melanoidines, *Geochem. Int.* **4** (1956) 339–355.
- [24] LOPATKINA, A.P., Conditions of accumulation of uranium in peat, *Geochem. Int.* **4** 3 (1967) 577–588.
- [25] DOI, K., HIRONO, S., SAKAMAKI, Y., Uranium mineralization by groundwater in sedimentary rocks, Japan, *Econ. Geol.* **70** 4 (1975) 628–646.
- [26] MUTO, T., HIRONO, S., KURATA, H., Some aspects of fixation of uranium from natural waters, *Min. Geol. (Japan)* **15** (1965) 287–298.
- [27] AMES, L.L., MCGARRAH, J.E., WALKER, B.A., SALTER, P.F., Uranium and radium sorption on amorphous ferric oxyhydroxide, *Chem. Geol.* **40** (1983) 135–148.
- [28] ARMANDS, G., Geochemical prospecting of a uraniferous bog deposit at Masugnsbyn, northern Sweden, In: *Geochemical Prospecting in Fennoscandia* (Kvalheim, Ed), Interscience Publishers (1967) 127–154.
- [29] BOWES, W.A., BALES, W.A., HASELTON, G.M., Geology of the uraniferous bog deposit at Pettit Ranch, Kern County, California, *US Atomic Energy Rep. RME-2063* (1957) 27.
- [30] PEREZ, L.E., *Depositos Superficiales de uranio en el Norte de Chile*, this Volume.
- [31] DALL'AGLIO, M., CASENTINI, E., The distribution of uranium between precipitates and brines in the solar salt plant of Margherita di Savoia; geochemical and geological considerations, *Bull. Soc. Geol. Italy* **89** (1970) 457–484.
- [32] BELL, K.G., Deposition of uranium in salt-pan basins, *US Geol. Surv. Prof. Paper 354-G* (1960) 161–169.
- [33] CULBERT, R.R., LEIGHTON, D.G., Uranium in alkaline waters – Okanagan Area, British Columbia, *Canadian Inst. Min. Metall.*, **71** 793 (1978) 103–110.
- [34] KOCHENOV, A.V., CHERNIKOV, A.A., The character of surface uranium concentrations in acid regions, *Lith. Min. Res.*, **11** (1976) 110–116.
- [35] PREMOLI, C., Formation of, and prospecting for, uraniferous calcretes, *Austral. Min.* (1976) 13–16.
- [36] MANN, A.W., Chemical ore genesis models for the precipitation of carnotite in calcrete, *CSIRO (Aust. Div. Mineral) Rep. No. FP.7* (1974) 18.
- [37] SEREBRENNIKOV, V.S., MAKSIMOVA, I.G., The deposition mechanism of uranium from mineral waters containing CO_2 , *Geochem. Int.* **5** (1976) 167–174.
- [38] HAMBLETON-JONES, B.B., SMIT, M.C.B., Calculation of the carnotite solubility index, this Volume.
- [39] HAMBLETON-JONES, B.B., Uranium occurrences in the surficial deposits of southern Africa, In: *Proc. 12th CMMI Congr.* (H.Glenn, Ed), *S. Afr. Inst. Min. Metall.* (1982) 13–136.
- [40] SAMAMA, J.C., Uranium in lateritic terranes, this Volume.

URANIUM IN LATERITIC TERRANES

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ABSTRACT

URANIUM IN LATERITIC TERRANES

The occurrence of uranium anomalies in iron-rich surficial formations (gossans and lateritic soils) is reviewed and most are classified according to their origin: the behaviour of uranium in lateritic landscapes is complex but two main physico-chemical processes control the geochemical behaviour of uranium. These are 1) co-precipitation of iron and uranium, and 2) physical adsorption on active iron-rich surfaces. Both processes are pH dependant. During the weathering of pyritic rocks, soluble uranium and iron sulphates are formed; their co-precipitation by neutralization results in high-grade uranium anomalies. Uranium is adsorbed by mainly amorphous iron hydroxides and, to a lesser extent, goethite, both of which have large adsorption surface areas. The pH of the surficial environment plays an important role in determining the distribution and density of the surface electrical charges that, in turn, control the adsorption efficiency of the iron hydroxide surfaces. The identification of the type of uranium anomalies and an understanding of the processes of concentration and dispersion can assist the interpretation and selection of field geochemical anomalies.

1. INTRODUCTION

During the last 25 years, many radiometric anomalies have been detected in laterites throughout the world by means of airborne or ground surveys. Although a great number have been confirmed as being due to uranium, their significance is generally not clear. There are two basic problems:

1. To these anomalies represent secondary dispersion patterns in lateritic soils above high-grade primary concentrations, or are they the result of extremely strong processes of concentration acting on source rocks?
2. If they are derived from primary concentrations, what are the dispersion mechanisms and the scales of migration of uranium and associated elements?

These problems are of great interest both for basic knowledge of the geochemical behaviour of uranium in lateritic terranes and for uranium prospecting in these environments. This subject has received little attention but in this paper, published and unpublished data have been used to formulate a provisional explanation of the geochemical behaviour of uranium in laterites. The most convenient approach to the problem seems to be to define the two types of ferric environments which are uraniferous, namely laterites and gossans, and then to interpret the data in terms of the geochemical behaviour of uranium in them.

2. LATERITES AND GOSSANS

The geochemical environments of both laterites and gossans are characterized by their high content of Fe (III) minerals, and their recognition in the field and in hand specimens is difficult in tropical areas, although they differ geochemically.

A gossan is generally defined as a local oxidized iron formation capping a primary sulphide deposit, even though the iron sulphide does not represent the entire source of iron [1]. The mineralogy and geochemistry, in both vertical and lateral profiles, are generally definitive and can be easily identified in the laboratory.

Lateritic environments as defined by Perelman [2] are geochemical terranes which have developed in hot and humid climates. The soils derived from these pedological processes are known as lateritic soils or, in the American soil taxonomy, "oxisols", in which iron oxy-hydroxides are associated with kaolinite and gibbsite in various quantities. The upper A and B horizons of the soils are developed under acid conditions at a pH of 4, with iron accumulating in the B horizon. The lower part of the profile consists of the so-called mottled zone, a saprolitic kaolinitic horizon having a pH of 5, underlain by a neutral or weakly basic weathered pallid zone. Iron caps may occur either at the base of small hills as a result of lateral transportation of dissolved iron by phreatic waters, or on extensive plateaus, developed under semi-arid conditions after a very long evolution.

The identification of young or old lateritic profiles is relatively easy, but there are many similarities between a gossan and the deep weathered zone of a lateritic profile. For this reason, the distinction between the two types may be rather difficult in some tropical areas.

In the following review of the uranium occurrences in laterites and gossans, the type of iron environment will be indicated, and the geochemical behaviour of uranium will be discussed.

3. REVIEW OF WORLD LATERITIC URANIUM OCCURRENCES

Many surficial iron-rich uranium occurrences are known throughout the world, but most have not been described in the literature because their significance has not yet been fully understood. Descriptions of several important occurrences follow, but are largely incomplete due to a lack of information.



Figure 1

World distribution of surficial iron-rich uranium occurrences. Numbers 1 to 14 refer to the localities

(a) Early Tertiary or older occurrences

(b) Tertiary to Recent occurrences

(c) Areas of laterite development according to G. Pedro [22]

Several occurrences appear to be outside the lateritic areas which can be interpreted as the Recent climatic evolution towards drier environments

3.1 Tanzania

The uranium occurrences in lateritic profiles in Tanzania (1 in Figure 1) are the best examples of such deposits within this geochemical environment [3]. A regionally developed lateritic soil, up to 20 m thick, overlies a uranium sandstone-type deposit within the Karoo Sequence in the Madaba area. Certain iron-rich facies occurring above a stone-line are considered to have formed from lateritization of reworked allogenic material, whereas others are autochthonous lateritic profiles which contain the uranium mineralization.

Up to 2 km away from the primary uranium occurrence, secondary uranium anomalies in the lateritic profiles occur in fractures and joints in the weathered sandstones or in roll-like accumulations in the lower part of the profile. Uranium is present as U(VI), either sorbed with selenium onto an iron-manganese hydroxide or associated with a nickel-chromium nontronite with small amounts of vanadium. In every occurrence, uranium is related to both vertical and horizontal acid/alkaline transition zones, the alkaline conditions being indicated by the formation of nontronite. Such deposits clearly show that high-grade secondary ores can be the result of migration and reconcentration of uranium in the lower part of lateritic profiles in zones of abrupt pH changes.

3.2 Mali

The Tin Azzir secondary uranium anomalies in eastern Mali (2, in Figure 1), which occur as elongated iron crusts, have no known primary source. They are usually associated with quartz veins in Lower Proterozoic sandstones which unconformably overlie older pelitic units [4]. Individual samples contain between 200 and 3 000 ppm uranium, associated with significant amounts of zinc, cobalt, nickel, copper, sulphur, and phosphorus (0.2 to 0.3%), no thorium is present. The uranium is concentrated mainly in the X-ray amorphous goethitic iron fraction, except where these iron species occur as recent precipitates in small cavities.

Disregarding the recent uranium-free iron precipitates, there appears to be a direct relationship between the uranium content and the active surface area of the iron species, usually between 6 and 23 m²/g. Mossbauer spectrometric analyses of this material show that the iron oxides are either amorphous or present as very small crystals of goethite or hematite. This indicates that the crystallinity of the iron species is in an early phase of evolution, at the stage where adsorption capacities are at their maximum. The lower the crystallinity, the higher is

the uranium content of the iron species. During evolution and crystallization towards hematite, iron species lose their adsorption capacities with a corresponding reduction in uranium content.

On the basis of texture, the iron-rich facies can be interpreted either as a lateritic crust or as a gossan, but the general morphology of the anomaly and the geochemical associations indicate the occurrence to be a gossan.

The lateritic terrane around Kenieko in western Mali (5 in Figure 1) consists of two types of geomorphologic units: an upper terrace, which appears to be the older regional surface and contains uranium along its margins, and a lower, younger, terrace hosting strings of uraniferous boulders (B. Moge, personal communication, 1983). The anomalies of the lower terrace consist of limonitic boulders containing 70 to more than 1 000 ppm uranium and up to 1.4 phosphorus %. The limonitic boulders occur either on the surface or within the iron crust. In the vicinity of boulders, the iron crust may be weakly enriched in uranium, containing up to 50 ppm compared to a background of about 20 ppm. Despite their morphological characteristics, the uranium anomalies in the lower terrace are considered to have formed as a result of the erosion and redeposition of the anomalous limonitic facies of the upper terrace, similar to occurrences elsewhere, for instance in India [5].

Other anomalies occur on the edge of the upper lateritic terrace; uranium concentrations are lower, reaching a maximum of 500 ppm at a depth of 1 to 2 m, just below the iron crust, and only 30 to 40 ppm at a depth of 8 m.

3.3 Upper Volta

Many weak radioactive anomalies were detected by airborne radiometric surveys in central north Upper Volta (3 in Figure 1) during the 1960's. These anomalies are all on the old lateritic plateau and several that are in the Zorghoo area have been investigated. The highest radioactivity is in a horizon occurring at a depth of 2 to 3 m immediately below the iron crust and is due to a few minute crystals of autunite. No primary concentrations of uranium are known in the underlying Birimian sedimentary formations.

3.4 Central African Republic

In the 1960's, systematic uranium surveys in the Central African Republic (4 in Figure 1) led to the discovery of several radiometric anomalies and the uranium deposit at Bakouma [6]. The first anomalies studied in detail were located at about 100 km from Bakouma and occur within the iron crust, about 1 m below the surface. The underlying rocks, gneisses and mica schists are rich in allanite containing both thorium and uranium.

3.5 Senegal

Several uraniferous anomalies occur in lateritic profiles of eastern Senegal (6 in Figure 1) where iron crusts between 0.5 to 1.2 m thick overlie deep weathering profiles (B. Moge, personal communication, 1983). Recent erosion has destroyed the main part of the iron crust except on small residual hills. The maximum radioactivity is at the base of the iron crust and could be related to primary uranium deposits within the granites.

3.6 Brazil

There are several radiometric anomalies associated with lateritic soils in Brazil [7]. In the State of Parnaiba (7 in Figure 1), four occurrences are known in reworked ferruginous facies overlying Lower Devonian and Lower and Upper Carboniferous rocks. They occur as blocks of lateritic crust, in places near pyritic schists. In the State of Amazonas, two occurrences overlie Lower and Upper Devonian rocks (8 in Figure 1). In all these cases, the iron-rich facies are composed of goethite, hematite and kaolinite. They can contain up to 1 700 ppm uranium, 1 380 ppm vanadium and over 1 % phosphorus, but with thorium contents of less than 100 ppm. Uranium minerals have not been detected by optical methods. In most places, relationships between these anomalies and primary deposits are unknown.

A peculiar deposit is known in the State of Goias [8] where roll-type uranium occurs in Devonian sandstones. One of the rolls is found in a deep surficial lateritic soil derived by the oxidation and remobilization of underlying uranium mineralization but without significant leaching having taken place.

3.7 France

In France, during the Early Tertiary, lateritic soils, crusts and gossans developed in a humid tropical climate. Most of the lateritic profiles have been eroded and are now recognized as redeposited clastic iron concretions, commonly associated with kaolinitic clays, forming the so-called siderolithic facies.

The uppermost level of the Bernardan deposit [9] (10 in Figure 1) is a uranium-rich gossan containing up to 1 to 2 % uranium developed on an episyenitic uranium deposit. Concentrations of 100 to 150 ppm uranium are found in the siderolithic facies for up to 3 km around the deposit, usually where iron concretions are associated with clay minerals such as kaolinite (80 %) and smectite (20 %). The uranium distribution is probably controlled either by post-erosional and depositional remobilization, or by a uranium concentration within the deep clay horizon of an older lateritic profile.

The Oligocene uranium sandstone-type deposit of Saint Pierre [10] (11 in Figure 1) presents two types of iron formation. Much of the iron impregnation in the arkosic sandstones is derived from pyrite-rich rocks and may be

compared to minute gossans. Uranium grades of up to 1 % are associated with poorly crystalline iron hydroxides that are also locally enriched in phosphorus and vanadium. Approximately 32 % of the iron is amorphous or contains goethite crystals less than 90 Å in diameter; the remaining 68 % consists of goethite with crystals less than 250 Å in diameter. The chemical and physical characteristics of the iron are given in Table 1. The strong correlation between the content of uranium and that of poorly crystalline iron hydroxide, which has a high surface capacities, indicates that adsorption phenomena or co-precipitation with iron oxy-hydroxides played dominant roles in the precipitation of the uranium.

Table 1
Composition of an iron concretion and its -40 μ fraction
from the St. Pierre deposit [4]

	Fe ₂ O ₃ %	UO ₂ %	PO ₄ %	VO ₄ %	Surface area (m ² /g)
Whole rock sample	8.42	1.09	0.7	0.02	25.8
-40 μ Fraction	28.8	4.58	3.45	0.07	104.8

Away from the deposit, the siderolithic iron concretions are probably remnants of lateritic crusts developed on rocks of Hercynian age during the Late Cretaceous or Early Tertiary that were reworked and deposited in sediments of Oligocene age. The concretions contain up to 50 ppm uranium, an enrichment relative to their source rocks.

The Bondon deposit [11] (12 in Figure 1) is a Tertiary-Quaternary gossan developed on a sulphide stockwork and is more than 1.5 m thick. The uranium has been adsorbed onto goethite-hematite and kaolinite surfaces and can attain grades of up to 1 %.

3.8 Morocco

The Hercynian metamorphic and granitic units of the Zaer Massif of Central Morocco (13 in Figure 1) are overlain by remnants of a Cretaceous lateritic profile. The profile is well preserved in the vicinity of uranium occurrences associated with goethite-hematite impregnations that are formed along fractures developed in a sulphide-uranium stockwork similar to the Bondon deposit (M. Eulry, personal communication, 1983). The uranium-bearing ferruginous facies may be classified as lateritic and, locally, gossanous.

3.9 India

According to Subramanyan [5], several occurrences of uraniumiferous limonitic boulders assisted in the discovery of low-grade primary uranium deposits associated with silicified breccia in the State of Bihar (14 in Figure 1). The limonitic boulders, which have been transported more than 35 m, have many large cubic boxworks after pyrite, with a marked peripheral zonation of limonite. Their uranium content can be as high as 1 000 ppm, whereas that of the primary breccia is much lower. It appears that these anomalies consist of transported blocks of a uraniumiferous gossan derived from a pyrite-rich primary deposit.

4. INTERPRETATION: PHYSICO-CHEMISTRY OF URANIUM CONCENTRATION IN LATERITIC GEOCHEMICAL TERRANES

Uranium anomalies in laterites and gossans can be classified into two groups [4, 13, 14].

1. High-grade anomalies containing 0.1 to 0.2 % uranium often related to primary uranium iron sulphide-bearing occurrences.
2. Low-grade anomalies containing up to 0.01 % uranium related to normal surficial lateritic processes, but which could also be related to primary uranium deposits.

There are two main physico-chemical fixation processes that can be invoked to explain the origin of lateritic uranium occurrences, namely **co-precipitation** and **surface adsorption** of uranium on poorly crystalline iron hydroxide minerals. Optimally, both processes occur in weakly acid to slightly alkaline conditions.

Co-precipitation processes are commonly associated with uranium anomalies in gossans, although surface adsorption may also play a prominent role in the removal of uranium from solution at the appropriate pH. Adsorption of uranium during co-precipitation stabilizes it sufficiently to resist further secondary dispersion. Co-precipitation of iron and uranium hydroxides from acidic sulphate solutions by neutralization, has been experimentally investigated by Sharkov et al [14], who found that the hydroxides attach themselves onto basic mineral species such as clays, feldspars, and carbonates, resulting in grades up to 0.1 % uranium. Such high-grade concentrations can occur during weathering of uranium-rich sulphide deposits or during weathering of pyritic rocks in the vicinity of very low-grade uranium source rocks.

In carbonate-rich environments, however, although acid solutions are effectively neutralized, precipitation of uranium may be inhibited by the formation of soluble uranyl carbonate complexes which can migrate and be dispersed over large distances.

Surface adsorption involves sorption and precipitation on active surfaces. True sorption is controlled by pH and occurs when ions are attracted to mineral surfaces having opposite electrical charges. Sorption of positive ions or complexes such as $UO_2(OH)^+$ implies negative charges on the surface of the sorbing species, which occurs as the result of an increase in pH. The transition point or zero point of charge (ZPC) between positive and negative charges varies according to the mineral species as shown in Table 2 [15].

Table 2
Values of the zero point of charge (ZPC) of some natural mineral species [15]

Mineral Species	pH
$Fe(OH)_3$ "amorphous"	7.1 – 8.5
$FeO(OH)$ goethite	3.2 – 6.7
$FeO(OH)$ lepidocrocite	5.4 – 7.4
Fe_2O_3 hematite	2.1 (?) – 8.6
Fe_2O_3 maghemite	6.7

Table 3
Geochemical enrichment factors (GEF) of uranium for natural sorbents at pH's between 5 and 8.5 [18, 23]

Mineral Sorbents	GEF
X-ray amorphous $Fe(OH)_3$	$1.1 \times 10^6 - 2.7 \times 10^6$
fine-grained goethite	4×10^3
"amorphous" $Ti(OH)_4$	$8 \times 10^4 - 10^6$
humic acids and peat	$10^3 - 10^4$
phosphorites	15
montmorillonite	6
kaolinite	2

The ability of a mineral species to fix or adsorb ions from solution can be measured by the geochemical enrichment factor (GEF). This is the ratio of the amount of uranium adsorbed by the mineral species to the uranium concentration remaining in solution. Examples of maximum enrichment for different minerals are given in Table 3.

Many authors [4, 16, 17, 18, 19, 20, 21] consider the sorption of uranyl ions onto iron oxy-hydroxide species as an important process for controlling the distribution of uranium in iron-rich geochemical terranes. Experimental work on natural lateritic material (G. Valence, personal communication, 1983) showed that, for pH of 4.5 to 5.5, uranium fixation is low, with a GEF of 3×10^2 , whereas between pH 6 and 7, the GEF increases to about 1.8×10^4 .

The sorption processes are complex and it is difficult to distinguish true sorption from precipitation on finely divided species of high surface area. In the case of sorption, the ZPC of the mineral species will control the process whereas, in precipitation, the kinetics of the reaction, in addition to the size of precipitating particles, are the main factors involved. Precipitation is very weak in an acid medium (pH 4 to 5.5), but highly active in a neutral or weakly acid medium (pH 6.5 to 7). In soil profiles, uranium tends to concentrate mostly in the transition zone between the upper levels (A horizon or iron crust), characterized by an acid pH, and the deeper horizons, in which pH is neutral to basic. This general geochemical principle is exemplified by the uraniferous lateritic anomalies of Tanzania, where uranium is strictly concentrated in the basic facies underlying the acid facies [3].

Based on the foregoing geochemical phenomena, the evolution of uraniferous laterites can be explained. As the lateritization proceeds, a front of soluble uranium will move downwards in the profile, motivated by changes in pH and the crystallization of iron hydroxides and the consequent loss of adsorption capacity. This process of

adsorption and desorption may repeat itself and the uranium front can gradually move to deeper zones or, on a slope, move laterally. The degree of vertical and lateral migration will depend upon the permeability of the host material, distances up to several hundreds of metres having been recorded in Tanzania.

5. CONCLUSION

Fourteen iron-rich uranium anomalies have been described and it appears that they fall into three general classes:

1. Lateritic occurrences formed within soil profiles, either:
 - with an underlying uranium deposit, as in Tanzania, or
 - without an underlying uranium deposit as in Upper Volta, Central African Republic, and the Bernardan and Saint-Pierre deposits of France.
2. Gossans associated with underlying primary sulphide deposits, either:
 - with an underlying uranium deposit, as in Goias (Brazil), Bernardan, Saint-Pierre and Bondons (France), and Bihar in India, or
 - without an underlying deposit, as in Parnaiba (Brazil), or
 - of unknown origin as eastern Mali.
3. Unknown or undifferentiated types, as western Mali, Senegal, Amazonias (Brazil) and Morocco.

This review illustrates the widespread concentration of uranium in the ferruginous terranes. There appears to be a fairly consistent ratio between the uranium contents of the source rocks and the lateritic deposits, and from the data obtained so far this relationship appears to be generally valid [12].

There are two important mechanisms concerned with the formation of lateritic uranium occurrences, namely, physical adsorption on active surfaces of various iron hydroxy mineral species, and the co-precipitation of iron oxides and uranium. Both processes are dependent on the pH of the solution, which, optimally, should be weakly acid to neutral.

During evaluation of lateritic uranium anomalies, there are several pertinent aspects that must be taken into consideration. Attention should be given to the regional and local geomorphology including the identification and age of the various weathering surfaces, the cycles of erosion and the slopes, which will determine the direction and rate of uranium migration within the ferruginous facies. Local studies of anomalies should take into account the vertical and horizontal forms of the uranium anomalies and their relationships with the various horizons or facies of the lateritic soils. Such data may assist in distinguishing lateritic enrichments from reworked uranium anomalies occurring as boulders and gossans.

Geochemical associations help in establishing the differences between the two types. For example, the abundances of sulphur and certain base metals such as vanadium, copper, lead and zinc, may characterize a gossan. High concentrations of nickel, molybdenum, arsenic and selenium are typical of lateritic uranium occurrences.

Using this information, it is possible to determine the nature of the primary uranium source, which could either be a nearby primary uranium deposit, or merely a background source rock with easily leachable uranium. The application of these principles may assist in the interpretation of uranium anomalies in ferruginous materials and the selection of the most favourable targets for further detailed and follow-up surveys.

REFERENCES

- [1] KOSAKEVITCH, A., "Chapeaux de fer", Problème de définition et de nomenclature pratique, Bull. BRGM Sect. II, 2-3 (1979) 141–149.
- [2] PERELMAN, A.I., Geochemistry of Epigenesis, Plenum Press, New York, (1967) 266.
- [3] KOSLAR, K., BIANCONI, F., BUTNER, W., Geochemical behaviour of uranium in lateritic profiles in southern Tanzania, (to be published).
- [4] MICHEL, D., Les oxy-hydroxydes de fer: Leur rôle dans La distribution de l'uranium dans le milieu supergène, Thèse Nancy (1983) 178.
- [5] SUBRAMANYAN, V., Radioactive limonite of Lota Pahar, Singhbhum district, Bihar, J. Geol. Soc. India 13 (1972) 329–338.
- [6] MOLINA, P., Exploration for uranium in a tropical country, a case history in Central African Republic, IAEA (1982), in press.
- [7] DE OLIVERA, I. Etude de quelques latérites uranifères du nord du Brésil, Unpublished report Nancy (France) (1980).
- [8] CONSONI, J.O., Contribution à l'étude de l'anomalie 12 du gisement uranifère de Amornopolis (Goias, Brésil), Unpublished report, Nancy (France) (1979).

- [9] MICHEL, J.J., Episyénites et concentrations uranifères associées dans le Massif de Saint-Sulpice-Les-Feuilles (Haute-Vienne, France), Thèse Nancy (1983) 461.
- [10] CARRE, J.L., Les minéralisations uranifères des dépôts oligocènes de Saint-Pierre (Cantal, France) dans leur cadre géologique régional et local, Thèse Nancy (1979) 121.
- [11] EULRY, M., VARGAS, J.M., Le rôle des altérations anté-Liasiques dans la métallogenèse de la périphérie du Mont Lozère (France), Cas de L'Uranium, In: Palaeosurfaces et Leur métallogenèse, Mem. BRGM 104, Orléans (1980) 15-175.
- [12] SAMAMA, J.C., Ore deposits and continental weathering: a contribution to the problem of inheritance of heavy metal contents of basement areas and of sedimentary basins, In: Ores in Sediments, Elsevier (1971) 247-265.
- [13] GRITSAIENKO, G.S., BELOVA, L.N., GETSEVA, R.V., SAYELYEVA, K.T., Mineralogical types of oxidation zones of hydrothermal uranium and sulfide uranium ores of the USSR, UN Intern. Conf. Peaceful Uses of Atomic Energy Proc. 2 (1958) 469-471.
- [14] SHARKOV, Y.V., YAKOLEVA, M.N., Concerning the origin of higher radioactivity of iron weathering zone, In: Prospecting for Uranium Ore Deposits in Mountain Taija, Atomizdat [in Russian] (1971).
- [15] PARKS, G.A., The isoelectric points of solid oxides, solid hydroxides and aqueous hydroxy complex systems, Chem. Rev. (1965) 177-198.
- [16] VAN DER VEIJDEN, C.H., ARTHUR, R.C., LANGMUIR, D., Sorption of uranyl by hematite. Theoretical and geochemical implications, Geol. Soc. Am. Abs. Prog. Annual meeting, Denver 10 (1974).
- [17] BARTON, P.B., Fixation of uranium in the oxidized base metal ores of the Goodsprings District Clark Co. Nevada, Econ. Geol. 51 (1956) 178-191.
- [18] LANGMUIR, D., Uranium solution-mineral equilibria at low temperature with application to sedimentary ore deposits, Geochim Cosmochim. Acta. 42 (1978) 547-569.
- [19] MICHEL, D., N'GANZI C. SAMAMA J.C. L'adsorption: implications sur la prospection géochimique de l'uranium en milieu tropical, IAEA (1982), in press.
- [20] ROJKOVA, E.V., RAZOUMNAIA, E.G., SEREBRIAKOVA, M.B., CHITCHERBAK, O.V., Le rôle de la sorption dans la concentration de l'uranium dans les roches sédimentaires, Conf. sur l'utilisation e l'énergie atomique à des fins pacifiques, ONU Genève (1958) 160-172.
- [21] ZHMODIK, S.M., MIRONOV, A.G., NEMIROVSKAYA, N.A., Uranium distribution in iron hydroxides from weathered mantle as shown by F-radiography, Dokl. Akad. Nauk. USSR, 250 6 (1980) 219-222.
- [22] PEDRO, G., Distribution des principaux types d'altération chimique à la surface du globe. Présentation d'une esquisse géographique, Rev. Geogr. Phys. et Geol. Dyn. Paris 10 (1968) 457-470.
- [23] CAPUS, G., Matières organiques et minéralisations uranifères: exemples des bassins permo-carbonifères de L'Aumance (Allier) et de Lodève (Hérault), Thèse Nancy (1979) 384.

EXPLORATION FOR SURFICIAL URANIUM DEPOSITS

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ABSTRACT

EXPLORATION FOR SURFICIAL URANIUM DEPOSITS

The more important surficial uranium deposits usually occur in granitic terranes and in arid environments and these criteria are universally used in the application of satellite imagery for the detection of target areas for further prospecting.

Evaluation of surficial deposits is particularly difficult due to the fact that the ore is usually out of equilibrium and erratically distributed in strata of varying degrees of consolidation. In order to cope with these variables special geochemical, geophysical and drilling techniques have been evolved. Some of the newer methods have shown that beta/gamma analysis and low-energy spectrometry hold considerable promise.

Reverse circulation drilling with double walled rods and dry stick auger drilling with the analysis of the chips or cores being corroborated by gamma logging techniques have been found to give the best results in Australia.

1. INTRODUCTION

Due to the unique characteristics common to most surficial uranium deposits a number of specialized prospecting techniques have been developed. This chapter briefly discusses the geophysical, geochemical, and drilling techniques which to date have been applied with the most success but does not discuss hydrogeochemical techniques or satellite imagery as they are dealt with elsewhere in this volume [1, 2, 3].

2. REGIONAL INVESTIGATIONS

Initial exploration strategy takes the form of regional geological evaluation for the identification of potential target areas. The most favourable regions for the location of the larger surficial uranium deposits are in the arid and semi-arid areas of the world. Of prime importance is the identification of sediment-filled palaeodrainage channels in tectonically stable parts of the earth's crust that contain source rocks, usually granites, which have a high proportion of leachable uranium and basic schists or laterites to provide a source of vanadium to enable the formation of carnotite.

As the larger surficial deposits frequently occur in palaeodrainages, it is important that a potential channel be located and possible structural traps be identified, behind which carnotite may have precipitated. False colour Landsat satellite imagery has played an important role in the delineation of suitable target areas in Australia and Namibia [2, 3].

The initial regional studies should, as a pre-requisite, be followed up by photogeological mapping, regional hydrological [1], geomorphological and palaeoclimatic studies prior to embarking on conventional prospecting methods.

The importance of these regional orientation surveys and an appreciation of the environment and geochemical conditions which gave rise to the formation of these deposits, cannot be over-emphasized. The regional investigations should, if considered justified, be followed up by airborne geophysical and photographic surveys, geological mapping and geochemical and ground geophysical investigations prior to the initiation of a drilling and pitting program.

3. FIELD INVESTIGATIONS

Surficial uranium deposits have certain characteristics in common which make their evaluation difficult. Due to the fact that the mineralization is usually out of equilibrium and erratically distributed in strata of varying composition and hardness, accurate evaluation presents many problems, some of which remain unresolved. Therefore, special evaluation techniques had to be developed, the most useful of which are described below.

3.1 Beta/Gamma Analysis

Beta/gamma analysis is a relatively recent development [4] and can be applied to both field or centrally situated laboratory environments. The technique utilises a stabilised CaF/NaI detector which is highly sensitive to both beta and gamma radiation. The main advantage of the method is that it can analyse for the elements uranium, thorium, and potassium and in addition, it can measure the degree of disequilibrium within the uranium decay chain. The uranium measurement is based on the ^{234m}Pa beta count rate, and therefore does not rely on gamma emissions from isotopes lower down in the decay chain, as is the case for conventional gamma-ray spectrometric determinations of uranium. For those situations where equilibrium has not been established, uranium can still be determined with a high degree of accuracy using a counting time of one minute, and 10 ppm U \pm 7 ppm can be measured with an accuracy comparable to XRF or chemical analysis [4].

3.2 Low-Energy Gamma-Ray Spectrometry

Low-energy gamma-ray spectrometry was developed for uranium exploration by Culbert and Leighton [5]. It is based on the principle of using the low-energy gamma emissions below 400 keV from the uranium and thorium decay series. This facilitates the direct determination of both elements, the result of which is unaffected by disequilibrium. Additionally, the disequilibrium can be determined from those isotopes lower in the decay chain such as ^{214}Pb . The main advantage of this method is that it is easily applied in the field and has recently been adopted for the logging of shallow boreholes [6].

3.3 Radon Detection Methods

Numerous radon techniques are commercially available including ROAC, Track Etch, alpha metres, alpha cards, emanometers, and several others. Experience in Namibia has shown that over the larger surficial uranium deposits the most effective radon surveys should be conducted regionally at probably 250 to 500 m spacings along lines up to 1 km apart, rather than at closer intervals. It has been found that in many instances the distribution of radon coincides with the palaeochannel, but significant displacements in excess of 250 m between the surface radon anomaly and the actual mineralization have been noted [7].

The depth to which the detectors are placed in the ground plays a very significant role in certain geological conditions. For example, at places in the Namib Desert, a dense crystalline layer of hardpan gypcrete occurs just below the ground surface which is virtually impenetrable to radon. Orientation surveys showed that it is imperative to locate the detector below this layer. Naturally, a hole has to be drilled to penetrate this layer, which will add to the cost of the survey and its justification would therefore have to be carefully evaluated.

Carnotite mineralization in the surficial sediments frequently occurs at or near the surface and consequently has radiometric expressions of varying magnitudes. An orientation experiment testing the merits of radon surveys, as compared to spectrometer surveys, showed that in certain parts of the Namib Desert, the spectrometer data were as reliable as those of radon, which in this instance militated against the use of the latter (J. Hartleb, personal communication). Successful radon surveys have been described from the Namib Desert [7, 8] but at Yeelirrie in Australia the results were unsatisfactory [9].

3.4 Radiometric Techniques

In the past, many uranium geologists tended to utilize gamma radiometry on a purely qualitative basis. Since the introduction of calibration facilities for the spectrometric determination of uranium, thorium, and potassium, there has been a dramatic switch to quantifying scintillometric and spectrometric data for airborne, ground, and borehole instruments. Such facilities exist in various parts of the world, some of which are to be found in the USA, Canada, Sweden, Australia and South Africa [10].

The application of radiometric techniques is particularly suited to prospecting for the larger surficial uranium deposits, as they tend to occur close to the surface. However, some of the very young surficial deposits, such as those found in Canada [5] and South Africa [11], have no or poor radiometric signatures, showing that the uranium is frequently out of equilibrium and therefore, for these types of surficial uranium deposits, the use of radiometric techniques is unsatisfactory.

3.5 Resistivity Surveys

Resistivity surveys have been used successfully in the surficial uranium province of Namibia to delineate palaeochannels, with a remarkable degree of accuracy. The technique used a constant separation pole-dipole array, since the basement rocks constituting the Damara Sequence have a higher resistivity than the valley-fill sediments. Readings can be made on lines at right angles to the channel, the plotting point being the mid point between the current electrode and the centre of the potential electrodes. The palaeochannel edge is taken where the resistivity gradient steepens abruptly, as is observed from an iso-resistivity map.

The depth of the palaeochannel can also be obtained by electrical sounding, using either the Wenner or Slumberger electrode arrays. Depth calculations are made by comparing the observed curves of apparent resistivity versus electrode separation with theoretical curves, such as Tagg's curves, based on various assumed layering conditions.

3.6 Seismic Surveys

Hammer or drop-weight seismic surveys are fairly cheap and reliable methods which can be used to obtain thicknesses of units and depths to interfaces, making it a potentially useful technique for outlining the geometry of palaeochannels. The accuracy of these methods is on a par with resistivity for shallow depths not exceeding approximately 100 m. Shot seismics can provide accurate results and greater depth penetration, but the cost would be much higher. As in the case of resistivity, only the structures favourable for uranium mineralization would be outlined and not the mineralization itself. A problem which may be encountered is that seismic velocities of certain calcified layers may be equal and often higher than those of the basement rocks, thereby giving a false interpretation of the depth of the channel floor.

4. DRILLING TECHNIQUES

In the event of the initial investigations proving encouraging, further investigation by means of drilling, pitting, trenching, and trial mining will be the natural course of events.

Great difficulties have been encountered in reconciling the lack of correlation between material extracted from borehole, radiometric logging and bulk samples from pits. This problem is partly due to the erratic nature or nugget effect of the mineralization but most important however, is that certain zones of the surficial uranium deposits are very friable and the violent action of the percussion drill may cause caving in the hole which could either enhance or reduce the mineral content of the rock cuttings collected at the surface. The deposits are frequently zoned with semi-consolidated ore-grade material overlying barren material. The upward surge of barren rock cuttings in the hole, due to the escape of the compressed air, may pick up the softer ore material, thereby enhancing the overall grade of the sample. In South Africa, conventional drilling techniques in deposits consisting of diatomaceous earth and peat were unsuccessful in obtaining representative samples, and a special technique was developed for drilling this material (J. Strathern, personal communication). Core barrels, 1 520 mm in length, containing a recoverable rigid plastic liner, are hammered, without rotation, into the ground using a down-the-hole hammer arrangement. The core barrels are recovered by overdrilling using a hollow-stemmed auger, which also keeps the hole open for further drilling. The rigid plastic liner is removed and cut open to release the contents for logging and sampling. This system is capable of drilling effectively down to a depth of 22 m to provide a virtually undisturbed, although slightly compressed, sample.

Haycraft [12] reports that at Yeelirrie there was little to choose between reverse circulation drilling and dry stick auger drilling. Dry stick augering involves drilling the required sample interval, withdrawing the auger line, removing the sample and then repeating the cycle. The possibility of contamination by the mixing of samples is thereby reduced. Due to the presence of intercalated bands of hard calcrete, the Namibian deposits are not amenable to auger drilling.

Reverse circulation drilling involves drilling with double-walled rods, the drilling fluid passing down the outer annulus and returning with the sample through the central tube. The sample does not come into contact with the wall of the hole, eliminating hole-wall contamination and, by balancing the drilling fluid pressure with the pressure of groundwater, contaminants carried with the groundwater can be excluded. Contamination in the sample collection system is minimized by flushing between samples and there is reasonable correlation between the reverse circulation XRF and gamma logging results.

Reverse circulation drilling was chosen as the drilling technique to be used in future drilling programs in Australia, but diamond drilling was used to provide detailed geological data and comparisons with the reverse circulation results [12].

It is recommended that the initial drilling program should involve the siting of percussion or auger holes along lines up to 2 km apart and at 250 m intervals. This spacing is determined by the size of the deposit which the exploration geologist postulates to be present. All drill cuttings should be assayed chemically and the holes radiometrically logged with suitably calibrated equipment within 3 days of being drilled so as to avoid a build up of radon in the hole.

Once an anomalous uranium zone has been located, drilling should be done on a more closely spaced grid with line spacing down to 1 km apart. If sufficient holes are positive, the grid can be reduced for delineation drilling using a grid spacing of as close as 200 x 50 m.

5. PITTING AND TRENCHING

In order to confirm the drilling results and to assist in resource evaluation of a surficial uranium deposit, it has been found necessary to excavate pits or trenches at selected intervals. Additionally, apart from the grade-control aspect, the pit provides access for detailed subsurface lithological mapping and bulk channel samples for preliminary metallurgical testing. On a larger scale, trenches (or sometimes mega-trenches) are excavated for trial mining purposes and to obtain bulk samples for extraction metallurgical tests and grade estimation at pilot-plant scale. The uranium mineralization usually occurs in the fines and it has been found that, and under dry, windy desert conditions, a reduction in the grade can result due to poor handling techniques. Great care has therefore to be exercised in reducing the samples to a manageable size.

6. CONCLUSION

Techniques for the exploration and evaluation of surficial uranium deposits have undergone considerable evolutionary change since their discovery in the early 1970's. It is now evident that many of the deposits were poorly evaluated initially and that a re-evaluation may be justified.

The geochemistry of uranium, although reasonably well understood, is highly complex and it is a prerequisite for the exploration geologist to have some understanding of the uranium decay series and their nuclear properties as

these are the corner-stones upon which certain geochemical and geophysical radiometric prospecting techniques are based.

The techniques and methodologies used in the evaluation of these deposits will need continued updating and review and should be regarded as a unique multidisciplinary specialist field that requires expertise and experience not normally acquired in the more conventional exploration field.

REFERENCES

- [1] MIDDLETON, W.G., An assessment of the use of hydrogeochemistry in the exploration for calcrete uranium in Australia, this Volume.
- [2] KRISCHE, E.U., QUIEL, F., The application of supervised classification to Landsat data in the exploration for surficial uranium deposits – an example from Western Australia, this Volume.
- [3] HAMBLETON-JONES, B.B., CAITHNESS, A., The application of Landsat imagery for delineating potential surficial uranium deposits in Namibia, this Volume.
- [4] SHARLAND, C.J., ROBERTSON, M.E.A., BRANDT, P.J., High-precision automated beta/gamma technique for uranium analysis, In: Uranium Evaluation and Mining Techniques, Proc. Symp., IAEA, Buenos Aires (1979) 309–319.
- [5] CULBERT, R.R., LEIGHTON, D.G., Low-energy gamma spectrometry in the geochemical exploration for uranium, *J. Geochem. Explor.* 14 (1981) 49–68.
- [6] CULBERT, R.R., BOYLE, D.R., LEVINSON, A.A., Surficial uranium deposits in Canada, this Volume.
- [7] HAMBLETON-JONES, B.B., SMIT, M.C.B., ROAC – A new dimension in radon prospecting, *S. Afr. Atomic Energy Board, PER-48* (1980) 24.
- [8] VAN AS, D., TOENS, P.D., A relationship between radon measurements and concealed uranium mineralisation, In: *Analytical Chemistry in the Exploration, Mining and Processing of Materials, Int. Symp., IUPAC, Johannesburg* (1976) 8.
- [9] SEVERNE, B.C., Evaluation of radon systems at Yeelirrie, Western Australia, *J. Geochem. Explor.* 1 (1978) 1–22.
- [10] CORNER, B., TOENS, P.D., RICHARDS, D.J., VAN AS, D., VLEGGAR, C.M., The Pelindaba facility for calibrating radiometric field instruments, *S. Afr. Atomic Energy Board, PEL-268* (1979) 23.
- [11] HAMBLETON-JONES, B.B., Surficial uranium deposits in South Africa, this Volume.
- [12] HAYCRAFT, J.A., Sampling of the Yeelirrie uranium deposit, Western Australia, *Aust. IMM, Sampling Symp., Melbourne* (1976) 20.

THE APPLICATION OF SUPERVISED CLASSIFICATION TO LANDSAT DATA IN THE EXPLORATION FOR SURFICIAL URANIUM DEPOSITS – AN EXAMPLE FROM WESTERN AUSTRALIA

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ABSTRACT

THE APPLICATION OF SUPERVISED CLASSIFICATION TO LANDSAT DATA IN THE EXPLORATION FOR SURFICIAL URANIUM DEPOSITS – AN EXAMPLE FROM WESTERN AUSTRALIA

The digital evaluation of Landsat data (supervised classification) can give substantial support to the regional selection of targets for valley-fill deposits in arid areas. The approach is described with an example from Western Australia.

1. INTRODUCTION

Landsat products are particularly suited for exploration for valley-fill uranium deposits because of the favourable geographic situation of the deposits, namely an arid climate, sparse vegetation and occurrence at or near the surface in drainage channels. In most instances, conventional imagery is used, as described, for example, by Premoli [1], for exploration for calcrete uranium deposits in Australia. Better results, however, are obtained by analyzing the original digital data.

Merifield et al [2] interpreted ratio images (red-green band) of digital data and could distinguish calcrete, caliche and marine limestone from calcareous soils with similar spectral characteristics. Pitt [3] preferred enhancement techniques of digital data and complementary techniques to delineate palaeodrainages in South Australia. Beaumont [4] successfully used digital data to locate calcrete in the exploration for road construction material.

Both approaches – conventional Landsat paper images and digital data – have also been applied in exploration for uranium in sandstones [5, 6, 7], uranium in alkaline intrusions [8] and uranium in unconformity-related rocks of Lower Proterozoic age [9].

This paper describes the results of a test using both conventional Landsat imagery and an evaluation of digital data (principally supervised classification) for the selection of regional exploration targets for uranium in a surficial calcareous environment. The approach is similar to that of Cary and Longman, (quoted by Williams, [10]), with the difference that no printout of supervised classification is used; instead, colour images can provide an easier orientation for field crews.

2. METHODOLOGY

For the test, a satellite scene was chosen covering the Yeelirrie uranium deposit and other deposits in Western Australia (Id No. 82 10 70 11 21 500, Landsat 1, date: 9 May 1975). The image analyzing system used for the test consisted of a mini-computer (PRIME 500) with 460 mbyte disc capacity, a colour display system, tape drive, printer and alphanumerical terminals, located at the Institute of Photogrammetry, Technical University, Karlsruhe, West Germany.

The following enhancement methods were applied to the digital data:

- **linear stretching**, to change the contrast of grey tones of each channel to emphasize particular geological features,
- **filtering**, smoothing of data to remove unwanted noise,
- **ratioing**, to emphasize the colorimetric variations and to avoid topographic lighting effects, and
- **supervised classification**, in which the picture elements of a Landsat scene (pixels) are classified according to training classes (i.e. grey tone intervals) chosen by the geological interpreter to represent the main features of the image and the selected target. A maximum likelihood algorithm is applied to calculate for each pixel the probability that it belongs to the specified classes and to assign it to the class with maximum likelihood. This is

done for all four channels for Landsat 1 to 3 products. Hence, it can search the entire satellite frame for similar reflectance after a geological interpretation has determined at least one representative training area for the target (in this case calcrete) and the other classes to describe the image characteristics. The scene classified by this procedure is then displayed on a screen in the same number of (pre-selected) colours as training classes used.

In order to optimize the classes and to avoid confusion due to overlapping ranges of tones of each training area, several attempts might be necessary with a possible relocation of the training areas. From our experience, the training area should be as homogeneous in brightness and colour as possible and the target should have its own distinct shape. The size of the training area should be ideally 1 km² or more.

A further suggestion for this kind of data evaluation is that where possible, the analyses should be reduced to geologically sensible target areas, in this case the actual drainages, thus decreasing computing costs and time [11]. Also, the unwanted interference from rocks having the same or similar reflectances as calcrete can be avoided from unlikely locations elsewhere (e.g. outside drainage areas).

Our experience shows that the delineation of drainages and the selection of training areas can best be done by a field crew using conventional Landsat paper products. After classification, the results are photographs from the colour screen as 35 mm slides, which can be used directly by the field crew during further follow-up.

3. RESULTS

Linear stretching in channels 4, 5 and 7 produced typical blueish to reddish colours over the Yeelirrie calcrete (Figure 1) and, in a less pronounced manner, over other calcretes. However, similar colours were also found in fire-affected areas. **Filtering and ratioing** emphasized the Yeelirrie channel slightly but did not clearly indicate its exposed calcrete. However, calcrete was emphasized by **supervised classification**.

The enhanced Yeelirrie channel and the location of training areas chosen in order to characterize the main colours and features of this subscene are shown in Figure 2. After the training classes were refined (Figure 3) to avoid overlapping of class intervals, the supervised classification was performed. The resulting image (Figure 4) clearly delineated the main parts of the exposed Yeelirrie calcrete in a typical colour combination (brown, red, light green) and in a distinct configuration. The same training characteristics were now applied to another subscene of interest within the same satellite frame. The same calcrete colour assignments are outlined over drainages in which other (uraniferous) calcretes are known – Hinkler Well, Centipede and North Lake Way (Figure 5). The results fit surprisingly well with published maps (e.g. [12]) showing area of exposed calcrete. As discussed above, this approach can be refined further by applying it only to known drainages in order to avoid unwanted data noise from areas which are not of interest. For example, northwest of the Hinkler Well-Centipede drainage (Figure 6), the classification has "identified" calcrete in an area having only an extensive cover of white quartz scree (R. Dudley, Esso Minerals Ltd., personal communication 1983).

4. DISCUSSION

The advantage of the described procedure is evident: with the help of defined calcrete training areas (minimum size 1 km²), the entire satellite frame (34 225 km²) can easily be searched for similar signatures. Such a procedure can substantially support the regional selection of targets during exploration for valley-fill deposits in arid areas. This could be of especial interest to countries for which only large-scale maps exist (e.g. Somalia, Sudan).

The 35 mm slides or prints have sufficient precision for field crews to be able to locate themselves. The additional accuracy of fully processed and geographically corrected scenes seems generally unnecessary and these are far more costly. During our exploration, many Landsat scenes from central Australia were investigated, and results were followed up successfully by applying the supervised classification.

The main disadvantage is that it is a method only for second-phase reconnaissance programs, because at least one calcrete must be known out of the entire scene in advance in order to be able to select the training classes for the above procedure. Other handicaps can be the exact recognition and location of calcrete training areas, masking effects of vegetation, soils or pedogenic duricrusts covering calcretes and finally, the spectral range of calcrete.

The related procedure of unsupervised classification, in which the data is classified statistically without geological input, has also been applied and used successfully in conjunction with supervised classification. In some instances the combined procedure was more effective than the method used above [11].

ACKNOWLEDGEMENT

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Figure 1
 Enhanced full Landsat scene (channels 4, 5, and 7) covering Yeelirrie channel (arrow) and Lake Way (white, northern portion of image) in Western Australia; vertical run of image runs approximately NNE. This and following images are only roughly geographically corrected, size of area 185 x 185 km.

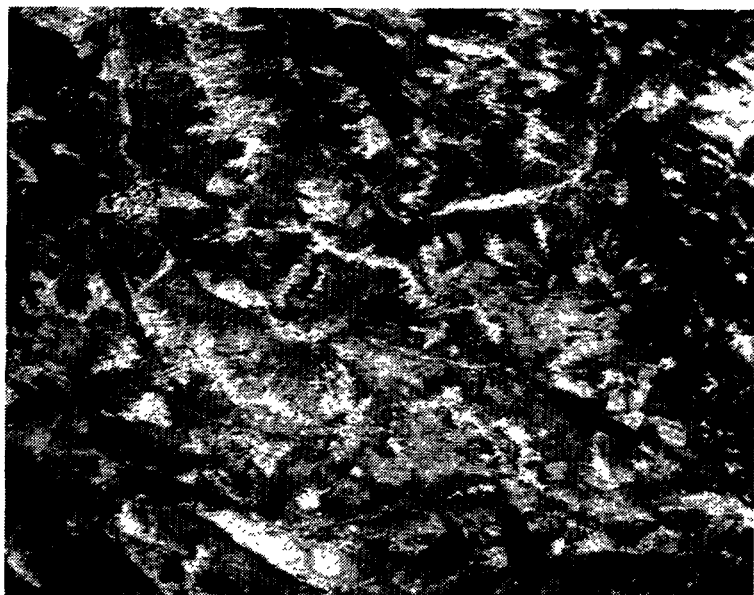


Figure 2
 Location of training areas for supervised classification in Yeelirrie subscene; enhanced image from channels 4, 5, and 7, area covers approximately 37.5 x 35 km, small training areas cover exposed Yeelirrie calcrete.

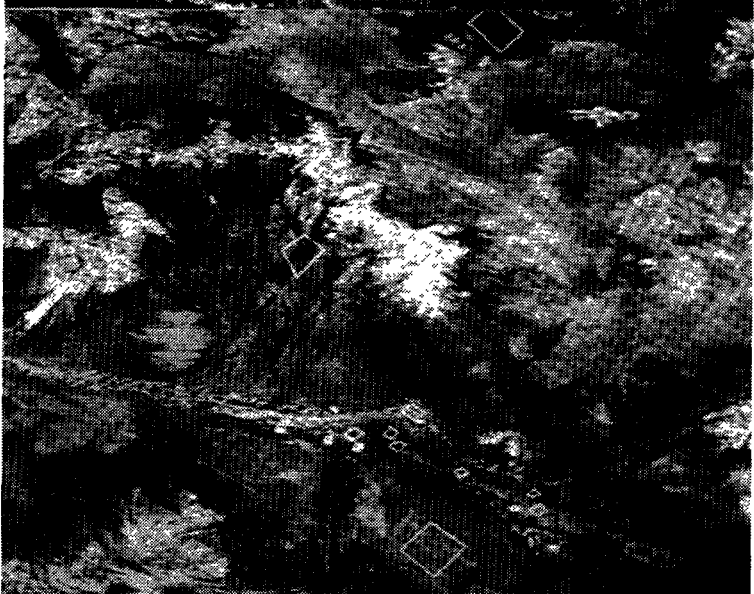
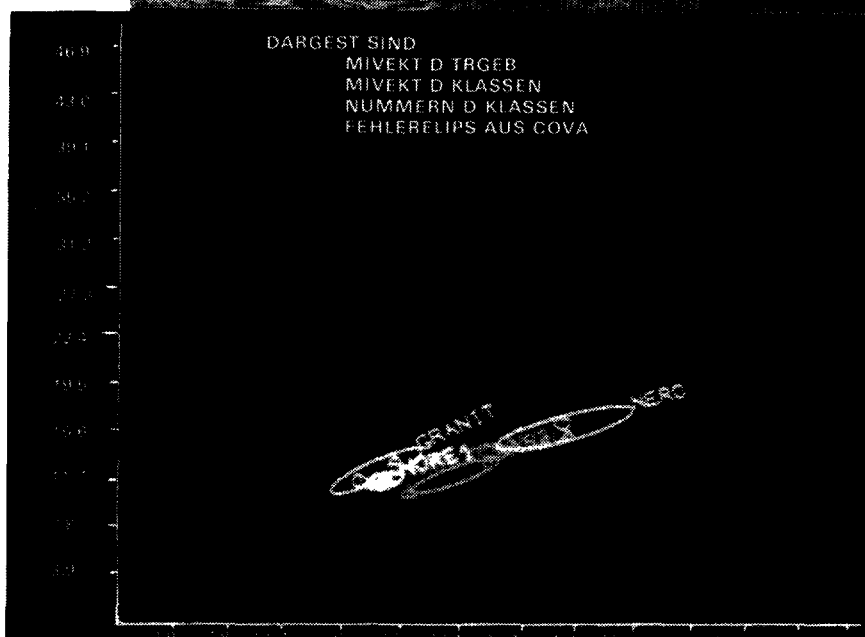


Figure 3
 Display of classes in two dimensional feature space show only few overlapping classes of the training areas used in Figure 1 (channels 5 and 7). ↓



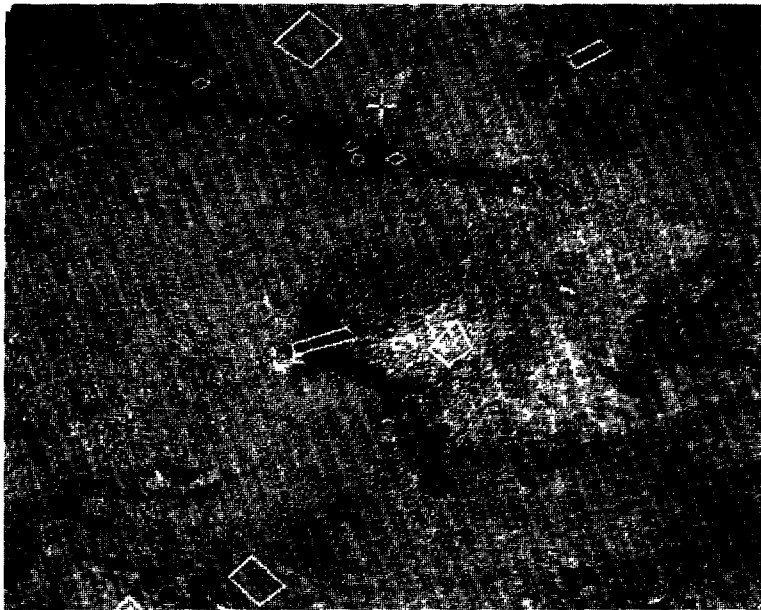


Figure 4
 Same subscene as Figure 2, supervised classification outlines Yeelirrie calcrete (length approximately 22 km in NW-SE) in colour combination brown, red and light green.

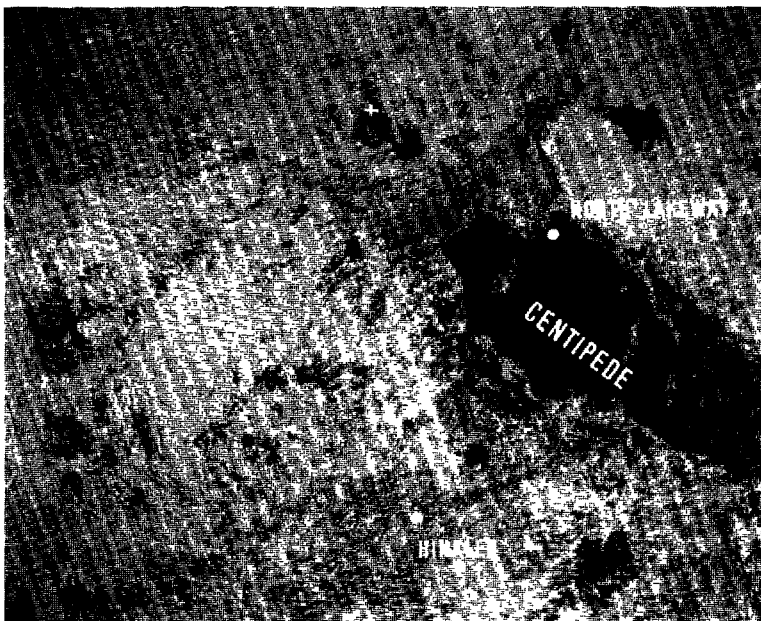


Figure 5
 Supervised classification over Lake Way subscene with same colour assignments as in Figure 3; exposed calcretes occur north and west of Lake Way drainages (Lake Way = dark blue, its length on picture approximately 30 km NW-SE, size of subscene approximately 52 x 43 km).

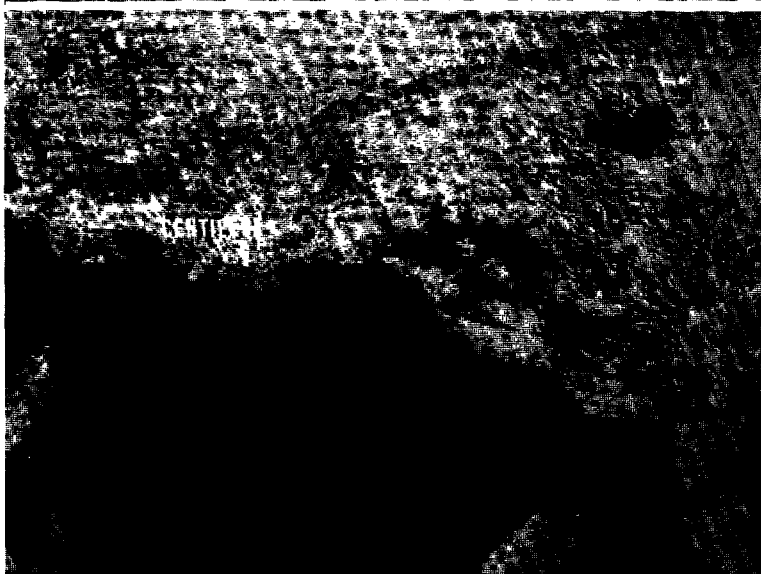


Figure 6
 Supervised classification over section of subscene from Figure 5, size approximately 19 x 19 km. Hinkler Well drainage running ENE-WSW with Centipede deposit (dot); same colour assignment as in Figure 4, area to the NW of Hinkler Well drainage is covered by white quartz scree having same reflectance as exposed calcrete areas.

REFERENCES

- [1] PREMOLI, C., Formation of and prospecting for uraniferous calcretes, *Aust. Min.* (1976) 13–16.
- [2] MERIFIELD, P.M., Enhancement of geologic Features near Mojave, California by spectral band ratioing of LANDSAT MSS data, Ann Arbor, Mich., Proc. 10th Int. Symp. on Remote Sensing of Environment (1975). Cit. in CARLISLE, D., MERIFIELD, P.M., ORME, A.R., KOHL, M.S., KOLKER, O., The distribution of calcretes and gypcretes in southwestern United States and their uranium favorability based on a study of deposits in Western Australia and South West Africa (Namibia), US Dept. of Energy, Open File Report GJBX-29(78) (1978) 274.
- [3] PITT, G.M., Palaeodrainage systems in western South Australia: Their detection by Landsat imagery, stratigraphic significance and economic potential, Paper presented at the 1st Australian Landsat Conf. Sydney, Australia (1979).
- [4] BEAUMONT, T.E., Remote sensing for route location and the mapping of highway construction materials in developing countries. Ann Arbor, Mich., Proc. 14th Int. Symposium on Remote Sensing of Environment, (April 1980, San Jose, Costa Rica), Vol. III (1979) 1429–1441.
- [5] OFFIELD, T.W., Remote sensing in uranium exploration, In: Exploration for Uranium Ore Deposits, Proc. Symp. IAEA, Vienna (1976) 731–744.
- [6] GABELMANN, J.W., Remote sensing in uranium exploration, In: Recognition and Evaluation of Uraniferous Areas, Proc. Tech. Comm. Meetings, IAEA, Vienna (1977) 251–261.
- [7] RAINES, G.L., OFFIELD, T.W., SANTOS, E.S., Remote sensing and subsurface definition of facies and structure related to uranium deposits, Power River Basin, Wyoming, *Econ. Geol.* **73** (1978) 1706–1723.
- [8] PARADELLA, W.R., ALMEIDA FILHO, R., Aplicao de imagens Landsat par o estudo do controle da mineralisacao uranifera no Planalto de Pocos de Caldas, Int. Rep. Instituto de Pesquisas Espaciais, Sao Paulo (1976). Cit. in Remote Sensing in Uranium Exploration, Basic Guidance, Technical Reports Series No. 208, IAEA, Vienna (1981).
- [9] ANON, Computer exploration, improved digital processing methods have enhanced image analysis as a uranium exploration tool. *Eng. Min. J.* (1979) 78–82.
- [10] WILLIAMS, R.S., Geological applications, In: R.N., Colwell (Ed.) *Manual of Remote Sensing* (second edition), Vol. II Interpretation and Applications, Amer. Soc. Photogram. (1983) 1667–1953.
- [11] QUIEL, F., KRISCHE, E.U., Einsatz von Landsat-Daten in der Exploration auf Uranlagerstätten vom Typ “Calcrete”, *Bildmess. u. Luftbildwesen (BUL)*, Karlsruhe (1977), in press.
- [12] BUTT, C.R.M., HORWITZ, R.C., MANN, A.W., Uranium occurrences in calcretes and associated sediments in Western Australia, Aust. CSIRO, Div. Mineral., Report FP16 (1977) 67.

THE APPLICATION OF LANDSAT IMAGERY FOR DELINEATING POTENTIAL SURFICIAL URANIUM DEPOSITS IN NAMIBIA

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Krische and Quiel [1] described the use of Landsat imagery as applied to surficial uranium deposits in Western Australia. They found that calcrete was significantly emphasized using a supervised classification, whereas linear stretching, filtering and ratioing were not as successful.

For the surficial uranium deposits located in the Namib Desert of Namibia, none of the above-mentioned techniques provided superior data than the conventional high quality Landsat images. This note therefore gives a brief outline of the technique used for delineating palaeodrainage environments in Namibia which could contain potential uraniferous valley-fill sediments.

The test area was located to the northeast of Walvis Bay (Figure 1). Figure 2 is a Landsat image of the area showing the Erongo Mountains as a round dark area in the centre right of the picture and Figure 3 is an enlarged area from the southwestern portion of the image. The terrane on the eastern half of the image in Figure 2 consists largely of basement rock outcrop whereas on the western half, the basement rocks outcrop only as inselbergs or as exposures within the valleys of the modern drainage channels such as the Omaruru River to the north and west of the Erongo Mountains.

Palaeodrainages containing the calcified valley-fill material show up as white to grey streaky areas occurring to the west of the Erongo Mountains and trend in a westerly direction towards the Atlantic Ocean. The most important surficial uranium deposits are found in the palaeodrainages occurring between the Omaruru River and the Erongo Mountains which are, namely, 1) Trekkopje, 2) Black Dyke, 3) Spitskoppe, and 4) Marinica (Figures 2 and 3). The Spitskoppe uranium deposit occurs on the southern flanks of the Spitskoppe granite inselbergs which are very prominent landmarks in the region.

The palaeodrainages have cut across the regional northeasterly structural trend and even large dolerite dykes as in the case for the palaeodrainage in the vicinity of the Black Dyke uranium occurrence (2 in Figure 2).

From the Landsat images in Figures 2 and 3 all the palaeodrainages are clearly visible as whitish areas and therefore digital enhancement did not provide additional information for the surficial uranium occurrences in Namibia.

REFERENCES

- [1] KRISCHE, E.U., QUIEL, F., The application of supervised classification to Landsat data in the exploration for surficial uranium deposits – an example from Western Australia, this Volume.

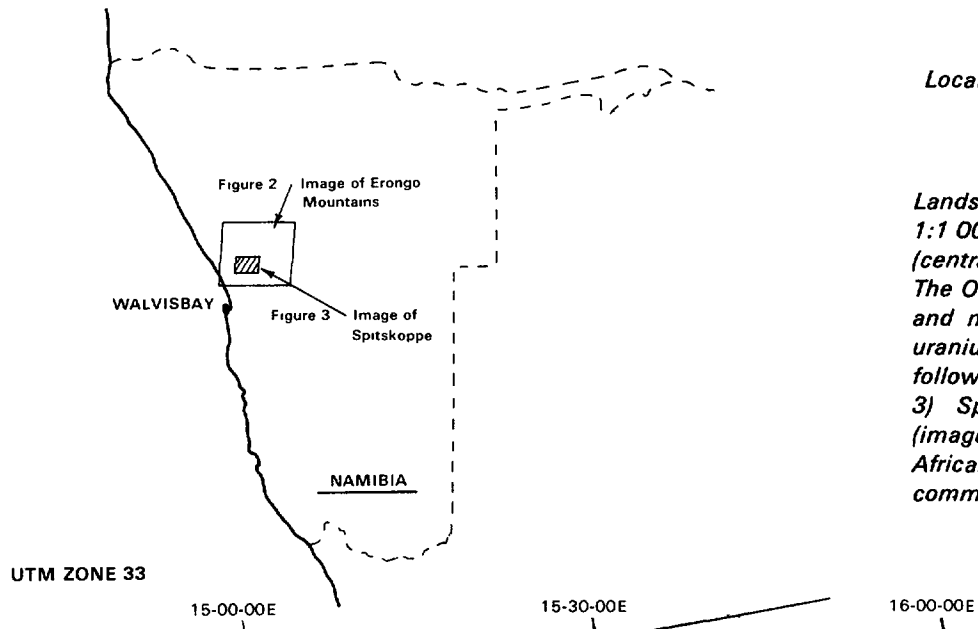
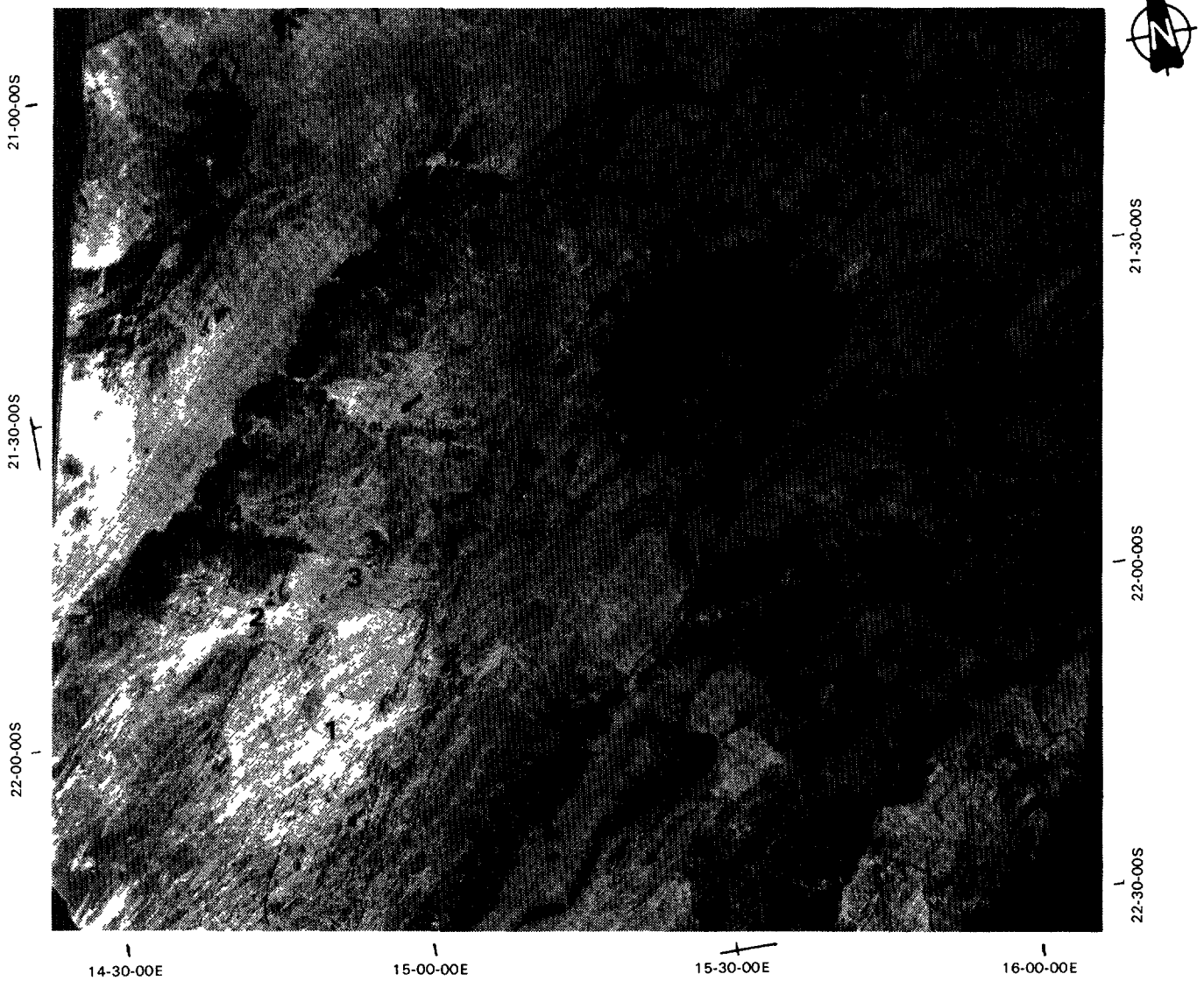


Figure 1
Localities of the Landsat images

Figure 2
Landsat image to a scale of 1:1 000 000 of the Erongo Mountain (central dark area) and environment. The Omaruru River runs to the west and north of the Erongo. Surficial uranium occurrences are shown as follows: 1) Trekkopje, 2) Black Dyke, 3) Spitskoppe, and 4) Marinica (image produced by the South African National Institute of Telecommunications Research, CSIR, Pretoria)



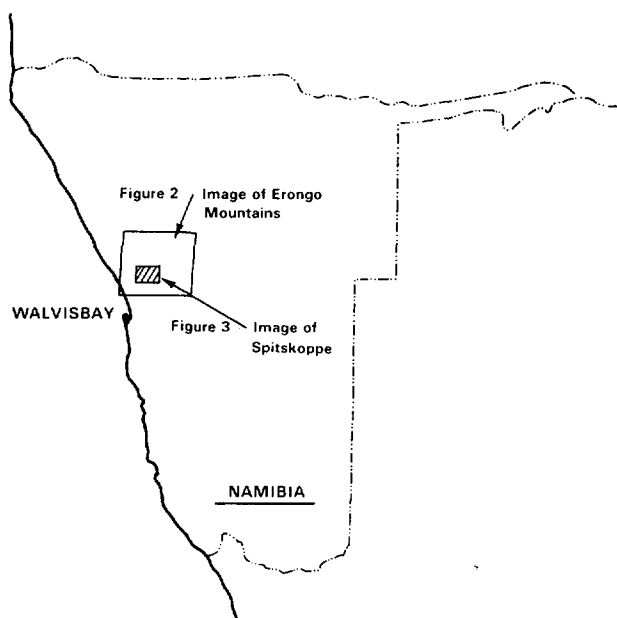
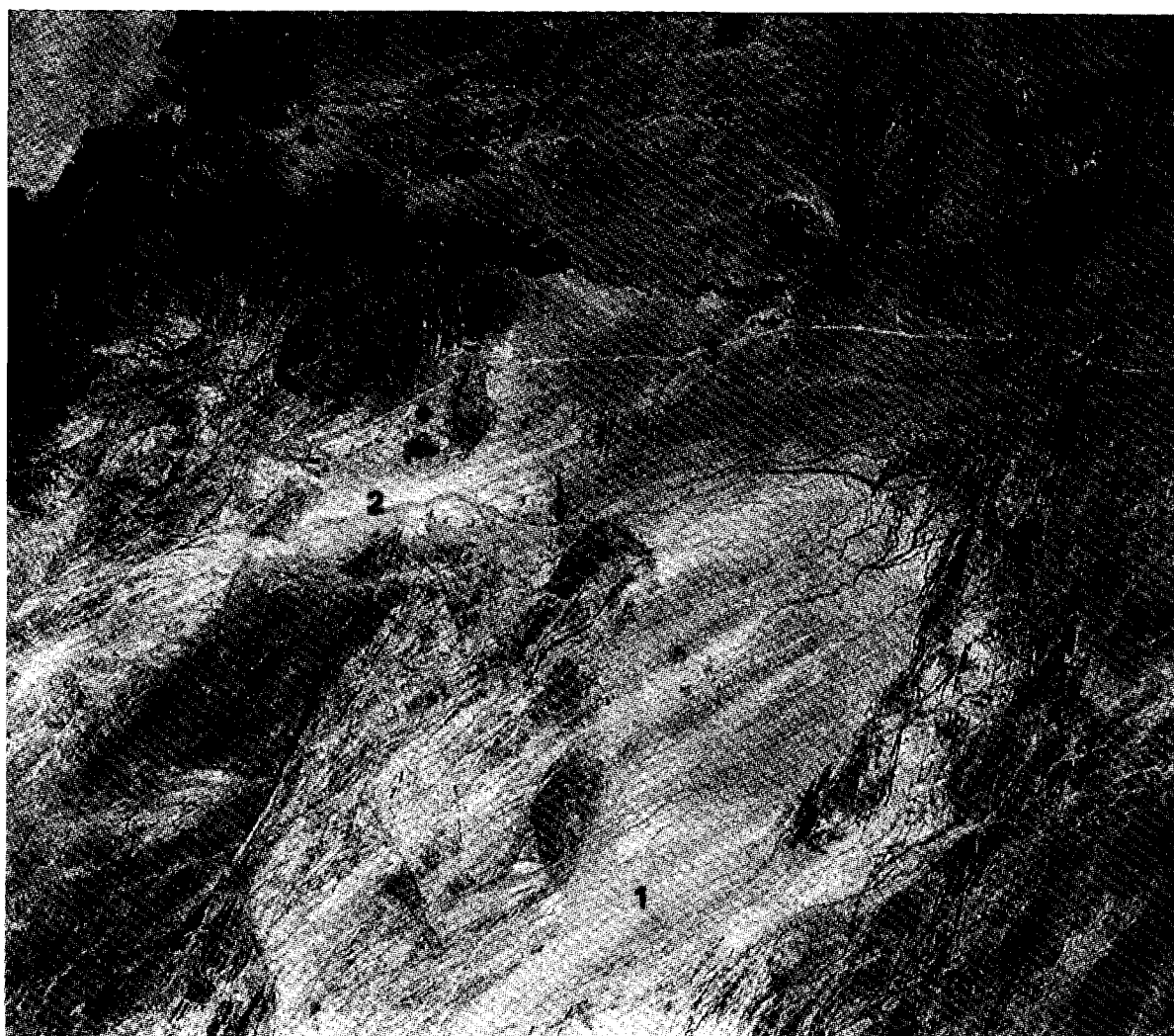


Figure 1
Localities of the Landsat images in the areas investigated in Namibia.

Figure 3
Landsat image to a scale of 1:250 000 of an area in the southwest portion of Figure 2. The Spitskoppe granites occur as prominent inselbergs in the northeast of the image. Surficial uranium occurrences are shown as follows: 1) Trekkopje, 2) Black Dyke, 3) Spitskoppe, and 4) Marinica (image produced by the South African National Institute of Telecommunications Research, CSIR, Pretoria).



AN ASSESSMENT OF THE USE OF HYDROGEOCHEMISTRY IN EXPLORATION FOR CALCRETE URANIUM IN AUSTRALIA

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ABSTRACT

AN ASSESSMENT OF THE USE OF HYDROGEOCHEMISTRY IN EXPLORATION FOR CALCRETE URANIUM IN AUSTRALIA

The role of hydrogeochemistry in exploration for calcrete uranium deposits in Australia is reviewed and the sampling and analytical procedures used are described. The concept of carnotite solubility index (CSI) is introduced and a simplified derivation,

$$\text{CSI} = \log \frac{(U)(V)(K^+)}{1.13 \times 10^4 (\text{HCO}_3)^2}$$

is given for field use. The various interpretation schemes are reviewed and compared. On the basis of experience in Australia, the uranium content of the aquifer was found to provide a guide to the fertility of the system, and anomalous vanadium concentrations in the groundwater could be related to carnotite mineralization. Using the simplified CSI function, values of -3 to zero and upwards were found to be indicative of prospective drainages. It is concluded that water sampling surveys carried out in conjunction with shallow drilling programs make for the most efficient use of hydrogeochemistry in calcrete exploration.

1. INTRODUCTION

A review of the descriptions of calcrete uranium occurrences identified in Western Australia indicates that the majority give either an enhanced radiometric signature [1, 2] or a regional hydrogeochemical anomaly [3]. Thus, in the early years of calcrete uranium exploration, airborne and ground radiometric methods used in conjunction with regional hydrogeochemical surveys were the standard approach. However, as the more obvious outcropping carnotite mineralizations were discovered, reconnaissance radiometric prospecting has been replaced by hydrogeochemical surveys [3] and follow-up drilling in areas selected, for example, by Landsat image palaeodrainage interpretation [4].

Research by government agencies and industry on the genesis of calcrete uranium deposits was undertaken concurrently with exploration, and this resulted in the development of more refined hydrogeochemical evaluation techniques. These innovative approaches were used increasingly as the exploration target changed to buried calcrete uranium deposits.

An example of the more sophisticated hydrogeochemical approach is the method based on calculation of the Carnotite Solubility Index (CSI). The derivation and use of the CSI function was described first by Mann [5] and later again by Mann and Deutscher [6] and is discussed further, elsewhere in this volume [2, 7, 8].

2. SAMPLING AND ANALYTICAL PROCEDURE

2.1 Sampling

For regional hydrogeochemical surveys, any stock wells, stock bores or abandoned drillholes are sampled. Stock watering points are usually equipped with windmills and it is important that water samples be taken directly from the pump outlet pipe only after the line has been flushed when the pump is operating. For unequipped stock wells and standing water drillholes, water samples are obtained by a down-hole sampler. Sufficient water is collected to give two 250 ml samples which are filtered on site. The temperature, pH and conductivity of the sample are measured. One sample is acidified to pH 2 using 10 ml of 10 % nitric acid. Polyethylene screw-top bottles are used for sample storage.

There has been considerable discussion in the literature about the advantages and disadvantages of acidifying water samples for uranium analyses. Waters with high iron or aluminium ion contents will tend to flocculate on standing, even after filtering, so that uranium in the waters will be adsorbed by the flocculant. Acidification prevents this effect and also increases the reliability and precision of any repeat analyses required after a period of storage.

Both samples are then despatched to the laboratory for analysis. The acidified water sample is analysed for uranium, vanadium and potassium and the unacidified sample for bicarbonate, sulphate, and total dissolved solids (TDS). Every tenth sample, or at least one sample per batch, is duplicated to maintain quality control on the analyses.

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2.2 Analyses

Water samples are analysed for vanadium and uranium by XRF using a proprietary method (limit of detection for both elements is 5 ppb). For potassium, a standard atomic absorption spectrometry analysis (AAS) is used and classical methods are used for the determination of sulphate, bicarbonate and TDS.

3. DATA EVALUATION

The data are best presented by preparing regional distribution maps for each element, contoured according to sample population boundaries, and by calculation of carnotite solubility indices. Sample populations are identified from cumulative frequency graphs having ten equal log-normal classes [9] either by calculation [10] or estimation.

The Carnotite Solubility Index (CSI) is calculated for each sample point, using a simplified function derived as follows [11]:

The solubility index for carnotite is given by

$$\text{CSI} = \log \frac{[\text{UO}_2^{2+}] [\text{H}_2\text{VO}_4^-] [\text{K}^+]}{[\text{H}^+]^2 1.41 \times 10^{-7}}$$

The total concentration of uranium in solution [U] is given by:

$$[\text{U}] = [\text{UO}_2^{2+}] + [\text{UDC}] + [\text{UTC}]$$

By rearranging and substituting for the various U, V and carbonate terms,

$$\text{CSI} = \log \frac{[\text{U}] [\text{V}] [\text{K}^+]}{(1 + K_{\text{UDC}} [\text{CO}_3^{2-}]^2 + K_{\text{UTC}} [\text{CO}_3^{2-}]^3) [\text{H}^+]^2 \times 1.41 \times 10^{-7}}$$

where K_{UDC} and K_{UTC} are the equilibria constants for the uranyl dicarbonate complex (UDC) and the uranyl tricarbonate complex (UTC) respectively. For waters with a pH below 8, the predominant complex present is UDC, so that $K_{\text{UDC}} [\text{CO}_3^{2-}]^2 \gg K_{\text{UTC}} [\text{CO}_3^{2-}]^3 \gg 1$ and the UTC equilibria reactions can be neglected. By substituting the HCO_3^- equilibria reactions, rearranging and converting molarities to ppm and ppb,

$$\text{CSI} = \log \frac{[\text{U}] [\text{V}] [\text{K}^+]}{1.13 \times 10^4 [\text{HCO}_3^-]^2}$$

where uranium and vanadium concentrations are in ppb or $\mu\text{g/l}$ and potassium and bicarbonate concentrations are in ppm or mg/l .

The CSI is a function of the uranium, vanadium and potassium interrelationships in carbonated groundwaters, and is a measure of the state of equilibrium between the groundwaters and carnotite mineralization, which may be present in the channel. When CSI is zero, the channel waters and carnotite within the same system are in equilibrium, and when CSI is negative, there will be a tendency for the carnotite to go into solution. When the CSI is positive, the solution is supersaturated with carnotite.

4. DISCUSSION

4.1 Interpretation of Hydrogeochemical Data

Interpretation of regional hydrogeochemical surveys is limited by the diversity of aquifers sampled, but can lead to a broad regional estimate of the amount of uranium in the hydrological system, i.e. the fertility of the system. Most stock wells and bores are restricted to areas of low to medium salinity that are nonprospective for this type of mineralization, although some abandoned bores may be in suitable areas.

To be efficient, detailed hydrogeochemical surveys need to be undertaken in conjunction with reconnaissance drilling. This allows control both of the siting and spacing of samples of the aquifer sampled. In calcrete terrane this can be significant, as the calcretes are themselves often good aquifers and the composition of their waters will differ from those below the calcrete.

Although the fertility of an aquifer can be gauged by the uranium concentration in the water, the CSI is a better overall guide to its prospectivity [12]. The discovery of the Lake Raeside deposit [7] exemplifies the use of this technique and highlights the advantages to be gained from this approach. Nonetheless, the CSI cannot be used uncritically. The calculations assume ideal behaviour of ions in solution, but this is not the case for brines, and experiments by the CSIRO have shown that the measured CSI differs from the theoretical CSI by as much as -2 (A.W. Mann, personal communication).

In hypersaline brines, carnotite tends to dissolve incongruently rather than form equilibrium concentrations of uranium, vanadium and potassium, furthermore, waters with a salinity of above 20 000 ppm inhibit the solution of uranium because of their low bicarbonate content.

Experimental errors resulting from field procedures such as on-site sample filtering also contribute to CSI variation from ideal behaviour through removal of bicarbonate from solution [8].

All the conditions mentioned above tend towards a lowering of the bicarbonate concentration in solution and therefore to more negative CSI values at equilibrium.

A fact seldom considered is that CSI calculations assume the vanadium content of a particular water to be in the pentavalent state. If this is not true and vanadium is present as V (IV), then the vanadium is not available for carnotite formation and the CSI calculation is meaningless.

Thus, calculated CSI values need to be used with caution in relation to previous experience and relative to CSI values in the same drainage. From experience, the lower threshold for uranium hydrogeochemical anomalies is 40 to 50 ppb U_3O_8 . It has been found that using the simplified CSI, prospective areas for calcrete uranium deposits were indicated by a CSI of -3 and upwards (towards positive values).

Generally, when the CSI tends to approach zero (from below the threshold of -3) downstream along the channel, it is indicative of an approaching site of carnotite deposition and a prospective area for calcrete uranium [5]. Within a prospective channel, significant variations in the CSI of the water usually take place within 1 km of the mineralization. Nonetheless, regional CSI variations indicative of mineralization within the channel waters may be defined by sample spacings up to 4 km apart along the channel axis. However, it must be emphasized that the main purpose of the CSI is to indicate prospective drainages rather than to pinpoint areas of carnotite mineralization. This is exemplified by the case study described below.

Research by Hostetler [in 12] on the carbonate-carnotite-gypsum precipitation sequence in maturing bicarbonate-rich waters, has documented the changes in concentration levels of the major components (U, V, K, Ca, bicarbonate and carbonate) that occur as precipitation proceeds within the hydrological system. Variations are compared against the potassium content of the water. Most carbonate precipitation occurs at 300 to 400 ppm potassium and, where sufficient uranium and vanadium are available, carnotite precipitation takes place in the range 700 to 800 ppm potassium. Carnotite precipitation tapers off until the potassium content reaches 1 000 ppm, when gypsum is precipitated.

As there is an apparent broad linear relationship between the potassium content, the salinity and the conductivity of a water, potassium content can be readily estimated in the field. The relationship varies regionally but can be established for a given area with a few orientation samples. Because waters of low to medium salinity are not considered prospective, conductivity field measurements can lead to reductions in analytical costs.

The potassium concentration equivalent to carnotite precipitation also may apply to the dissociation of carnotite. However, as carnotite may dissolve incongruently, the channel waters can have enhanced vanadium contents. Therefore, the presence of anomalous vanadium concentrations may be an important criterion for the recognition of prospective calcrete channels [6].

When CSI function values forming a local data set are evaluated individually with reference to the potassium concentrations derived from Hostetler's precipitation sequence, the efficiency of the CSI approach is increased. An example of this is described below.

4.2 Hydrogeochemical case study from Central Australia

From interpretation of Landsat imagery, it was noticed that an extensive valley system formed the source to an area where patchy carnotite mineralization within calcretes was previously known. It was considered that the valley may contain valley-fill uranium deposits.

The valley area was auger drilled on 4 x 1 km centres and all holes geologically and radiometrically logged. Where the water table was intersected, water samples were taken and the temperature, pH and conductivity of the water noted. A selection of water samples was analysed for uranium, vanadium, potassium, bicarbonate and total dissolved solids (TDS).

The data in Table 1 represent a traverse of drillholes within the calcreted valley, extending for 32 km downstream from the headwaters to the confluence with the mineralized channel. Samples WS777 and WS799 are taken from within the area containing calcrete uranium mineralization.

Although the uranium and vanadium concentrations are moderately enhanced within the valley, the potassium content is consistently less than 100 ppm and reflects the low salinity of the water. Even the sample point furthest downstream (MH24), which contains 95 ppb U_3O_8 , has a potassium content far less than the carnotite precipitation value. The two samples from within the mineralized area are also low in potassium but others in the vicinity contain several thousand ppm potassium. Sample WS65, taken during an earlier survey within the mineralized channel, is an example. The influence of salinity both on the concentration of uranium in solution and the potassium concentration is exemplified by WS65. Although the uranium content is only marginally anomalous, the high vanadium concentration and the -1.90 CSI mark this sample as being derived from a mineralized channel. For further illustration, the results from WS56, sampled at the same time and in the same area as WS65, are also given. Although these samples from within the mineralized channel show a range of values for uranium, vanadium, and potassium, all CSI's were in the -3 to zero range.

It is suggested that the carnotite mineralization is the result of the mixing of uraniferous waters of low salinity and hypersaline ponded waters. Because carnotite equilibrium is approached only after the valley confluence with the

Table 1
Hydrogeochemical results, central Australia

Sample Point	Water Table Depth (m)	pH	U ₃ O ₈ (ppb)	V (ppb)	K (ppm)	HCO ₃ (ppm)	TDS (ppm)	CSI
MH 73	8.5	7.4	18	18	37	265	835	-4.9
MH 77	6.5	7.4	35	30	51	375	615	-4.5
MH 83	6.7	7.5	70	120	83	795	1 360	-4.1
MH 61	7.0	7.7	15	25	52	480	1 340	-5.2
MH 50	6.5	7.8	30	90	80	710	1 370	-4.5
MH 35	7.5	7.8	50	35	69	575	1 770	-4.6
MH 24	7.5	7.6	95	35	137	470	2 940	-3.8
WS 777	2.5	7.5	70	250	220	560	40 630	-3.0
WS 799	4.0	7.3	210	240	185	325	31 020	-2.2
WS 56	4.0	7.6	244	120	890	585	27 320	-2.3
WS 65	4.0	7.2	42	120	2 725	280	93 810	-1.9

mineralized area, it is considered that the valley area holds no potential for calcrete uranium deposits. This conclusion is reinforced by the geological characteristics of the valley-fill sediments.

The variation in results for the mineralized channel highlights the difficulties experienced when comparing hydrogeochemical results from different sampling programmes. The greatest variation is shown by potassium and this may be the result of one or several factors:

1. areal and/or vertical inhomogeneity within the aquifer, giving rise to compositional differences;
2. partial adsorption of potassium by clays;
3. variation in solution equilibria within the mineralized channel over the period between the two sampling programs;
4. variation in sampling practice such as difference in time elapsed between sampling and drilling of boreholes.

5. CONCLUSION

The most effective method of exploration in Australia is shallow auger drilling combined with geological and hydrogeochemical sampling and downhole radiometry within the calcreted channel. The fertility of a channel system can be gauged by the uranium content of the water, but a better overall guide to prospectivity is the Carnotite Solubility Index (CSI).

ACKNOWLEDGEMENT

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REFERENCES

- [1] BUTT, C.R.M., HORWITZ, R.C., MANN, A.W., Uranium occurrences in calcrete and associated sediments in Western Australia, Aust. CSIRO Div. Mineral. Report FP16 (1977) 67.
- [2] BUTT, C.R.M., MANN, A.W., HORWITZ, R.C., Regional setting, distribution and genesis of surficial uranium deposits in calcretes and associated sediments in Western Australia, this Volume.
- [3] CAMERON, E., MAZZUCHELLI, R.H., ROBINS, T.W., Yeelirrie calcrete uranium deposit, Murchison Region, W.A., In: Conceptual Models in Exploration Geochemistry Butt, C.R.M., Smith, R.E., (Ed.), 4, J. Geochem. Explor. 2 (1980) 350-353.
- [4] KRISCHE, E.U., QUIEL, F., The application of digital analysis to Landsat imagery for locating surficial uranium deposits in Western Australia, this Volume.
- [5] MANN, A.W., Nature and origin of uranium deposits in calcrete, In: Recent Geological Research Relating Low Temperature Aqueous Geochemistry to Weathering, Ore Genesis and Exploration, Glover, J.E., Groves, D.E., (Eds.), Western Aust. Geol. Dept. and Extension Service, Publ. 1 (1980) 14-27.
- [6] MANN, A.W., DEUTSCHER, R.L., Genesis principles for the precipitation of carnotite in calcrete drainages in Western Australia, Econ. Geol. 73 (1978) 1724-1737.
- [7] GAMBLE, D.S., The Lake Raeside uranium deposit, this Volume.
- [8] HAMBLETON-JONES, B.B., SMIT, M.C.B., Calculation of the carnotite solubility index, this Volume.

- [9] LEPELTIER, C., A simplified statistical treatment of geochemical data by graphical representation, *Econ. Geol.* 64 (1969) 538–550.
- [10] SINCLAIR, A.J., Applications of Probability Graphs in Mineral Exploration, *Special Publ. Vol. 4, Assoc. Explor. Geochemists* (1976) 95.
- [11] APPLEYARD, S.J., The occurrence and distribution of uranium at Lake Moore, Western Australia, *Hons. Thesis, University of Western Australia* (unpubl.) (1979).
- [12] SHARP, W.H., Hydrogeochemical exploration for calcrete uranium deposits in Western Australia, *M.Sc. Project, Townsville University* (unpubl.) (1981).

CALCULATION OF THE CARNOTITE SOLUBILITY INDEX

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ABSTRACT

CALCULATION OF THE CARNOTITE SOLUBILITY INDEX

The carnotite solubility index (CSI) has been found to be a useful prospecting technique for carnotite-rich uranium ore deposits. The approach adopted here for the calculation of the CSI utilizes actual concentrations of U, V, K, HCO_3^- and pH determined in groundwaters which are used directly in a formula. A comparison is made of the CSI formulae proposed in this paper with those of Middleton [3]; and Gamble [4].

1. INTRODUCTION

Based on the principles of chemical equilibrium, and under certain conditions of pH and HCO_3^- concentration, the elements potassium, vanadium and uranium will combine to form carnotite. Figure 1 shows the field of carnotite stability in terms of the ion product ($\Sigma K \cdot \Sigma V \cdot \Sigma U \text{ ppm}^3$) and pH [1]. Maximum carnotite stability occurs at pH = 6, whereas above and below this value carnotite begins to dissolve.

At equilibrium and at the stage where carnotite starts to precipitate, the following relationship will hold:

$$\text{CSI} = \frac{10^{\text{pH}-9.02} \Sigma K \cdot \Sigma U \cdot \Sigma V}{1 + 10^{4.15-\text{pH}} + 10^{-5.69+\text{pH}}(\text{BC})^2 + 10^{-17.00+2\text{pH}}(\text{BC})^3} \dots\dots\dots (\text{A})$$

- where CSI = carnotite solubility index
K = total potassium concentration (expressed as ppm or mg/l of the metal in solution)
U = total uranium concentration (expressed as ppb or $\mu\text{g/l}$ of the metal in solution)
V = total vanadium concentration (expressed as ppb or $\mu\text{g/l}$ of the metal in solution)
(BC) = bicarbonate concentration, excluding CO_3^{2-} and H_2CO_3 , in aqueous solution (expressed as ppm or mg/l).

With the aqueous solution in contact with carnotite, the following generalizations can be made:

- when $\text{CSI} > 1$ the solution is oversaturated with carnotite and it will precipitate;
- when $\text{CSI} = 1$ carnotite is in equilibrium with the aqueous solution;
- when $\text{CSI} < 1$ the solution is undersaturated with carnotite and the latter will dissolve.

It is important to note that the CSI is determined using actual concentrations of the active species in solution e.g. K, U, V, HCO_3^- and pH.

In practice it is very cumbersome to calculate the CSI using this formula. To simplify the calculation, two methods are described, (1) a graphical technique and (2) the use of a programmable HP41CV pocket calculator.

2. GRAPHICAL METHOD

This method employs a series of curves (Figure 2) determined for various concentrations of U, V, K, HCO_3^- and pH where isovalues of the ion product $\Sigma U \cdot \Sigma V \cdot \Sigma K \text{ ppm}^3$, are affected by changes in HCO_3^- and pH values [2].

The following procedure is adopted when calculating the CSI using the concentration values obtained from chemical analyses in either ppb or ppm as specified for the formula above.

1. Multiply the concentrations of K, V, and U together from the analyses to obtain the ion products $K \cdot V \cdot U \dots(\text{A})$
2. Using the analyses of HCO_3^- and pH, determine the point on Figure 2 and then interpolate another $K \cdot V \cdot U$ value from between the $K \cdot V \cdot U$ isolines $\dots(\text{B})$

3. Calculate the ratio

$$\frac{\text{A}}{\text{B}} = \text{CSI}$$

As the values tend to be rather small, use Log CSI instead.

3. HP41CV METHOD

The HP41CV pocket calculator can easily be programmed to calculate the CSI from the above equation. Below, a listing of the program followed by the operating instructions is given (R.G. Heard, personal communication).

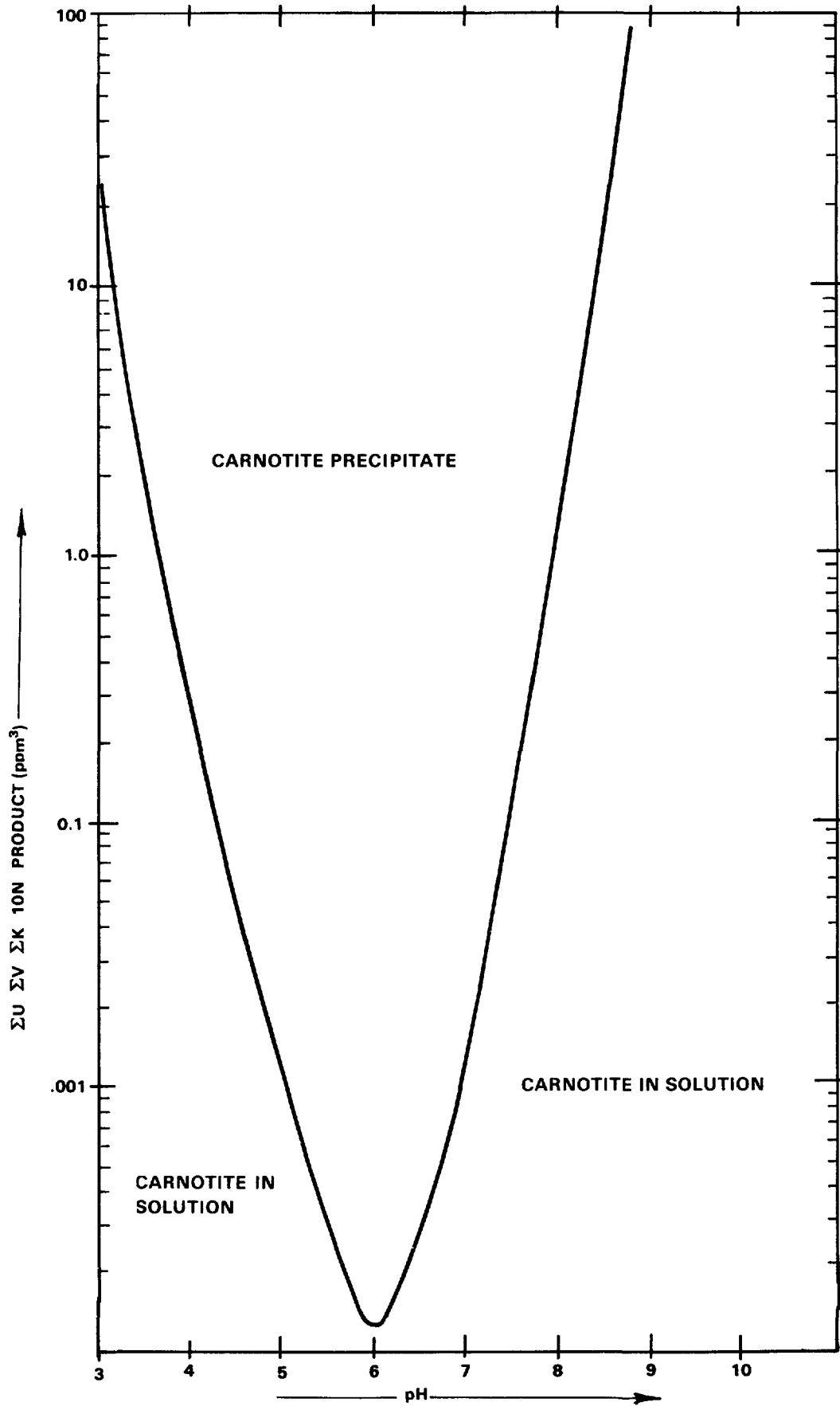


Figure 1
 The stability of carnotite $K_2(UO_2)_2(VO_4)_2 \cdot 3H_2O$, defined in terms of the ion products, $\Sigma K \cdot \Sigma V \cdot \Sigma U$ ppm³ and pH [1].

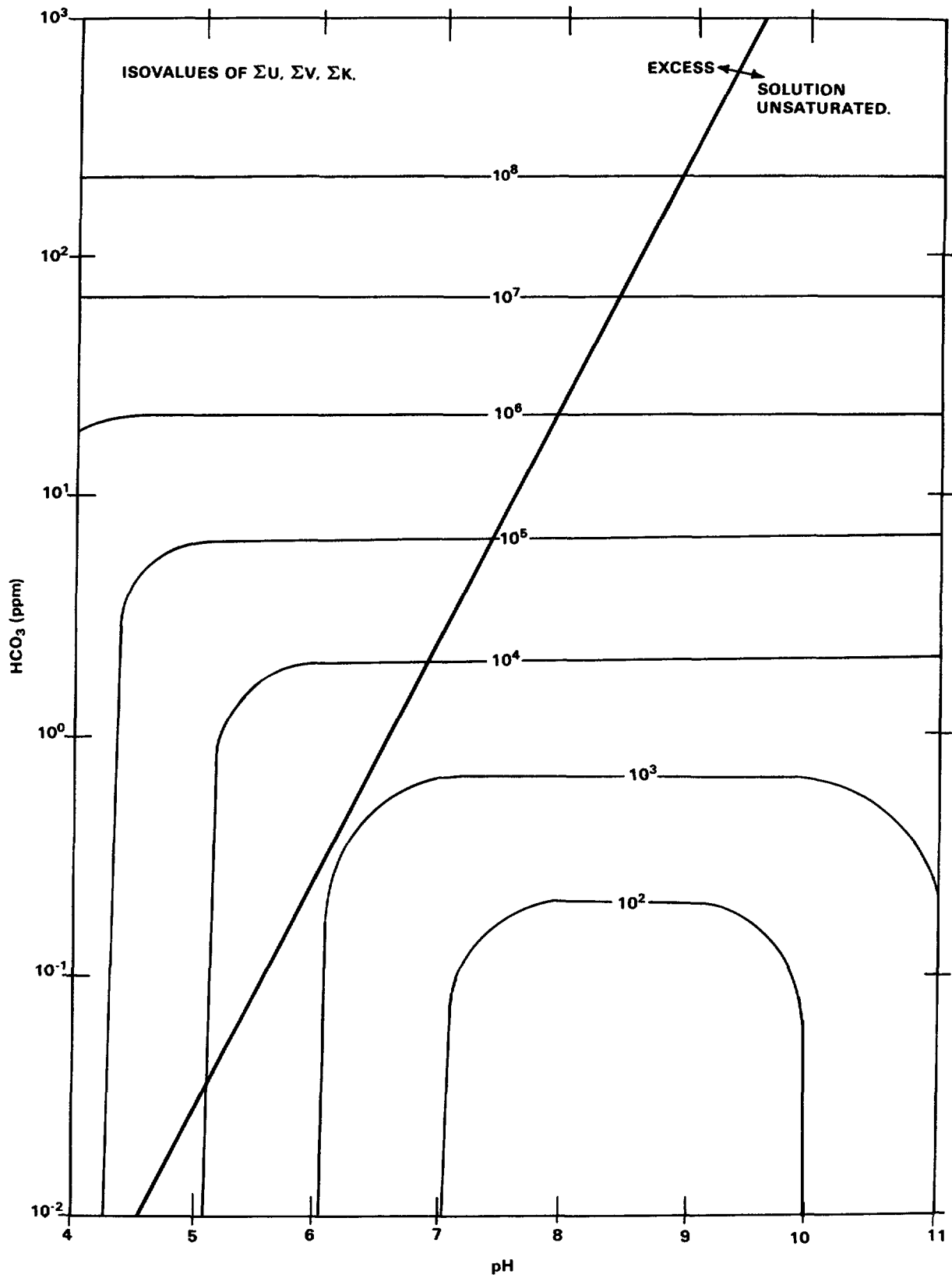


Figure 2
 The $\text{CO}_2/\text{HCO}_3^-/\text{CO}_3^{2-}$ equilibrium plotted in terms of HCO_3^- and pH is shown. The curves of the isovalues of the ion product $\Sigma K, \Sigma V, \Sigma U$ are also given [2].

3.1 Program Listing

(a) Used **with** accompanying HP printer

01 LBL "CSI"	28 STO 01	55 10 \uparrow X	82 1
02 CLRG	29 "U?"	56 STO 06	83 ENTER \uparrow
03 SF 12	30 PROMPT	57 CLX	84 RCL 06
04 "CSI"	31 STO 02	58 -5.69	85 +
05 PRA	32 "V?"	59 ENTER \uparrow	86 RCL 07
06 CF 12	33 PROMPT	60 RCL 00	87 +
07 LBL 01	34 STO 03	61 +	88 RCL 08
08 ADV	35 "BC?"	62 10 \uparrow X	89 +
09 FIX 0	36 PROMPT	63 RCL 04	90 STO 09
10 "SAMPLE NO"	37 STO 04	64 X \uparrow 2	91 RCL 05
11 AVIEW	38 RCL 00	65 *	92 ENTER \uparrow
12 PSE	39 ENTER \uparrow	66 STO 07	93 RCL 09
13 AON	40 9.02	67 CLX	94 /
14 "ALPHA?"	41 -	68 RCL 00	95 LOG
15 PROMPT	42 10 \uparrow X	69 ENTER \uparrow	96 "CSI="
16 ACA	43 RCL 01	70 2	97 ARCL X
17 AOFF	44 *	71 *	98 AVIEW
18 "NUMBER?"	45 RCL 02	72 17	99 STOP
19 PROMPT	46 *	73 -	100 XEQ "LINE"
20 ACX	47 RCL 03	74 10 \uparrow X	101 ADV
21 ADV	48 *	75 RCL 04	102 LBL "LINE"
22 FIX 2	49 STO 05	76 ENTER \uparrow	103 SF 12
23 "PH?"	50 CLX	77 3	104 "-----"
24 PROMPT	51 4.15	78 Y \uparrow X	105 PRA
25 STO 00	52 ENTER \uparrow	79 *	106 CF 12
26 "K?"	53 RCL 00	80 STO 08	107 GTO 01
27 PROMPT	54 -	81 CLX	108 END

(b) Used **without** printer

From the program listing in (a) above:

1. Delete the following steps, 03-21 and 100-106
2. Change 107 to read GTO "CSI"

3.2 Operating Instructions

(a) Used **with** accompanying printer

1. Switch on printer and calculator
2. Set printer mode to either MAN or NORM
3. ASN (assign) the program to any key in user mode, i.e. press USER 2nd ASN alpha CSI alpha TAN (25)
4. Press TAN, i.e. XEQ "CSI"
5. Calculator prompts for SAMPLE NO? (PSE) ALPHA?
Key in letter, e.g. P, Press R/S
6. Calculator prompts NUMBER?
Key in sample number, e.g. 125 R/S.
7. Calculator prompts pH?
Key in pH, e.g. 7.7 R/S
8. Calculator prompts K?
Key in K, e.g. 570 R/S
9. Calculator prompts U?
Key in U, e.g. 25 R/S
10. Calculator prompts V?
Key in V, e.g. 40 R/S
11. Calculator prompts BC?
Key in BC, e.g. 110 R/S
12. Calculator prints **CSI = - 1.67 (ANSWER)**
13. Press R/S for next sample.

(b) Used **without** printer

Delete steps 2, 6 and 7.

4. COMPARISON BETWEEN CSI FORMULAE

In this volume three formulae are given by 1) Hambleton-Jones and Smit (this paper); 2) Middleton [3]; and 3) Gamble [4] for the calculation of the carnotite solubility index. This could be very confusing for those unfamiliar with the chemical equilibria of the uranium species in solution, and an attempt is made here to clarify the differences involved.

Middleton [3]; Gamble [4] and Hambleton-Jones and Smit (this paper) use different definitions of the solubility index so that:

$$\text{CSI (Middleton)} = \log \text{CSI (Gamble; Hambleton-Jones and Smit)}$$

Middleton states:

$$\text{CSI} = \log \frac{[\text{UO}_2^{2+}] [\text{H}_2\text{VO}_4^-] [\text{K}^+]}{[\text{H}^+]^2 1.41 \times 10^{-7}} = \log \frac{[\text{UO}_2^{2+}] [\text{H}_2\text{VO}_4^-] [\text{K}^+]}{[\text{H}^+]^2 10^{-6.85}}$$

This is equivalent to Gamble (except for log)

But it is only possible to measure the **total uranium**

$$[\text{U}] = [\text{UO}_2^{2+}] + [\text{UO}_2(\text{OH})^+] + [\text{UO}_2(\text{CO}_3)_2^{2-}] + [\text{UO}_2(\text{CO}_3)_3^{4-}].$$

Both Gamble and Middleton ignore $\text{UO}_2(\text{OH})^+$. In practice this should not be so because for $\text{pH} > 4.2$, $[\text{UO}_2(\text{OH})^+] > [\text{UO}_2^{2+}]$ and therefore their simplification may not be justified. In Figure 3 the relative stabilities and contributions of the uranyl ion species between pH 3 and 10 for solutions saturated with CO_2 , (i.e. air at STP where $P_{\text{CO}_2} = 10^{-3.5}$) are given, which illustrate the significance of $\text{UO}_2(\text{OH})^+$ in relation to UO_2^{2+} and $\text{UO}_2(\text{CO}_3)_2^{2-}$.

It is assumed that

$$[\text{UO}_2(\text{OH})^+] = 0$$

$$[\text{UO}_2(\text{CO}_3)_2^{2-}] / [\text{UO}_2^{2+}] [\text{CO}_3^{2-}]^2 = K_{\text{UDC}}$$

$$[\text{UO}_2(\text{CO}_3)_3^{4-}] / [\text{UO}_2^{2+}] [\text{CO}_3^{2-}]^3 = K_{\text{UTC}}$$

$$[\text{U}] = [\text{UO}_2^{2+}] + [\text{UO}_2^{2+}] [\text{CO}_3^{2-}]^2 K_{\text{UDC}} + [\text{UO}_2^{2+}] [\text{CO}_3^{2-}]^3 K_{\text{UTC}}$$

$$\text{or CSI} = \log \frac{[\text{U}] [\text{H}_2\text{VO}_4^-] [\text{K}^+]}{(1 + [\text{CO}_3^{2-}]^2 K_{\text{UDC}} + [\text{CO}_3^{2-}]^3 K_{\text{UTC}}) [\text{H}^+]^2 \times 1.41 \times 10^{-7}}$$

as given by Middleton

$$\text{or CSI} = \log \frac{[\text{U}] [\text{H}_2\text{VO}_4^-] [\text{K}^+]}{[\text{CO}_3^{2-}]^2 K_{\text{UDC}} [\text{H}^+]^2 1.41 \times 10^{-7}};$$

it assumes $[\text{UO}_2^{2+}]$ and $[\text{UO}_2(\text{CO}_3)_3^{4-}] \ll [\text{UO}_2(\text{CO}_3)_2^{2-}]$.

Using equation (A) and making the following assumptions:

$$[\text{UO}_2^{2+}] \ll [\text{UO}_2(\text{CO}_3)_2^{2-}], \text{ term "1" disappears}$$

$$[\text{UO}_2(\text{OH})^+] \ll [\text{UO}_2(\text{CO}_3)_2^{2-}], \text{ term } 10^{4.15-\text{pH}} \text{ disappears}$$

$$[\text{UO}_2(\text{CO}_3)_3^{4-}] \ll [\text{UO}_2(\text{CO}_3)_2^{2-}], \text{ term } 10^{-17+2\text{pH}} (\text{BC})^3 \text{ disappears}$$

and introducing the log of Middleton,

$$\begin{aligned} \text{CSI} &= \log \frac{10^{\text{pH}} \cdot 10^{-9.02} [\text{K}] [\text{U}] [\text{V}]}{10^{\text{pH}} \cdot 10^{-5.69} [\text{HCO}_3^-]^2} \\ &= \log \frac{[\text{K}] [\text{U}] [\text{V}]}{[\text{HCO}_3^-]^2 \times 10^{3.33}} = \log \frac{[\text{K}] [\text{U}] [\text{V}]}{2.14 \times 10^4 [\text{HCO}_3^-]^2} \end{aligned}$$

$$\text{Compare CSI} = \log \frac{[\text{K}] [\text{U}] [\text{V}]}{1.13 \times 10^4 [\text{HCO}_3^-]^2} \text{ from Middleton.}$$

Therefore, making all the above assumptions, it appears that the three formulae of Hambleton-Jones and Smit; Middleton; and Gamble are reasonable approximations, but in the cases of the latter two authors, oversimplifica-

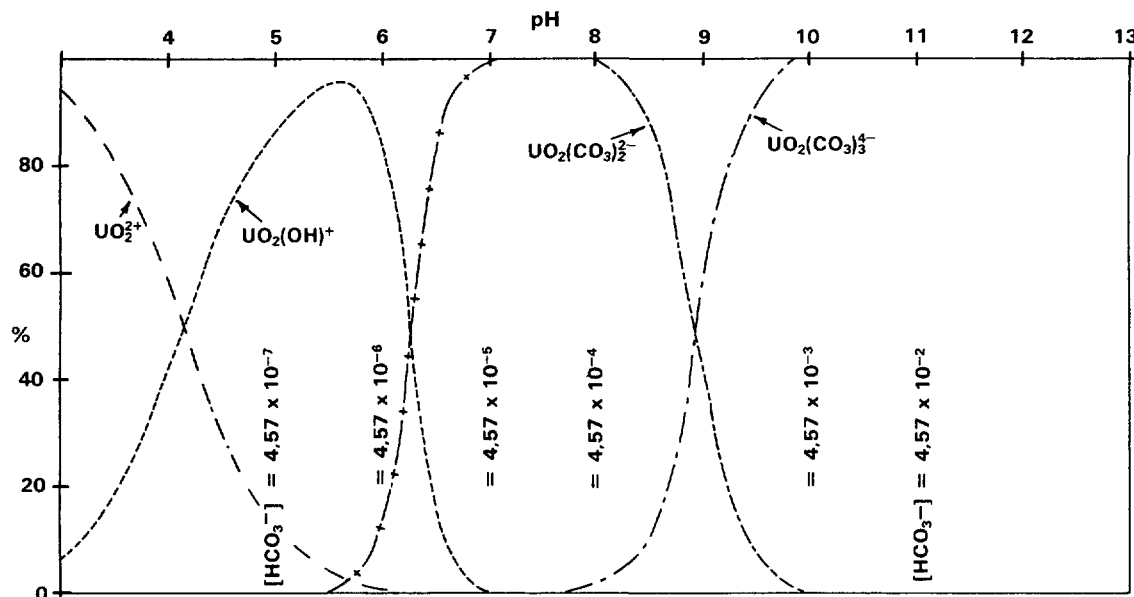


Figure 3

Relative abundance of the uranyl carbonate complexes at different pH values. Solution saturated with CO_2 (i.e. air at STP giving $P_{\text{CO}_2} = 10^{-3.5}$).

tions have been introduced. However, considering the likelihood that large analytical inaccuracies may arise during the determination of U, K, V, pH and HCO_3^- and the inability to quantify natural variations in P_{CO_2} , oxidation potential and adsorption phenomena, any differences in the three formulae may, to all intents and purposes, be ignored.

5. CONCLUSION

From experience it has been found that even under ideal conditions, i.e. a possible equilibrium situation, the CSI does not reach 1, but is generally very much lower. It is not uncommon to have CSI values of ~ 3 in those areas favourable for carnotite mineralization. These low CSI values are due to the fact that the equations are based on theoretical chemical equilibria for ideal solutions. In nature the precipitation of carnotite does not take place from ideal solutions, but from ones that may be relatively concentrated with other salts. Furthermore, the precipitation of carnotite is also influenced by the oxidation potential of the groundwater and the presence of clays and hydrated iron oxides where nucleation and adsorption onto the surfaces can take place. It might therefore be advisable to use a CSI value which may be below unity as the threshold between anomalous and background values.

In addition, the accuracy of the CSI is also determined by the technique of sample collection; for example, HCO_3^- may dissociate to CO_3^{2-} and consequently a higher pH if it has not been analysed before periods longer than a few hours. Another problem is the phenomenon of adsorption of uranium and vanadium ions onto interior walls of plastic sample bottles. Therefore, in interpreting the CSI data, these factors should be taken into account.

The three formulae used to calculate the CSI as defined in this paper; by Middleton [3]; and by Gamble [4], although different, are all comparable because natural variations of some parameters and analytical inaccuracies cannot be taken into account.

REFERENCES

- [1] MANN, A.W., Calculated solubilities of some uranium and vanadium compounds in pure and carbonated waters as a function of pH, CSIRO Report no. FP6 (1974) 39.
- [2] HAMBLETON-JONES, B.B., JAKOB, W.R.O., SMIT, M.C.B., Geochemical techniques for the prospecting of uranium ore deposits. Training Course on Radiometric Prospecting, Pelindaba Lecture 11 (1979) 36.
- [3] MIDDLETON, W.G., An assessment of the use of hydrogeochemistry in exploration for calcrete uranium deposits in Australia, this Volume.
- [4] GAMBLE, D.S., The Lake Raeside uranium deposit, this Volume.

NATURAL AND INDUCED DISEQUILIBRIUM IN SURFICIAL URANIUM DEPOSITS

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ABSTRACT

NATURAL AND INDUCED DISEQUILIBRIUM IN SURFICIAL URANIUM DEPOSITS

Natural disequilibrium within a surficial uranium deposit can vary widely, and care should be taken when comparing radiometric uranium concentration data from specific zones. For the deposit as a whole, the average disequilibrium tends approximately to unity. This implies that within a deposit, the uranium is constantly being dissolved and reprecipitated.

Induced disequilibrium is brought about by the loss of ^{222}Rn during percussion drilling. This causes an apparent lowering of the uranium concentration due to a decrease in gamma-ray activity. This can be compensated for by applying a radon correction factor or allowing the sample to re-equilibrate after 13 d. The procedure of compensating for induced disequilibrium is suitable for those situations where chemical analytical facilities are not easily available and where on site radiometric monitoring of uranium grade is desirable.

1. INTRODUCTION

During prospecting for surficial uranium deposits, the geologist should be aware of two main sources of disequilibrium:

1. **Natural disequilibrium.** This is a problem which can lead to errors in the ore resource estimation. Uranium in the ore is mobile, as a result of periodic fluctuations in the elevation of the groundwater table caused by changes in the climatic conditions.
2. **Induced disequilibrium.** This occurs during percussion drilling and is caused by the degassing of radon, whereby errors are induced in the on site radiometric determination of uranium.

2. NATURAL DISEQUILIBRIUM IN A FLUVIATILE SURFICIAL DEPOSIT: A CASE STUDY

Natural disequilibrium in an uranium ore deposit can take place in one of several ways, the most common being:

1. the uranium may be freshly deposited from solution so that insufficient time has lapsed for the radioactive growth of ^{226}Ra and its daughter gamma-emitting isotopes;
2. the uranium has been leached from originally ore-grade material, leaving behind unsupported ^{226}Ra .

Therefore, in the first case, if a scintillometer or spectrometer is used for grade control, the equivalent uranium will be low, whereas in the second, the equivalent uranium will be high. These factors will have serious implications for spectrometric ore resource estimation and grade control during mining, in, for example, bulk grade determination of ore on trucks and the use of radiometric sorting methods [1].

These problems were investigated in a case study during the evaluation of a surficial uranium deposit. Percussion borehole chip samples were packed in plastic bags on site and a portion of each was sent for a chemical assay. The grades of the percussion pulps were determined in the field using a calibrated spectrometer and a fixed sample geometry. The ratio

$$\frac{\text{Chemical } \text{U}_3\text{O}_8}{\text{Spectrometric } e\text{U}_3\text{O}_8}$$

is therefore a measure of the disequilibrium in the ore deposit. On this basis the following relationships apply:

Values

greater than 1 = **Positive disequilibrium.** Uranium has been freshly deposited giving a low equivalent grade and a high chemical assay. This implies that uranium is young and the ^{226}Ra has had insufficient time to attain secular equilibrium.

equal to 1 = **Secular equilibrium.**

less than 1 = **Negative disequilibrium.** Uranium has been leached, leaving a proportion of unsupported ^{226}Ra behind. This will result in a high equivalent grade and a low chemical assay.

In individual percussion drill holes, disequilibrium values were calculated for all samples having a chemical assay in excess of 75 ppm U_3O_8 . A mean disequilibrium value was calculated for the individual holes studied and plotted on a map (Figure 1). The contours show that there are distinct zones of both positive and negative

disequilibrium. Furthermore, there is a correlation between the thickness of the surficial sediment (Figure 2) and the state of disequilibrium in the uranium ore. Generally, where the mineralization occurs in shallow portions of the channel, the disequilibrium is positive, with the converse applying to the deeper areas. It appears, therefore, that in the shallower areas the "barrier effect" applies, causing "younger" uranium to precipitate. In the western portion of Figure 1, a "wedge" of positive disequilibrium occurs behind a basement marble barrier. Towards the centre of the deposit the channel narrows considerably, having the same effect, with the positive disequilibrium extending eastwards along the southern shoulder of the palaeodrainage.

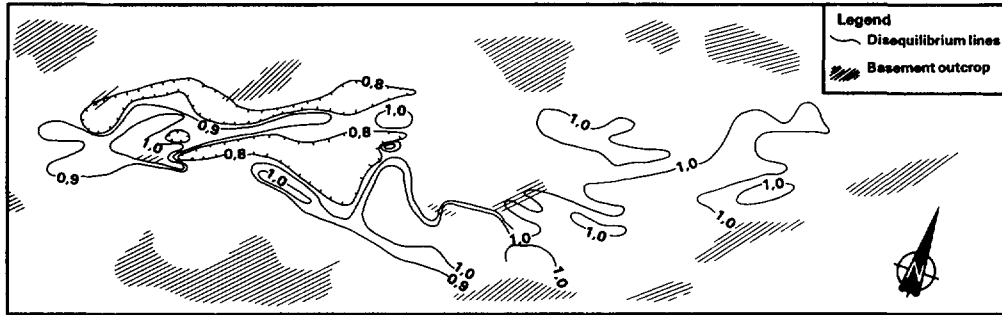


Figure 1
The distribution of disequilibrium values in a surficial uranium ore deposit.

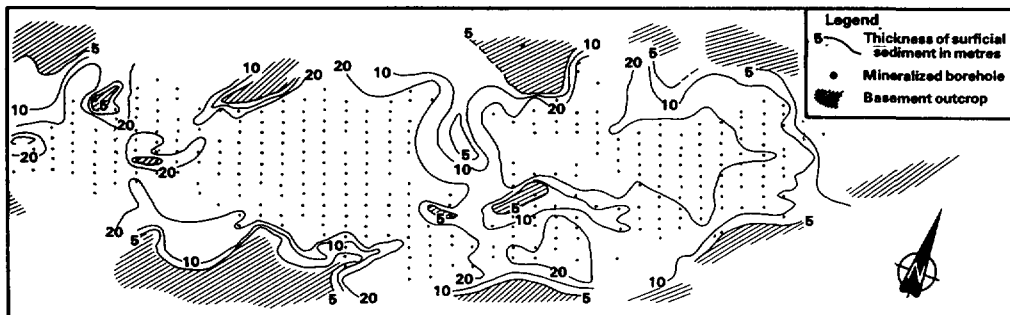


Figure 2
Thickness contours of the surficial sediments in the same deposits as in Figure 1.

A histogram (Figure 3) of all the data totalling 773 analyses shows a distinct positive skewness with a mode at about 0.85. After plotting the results on log probability graph paper (Figure 4), two populations, A and B, appeared which are both log-normally distributed. The means and percentage distributions for both populations are as follows:

Population	Mean	% Distribution
A	1.7	9
B	1.1	91

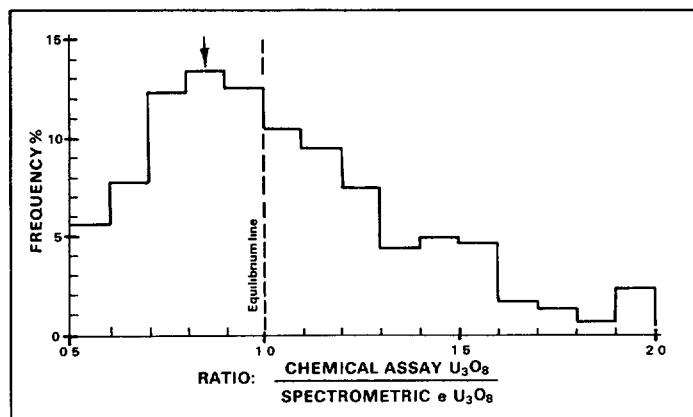


Figure 3
Histogram showing the distribution of the disequilibrium.

The major portion of the data (91 %) falls into population B, with only a minor portion (9 %) associated with population A. Although the uranium in population B has a wide range in disequilibrium values of between 0.5 and approximately 1.4, the mean value of 1.1 is very close to equilibrium. This indicates that the uranium has remained in the closed system of the deposit, but that it is being continually dissolved and reprecipitated, due to

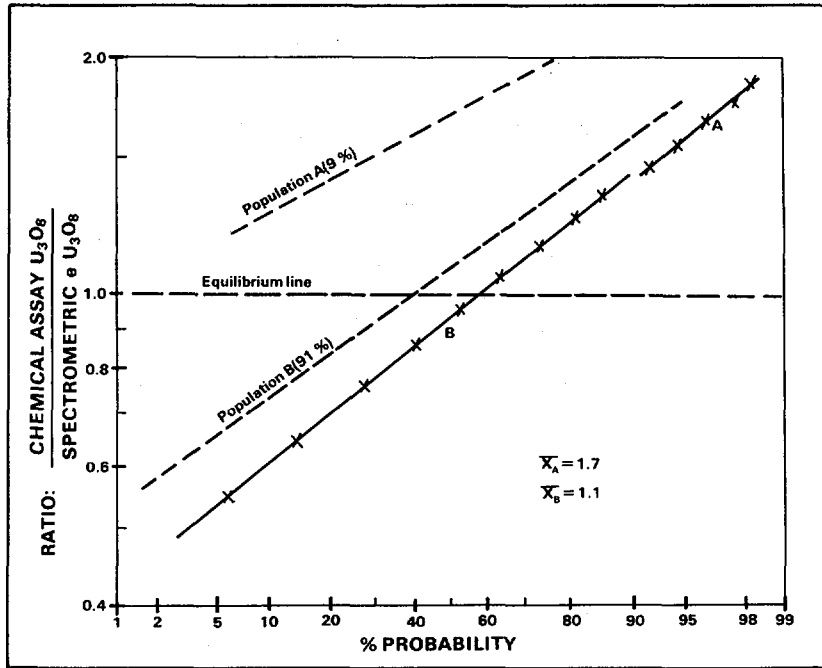


Figure 4
Probability graph of the disequilibrium data for the deposit in Figure 3.

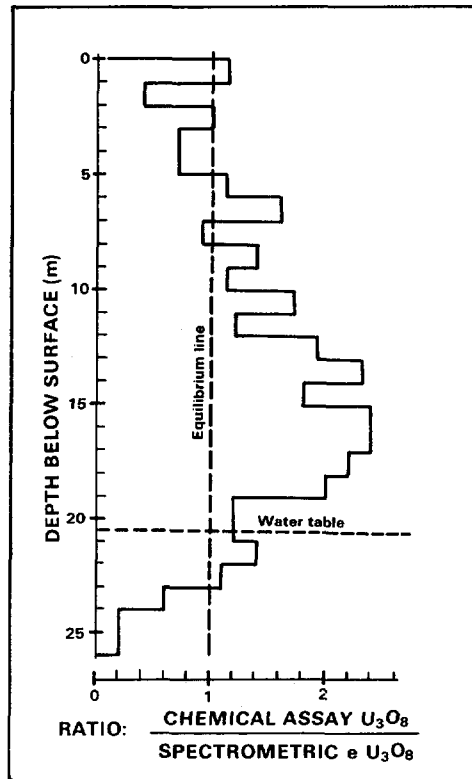


Figure 5
Vertical distribution of the disequilibrium data for the deposit in Figure 3.

fluctuations in the groundwater table. A profile (Figure 5), showing the state of disequilibrium in the deposit, clearly demonstrates this phenomenon. The degree of disequilibrium tends to increase towards the groundwater table, reaching a maximum of 1.24 at about 15 m depth and again decreases slightly to 1.12 at the groundwater table.

Only the minor fraction, constituting population A, can be classed as being the result of a new influx of uranium derived from either an in-situ or external source area as suggested by the high mean disequilibrium value of 1.7. Additionally, the data show that inaccurate ore reserve estimates could be obtained if the calculations are based

on radiometric results. Similarly, if a radiometric sorting technique is used, the acceptance of lower-grade material and rejection of the higher-grade ore may cause a decrease in the overall mining and extraction efficiency, making the process less cost-effective.

3. INDUCED DISEQUILIBRIUM AND THE RADIO-METRIC ASSAY OF PERCUSSION BOREHOLE PULPS

One of the most cost-effective methods for the prospecting and evaluation of a valley-fill surficial uranium deposit is to drill it by means of a percussion drill [2]. Simplistically, the hole is drilled dry using compressed air to drive the drill and also to blow the chips from the hole up to the surface, where they are collected by a suitable method, usually a cyclone. The sample is collected in a bag at the bottom of the cyclone and a small, fine-grained, but commonly high-grade portion, is blown away as dust. The geologist may then radiometrically log the powder in the bags on site a short time (e.g. 0.5 to 3 h) after the sample has been taken, or alternatively in a storage area after a few days. In this way, a rapid continuous "grade control" program is conducted, the results of which could mislead the geologist and cause errors in the calculation of the resources.

By the nature of the drilling operation, compressed air is forced into the hole and blows out the pulp with the simultaneous loss of ^{222}Rn . This causes severe disequilibrium between the gamma-emitting isotopes ^{214}Pb ($t_{1/2} = 26.8$ m in) and ^{214}Bi ($t_{1/2} = 19.8$ m in) and their longer-lived parent ^{226}Ra ($t_{1/2} = 1600$ y). Because of the very short half-lives of ^{214}Pb and ^{214}Bi , as compared to the parent isotope, ^{222}Rn , they will decay very rapidly without significant replenishment. The theory behind this phenomenon can be described in the following way:

The gamma-emitting isotope that is measured with a spectrometer is usually the 1.76 MeV line of ^{214}Bi , the daughter isotope of ^{214}Pb , ^{222}Rn and ^{226}Ra . As ^{214}Pb is the immediate parent of ^{214}Bi and the daughter of ^{222}Rn , it can be regarded as the rate-controlling isotope for the growth and decay of ^{214}Bi . In Figure 6 the decay curve for ^{214}Pb and the growth curve for ^{222}Rn are shown. After about 1.5 h, about 10 % of the ^{214}Pb remains because of its short half-life. Simultaneously, the growth of its parent ^{222}Rn is negligible after the same period. Therefore, the intensity of the emitted gamma rays will decrease proportionately so that a sample can be falsely rejected, as it appears to contain a low uranium grade due to the analysis being based on incorrect assumptions inherent in the technique of field gamma-ray spectrometry.

Nevertheless, the field application of a gamma-ray spectrometer is a very useful and versatile technique if the operator is aware of the pitfalls. On site grade control is essential to the exploration geologist if he is to maintain an efficient prospecting program. This is possible, all things being equal, if the necessary procedures are followed and certain corrections applied.

Assume that during the percussion drilling operation 70 % of the free radon (^{222}Rn) gas is blown away and that the remaining 30 % is retained in the sample. That proportion of ^{214}Pb , unsupported by the 70 % radon that was lost, will decay as shown in Figure 7, but the 30 % fraction, supported by the remaining radon, will continue to emit gamma rays. Accordingly, the activity of the retained ^{222}Rn and the supported ^{214}Pb will be in equilibrium, but the unsupported ^{214}Pb will decay without replenishment. The combined activity of the system, for up to a period of 3.5 h, will follow the curves as shown in Figure 7 for various radon losses, and assumes an initial grade of uranium of 1 kg eU/t. After a decay period of three hours, the unsupported ^{214}Pb disappears and the gamma activity of the sample will asymptotically approach an equilibrium condition where the curve becomes flat. After extrapolation of this flat portion of the curve horizontally to "time zero" (i.e. zero decay), the relative percentage of radon retained in the ore can be estimated on the vertical scale.

In practice, this phenomenon can be used by geologists to compensate for the radon loss during percussion drilling, thereby enabling them to determine the true grade of uranium with a greater degree of confidence. It can be suitably applied to surficial uranium deposits where radon is easily lost because of its inherently high escape/production ratio.

The degree of radon loss will depend on many factors, for example, the pressure of air from the compressor, the friability and porosity of the ore, the mineralogy and radon release tempo of the uranium minerals, etc. Therefore each geological environment will have its own radon escape characteristics.

A practical example using this technique can be explained in the following way:

It is important to know the time that the sample was percussion drilled. Usually, the sample collected is representative of a 0.5 to 1 m depth section and the time at which this section was drilled (not finally collected) is regarded as "time zero". It is from this point in time that the unsupported ^{214}Pb will start to decay. The geologist will select a few samples with different lithologies and for the next three hours measure the activity of each sample about every 15 min, using fixed sample and instrument geometry in a low-background area. It is assumed that the spectrometer is calibrated, and the value obtained will have the units kg eU/t. These data are plotted onto a graph as shown in Figure 8, where the function "time lapsed after percussion drilling of sample" is the difference in time between "time zero" and the actual time that the "grade" of the samples was determined. A curve drawn through the plotted points represents the decrease of radioactivity (resulting from the decay of ^{214}Pb) and, when extrapolated to time zero, the true grade of the sample can be determined. In this example it is 0.72 kg eU/t (curve 1).

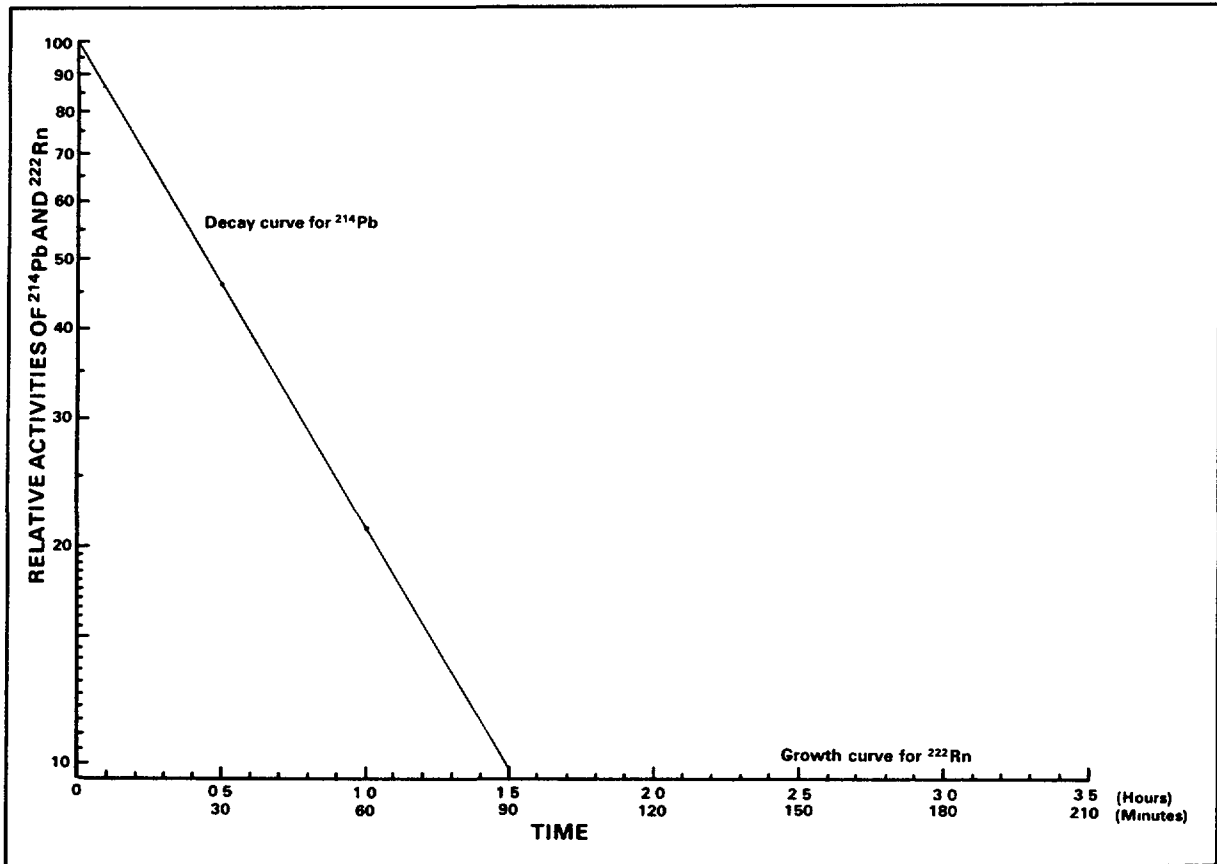


Figure 6
Decay and growth curves for ^{214}Pb and ^{222}Rn respectively.

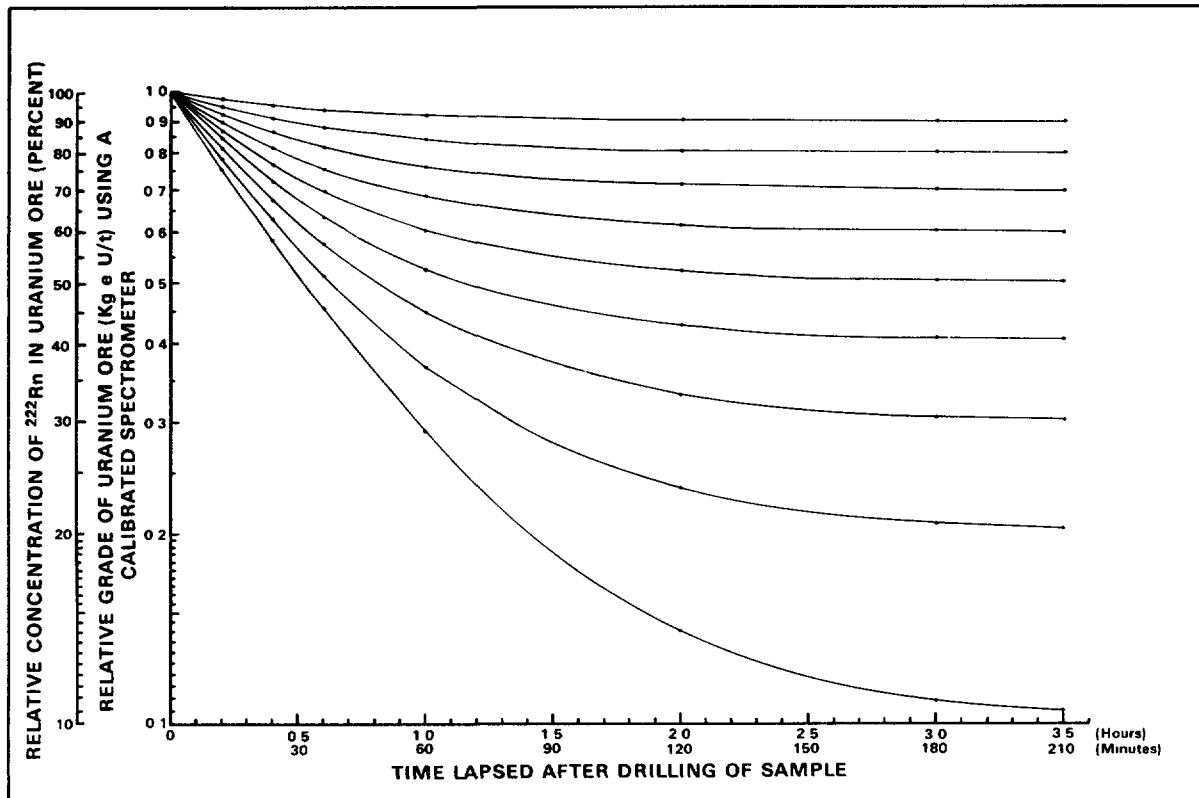


Figure 7
Family of decay curves for ^{214}Pb for surficial ore that has been partially degassed of ^{222}Rn to varying degrees.

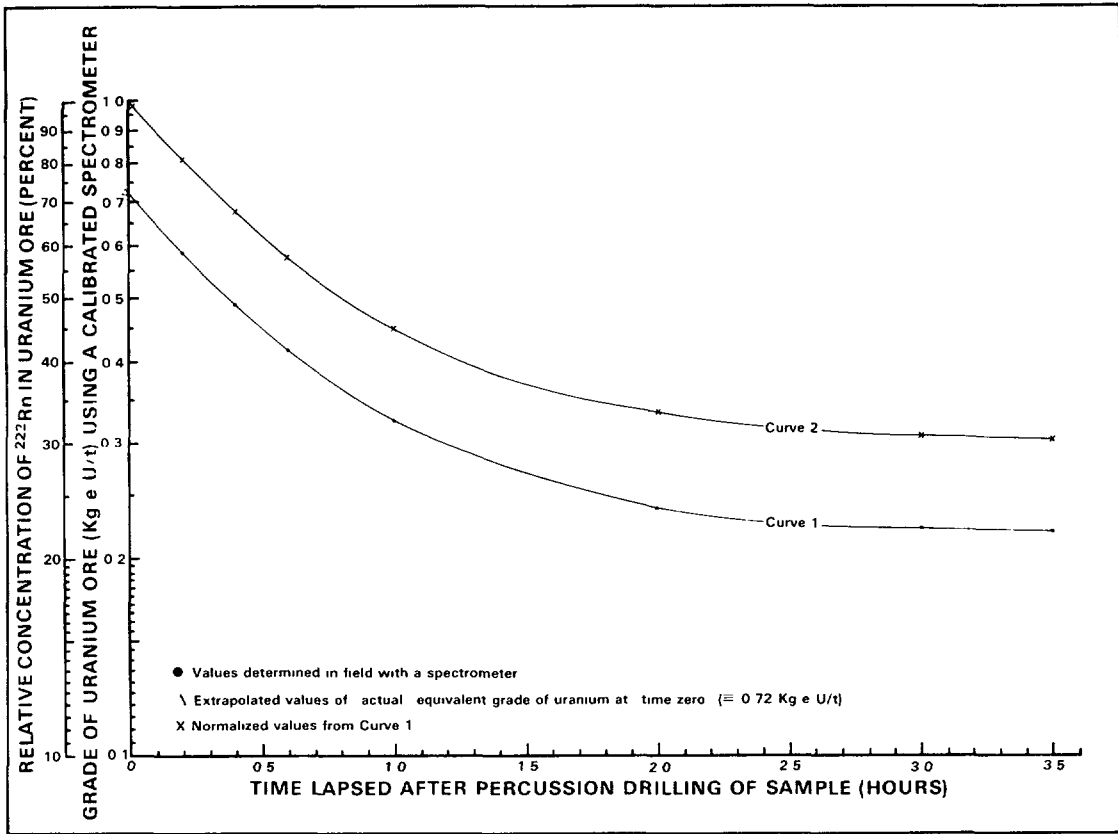


Figure 8
Experimentally determined decay curve (1) for ²¹⁴Pb and the normalized decay (2) for the same data.

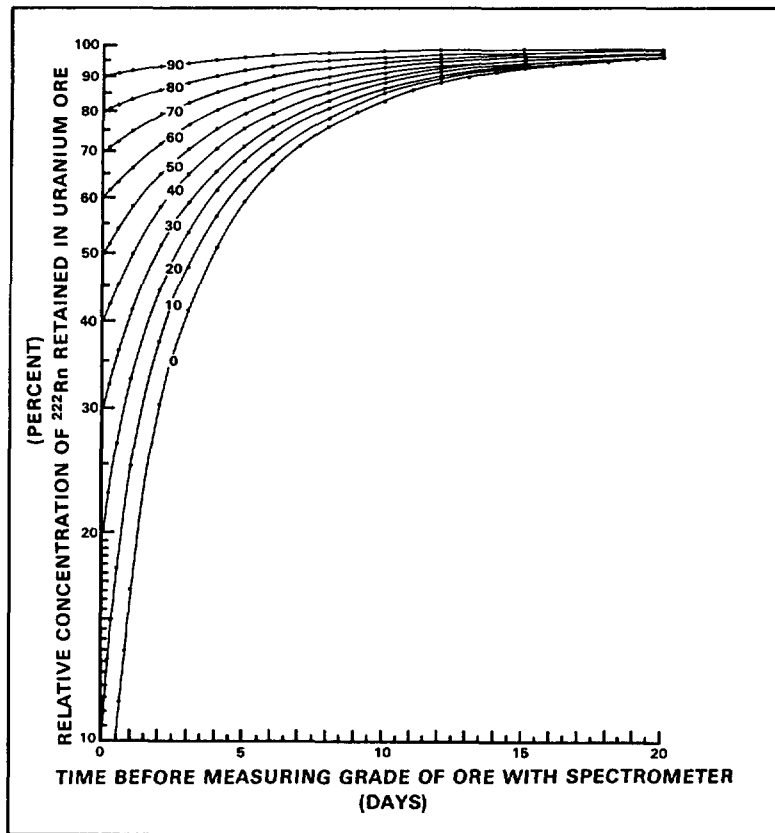


Figure 9
Correction curves for surficial uranium ore that has been partially degassed of ²²²Rn.

Naturally, it is not possible to analyse every sample in this manner because it is too time-consuming, but the lithologies chosen should be representative of the orebody to be used as future standard reference samples for the specific conditions and environment.

The next step is to normalize all the data of curve 1, such that the 0.72 kg eU/t becomes 1 kg eU/t and the new curve derived will have the form of curve 2 in Figure 8, which is similar to those of Figure 7. Extrapolation of the horizontal portion of the curve to time zero produces the "relative concentration of ^{222}Rn in the uranium ore (%)" which in this example is 30 %. Assuming that the lithologies chosen are fully representative of the orebody, each ore sample is assigned a radon value which will be characteristic of that type of sample. (In practice a mean value for each lithology should be used). Once these radon values have been established with a reasonably high degree of confidence, the grade estimation procedure during normal field operating conditions can proceed. The geologist is commonly hard-pressed to keep up with the logging of his percussion chip samples and usually he can log them only after a few days. If 3 d lapse before logging and the lithology in question has retained 30 % radon, as determined previously during the standardization procedure, then these two values are used to select the appropriate curve on Figure 9. In this case it is the 30 % curve for which the relative concentration of retained radon in the ore is 59.5 %. The equivalent grade of uranium in kg eU/t is then multiplied by a factor of 100/59.5 (or 1.68), which is a close approximation to the chemical uranium grade.

The alternative to this procedure is to seal the samples in a suitable gastight container and store them for 13 d or more before measuring the equivalent grade of uranium. This is demonstrated in Figure 9 where, after 13 d the curves flatten out at 90 % radon retention, which allows for a 10 % experimental error.

4. CONCLUSION

The choice between the two techniques in (a) correcting for the induced disequilibrium, and (b) allowing the production of the radon gamma-emitting daughters before measuring the equivalent uranium, is determined by the necessity of evaluating the orebody on an on-going basis. If this is to be done soon after drilling, the radon compensation method must be applied. Care should be taken, however, because the method will not correct for natural disequilibrium inherent in the ore, for which only chemical analyses will provide reliable data.

This procedure for determining and compensating for the amount of induced disequilibrium would be particularly suitable for those situations where chemical analytical facilities are not readily available, and where on-going monitoring of the uranium grade on site is desirable.

REFERENCES

- [1] DICKSON, B.L., Uranium series disequilibrium in the carnotite deposits of Western Australia, this Volume.
- [2] HAMBLETON-JONES, B.B., HEARD, R., TOENS, P.D., Exploration for surficial uranium deposits, this Volume.

A GEOSTATISTICAL EVALUATION OF THE NAPPERBY SURFICIAL URANIUM DEPOSIT, NORTHERN TERRITORY, AUSTRALIA

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ABSTRACT

A GEOSTATISTICAL EVALUATION OF THE NAPPERBY SURFICIAL URANIUM DEPOSIT, NORTHERN TERRITORY, AUSTRALIA

A "highly erratic" distribution of the mineralization seems to be a characteristic common to all surficial uranium deposits. The distribution of the mineralization within the Napperby deposit, Northern Territory, Australia, has been investigated by means of geostatistical methods. The structural analysis, based on the calculation of semivariograms in several directions and on two different scales, revealed the presence of a large nugget effect and of small-scale and large-scale structures with anisotropies controlled by the drainage directions. The large nugget effect and the small-scale structure, the latter partly with a high amplitude, are the result of, and also quantify, the erratic distribution and the relatively high variability of the mineralization. Based on the obtained semivariograms, further geostatistical methods can be applied to optimize drilling patterns and spacings and to estimate reserves with minimal estimation errors.

1. INTRODUCTION

The major problem in the sampling, delineation, and evaluation (including ore reserve estimations) of surficial uranium deposits results from the distribution of the mineralization, which is typically highly erratic (as defined by the geologist) within an orebody of rather simple, tabular geometry. Examples of the erratic nature of the ore distribution are known from Australia and Namibia.

The sampling problems of the Yeelirrie deposit in Western Australia are described in [1]. The high variations in grade within the same deposit are exemplified by Dickson [2], who also noted that the disequilibrium ratio shows a much more gradual variation than the grade variation; this discrepancy is explained by a considerable leaching and redeposition of both uranium and radium within the deposit. In the Lake Way deposit in Western Australia, trial mining studies showed that in order to have agreement between quantity of metal extracted from a mined-out block and the reserves for the same block estimated from exploratory drilling, a very closely spaced drilling grid of 4.6 m centres was required [3].

In a deposit in Namibia, Hambleton-Jones and Heard [4] explained that the average grade \times thickness (GT) value decreased from 11.8 m kg U_3O_8 /t for a drilling grid of 50 m centres to 8.8 m kg U_3O_8 /t for a drilling grid of 10 m. The uranium mineralization of the Langer Heinrich deposit, in Namibia, is described [5] as "totally irregular and discontinuous" with high variations within a metre or less. The high variation is explained by the patchy nature of the mineralization, which "formed in pods, veins and lenses but mainly as cavity fillings. The highest uranium grades are localized in those portions which are least consolidated, i.e. zones that are low in carbonate cement and therefore possess the highest porosity".

The genetic considerations given for the Langer Heinrich deposit, in some instances possibly coupled with post-mineralization redistribution processes, such as described for the Yeelirrie deposit in [2], can most likely be applied to all deposits of this type to explain the high variability of ore distribution, although a generalization must await further detailed studies.

The distribution characteristics of the mineralization can be investigated and quantified by using the basic tool of geostatistics, the **semivariogram**, in a **structural analysis** (for descriptions of semivariogram calculations and applications, the reader is referred to the pertinent literature, e.g. [6]). This analysis allows a better understanding of the distribution of the mineralization within an orebody and the quantification of the variability as a function of distance and direction. The results of this analysis form the basis upon which to apply more sophisticated geostatistical methods, as explained below.

A structural analysis based on semivariogram calculations was carried out on the surficial uranium deposit of Napperby, owned and explored by Uranerz Australia (Pty) Ltd.

2. LOCATION AND GEOLOGY

The Napperby uranium deposit is located in central Australia, about 150 km northwest of Alice Springs, Northern Territory (Figure 1). The deposit occurs within a drainage system that originates in the Palaeozoic Ngalia Basin to the north, where sandstone-type uranium deposits are present. The drainage system mainly overlies the Arunta Block of Proterozoic age, which includes uranium-bearing granitic rocks. Tertiary weathering has altered the surface of the granitic rocks to regolithic sands with minor clay. Within wide but rather shallow channels, the palaeosols are overlain by Upper Tertiary to Quaternary sediments comprising fluvial and aeolian sands with

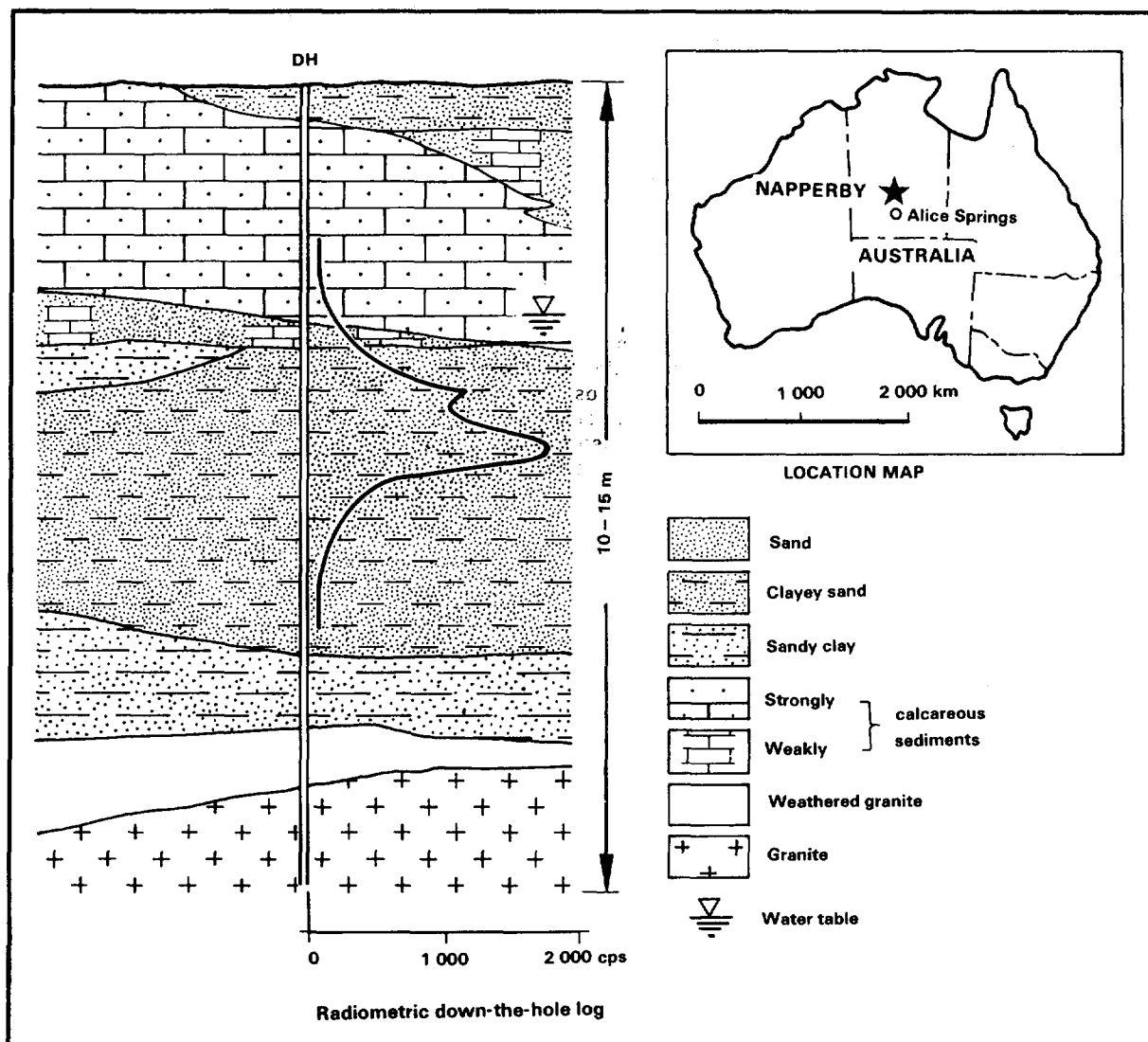


Figure 1
Location map and typical drill section of the Napperby surficial uranium deposit.

varying amounts of clay, and epigenetic gypsum and carbonate. Calcareous sediments occur on the top of the sequence while uranium mineralization, in the form of carnotite and minor tyuyamunite, is concentrated mainly below these sediments and the present water table, particularly in the upper part of only slightly calcareous clayey sands (Figure 1). The total mineralized area is several kilometres long, approximately 1 500 m wide and 1 to 3 m thick, depending on the cut-off applied. According to the nomenclature of Toens and Hambleton-Jones [7], the Napperby deposit belongs to the flood plain to deltaic classes of the fluvial group of surficial deposits. The Napperby deposit contains moderate uranium reserves, mainly of low grade, with occasional higher-grade lenses.

3. EXPLORATION

The initial drilling phase was carried out over a 300 x 400 m rectangular grid orientated in a north-south direction. The objectives were to delineate the mineralized area and to obtain a preliminary estimate of the reserves. In a second drilling phase the spacing was reduced to 100 x 100 m over an area of 700 x 1 300 m containing mineralization of higher grade; a few smaller blocks were also investigated at 20 m centres. The main aim of the detailed drilling phase was to obtain a better understanding of the distribution characteristics of the mineralization on a smaller scale, which is essential in the development and mine-planning stages. In order to minimize contamination problems, which are common in drilling surficial uranium deposits [4], the technique of twin-tube core drilling with reverse air-flush circulation was applied. Due to the presence of radiometric disequilibrium, all mineralized intersections (sampled over 0.5 m or 1.0 m intervals) were analysed chemically for uranium.

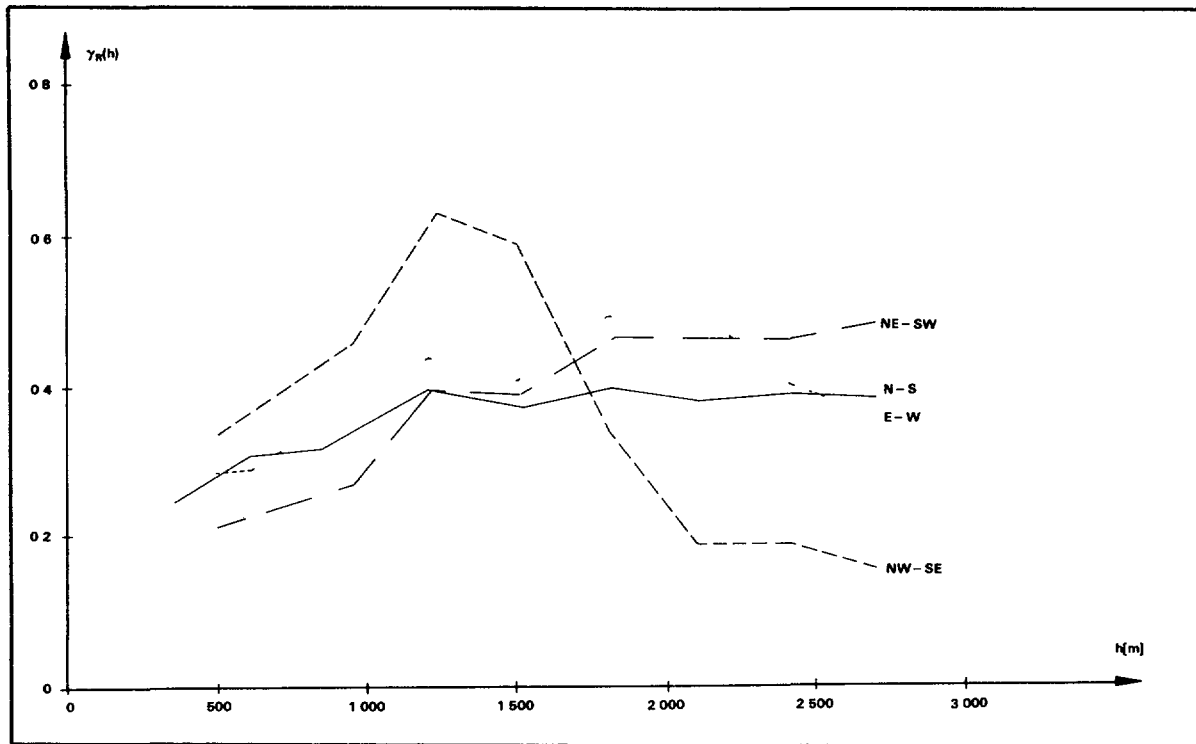


Figure 2
Large-scale relative experimental variograms of the variable T (thickness); no cut-off applied.

4. STRUCTURAL ANALYSIS BASED ON SEMIVARIOGRAMS

The chemical data were firstly analysed using standard statistical methods at different cut-off grades. These methods were applied in order to define the statistical characteristics, such as distribution laws, means and variances, and correlation coefficients. The investigated variables were G (grade), T (thickness) and GT (grade x thickness or accumulation value). Two-parameter, log-normal distribution models have been obtained for these variables.

The distribution characteristics of the mineralization, based on the variables GT and T, have been investigated by means of semivariograms which were calculated with relatively long or short lags, depending on whether they utilised data from the first or second-phase drilling as described above.

Firstly, large-scale semivariograms were calculated over distances of a few kilometres using lags of approximately 300 m and were based on data obtained from the initial drilling phase at 300 x 400 m spacings. Secondly, small-scale semivariograms were calculated over a few hundred metres with lags of 50 m and were based on the data of the second drilling phase. Several cut-off grades were applied; however, only the results related to two of them are presented here, i.e. a cut-off of zero (or no cut-off) and a cut-off of 200 ppm U_3O_8 . Semivariograms were calculated for four geographic directions, i.e. N-S, E-W, NE-SW and NW-SE.

4.1 Large-Scale Semivariograms

The large-scale experimental semivariograms are shown in Figures 2 and 3, from which the following information was deduced:

- The GT and T semivariograms (with no cut-off) show very similar characteristics and an **anisotropy** which conforms to the main geologic directions, NE-SW and NW-SE, which are parallel and perpendicular respectively, to the drainage axis
- A large **nugget effect** (C_0), (Figure 3) is suggested by the behaviour of the experimental semivariogram, and could be caused by the occurrence of smaller-scale structures undetected by the 300 x 400 m drill grid and/or inadequate sampling and analytical procedures (i.e. contamination during drilling or sampling and/or unsuitable sampling intervals). From the results of the drilling at 20 m centres and from exposures in trenches it was noted that the major portion of the nugget effect was due to small-scale structures of high variability.
- Spherical-type** models can easily be fitted to the individual experimental semivariograms
- A **hole effect** is present, particularly in the NW-SE direction, i.e. perpendicular to the drainage axis. This effect could possibly indicate a periodicity in the distribution of sample values [8, 9]

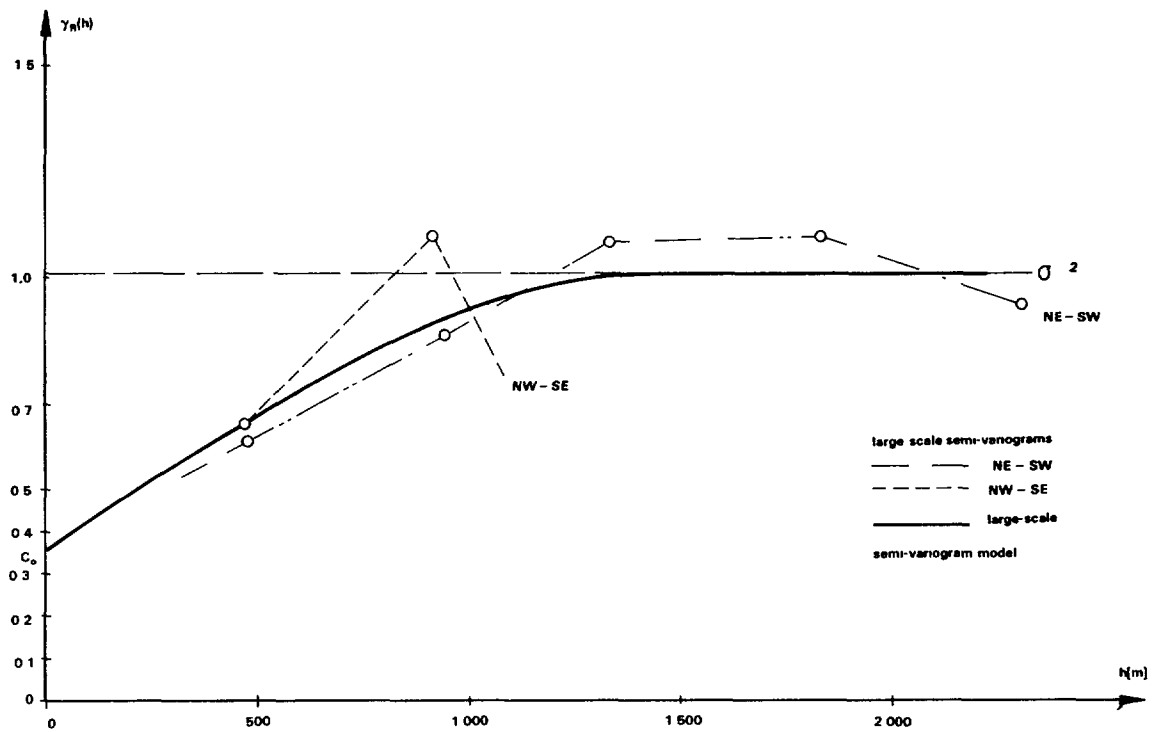


Figure 3
Large-scale relative experimental variograms of the variable GT (grade x thickness) and fitted model; cut-off 200 ppm U_3O_8

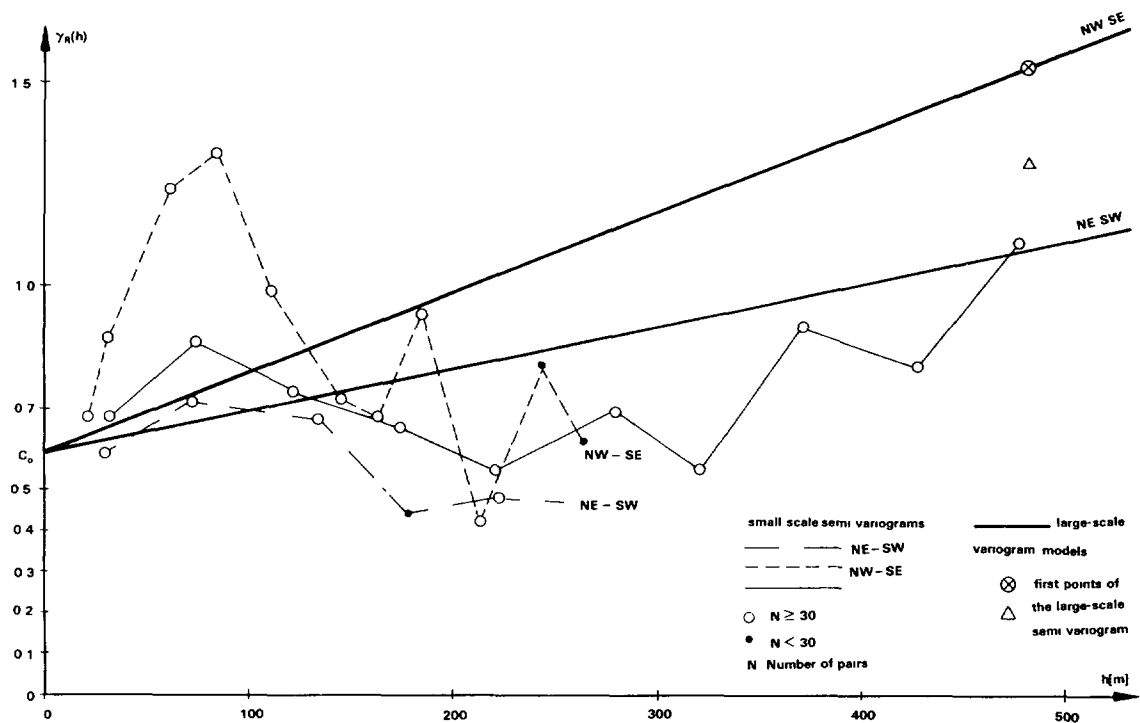


Figure 4
Small-scale relative experimental variograms of the variable GT (grade x thickness) compared with the starting part of the fitted models of the large-scale variograms; no cut-off applied.

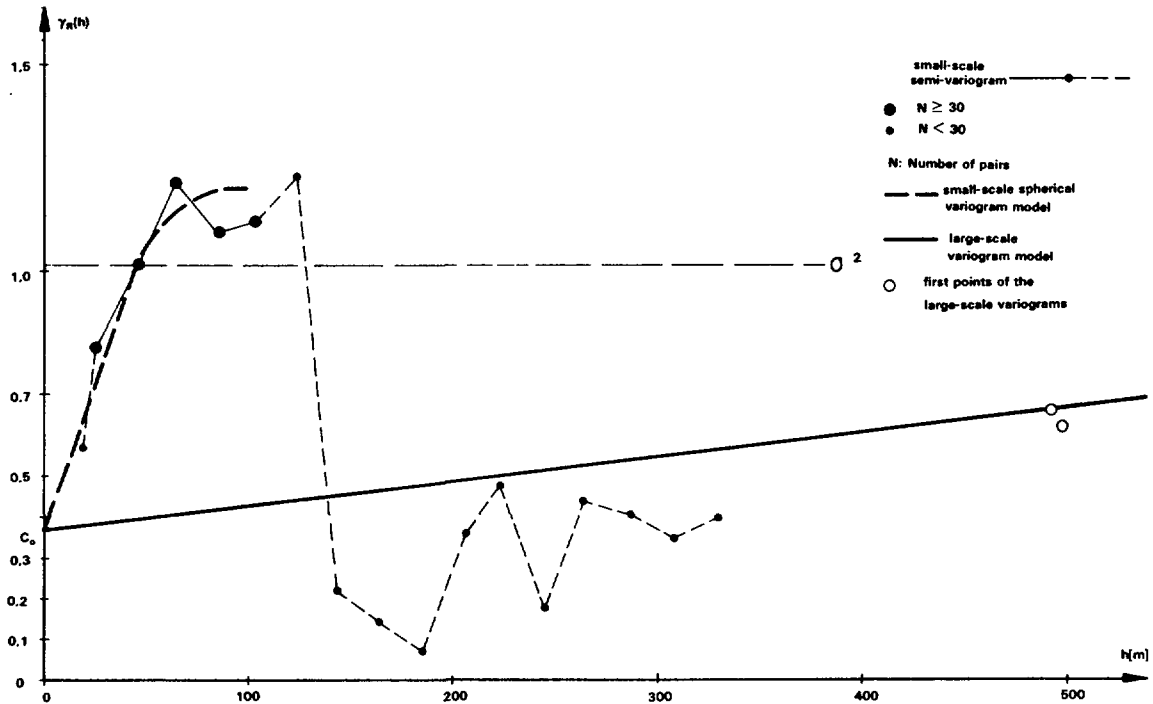


Figure 5

Small-scale relative (overall) experimental variogram of the variable GT (grade x thickness) compared with the fitted model of the large-scale variograms from Figure 3; cut-off 200 ppm U_3O_8

- (e) A **zonal anisotropy** is evident from the behaviour of the semivariograms along the NW-SE and NE-SW directions up to a distance of 1 500 m (Figure 2). This anisotropy is typical of deposits displaying sequences of alternately richer and poorer mineralized zones [10]. The anisotropy weakens in the semivariograms by applying a cut-off of 200 ppm U_3O_8 , possibly because a considerable amount of data is eliminated. Therefore, a simpler model with isotropic structures (Figure 3) was fitted for ore resource assessment purposes.

4.2 Small-Scale Semivariograms

The small-scale experimental semivariograms are shown in Figures 4 and 5 and have the following characteristics:

- (a) **Nugget effect** The study of the experimental semivariograms and their models is inconclusive in this regard for lack of sampling values at very close distance from each other. Figure 4 suggests the presence of a nugget effect with 0.6 sill, while the values of the first three points in Figure 5 could be equally fitted by the spherical model alone or by a combination of spherical and nugget effect models. However, detail mapping and sampling of trenches proved the presence of high-grade discontinuities in the mineralisation at small scale. Thus the nugget effect was used in modelling the experimental semivariograms. In this deposit the nugget effect results primarily from the occurrence of small-scale structures but incomplete recovery and errors in the assaying procedures cannot be excluded.
- (b) An **additional small structure** with a range of less than 100 m for GT and slightly over 100 m for T is present. It shows a zonal anisotropy orientated as in the large-scale structure (Figure 4).
- (c) The behaviour of the semivariograms up to a distance of approximately 400 m indicates the presence of a **hole-effect** structure. The semivariograms show a tendency to increase again at distances over 400 m; a periodically increasing behaviour may exist over larger distances.
- (d) An unexpected result is the **high amplitude** of the small-scale structure, particularly at cut-off 200 ppm U_3O_8 (Figure 5), which exceeds the sill value of the corresponding large-scale structure (Figures 3 and 5).

5. APPLICATIONS

Several further geostatistical operations can be carried out, based on the semivariogram models obtained from the structural analysis. The first group of applications comprises simply the calculation of the dispersion and of the extension or estimation variances. The second group of applications comprises the estimation of the local (block) and global in-situ reserves by using kriging techniques: the estimation is then optimal in that the

estimation variances are minimized. Calculations of estimation variances, including kriging variance, are very useful for optimizing drilling patterns and spacings in exploration and development drilling.

These techniques have been applied to the Napperby surficial uranium deposit with the two objectives of defining optimum drill spacings and of obtaining preliminary global reserves for an economic and technical evaluation. Results are given in Akin [11]. However, only the large-scale semivariograms have been used so far and only linear techniques were applied, although the log-normal distribution characteristics of the variables might require the use of log-normal kriging techniques, e.g. [6]. Furthermore, the small-scale structures, so far detected only in one area of the deposit by detailed drilling, might or might not have validity for the whole deposit and thus require the computation of local variograms (of course based on additional detailed drilling) for more precise results on smaller scales, particularly at higher cut-offs.

Further applications, in the more evolved development stage, again based on the obtained semivariogram models, include advanced geostatistical techniques, such as disjunctive kriging and simulation techniques, for the estimation of recoverable reserves and for mine planning purposes.

6. CONCLUSION

The investigation of the structural characteristics confirms and quantifies the presence of an erratically distributed component and relatively high variability of the mineralization in the Napperby uranium deposit which is in excellent agreement with observations from other deposits of the same type. This type of distribution is characterized by the **large nugget effect** and by the presence of a relatively **small-scale structure** with a range of approximately 100 m or less. However, a **large-scale structure** with a range of over 1 000 m in all directions is also present, which reflects a large-scale continuity of the mineralization. An anisotropy is clearly detected by the semivariograms on both scales. The main anisotropy direction coincides with the drainage axis and is, therefore, clearly controlled geologically.

ACKNOWLEDGEMENT

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REFERENCES

- [1] HAYCRAFT, J.A., Sampling of the Yeelirrie uranium deposit, Western Australia, In. Aust. IMM Sampling Symp., Melbourne (1976) 51–62.
- [2] DICKSON, B.L., Uranium series disequilibrium in the carnotite deposits of Western Australia, this Volume.
- [3] FRENCH, R.R., ALLEN, J.H., Lake Way uranium deposit, Wiluna, Western Australia, this Volume.
- [4] HAMBLETON-JONES, B.B., HEARD, R., TOENS, P.D., Exploration for surficial uranium deposits, this Volume.
- [5] HAMBLETON-JONES, B.B., Surficial uranium deposits in Namibia, this Volume.
- [6] JOURNEL, A.G., HUIJBREGTS, C.J., Mining geostatistics, Academic Press, London (1978) 600.
- [7] TOENS, P.D., HAMBLETON-JONES, B.B., Definition and classification of surficial uranium deposits, this Volume.
- [8] SERRA, J., Échantillonnage et estimation locale des phénomènes de transition miniers, Doctoral Thesis, IRSID and C4, Fontainebleau (1967).
- [9] CAMISANI-CALZOLARI, F.A.G.M., Geostatistical appraisal of a tabular uranium deposit in South Africa, In. 2nd NATO Symp. ASI Lake Tahoe, California (1983).
- [10] GUARASCIO, M., Optimization of sampling patterns and of block estimation methods, Proc. Adv. Gp. Mtg., IAEA, Vienna (1979) 145–178.
- [11] AKIN, H., Beispiel einer geostatistischen Vorratsermittlung für eine sedimentäre Uranlagerstätte (Napperby/Zentralaustralien), in Klassifikation von Lagerstättenvorräten mit Hilfe der Geostatistik, Schriftenreihe der GDMB, Hft. 39, Vers. Chem. (1983) 101–109.

BENEFICIATION OF SURFICIAL URANIUM DEPOSITS

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ABSTRACT

BENEFICIATION OF SURFICIAL URANIUM DEPOSITS

Surficial uranium deposits are of interest to mining and utility companies because of the relative ease with which most of them can be mined. The recovery of uranium from surficial deposits poses some special problems that may tend to offset the cost advantages inherent in the potentially simple mining processes. The mineralogical characteristics of the surficial uranium deposits are used to provide constraints in the selection of beneficiation processes and the problems likely to be encountered in their application to the extraction of uranium.

1. INTRODUCTION

Surficial uranium deposits, consisting dominantly of a regolith of uraniferous sand particles, with various degrees of cementation, comprise a small but potentially important source of uranium. Such deposits are typically found in arid areas and exhibit high carbonate, sulphate and soluble salt contents. The extraction of their uranium content is likely, therefore, to pose special processing problems.

The geology and mineralogy of different types of surficial uranium deposits occurring in many parts of the world are reviewed in this volume to which the reader is referred for further information. It should be emphasized, however, that mineralogy places significant constraints on process selection.

2. MINING

The surficial uranium deposits are characterized by a number of features as regards the selection of mining processes:

1. They are generally of a relatively shallow depth.
2. The degree of the cementation of the clastic material varies from good to tenuous. In most cases material can be mined using conventional earth-moving equipment with a minimum use of explosives.
3. In certain areas the management and disposal of groundwater could be a problem. In at least one instance in-situ fluidization has been proposed as a mining method.

At **Yeelirrie**, economic mineralization covers an area of approximately 6 x 0.5 km. The average depth of the mineralized profile is 8 m with occasional extensions to 14 m. Estimated reserves amount to 40 000 tonnes of uranium and the planned mill feed grade will be about 0.15 % U₃O₈.

Mining of the Yeelirrie deposit will be along the following lines:

1. Pre-drilling on a close pattern with radiometric sampling.
2. The use of large self-propelled scrapers with pusher bulldozer-rippers to remove large barren areas of material.
3. The use of smaller self-elevating scrapers to remove the waste close to the ore layers.
4. Removal of the ore using hydraulic excavators operating in either the back-hoe, or front-loader configuration.

The ore will be weighed and its ore grade assessed using a radiometric assaying tower prior to transportation to variously graded stockpiles at a storage area.

At **Langer Heinrich**, uranium mineralization greater than 0.10 % U₃O₈ forms an irregular, discontinuous, and undulating layer within the lower calcrete. This zone varies from 5 to 15 m in thickness being 30 m deep at the maximum and extends over an area of 13 x 0.5 km.

Although no mining plans have been revealed for the Langer Heinrich deposit, opencast techniques are likely to be selected. The Langer Heinrich calcrete is dense and tough, and drilling and blasting requirements could be more rigorous than in the case of Yeelirrie type ores.

A major difference between the Yeelirrie and Langer Heinrich deposits is the water-logged nature of the former.

3. PROCESS CONSIDERATIONS

Chemical metallurgy is still the major route to uranium extraction and most uranium minerals can be taken into solution with a fair degree of selectivity by acid or alkaline lixiviants.

However, the reactivity of the gangue minerals and the contribution made by their dissolution products to downstream processing, must be taken into account when designing a flowsheet for particular surficial deposits. The presence of carbonate minerals, for example, is usually the prime consideration for the selection of an alkaline leach process. Phosphate minerals can result in phosphate going into solution to complex ferric ions and thus inhibit their role in the oxidation process. Should the pH of the solution rise above a value of two, moreover, phosphate ions can cause uranium to precipitate. Biotite, chlorite, sericite and various clay minerals tend to react with the lixiviant at pH values of less than 2.0. In certain deposits gypsum comprises the major cementing component in which case an acid leach may be desirable.

The processes involved in the general beneficiation of a uranium ore include:

- Comminution
- Preconcentration
- Leaching
- Liquid/solid separation
- Uranium recovery

These will be briefly described as they apply to the recovery of uranium from surficial deposits.

3.1 Comminution

Comminution is required to:

1. Liberate uranium from gangue minerals to permit physical separation and to provide lixiviant access.
2. To increase the surface area of the uranium mineral to permit a more rapid rate of dissolution.

When the ore is sufficiently coherent, as in the case of some of the calcrete deposits, primary crushing can be used to provide a size category suitable for radiometric sorting. Further comminution should, however, be constrained to the extent at which adequate uranium surfaces are exposed for dissolution. Finer comminution is likely only to enhance such problems as the consumption of lixiviant by gangue minerals, increased power requirements for agitation and pumping and poor efficiencies at the liquid/solid separation stage.

In the case of calcrete ores grinding to 0.5 mm is considered to be adequate for dissolution whereas for certain occurrences in the northwestern Cape and Botswana, a screening out of + 48 mesh (300 μm) material is recommended as the only feed preparation required. Removal of this size is particularly necessary when resin-in-pulp techniques are to be employed as the resin retention screens are usually around 35 mesh (420 μm) in size. For the Yeelirrie deposit in Western Australia it has been suggested that the ore be crushed in impact crushers to about minus 20 mm and then dried and roasted in a rotary kiln. The roasting stage is proposed with the primary objective of destroying the lattice of clay minerals by dehydration with subsequent benefit to the liquid/solid separation stages. The ore will then be quenched in a spiral classifier, the underflow of which will be fed to a rod and ball mill grinding circuit which will comminute the ore to some 80 % minus 48 mesh.

3.2 Preconcentration

The mineralogical and textural features of most uranium deposits have not generally favoured the use of preconcentration processes. In some instances however, a screening process was employed to upgrade the feed to a dissolution stage with some success. It is possible that brushing techniques could also be used to remove surface coatings of uranium. Furthermore surficial deposits, which feature such textures as nodular concrete particles coated with secondary uranium ochre, could respond to such techniques as datac radiometric sorting. Experimental results (Table 1) obtained for material from one calcrete deposit appear to support the application of radiometric sorting in some cases. The frequent correlation between uranium deposition and the presence of carbon, peat, etc., suggests the application of flotation to upgrade the ore from an initial feed concentration as low as 0.3 kg $\text{U}_3\text{O}_8/\text{t}$ to a level commonly in excess of 1 kg $\text{U}_3\text{O}_8/\text{t}$.

3.3 Leaching

With few exceptions the surficial deposits require alkaline lixiviants because of the large quantities of acid-consuming constituents they contain. Apart from their high carbonate contents as well as quantities of gypsum and clay minerals, some of the deposits contain soluble salts, for example halite (NaCl). This is a matter of concern in the selection of recovery processes as well as material for plant construction. In these instances attention should be given to the economics of a pre-leach washing operation and the use of softened water in all plant operations. This requirement is not aided by the fact that many surficial deposits are located in arid areas where process water recycling is an important component of overall plant economics. Where careful material selection permits, processing is feasible even where sea water is employed.

Carbonate leaching is the only economic approach to the recovery of uranium from ores with a high carbonate mineral content. Oxidation is required where the uranium is in the tetravalent state and pressure digestion is frequently resorted to. Although compounds of iron, aluminium, titanium, etc., are nearly insoluble in carbonate solution, small amounts of molybdates, silicates, vanadates, phosphates and aluminates do go into solution.

Table 1
Experimental Radiometric Sorting Results for a Calcrete Type
Uranium Deposit Using a Feed Grade of 1.24 kg U₃O₈/t

% ACCEPTED	CUTOFF GRADE	ACCEPTED GRADE	REJECT GRADE	% RECOVERED U ₃ O ₈
3.6	11.15	11.65	0.85	34.0
20.0	2.27	4.39	0.46	70.5
31.9	1.36	3.39	0.24	86.7
40.2	0.63	2.90	0.13	93.8
49.1	0.25	2.46	0.07	97.2
60.3	0.13	2.03	0.04	98.6
69.5	0.06	1.77	0.03	99.2
75.5	0.04	1.64	0.03	99.4
82.7	0.04	1.50	0.03	99.6
90.0	0.03	1.38	0.02	99.8
100.0	0.02	1.24	0.00	100.0

Vanadium is readily dissolved from carnotite although silicates of vanadium are not too easily solubilized unless subjected to a prior roast with NaCl.

The recycling of solutions is an economic necessity as up to 200 kg/ton of sodium carbonate, added as an admixture with sodium bicarbonate, can be required to effect an adequate dissolution of the uranium. Once the uranium has been precipitated, using an excess of caustic soda neutralizes the bicarbonate, the barren caustic-sodium carbonate solution is regenerated using CO₂ to restore the carbonate-bicarbonate ratio of approximately 4:1. The rejuvenated lixiviant is then passed forward to the leach stage.

The rate of uranium dissolution is thought to be related to the oxidation reactions proceeding at the mineral surfaces. It follows, therefore, that oxygen partial pressure and temperature variation can be used to enhance the uranium dissolution rate. The presence of clay minerals generally has an adverse effect on the rheological properties of the pulp containing the ore particles. Mineral suspensions, showing behaviour that is probably non-Newtonian, require large energy inputs when stirring or pumping is implemented. The use of air-agitated Pachuca-type leaching tanks is largely excluded due to the decomposition of the NaHCO₃, brought about by the stream of air (an effect that can be largely offset by including 1 % of CO₂ in the aeration stream).

Dissolution can be considerably speeded up by employing heated pressure reactors of the "Sherrit-Gordon" or "Tube" type. The use of such apparatus on the smaller and lower grade surficial deposits may be excluded on the grounds of cost, apart from those problems associated with the viscosities of many surficial ore pulps.

Work by Uranerzbergbau has shown that 95 % uranium can be extracted from the calcrete ores of Western Australia when leached at 60 to 80 °C for 20 h at atmospheric pressure using a lixiviant consisting of 180 kg Na₂CO₃/t of ore having a pulp density of 50 % solids.

From carbonaceous and diatomaceous earth type deposits in South Africa, about 90 % of the uranium was extracted using 10 g/l of (NH₄)₂CO₃ at a temperature of 30 °C and a pulp density of 5 % solids. In practice the use of sodium carbonate would probably be more cost effective than ammonium carbonate. Values of 5.5 kg of Na₂CO₃ and 15.5 kg NaOH per tonne of ore have been quoted as typical consumption rates when alkaline pressure dissolution of a uranium ore is employed.

Leaching in a low-strength soda solution is adequate to recover 90 % of the uranium from the Yeelirrie ore. The residues are then classified into sands and slimes which can be further leached using separate high and low strength soda solutions respectively. Furthermore experiments have shown that the leaching of ground and thickened ore at between 120 and 150 °C in autoclaves with sodium carbonate/bicarbonate as lixiviant, should provide recoveries in excess of 95 % of the contained uranium.

3.4 Liquid-Solid Separation

It is in this area that some difficulty can be anticipated due to the presence of, inter alia, fine clay mineral particles. The combined effects of roasting and pressure leaching of the Yeelirrie ore appear to render the pulp amenable to countercurrent decantation (CCD.). In the case of Namibian calcrete ores, resort has had to be made to the use of centrifuges for liquid-solid separation. Experimental work by Uranerzbergbau suggests that, with the aid of suitable ionic flocculants and a pulp density of 55 % solids a thickener capacity of between 0.1 and 0.4 m² per tonne per day can be attained for CCD operations on certain calcrete ores.

Contrary to other experiences with Namibian ores Uranerzbergbau were able to obtain vacuum filter duties of 2 t per m² per day for belt filters which suggests that a pessimistic view of liquid-solid separation performance is not necessarily applicable to all calcrete ores.

In the case of alkaline leached surficial clay deposits from South Africa, thickener duties of the order of 0.6 m² per tonne per day were obtained. When less than 0.5 g/l of suspended solids were required in the overflow and underflow, densities of 25 % solids were accepted.

In practice, assuming that CCD is the most probable liquid-solid separation route for leached surficial deposits, a 98 % washing efficiency will require between 4 and 8 washing stages depending upon the wash water flow rate through the circuit. Higher grade pregnant liquors are produced with a larger number of washing stages and, in view of the low feed grades envisaged in many cases, this somewhat expensive solution may prove necessary.

3.5 Uranium recovery

Because of the inherent selectivity of most alkaline leaches it is often possible to precipitate a final product directly from the leach solution. However, the low pregnant values associated with the comparatively low grades of most surficial deposits and problems encountered in the liquid-solid separation stages suggests that upgrading, using ion exchange, will probably be required.

The development of modern "heavy" resins has opened the way to using an ion-exchange process following a minimum amount of liquid-solid separation and solution clarification. Sentrachem "Senbrix" anionic heavy resins have been employed in a NIMCIX continuous ion exchange column to process a pregnant liquor containing 5 to 6 % solids obtained from the alkaline leaching of diatomaceous clay material. Chloride levels in the circuit were found to depress resin loadings quite markedly.

Similar effects were noted by Uranerzbergbau when employing Dowex 21K resin to extract uranium from calcrete-derived pregnant liquors. At salt concentrations of more than 8 g Cl/l and 8 g SO₄/l, a resin loading of only 6 to 10 g U₃O₈/l of resin could be obtained from a liquor containing between 120 and 140 ppm of U₃O₈. When desalting prior to leaching was employed and salt levels were lowered to 0.7 g Cl/l and 2 g SO₄/l, resin loadings of between 46 and 53 g U₃O₈/l of resin were obtained.

The employment of full resin-in-pulp (RIP) processes to recover uranium from surficial deposits is unlikely because of rheological problems, difficulties in dealing with chloride build-up when using sodium chloride as an eluant, and excessive losses of the comparatively expensive alkaline lixiviant.

The precipitation of uranium from alkaline solutions is usually accomplished by the addition of a strong base, or by hydrogen reduction. When caustic soda is used, it both precipitates the uranium and replenishes the lixiviant but precipitation is however, incomplete. Acidification of the alkaline solution followed by neutralization with ammonia provides an alternative route.

Where sodium chloride elution of the anionic resins is employed, usually in the presence of sodium carbonate, or bicarbonate to prevent hydrolysis, the complete conversion of the resin to the chloride form usually results in the absorbed chloride being displaced into the barren solution when the resin is returned to absorption service. A proportion of this chloride will then return to the post-leach pregnant solution where it will exert a depressing effect upon resin loading. It has been suggested that a strong alkaline carbonate solution be used instead to elute uranyl tricarbonate. Uranium can then be precipitated by hydrogen reduction leaving a barren solution suitable for recycling to the leaching operation.

Vanadium, when present, can be removed either from solution by precipitation as an insoluble vanadate, or by roasting the yellow cake after the addition of supplemental sodium carbonate to provide a water soluble sodium vanadate.

4. CONCLUSION

Technology is available for the recovery of uranium from many of the surficial deposits identified to date. However, the process complexities and associated costs coupled with the low grade and remote location of many of these deposits is likely to delay their beneficiation to a future date associated with a much improved uranium price. On the other hand some of the more viable deposits, whilst appearing more amenable to profitable exploitation, are likely to be delayed because of geopolitical uncertainties.

It is quite probable that research on the beneficiation of the surficial deposits will not receive the attention it deserves until that point in the future when the demand for uranium is again associated with a price level that will make the exploitation of these resources economically attractive to the mining and utility companies.

BIBLIOGRAPHY

CARLISLE, D., MERIFIELD, P.M., ORME, A.R., KOHL, M.S., KOLKER, O., The distribution of calcretes and gypcretes in southwestern United States and their uranium favourability based on a study of deposits in Western Australia and Namibia, US Dept. of Energy Report GJBX-29(78) (1978) 274.

WESTERN MINING CORPORATION EXPLORATION DIVISION, A general account of the Yeelirrie uranium deposit, Privately published and distributed to 25th Int. Geol. Congress Tours. (1975) 14.

WESTERN MINING CORPORATION LTD, Environmental review and management programme for proposed metallurgical research plant at Kalgoorlie initially for Yeelirrie Uranium ore (1978).

CAMERON, E., Uranium in a calcrete environment – Western Australia, (Unpublished) Hobart, 47th ANXAAS Congress, May 10–14 (1976).

SCHAPPER, M.A., *The gamma sort*, *Nuclear Active*, 21 (1979) 11–15.

MERRIT, R.C., *The extractive metallurgy of uranium*, Colorado School of Mines Res. Inst. (1971) 576.

KHAN, HAG NAWAZ, Mining method and grade control practices at Baghalchur Dera Ghazi Khan, Pakistan, In: *Uranium Evaluation and Mining Techniques*, IAEA/NEA(OECD), OAS-IANEC Symposium, Buenos Aires (1979) 233–239.

SIMONSEN, H.A., BOYDELL, D.W., JAMES, H.E., *The impact of new technology on the economics of uranium production from low-grade ores*, 5th Int. Symposium of the Uranium Institute (1980) 87.

LAUDSIEDEL, K., SCHOENING, G., FLOETER, W., *Uranium recovery from low-grade calcrete ore*, (Unpublished) (1983).

Significance of mineralogy in the development of flowsheets for processing uranium Ores, Tech. Report Series No. 196, IAEA (1980) 265.

BOYDELL, D.W., *Impurities in uranium process solutions*, In: *Production of Yellow Cake and Uranium Fluorides*, IAEA, Vienna (1980) 29–49.

BUTT, C.R.M., HORWITZ, R.C., MANN, A.W., *Uranium occurrences in calcrete and associated sediments in Western Australia*, Aust. CSIRO Div. Mineral., Report No. FP. 16 (1977) 67.

KELLY, E.G., SPOTTISWOOD, D.J., *Introduction to Mineral Processing*, John Wiley & Sons (1982) 491.

BECHTEL NATIONAL INC., *U₃O₈ production cost analysis study*, EPRI EA-730, 2, August (1978) 3–31.

DEPOTS SUPERFICIELS D'URANIUM EN ALGERIE

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ABSTRACT – RESUME

SURFICIAL URANIUM DEPOSITS IN ALGERIE

Along southern border of the Hoggar (Algeria) Precambrian shield, Lower Palaeozoic sediments lie unconformably on weathered metamorphic rocks. Along the eastern border of the Tin Seririne basin some good examples of the weathered rocks underneath the unconformity are exposed. The palaeosurface is a peneplain with only minor topographical reliefs from one to a few metres high. The nature and intensity of the weathering process was controlled by the topography, and the existence of badly drained areas is particularly important. At one such area the Tahaggart uranium ore deposit was discovered. The uranium ore consists mainly of torbernite and autunite. The deposit is present in the weathered gneiss underneath the palaeosurface. Mineralogical and geochemical observations indicated that the ore deposit was formed during the period of weathering which was controlled by climatological and palaeotopographical factors.

DEPOTS SUPERFICIELS D'URANIUM EN ALGERIE

Le long de la bordure limite sud du massif précambrien du Hoggar, des sédiments paléozoïques inférieurs constituent une couche discordante avec des roches métamorphiques décomposées. A la limite est du bassin de Tin Seririne, quelques bons exemples de roches décomposées sous la discordance sont exposés. La paléosurface est une pénéplaine avec seulement des reliefs topographiques mineurs de un à quelques mètres de haut. La nature et l'intensité du processus de décomposition, processus régi par la topographie, et l'existence de zones mal asséchées est particulièrement importante. Dans une telle zone, un gisement de minerai d'uranium a été découvert. Le gisement d'uranium est constitué principalement de torbernite et d'autunite le gisement est présent dans le gneiss décomposé sous la paléosurface. Des observations minéralogiques et géochimiques tendent à montrer que le gisement de minerai fut formé pendant la période de décomposition, laquelle était contrôlée par des facteurs climatologiques et paléotopographiques.

1. INTRODUCTION

La présence de calcrètes en Algérie a été citée par nombre d'auteurs, dans les études concernant le Tertiaire supérieur et le Quaternaire du Sahara [1]. Ces calcrètes appartiennent en fait à des types différents:

- Hamadas calcifiées semblables à celles de Mauritanie
- Calcaires lacustres partiellement dolomitisés

Ces formations sont particulièrement bien développées sur le socle cristallin de l'Eglab (partie occidentale du Sahara algérien) avec les mêmes caractères qu'en Mauritanie (voir ce chapitre) et sur les bordures du bouclier précambrien du Hoggar. Les variations climatiques durant le Tertiaire supérieur et le Quaternaire du Sahara avec des changements allant de conditions humides à arides (le dernier "grand pluvial" remontant à 7 000 ans), sont favorables à la formation de calcrètes uranifères. Cependant, aucun indice n'a été décrit à ce jour.

D'autres concentrations uranifères en Algérie plus anciennes, semblent elles aussi pouvoir être rapportées quant à leur genèse à des phénomènes superficiels. Des dépôts de type "surface" et d'âge ancien sont rares. Les caractères mêmes de ce type de concentration rendent leur conservation difficile. Dans de très rares cas seulement, lorsque le bouclier continental a été préservé de toute érosion avant le dépôt d'une couverture sédimentaire protectrice, il a pu y avoir préservation des paléosurfaces et de leurs concentrations uranifères.

2. GEOLOGIE

Un exemple en est fourni en Algérie par le gîte de Oued Tahaggart, sur la bordure sud du Hoggar [2].

Sur la bordure sud du bouclier cristallin du Hoggar, les formations sédimentaires paléozoïques débutent, en discordance sur le socle, par une formation détritique attribuée au Cambro-Ordovicien. La limite du sédimentaire forme une indentation triangulaire vers le Nord: le bassin de Tin Séririne (Figure 1). Le gîte de Tahaggart est situé sur la bordure Nord-Est de ce bassin. La minéralisation est localisée dans des gneiss et des micaschistes altérés sous la surface du Cambro-Ordovicien transgressif sur le socle. Celui-ci montre, sous le contact, une altération d'origine pédologique d'une extension verticale d'une vingtaine de mètres. La surface d'inconformité n'est accidentée que par des reliefs faibles. Sous le contact on observe la présence d'une croûte siliceuse pluricentimétrique. En dessous de cette croûte, les gneiss et micaschistes altérés présentent des profils d'altération pédologique relativement peu diversifiés parmi lesquels il est toutefois possible de distinguer des

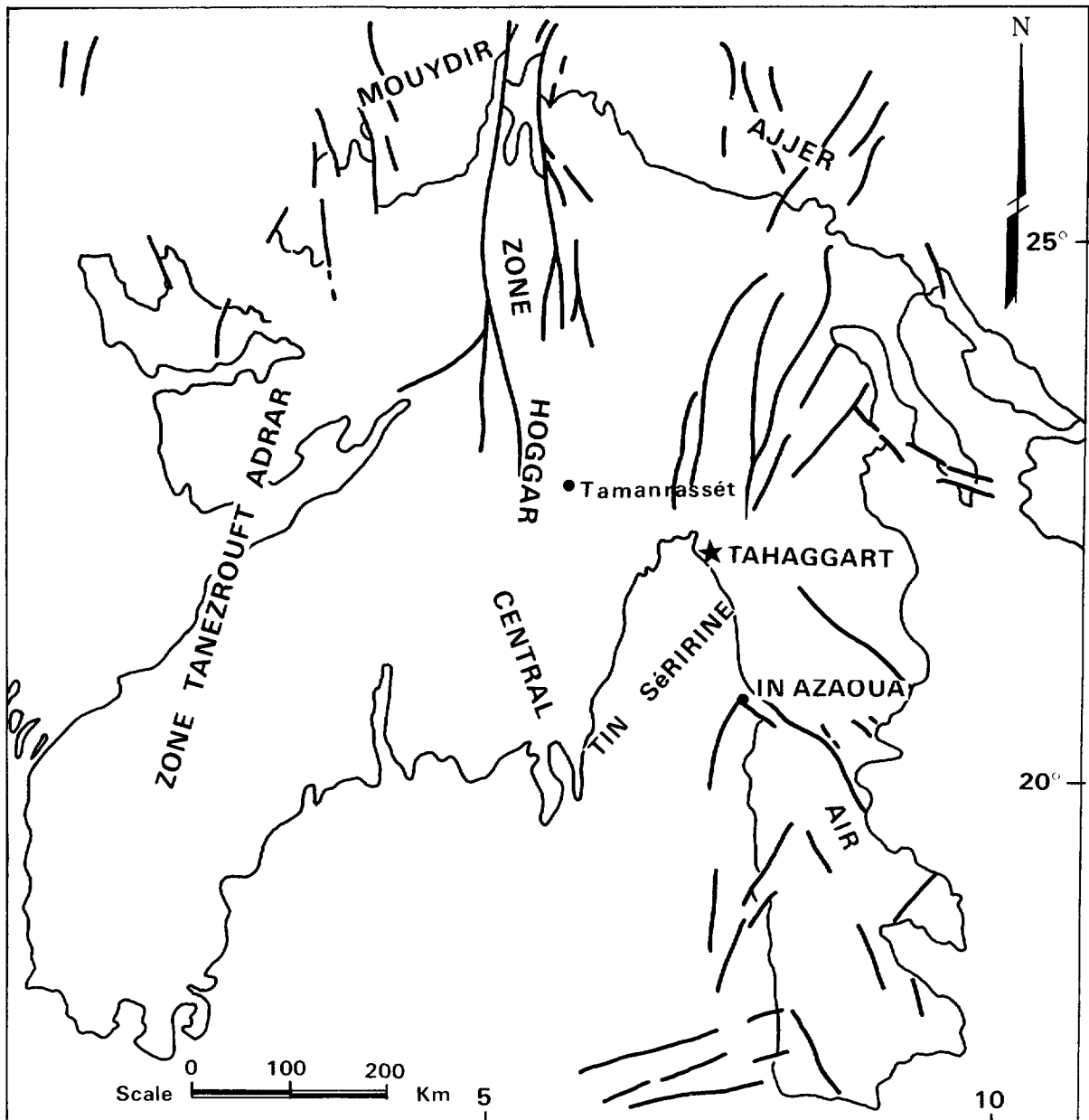


Figure 1
 Carte de situation du gîte de Tahaggart (Algérie)
 Locality map of Tahaggart uranium deposit (Algeria)

La kaolinite et des illites mieux cristallisées constituent les minéraux argileux des profils d'accumulation localisés sous les dépressions peu marquées de la paléosurface. Deux générations de kaolinite sont présentes:

profils de lessivage et des profils d'accumulation. Dans les profils de lessivage, la roche altérée comprend essentiellement du quartz, de la muscovite, de la kaolinite, de l'illite et de la goéthite, laquelle est souvent associée à la kaolinite. Ce type de profil se caractérise par le peu d'importance des processus de silicification secondaire et par contre une kaolinitisation et une illitisation intenses.

– une kaolinite en houppes formée in situ par transformation de la muscovite et une kaolinite de néogène, en puzzles, formée par la combinaison de l'alumine et de la silice libérées lors de l'hydrolyse des silicates.

Hématite et goéthite sont eux aussi présents. Dans ces profils d'accumulation le quartz présente des habits très caractéristiques. Les grains ont des contours irréguliers. Dans une première phase, le quartz a subi un phénomène de corrosion puis ensuite un phénomène d'accrétion avec croissance d'une bordure de quartz secondaire. La bordure de quartz de néogène est séparée du noyau primitif par des vermicules de kaolinite. Dans le noyau primitif lui-même un certain nombre de kaolinite néoformées, issues de la phase d'altération peuvent être observées. Sur la bordure, les kaolinites sont disposées perpendiculairement à la bordure du cristal de quartz. Des quartz isométriques, de forme amiboïde à bordures bourgeonnantes sont aussi observables. Les quartz automorphes hexagonaux ne sont pas rares et ont été trouvés dans des sondages localisés au niveau de

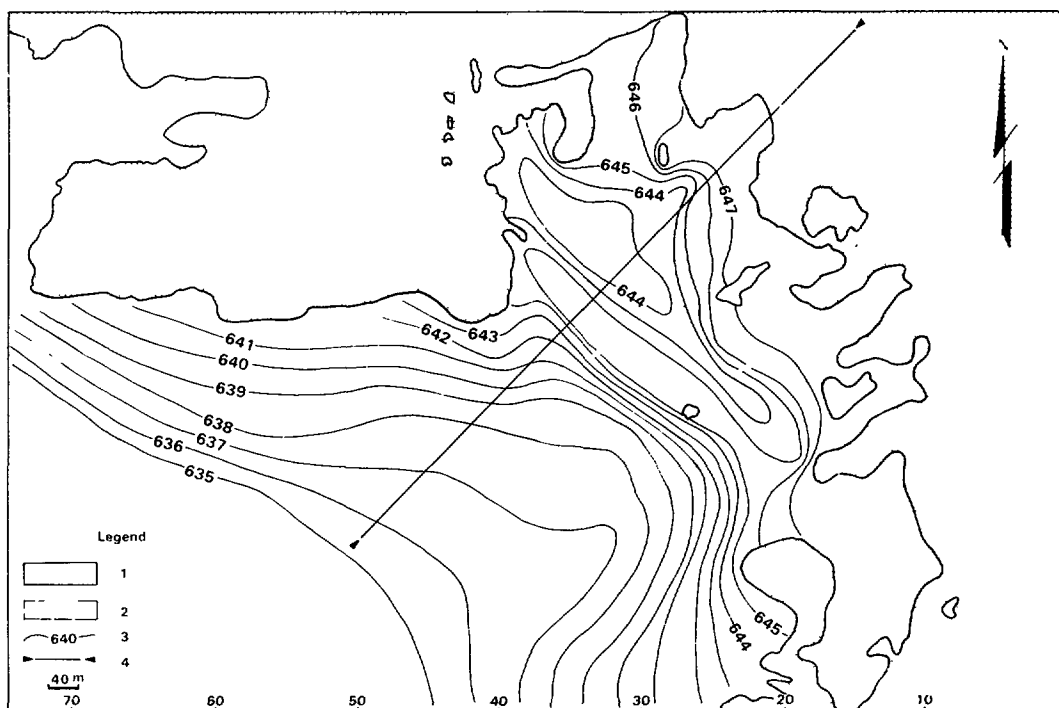


Figure 2

Carte des isohypses du toit du socle à Tahaggart.

Palaeotopographical map of the unconformity surface at Tahaggart.

- | | |
|---|---|
| <p>1. Dépôts cambro-ordoviciens
<i>Cambro-Ordovician sediments</i></p> <p>3. Isohypse (m)
<i>Topographic contours in metres</i></p> | <p>2. Roches métamorphiques à l'affleurement
<i>Outcropping metamorphic rocks</i></p> <p>4. Tracé de la coupe Figure 3
<i>Location of the profile in Figure 3</i></p> |
|---|---|

dépansions de la paléosurface. Il paraît évident que le quartz dans les profils d'accumulation a une histoire complexe. Dans une première période se sont produits des phénomènes de dissolution des silicates et du quartz primaire comme l'atteste la présence de quartz corrodés; par la suite la silice libérée a pu reprécipiter, donnant des silicifications authigènes sous forme:

- De bordure d'accroissement secondaire autour de quartz primaire.
- De grains de quartz à bordure bourgeonnante et quartz néogénétiques subautomorphes.

Un certain nombre d'observations permettent de compléter l'étude des phénomènes d'altération pédologique. Dans les profils de lessivage la teneur moyenne en SiO_2 est plus basse (60 % environ) que dans les profils d'accumulation (68 % environ). L'aluminium montre une évolution en sens inverse passant de 20 à 30 % d' Al_2O_3 dans les profils lessivés (riches en kaolinite) à des teneurs variant de 12,5 à 21 % (moyenne 16 %) dans les profils d'accumulation. L'enrichissement en Al_2O_3 des profils lessivés provient d'un départ sélectif d'autres éléments (SiO_2 , alcalins et alcalinoterreux) que d'apport d' Al_2O_3 . En ce qui concerne le fer, on note qu'il y a évolution du sommet vers la base des profils. Toutefois, l'enrichissement en fer est plus faible dans les profils lessivés (de 5 % au sommet à 7 % à la base) que dans les profils d'accumulation (de 3.2 % teneur moyenne entre 0 et 2 m. sous la surface à 10 % teneur moyenne à 4 m.). Il semble établi qu'une partie du fer lessivé peut migrer latéralement et verticalement vers les parties profondes des profils d'accumulation.

L'altération s'est développée sur une topographie peu accidentée (Figure 2) avec des reliefs de 1 à 6 m qui sont toutefois responsables d'une différenciation en profils de lessivage et d'accumulation. Le type d'altération observé semble lié à des conditions climatiques particulières. A l'exception du quartz, souvent corrodé d'ailleurs, les minéraux primaires ont disparu. L'importance du phénomène de kaolinisation indique un milieu acide avec des phénomènes de lessivage limités sous un climat chaud et humide.

Le drainage restreint, la quantité relativement faible de fer dans un milieu où il reste longtemps mobile, tous ces éléments sont favorables à la néoformation de kaolinite par piégeage de la silice et de l'alumine en solution. Ces conditions de lessivage modéré sont attestées par le rapport $\text{SiO}_2/\text{Al}_2\text{O}_3$ dans les produits d'altération où il varie de 2.0 à 2.6 dans les profils de lessivage et de 3.11 à 4.62 dans les profils d'accumulation. Les valeurs obtenues sur des échantillons provenant de profils d'accumulation, toutes supérieures à 3, varient irrégulièrement avec la profondeur. Elles confirment que l'environnement était peu lessivant.

Pour résumer, on peut dire que les produits d'altération se sont formés sous une surface faiblement ondulée durant une période à climat chaud et humide. Les zones de dépressions mal drainées pourraient donner naissance à des milieux semi-confinés. Des cylindres de 5 à 20 cm. de diamètre observés dans la partie sommitale des paléoprofiles sur le bord des paléodépansions seraient des marques d'insertion de plantes de type

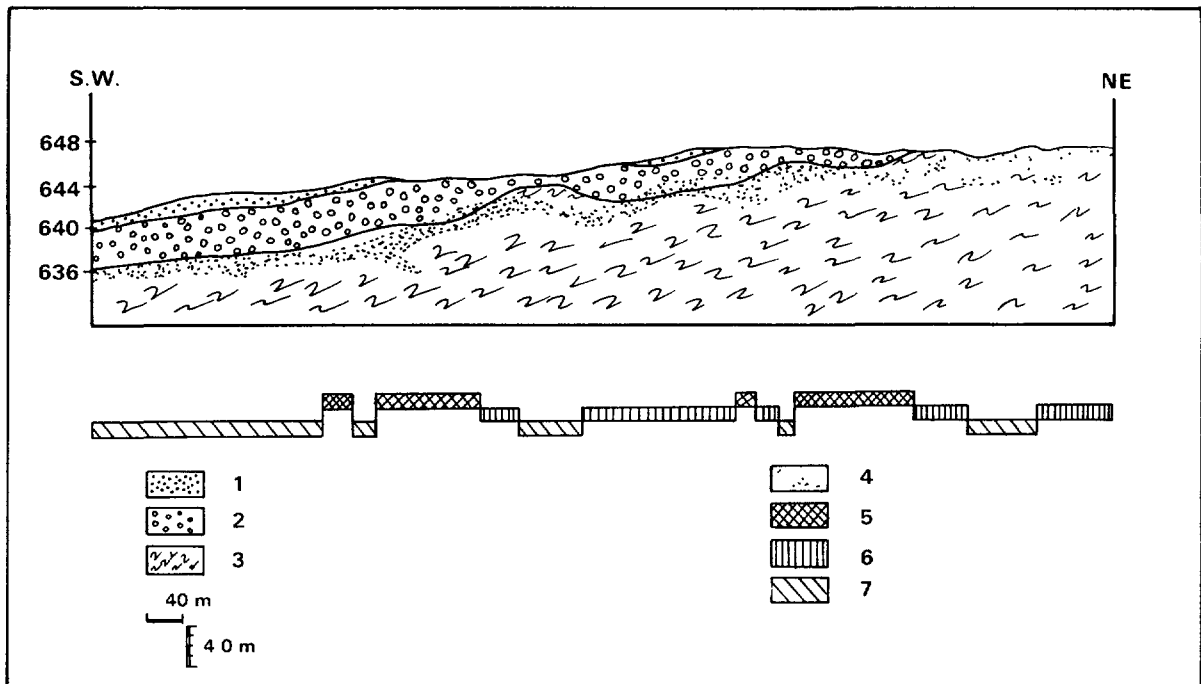


Figure 3
Agencement des produits: teneurs x puissance dans la coupe.

Lithology and distribution of the uranium mineralization: grade of ore x thickness of the mineralized horizon within the profile.

- | | |
|---|---|
| 1. Grés
Sandstones | 2. Conglomérat de base
Basal conglomerate |
| 3. Gneiss
Gneiss | 4. Minéralisation
Uranium mineralization |
| 5. Valeurs très élevées du produit
Very high values of uranium | 6. Valeurs élevées du produit
High values of uranium |
| 7. Valeurs moyennes
Medium values of uranium | |

des nématophytes [3]. Cette localisation en bordure des zones mal drainées permet de préciser la paléogéographie de la surface et on peut en déduire que la matière organique, même en faible quantité était présente dans le milieu.

3. MINERALISATIONS

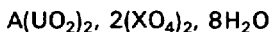
Dans le paléoprofil pédologique sous la surface d'inconformité les minéraux d'uranium suivants ont été décrits: Autunite, Torbernite et Carnotite. Il n'y a pas de sulfures et la pyrite elle-même est absente. La minéralisation est localisée dans les gneiss altérés. Elle se trouve dans des cavités (1 à 15 mm de diamètre), dans des microfissures et dans les plans de schistosité. Une partie importante de la minéralisation est associée à la kaolinite et au quartz. Dans le quartz, la minéralisation se rencontre seulement dans la frange de néoformation. Les cristaux d'autunite et de torbernite sont piégés dans la bordure néoformée, à l'intérieur des quartz à forme bourgeonnante et des cristaux de quartz subautomorphes. Une autre partie de la minéralisation est uniquement piégée sur les kaolinites de néoformation des gneiss altérés, et on observe de plus que les conglomérats de base et les grès de Cambro-Ordovicien ne présentent aucune trace de minéralisation.

Par contre, sous les zones déprimées la minéralisation, essentiellement localisée dans le profil d'altération, se retrouve aussi dans la croûte silico-ferrugineuse et le conglomérat de base. (Figure 3). La minéralisation y est représentée par de l'autunite dispersée dans la matrice ferrugineuse et de la torbernite formant des enduits dans des fissures tardives. Dans les paléoprofils d'altération, sous les zones basses (profils d'accumulation), les minéraux uranifères se localisent dans les quartz de néogénèse ou bien sont associés à la kaolinite et aux hydroxydes de fer.

La minéralisation uranifère de Tahaggart est très étroitement liée au processus d'altération pédologique développé sous la paléosurface avant le dépôt des formations cambro-ordoviciennes. La localisation des minéraux uranifères dans la frange néogénétique ou les quartz néoformés, leur association à de la kaolinite de néogénèse indiquent que l'âge est contemporain des phases ultimes de l'évolution de la pédogénèse.

Sur les parties élevées de cette topographie très mature, l'altération superficielle s'accompagne du développement d'une zone oxydée ferrugineuse. Dans les parties déprimées, le battement de la nappe détermine l'existence d'un front d'oxydo-réduction. Dans les horizons les plus profonds du paléoprofil, le fer lessivé précipite. Le mauvais drainage entraîne essentiellement sous les dépressions, la formation en abondance de kaolinite de néoformation et des silicifications.

Dans ces zones mal drainées les éléments métalliques et plus spécifiquement l'uranium mais aussi l'arsenic, le phosphore, le cuivre, le plomb le zinc et le vanadium sont concentrés. Leur présence influe sur la qualité de la minéralisation déterminant la formation de minéraux du groupe de l'autunite avec pour formule générale:



où: A = Ca, Mg, Cu, Mn

X = As, P, V [4]

Le mécanisme de dépôt de l'uranium à partir de l'eau des nappes à Tahaggart diffère de celui décrit pour le gîte des Bondons (France) [5] localisé dans un paléoprofil sous l'Hettangien. L'absence de sulfures à Tahaggart rend ce gîte différent des Bondons. On peut estimer qu'à Tahaggart les phénomènes d'adsorption sur les minéraux argileux néoformés ont pu jouer un rôle plus important dans le dépôt de l'uranium que les phénomènes d'oxydo-réduction.

4. CONCLUSION

Il convient de souligner qu'il existe probablement un grand nombre de telles concentrations associées à d'anciens profils d'altération sous inconformité, préservés par une couverture sédimentaire. Une prospection systématique, basée sur des études paléomorphologiques et paléoclimatiques des environnements favorables (socle fertile) pourrait amener des découvertes intéressantes.

REFERENCES

- [1] CONRAD, G., L'évolution continentale post-hercynienne du Sahara algérien. Publ., CRZA. No. 1 (1969) 528.
- [2] MOKADDEM, M., Le bassin de Tin Séririne et ses minéralisations uranifères (Hoggar, Algérie), Thèse 3^{ème} cycle Orsay (1980).
- [3] ARBEY, F., KOENIGER, J.C., Les nématophytes et les algueraies de l'Ordovicien et du Dévonien du Sahara, Bull. Centre Pau (1979) 409-418.
- [4] STEACY, H.R., KAIMAN, S., Uranium minerals in Canada, Miner. Ass. of Canada Toronto (1978).
- [5] EULRY, M., VARGAS, J.M., Les altérations anté-liasiques des Cévennes méridionales. Leur rôle dans la métallogénèse des concentrations uranifères, Thèse 3^{ème} cycle INPL, ENSG Nancy (1979) 388.

SURFICIAL URANIUM DEPOSITS IN ARGENTINA

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ABSTRACT

SURFICIAL URANIUM DEPOSITS IN ARGENTINA

In Argentina, several surficial Cenozoic uranium occurrences have been found. They are all of low grade, wide areal extent, occur near the surface, have varied thicknesses, are highly irregular in distribution, and have significant potential. Two deposits only have been fully evaluated, while the rest have only been found recently and remain unexplored.

Three main types have been identified:

1. Uraniferous calcite- and gypsum-cemented clastic sediments of Cenozoic age.
2. Autunite and meta-autunite in intensely fractured granites.
3. Uraniferous calcareous sediments associated with hot springs in Quaternary volcanic fields.

1. INTRODUCTION

Several Cenozoic uranium deposits have been found in Argentina (Figure 1). Some deposits are merely showings and are not economically viable, while others have considerable uranium resource potential.

Three main types of surficial uranium deposits have been identified:

1. Those associated with calcite and gypsum, cemented Cenozoic clastic sediments, which contain small amounts of manganese and iron oxides. They are generally of a low grade but have a significant uranium resource potential.
2. Occurrences associated with areas of intense fracturing in Carboniferous granites.
3. Occurrences in travertine, aragonite, crystalline limestone, and tufa deposited by hot springs in the Late Pleistocene volcanic cycle.

2. TYPE 1 — IN CENOZOIC CLASTIC SEDIMENTS

2.1 Valle de Punilla-Rodolfo Deposit

The Rodolfo deposit occurs in Cordoba Province at latitude 31°15' south and longitude 64°30' west.

General Geology

It is one of a number of uranium deposits that are hosted by Tertiary continental sediments situated on the eastern flank of the north-trending Punilla valley. They are found in a 50 km belt between the towns of Biale Masse in the south and Capilla del Monte in the north. The most important occurrence is Rodolfo, which has a mineralized zone of 6 km in length, 50 to 300 m wide, and a thickness of 1 to 2 m that locally reaches a maximum of 8 m.

The uranium occurs principally in the middle section of the Eocene Cosquin Formation, which is overlain by the non-uraniferous Casa Grande Formation, both of which unconformably overlie Palaeozoic granites similar to those of the Sierra Grande. Covering these rocks are Quaternary sediments such as fanglomerates and loess (Figure 2).

The **Cosquin Formation** is about 115 m thick and can be divided into three members:

1. A lower member consisting of 90 m of calcite-cemented arkosic sandstones with siltstone lenses;
2. a middle member consisting of 5 to 12 m of calcite-cemented red silts and montmorillonitic clays; and
3. an upper member consisting of calcite-rich sediments, similar to the lower members in composition, but with a greater abundance of calcite cement.

Clastic sediments of all three members were derived from the granitic rocks of the Sierra Grande to the west. The lower two members are red with green-grey bleached zones, mostly along joints and in sandy layers. The upper member contains abundant limestone nodules, and a few sandstone lenses and siliceous beds are present. These sediments were deposited in a lacustrine or low-energy stream environment.

Clastic sediments in the three members are composed of clear to white, sometimes smoky, quartz, potassic feldspars, pistacite, minor light-blue fluorite, white mica, red garnets, magnetite, ilmenite, and trace monazite.

The **Casa Grande Formation** is more than 150 m thick and consists of a monotonous sequence of calcite-cemented silty sandstones and gravelly conglomerates. A basal well-cemented conglomerate is similar to the

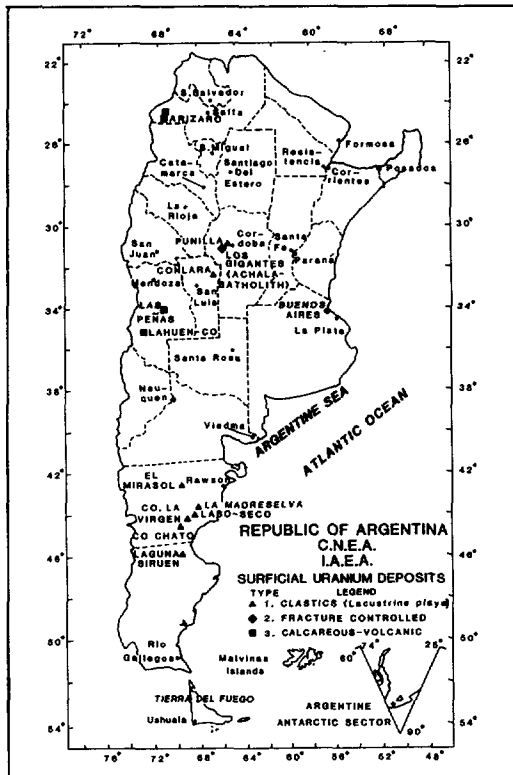


Figure 1
The distribution of surficial uranium deposits in Argentina.

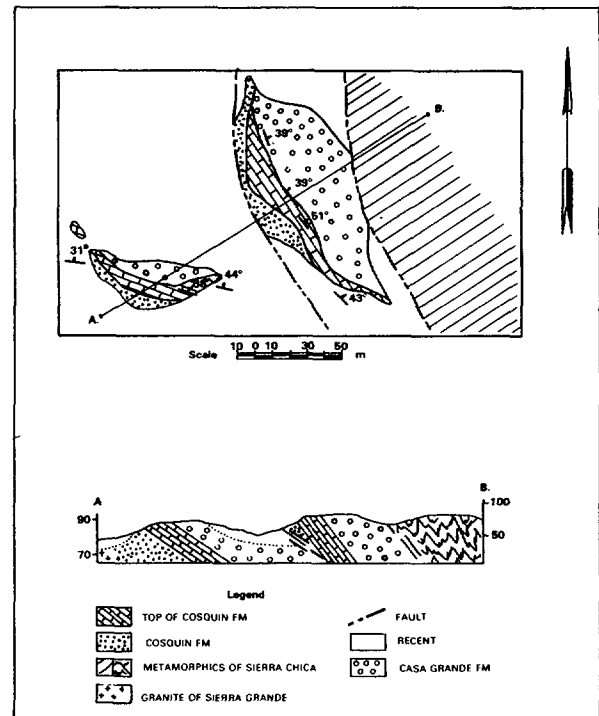


Figure 2
Geological cross-section of Valle de Punilla-Rodolfo uranium deposit.

upper Cosquin Formation, but with some compositional differences. The conglomerates are polymictic and contain clasts derived from the metamorphic terrane of the Sierra Chica to the east.

These clastic sediments are composed principally of milky quartz, feldspar, pistacite, muscovite, biotite, minor magnetite, garnet, hematite, and monazite. Abundant plutonic and metamorphic rock fragments transported from the east and northeast are present.

Tectonics

The Cosquin and Casa Grande Formations dip homoclinally 40° to 50° to the east and are repeated by the north-to northwest-trending east-dipping thrust faults. To the east, a major fault at the foot of the Sierra Chica juxtaposes Precambrian and Lower Palaeozoic rocks against the Tertiary formations (Figure 2). To the west, another fault juxtaposes Tertiary and Quaternary sediments. This north-south system of faulting is intersected by a later east-west system.

Mineralization

The uranium is hosted by red and silty clays of the middle member of the Cosquin Formation. It occurs as carnotite- and tyuyamunite-cemented nodules and lenses that occur over an average thickness of 3.3 m. The uranium is irregularly distributed and tends to follow different layers in the middle part of the formation. No uranium has been found in the Casa Grande Formation or in the Quaternary sediments. Reasonably assured resources are 3 700 t U₃O₈ with a grade of 0.04 % U₃O₈.

2.2 Valley Conlara

In the Conlara River valley of San Luis Province, uranium resources occur in an area 40 km long and 10 km wide, against the flanks of the valley from Santa Rosa to the north to Concaran to the south between the Comechingones ridge to the east and the Santa Luis ridge to the west.

Uranium occurs as carnotite and tyuyamunite in silts and sandy silts, and in the regoliths of metamorphic rocks. The sediments are Tertiary in age and are found along the rims of the valley. Two occurrences have been studied:

Las Toscas

Las Toscas occurs near Santa Rosa at latitude 32°30' south and 65°14' west. Spotty impregnations of carnotite and tyuyamunite occur in a silty sandstone in an area 300 by 300 m which has a thickness of 2 m. Some samples

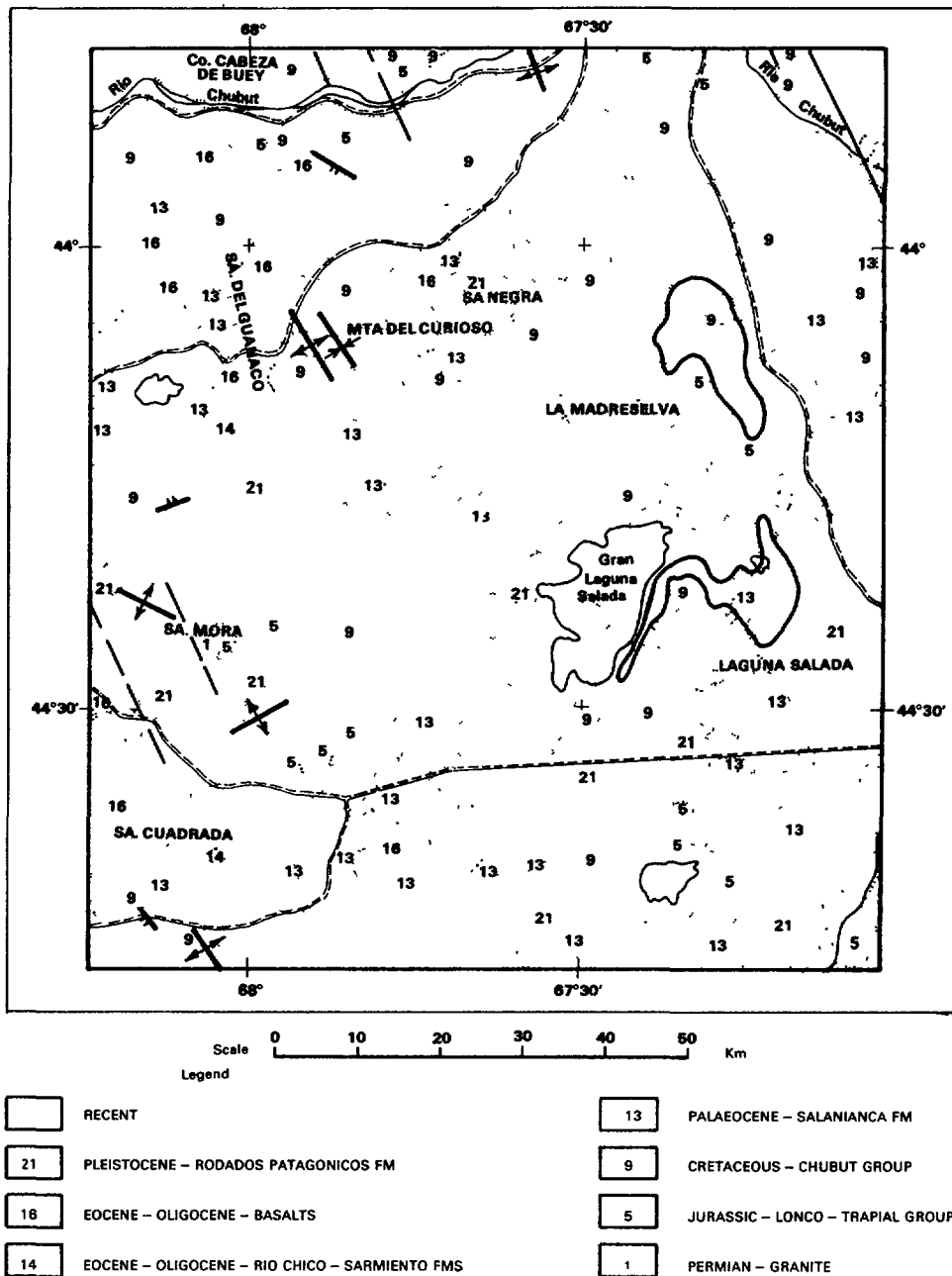


Figure 3
Surficial uranium deposits in Patagonia.

yield up to 1 000 ppm U_3O_8 over a thickness of 0.8 m. The mineralized beds are high on the rim of the valley in the old river terraces lying on the Precambrian and Lower Palaeozoic schists and gneisses.

Humberto

Humberto is located at latitude $32^{\circ}34'$ south and $65^{\circ}15'$ west. Carnotite and tyuyamunite impregnate strongly fractured and altered metamorphic rocks with abundant kaolinite and calcium carbonate. The mineralization is controlled by a faulted zone that strikes 330° . Biotite schists with some muscovite and yellow uranium minerals are found to the west of this area. To the east, there is an increase of hematite and a decrease of carbonates and uranium mineralization. Drilling in the faulted area gave no indication of uranium mineralization below the water table and is considered to be epigenetic and surficial. The resources of the deposit have been estimated at 50 t U_3O_8 at a grade of 220 ppm.

2.3 Patagonia

Many surficial uranium deposits occur in Chubut Province in the southern region of Argentina known as Patagonia (Figure 3). The region is deserts, receiving less than 200 mm rain per year, a mean temperature of about $12^{\circ}C$, and a high evaporation rate, due to strong winds.

The uranium occurrences are associated with closed lacustrine basins which are highly calcareous and usually contain gypsum. Since they have not been explored, little is known about their potential uranium resources or detailed geology.

The source of uranium is the Manuel Arce Formation, a fluvial conglomeratic sandstone which forms the upper part of the middle Upper Cretaceous Chubut Group. The Chubut Group is a continental volcano-sedimentary sequence that contains uranium deposits and occurrences in many different stratigraphic horizons. The Manuel Arce Formation contains autunite, schroeckerite, carnotite, and tyuyamunite associated with plant debris, mostly partially silicified fossil logs. It occurs within the drainage basin of the Laguna Salada (Salt Lake), is about 200 km long and has an associated playa with an area of about 1 500 km² (Figure 3).

The eastern playa is composed of 1 m of thick brown sandy silt covered by the unconsolidated conglomerates of the Rodados Patagonicos Formation of Pleistocene age. Both the silts and the conglomerates are locally impregnated with tyuyamunite and calcium carbonate in an area of about 70 x 20 km.

Four groups of occurrences have been located in the Laguna Salada and adjacent areas in the Chubut Province:

Laguna Salada

Laguna Salada occurs between latitudes 44°18' and 44°26' south and between longitudes 67°11' and 67°28' west. Tyuyamunite occurs as coatings on pebbles and in fractures, joints, and cracks in the underlying sandy silts, all of which contain abundant calcareous cement. The uraniumiferous layer is 1 m thick, but only 0.4 m has a grade as high as 300 ppm. There is a direct correlation between the calcium carbonate and the uranium concentration.

La Madreselva

La Madreselva occurs between latitudes 44°02' and 44°14' south and between longitudes 67°11' and 67°22' west, and constitutes another group of anomalies in the same environment with calcareous and gypsiferous cement. Tyuyamunite occurs in layers 0.2 to 0.5 m thick in sandy silts with uranium grades of up to 650 ppm.

Cerro La Virgen

Cerro La Virgen is the third group of anomalies in the Laguna Salada area which occur at latitude 44°19' south and 68°03' west.

El Mirasol

El Mirasol, occurring at latitude 43°07' south and longitude 67°13' west, constitutes another group of radiometric anomalies in Chubut Province.

3. TYPE 2 — IN FRACTURED GRANITIC TERRANES

3.1 Los Gigantes

In the Los Gigantes area, surficial uranium deposits are formed in zones within a granitic terrane where the intense fracturing created paths through which solutions could move. These fractures, which contain finely divided material, acted as sponges, thereby retaining the uranium. Exploration has failed to show uranium mineralization at depths of more than 40 to 50 m, in particular at Schlagintweit, the most important of this type of uranium deposit.

Schlagintweit

Schlagintweit is located on the eastern slope of the Los Gigantes ridge at latitude 31°20' south and longitude 67°47' west in Cordoba Province and has been extensively explored. It is situated within the granites of the Achala batholith which intruded into Upper Precambrian-Lower Palaeozoic high-grade metamorphic rocks that form the Sierras Pampeanas. The granite (329±15 Ma) is coarse-grained and locally porphyritic with pegmatitic textures and contains potassic feldspar (perthitic microcline), lesser oligoclase, and xenomorphic quartz. During the upper Tertiary it was exposed and extensively fractured.

The granite is cut by NNW-trending thrust faults which control the orientation of the Los Gigantes ridge forming part of the Sierra Chica. Another thrust fault system strikes WNW-ESE. The intersection of the two systems has created structural traps which contain concentrations of uranium. At Schlagintweit, there is a long compressive NNW-SSE fault, dipping WSW, that is intersected by a WNW-ESE fault to form a dihedral angle where the granite is intensely fractured and uranium occurs as a massive body. There are several sets of joints, the horizontal set being the most important in the distribution of uranium. The mineralized body has an elliptical shape with a long axis of about 600 m and a maximum depth of 45 to 50 m. The uranium minerals are of secondary origin and consist of autunite and meta-autunite with lesser beta-uranophane and phosphuranylite.

Schlagintweit was formed by leaching of the granitic rocks of the Achala batholith, which is slightly anomalous, having a uranium content of 6 to 9 ppm U₃O₈, mainly as disseminated uraninite and uranium in biotite grains. The intense fracturing in the granite created favourable conditions for leaching of uranium from the biotites and was

transported and deposited in the topographic depressions in the granite which occur in areas of more intense faulting and fracturing. The main faults acted as paths that controlled the movement of the mineralizing solutions. Reserves of the deposit are approximately 2 000 t of U_3O_8 with an ore grade of 250 ppm. The average thickness of the deposit is 33 m. Other lesser important occurrences located along the NNW-SSE fault include **Los Europeos**; **La Morenita**; and **Cerro Aspero**. On the western flank of the Achala batholith, there are other similar uranium deposits such as the **Los Riojanos**, **Don Vicente**, and **Don Alberto**, but these have not been completely explored. The uranium minerals are autunite, meta-autunite, and phosphuranylite, with uraninite in the biotite.

4. TYPE 3 — CALCAREOUS SEDIMENTS ASSOCIATED WITH QUATERNARY VOLCANIC ROCKS

4.1 Las Penas

The Las Penas uranium occurrence is found at latitude $34^{\circ}14'$ south and longitude $68^{\circ}49'$ west in the Sierra Pintada area of the Mendoza Province, where subeconomic uranium occurs in Pleistocene calcareous sediments. These rocks are more than 20 m thick and are composed of travertines, aragonite, crystalline calcite, and tufas. The mineralized unit is a banded travertine 1 m thick and 400 m long which contains 100 ppm U_3O_8 .

4.2 Lahuen-Co

Lahuen-Co is situated at latitude $35^{\circ}10'$ south and longitude $69^{\circ}50'$ west in Mendoza Province where limonitic travertine, deposited by hot springs, contains up to 200 ppm U_3O_8 . Radioactivity is low and the mineralization appears to be out of equilibrium.

4.3 Arizaro

Arizaro is situated at latitude $25^{\circ}01'$ south and longitude $67^{\circ}53'$ west in Salta Province. There are several occurrences of uranium located around the closed basin of the Arizaro Salt Lake, the most important of which are:

Verde I

Verde I consists of clastic rocks cemented with aragonite overlying beds of aragonite and onyx. Uranium mineralization occurs in a 1 m thick bed having uranium values up to 700 ppm U_3O_8 . The uranium minerals are uranophane and beta-uranophane.

Verde II

Verde II is similar to Verde I. It underlies an area of 300 x 50 m, with an average thickness of 0.65 m and an average grade of 530 ppm U_3O_8 .

Verde III and Nuclear IV

Verde III and Nuclear IV uranium occurrences occur in an onyx quarry in aragonite and have an average thickness of 1.5 m and an average grade of 200 ppm U_3O_8 .

SURFICIAL URANIUM DEPOSITS IN AUSTRALIA

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INTRODUCTION

Uranium mineralization in sediments of drainage channels in the semi-arid Yilgarn Block of Western Australia was discovered in 1969/70 by Western Mining Corporation, who investigated the source of radiometric anomalies delineated by airborne surveys [1.] Following the announcement of their deposit at Yeelirrie, much exploration activity ensued and numerous other occurrences of similar mineralization were found in western and central Australia [2]. It has become evident that the distribution of these deposits is controlled by the geology, geomorphology and climate of these regions. In this chapter, these factors are considered, with particular reference to their influence on the genesis of the Western Australian deposits. Various aspects of the occurrence and genesis of the deposits are exemplified by the descriptions of the six deposits explored and studied in most detail – Yeelirrie, Lake Way, Hinkler-Centipede, Lake Raeside, Lake Austin and Lake Maitland. Thereafter, radiometric disequilibrium studies of four of the deposits, conducted mainly for grade control purposes, are discussed, emphasizing their implications for the age and origin of the mineralization.

In these accounts, the term "calcrete" is used to describe "those limestone deposits associated with valley-fill sediments that occur in both broad fossil valleys and existing trunk drainage systems" [3]. They are formed by precipitation of calcium and magnesium carbonates from groundwaters and are equivalent to the groundwater calcretes of Netterburg [4]. They are distinct from the pedogenic calcretes, or kankars, that occur in the southern Yilgarn Block and, with one possible exception, are not hosts to uranium mineralization.

REFERENCES

- [1] HAYCRAFT, J.A., Sampling of the Yeelirrie uranium deposit, Western Australia, Aust. Inst. Min. Metall. (Melbourne Branch) Sampling Symp. (1976) 51–62.
- [2] BUTT, C.R.M., HORWITZ, R.C., MANN, A.W., Uranium occurrences in calcrete and associated sediments in Western Australia, Aust. CSIRO Div. Mineral. Report FP16 (1977) 67.
- [3] SOFOULIS, J., The occurrence and hydrological significance of calcrete deposits in Western Australia, West. Aust. Geol. Surv. Ann. Report 1962 (1963) 38–42.
- [4] NETTERBURG, F., The interpretation of some basic calcrete types, S. Afr. Arch. Bull. 24 (1969) 117–122.

REGIONAL SETTING, DISTRIBUTION AND GENESIS OF SURFICIAL URANIUM DEPOSITS IN CALCRETES AND ASSOCIATED SEDIMENTS IN WESTERN AUSTRALIA

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ABSTRACT

REGIONAL SETTING, DISTRIBUTION AND GENESIS OF SURFICIAL URANIUM DEPOSITS IN CALCRETES AND ASSOCIATED SEDIMENTS IN WESTERN AUSTRALIA

Surficial uranium deposits in Western Australia are largely in the Yilgarn Block in areas of Archean granitoids and greenstones, and in the Gascoyne Province in Proterozoic granites and gneisses. The region has had a long weathering history marked by continuous planation developing a regolith up to 100 meters thick. The distribution of calcrete type uranium deposits is controlled by geologic as well as weathering, erosion and climatic factors. Valley, playa and terrace deposits are recognized. The principal known surficial uranium deposit, Yeelirrie, occurs in the Yilgarn block as a valley deposit.

1. LOCATION

The majority of the surficial uranium deposits occur in the north of the Yilgarn Block and in the Gascoyne Province of Western Australia, within the area bounded by longitudes 115°30' and 124°00'E and latitudes 24°30' and 30°00'S.

2. BASEMENT GEOLOGY

The basement is the central part of the Precambrian Western Shield, which is flanked by the Phanerozoic Officer Basin in the east and the Carnarvon and Perth Basins in the west (Figure 1). The shield consists of Archean granitoids and greenstones in the Yilgarn Block, Proterozoic granites and gneisses in the Gascoyne Province and Proterozoic sedimentary rocks in the Nabberu and Bangemall Basins.

3. WEATHERING, GEOMORPHOLOGICAL AND CLIMATIC HISTORY

The Western Shield has had a long and complex weathering and geomorphological history [1, 2] and this has had a considerable influence on the development of the uranium deposits [3, 4], even though they themselves appear to be only of Quaternary age [5]. This history commences, in effect, 250 million years ago, from the Sakmarian glaciation of the Permian, since when the western two-thirds of the Australian continent have been relatively quiescent tectonically, except for minor epeirogenic movements. Much of the area has been emergent throughout and continuously exposed to subaerial weathering. During intervals of subsidence in the Mesozoic, sedimentation occurred in the intracratonic basins, but these too were weathered during periods of uplift. Climates varied from temperate to warm in the Mesozoic, becoming humid-tropical to subtropical in the Oligocene-Miocene. This, combined with tectonic stability, allowed the formation and preservation of a mantle of deep weathering, lateritic in nature. From Mid- to Late Miocene, there has been a trend to aridity, spreading from the centre of the continent [1]. Although this climatic change slowed the rate of deep weathering and caused local instability and erosion, the weathered mantle has been largely preserved.

The broad valleys, which now contain chains of playas, are possibly the oldest geomorphological features of the landscape. They follow ancient river systems, perhaps pre-Permian in age, modified by lateral migration and infilling by sedimentation. As the aridity developed, these drainages became disconnected, and evaporites and calcretes were deposited. Together with associated alluvium, these sediments are the hosts to uranium mineralization. Some rejuvenation has occurred as the result of epeirogenic uplift of the continental margins. The upstream extent of rejuvenation – the Meckering Line [6] – marks the western limit of the surficial uranium deposits on the Yilgarn.

This long history of weathering has been one of continuing planation, by glaciation in the Permian, by fluvial erosion in the Early Mesozoic, by land-surface reduction through chemical wasting in the Late Mesozoic-Early Tertiary, and by etch planation since the Mid-Miocene. The resultant landscape is characterized by a low elevation, rarely exceeding 650 m, low relief and overall flatness.

The present climate of the area is semi-arid, with hot summers and mild winters. Rainfall is irregular, occurring mainly in the summer months, with an annual mean of less than 250 mm.

3.1 Regolith of the Northern Yilgarn Block and Gascoyne Province

The regolith, which is composed of the deep weathering mantle and overlying transported overburden, is up to 100 m or more in thickness, especially in the valley centres. The weathering profiles vary according to

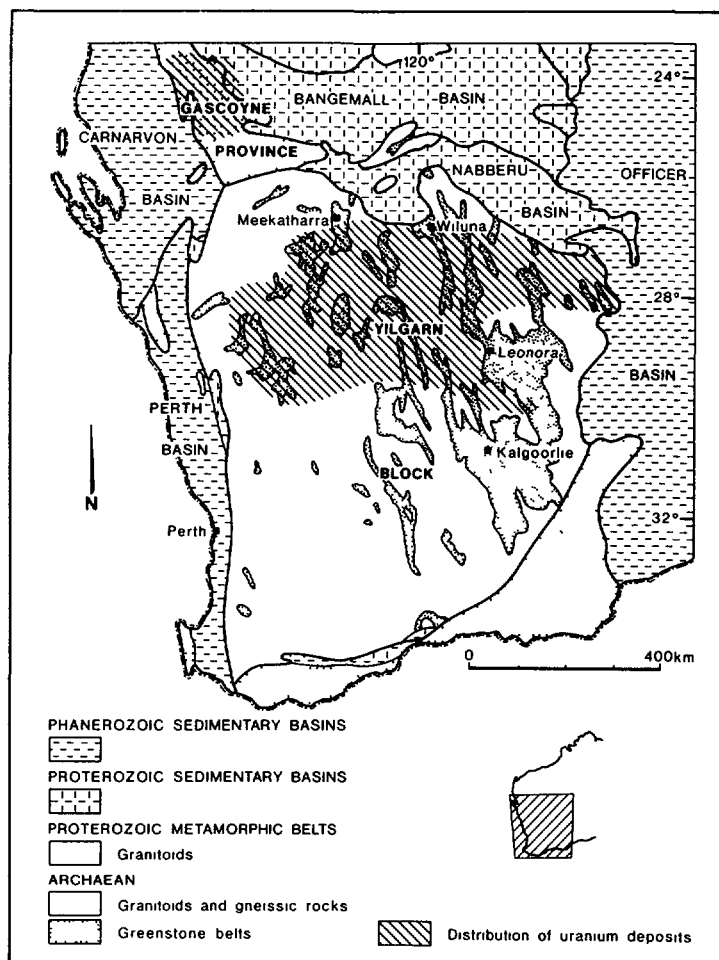


Figure 1
Distribution of surficial uranium mineralization in south-western Australia in relation to some geological and tectonic units.

topographic and regional setting and, particularly, to parent lithology [7]. Granitoids are the predominant lithology and the profiles generally consist of a bleached saprolite of kaolinite and quartz (commonly over 30 m thick) overlain by sands and grits. In exposures in erosion scarps (breakways) these are cemented by anatase (to form silcretes) and by aluminosilicates [8]. The upper horizons can have ferruginous mottlings and accumulations of pisolites are present in some overlying sandy sediments; however, ferruginous duricrusts (ferricretes) do not appear to have developed over the granitoids, although present on more basic rocks, and the profiles thus differ from the lateritic bauxites developed in the southwest of the Yilgarn Block.

In upland areas, the granitoid profiles are overlain by aeolian sands and colluvium, derived from the reworking of the weathered zone. In lower parts of the landscape, the residual profile is overlain by colluvial and alluvial sediments, some of which may themselves have been deeply weathered. The chemical deposits, calcretes and playa evaporites, overlie this sequence. The alkalis have been derived from rainfall [9] and continued slow weathering, and have accumulated under arid conditions, probably being recycled by deflation of the playas and redistribution across the landscape. The calcretes have precipitated close to the water table, possibly replacing alluvial sediments. They can exhibit positive relief features due to upward growth [10], but nevertheless are commonly overlain by aeolian, colluvial or alluvial sediments, particularly in the upper parts of the valleys. Down-profile, they are transitional to clay-quartz units, which may be alluvial or part of an in-situ deep weathering profile.

A silicified colluvium, the Wiluna Hardpan [11], is present over much of the area where calcrete has developed; these units are interrelated inasmuch as they are products of the same environment, but any closer relationship is conjectural.

3.2 Regional Zoning

The distribution of groundwater (or valley) calcrete has been of considerable importance during exploration, although not all uranium mineralization is hosted by calcrete. Calcretes are found over much of the Precambrian Western Shield and adjacent sedimentary basins. However, their development ceases in the south and

southwest, where pedogenic calcretes are found instead. The zonal boundary – the Menzies Line – is defined by a number of interrelated environmental characteristics and has been recognized informally by many workers for several years [3].

South of the Menzies Line, soils are predominantly neutral to alkaline, orange to red, non-calcareous earths and earthy sands, with associated and often abundant saline and calcareous loams with kankar development. Groundwaters tend to be saline, and neutral to acid. Average annual rainfall generally exceeds 225 mm, falling mainly in winter; annual evaporation is less than 2 500 mm and annual mean temperature below 19 °C. Vegetation immediately south of the lines is that of the Coolgardie Botanical District [12], of open forests of salmon and gimlet gums (*Eucalyptus salmonophloia* and *E. salubris*) and shrublands of mulga (*Acacia* spp), *Grevillea* spp, mallee eucalyptus and *Casuarina* spp.

North of the Menzies Line, soils are predominantly neutral to acid, red, non-calcareous earths, sands and lithosols, with an extensive development of hardpan. Calcretes are common in drainages. Groundwaters are less saline than to the south, especially in calcretes, and are neutral to alkaline. Annual rainfall is generally less than 225 mm, falling mainly in the summer, with annual evaporation exceeding 2 500 mm and annual mean temperatures exceeding 19 °C. The vegetation is that of the Austin Botanical District, consisting of shrublands dominated by mulga, with *Eucalyptus* spp, such as the river red gum (*E. camaldulensis*) common only along watercourses.

It is interesting to note that the Menzies Line appears to cross major lakes such as Lake Barlee and Lake Moore. In Lake Moore, we have found that the pH of waters north of the line generally exceeds 7.0, but to the south can be below 4.0.

4. SURFICIAL URANIUM MINERALIZATION

4.1 Distribution

Numerous occurrences of surficial uranium mineralization have been located in calcreted drainage channels in granitoid terrains of the northern Yilgarn Block, the Gascoyne Province, the Pilbara and parts of South Australia and the Northern Territory. Nearly all calcretes in these terrains have traces of mineralization and only the more significant occurrences are shown on Figure 2, which also gives the location of the deposits described therein.

Descriptions of all the occurrences are given elsewhere [3]. The distribution of the Western Australian deposits is controlled by the following features:

- (a) Enrichment is in the form of oxidized uranium minerals; suitable environments for the concentration of uranium in this manner exist only north of latitude 30 °S. The most southerly occurrences are in playas.
- (b) With only one exception, the calcrete uranium occurrences are restricted to areas where granitoids are the predominant rocks in the catchment, which suggests a close genetic link with granitic terrain.
- (c) In the west and northwest, active erosion by major rivers and their tributaries has tended to destroy the calcretes and other sedimentary hosts to mineralization, by either erosion or leaching. Thus, no deposits are found west of the upstream limit of erosion (the Meckering Line) on the Yilgarn Block. In the Gascoyne, however, several small deposits are present in dissected terrain and this may reflect a slightly different mode of origin.

4.2 Classification

The main uranium deposits can be classified by their geomorphological situation into three main types.

Valley Deposits

These occur in calcretes and associated underlying sediments in the central channels of major drainages, and in the platforms and chemical deltas where the drainages enter playas. The Yeelirrie, Hinkler-Centipede, Lake Way, and Lake Raeside deposits are of this type. The calcretes occur as elongated sheets occupying central tracts in trunk valleys and form important aquifers. They vary in width from a few hundred metres to 3 to 5 km or more and may be over 100 km in length; thickness is usually 5 to 10 m but often exceeds 30 m along the axis. Longitudinal gradients are commonly less than 1:1 000. They frequently lead to playa lakes where they broaden out to deltaic platforms. At Centipede and North Lake Way, the chemical deltas may represent a facies change, with the development of sepiolite and aragonite.

The calcretes frequently form positive relief features in the valleys, being raised and mounded to 3 m or more above the flanking alluvial plains [3, 10]. This was probably due to the precipitation of dolomite or calcite at the water table – as a “groundwater evaporite” – with voids often infilled by sepiolite and other magnesian clays. The relief may be emphasised by erosion by creeks and washes flanking the calcrete body. However, particularly in upper sections of the valleys, the calcretes may be covered by hardpan sediments such as alluvium, evaporites and aeolian sands. Discontinuous beds of hardpan and alluvium also occur within the calcrete, appearing to have been engulfed by the precipitating carbonate. Calcrete precipitation is probably still active and must have continued for an extensive time: the older parts of these profiles probably equate with the perched, terraced calcretes west of the Meckering Line, discussed later.

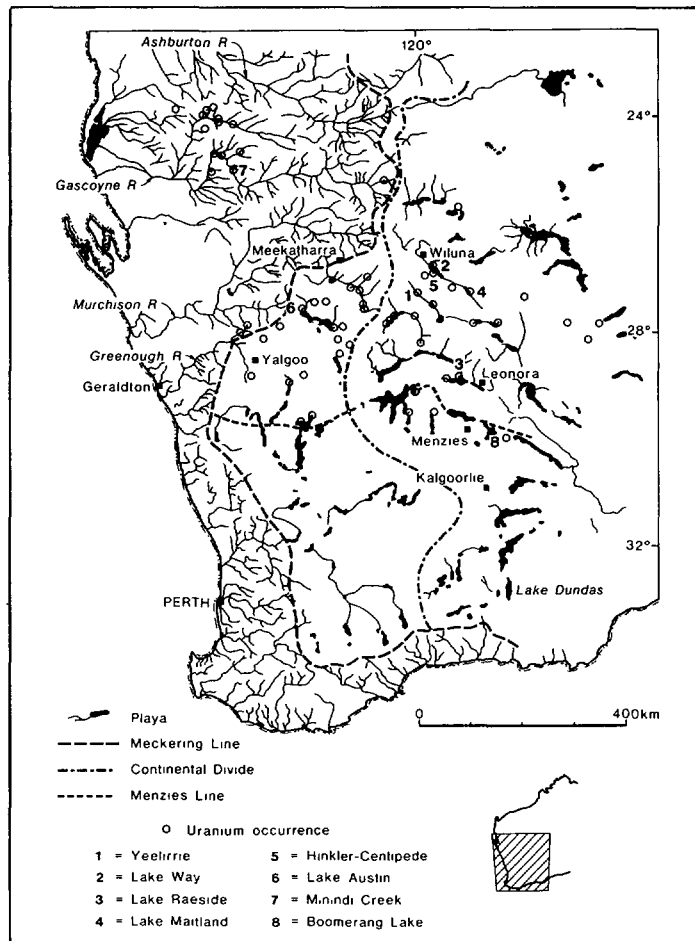


Figure 2
Distribution of surficial uranium mineralization in south-western Australia in relation to drainage and some geomorphological zoning. The locations of deposits discussed in detail in this paper are given.

The calcretes frequently exhibit karst features with evidence of slumping and caving, due to the solution of carbonate [10]. Elsewhere, the calcrete can be mounded, suggesting upwelling of waters and active carbonate precipitation. A mound structure exposed at Yeelirrie is diapiric in form and fault-bounded. Slickensided carnotite and carnotite on slickensides indicate a complex intermingling of periods of movement and uranium mineralization. The structure may be due either to upward movement of the "diapir" or caving and collapse of the surrounding material.

The calcretes are generally transitional downwards into a clay-quartz unit, alluvial in origin. Occasionally, calcretes are present more or less directly overlying lateritic profiles over granitic and, occasionally, mafic and ultramafic rocks.

The zone of uranium enrichment is often very large, and may extend for several kilometres along the drainage. However, the mean content is generally quite low (below 100 ppm U), with higher-grade mineralization patchily distributed within the overall anomaly. With few exceptions, the available tonnages of exploitable material are too small to be economic.

In general, the uranium enrichments are not specifically associated with the calcretes, but transgress into all the units present, with the greatest concentration in the vicinity of the water table. Since the calcretes are the principal aquifers, they are the most frequent hosts to the mineralization; nevertheless, in several occurrences, including North Lake Way, the main accumulation can be in subcalcrete clays and clay-quartz horizons.

Mineralization occurs almost entirely as carnotite, commonly as a late-stage precipitate in cavities in which it may be associated with coatings (normally 10 to 50 m thick) of calcite, dolomite, silica and/or sepiolite. Carnotite may also be finely disseminated, particularly in clay-quartz units. Some uranium occurs in thin veins of opaline silica. The uranium, in concentrations of 50 to 400 ppm, is probably absorbed in the silica, which is highly fluorescent.

Playa Deposits

These occur in near-surface evaporitic and alluvial sediments of playas and are exemplified by the Lake Maitland and Lake Austin deposits. North of latitude 29° S, the major playas have calcretes as the principal supplying

aquifers. Calcretes also appear to link some playas — for example, Lakes Way and Maitland — but whether these are connected aquifers is uncertain. It is likely that Lakes Way and Austin, as well as some of the other playas, are drainage sumps. In extremely wet seasons, there may be a connected surface flow; however, this is no clear indication of subsurface flow.

The playas mainly occur east of the Meckering Line and act as local base levels for erosion. Evaporite and suspended load sediments deposited in the lakes are subject to deflation and the level is thereby retained. Sand and kopi dunes ring the lakes, being particularly abundant on the east and south sides as the lakes migrate westwards against the prevailing wind direction [13].

The uranium occurrences in the playa lakes north of the Menzies Line are usually closely associated with calcrete drainages which themselves have at least minor uranium enrichments in either the main channel or the chemical delta (e.g. Lake Austin). South of the Menzies Line, however, calcretes are not present in the drainages and the enrichments are less obviously associated with a supplying aquifer.

Mineralization in the playas generally occurs near the water table, in near-surface sediments which consist of brown, orange or red saline and gypsiferous clays and muds up to 2 m thick. These commonly overlie sandy and silty clays, sometimes with calcareous nodules; in some playas, these can be equated with calcareous clay-quartz horizons beneath the calcretes. At Lake Maitland, however, uranium mineralization is in thin calcretes, which, rather unusually, occur at 2 to 4 m in the playa itself.

With one exception, the uranium is found as finely disseminated carnotite, with a grain size often less than 30 μm . However, in Boomerang Lake in the far southeast of the distribution range, the host mineral is a novel variety of autunite, sodian potassian hydroxonian meta-autunite [14]. Its mode of occurrence is similar to carnotite mineralization, namely as disseminations in saline muds, close to the water table.

Terrace Deposits

These occur in calcrete terraces in dissected valleys west of the Meckering Line, mainly in the Gascoyne Province. Near the divide, the Gascoyne River has only one terrace, 2 m above the present channel, but farther downstream there can be several, at least two of which have calcrete. Here, in the upper terraces, 30 to 35 m above the riverbed, silcrete and silicified calcretes 3 to 5 m thick overlie up to 8 m of massive calcrete and variable thicknesses of alluvial and colluvial clay-quartz, resting (usually) on gneissic bedrock. In the lower terraces, up to 10 m above the riverbed, relatively thin calcretes (1 to 3 m) and calcareous earths overlie and are transitional to clay-quartz horizons and weathered gneissic bedrock. Both the clay-quartz horizons and weathered bedrock can be highly calcareous. The thickness of this profile varies from about 2 to 10 m to 50 m.

Only minor concentrations of uranium — up to 50 ppm — are present in the upper terraces, in the silica of the cap rocks. Although widespread, they have no economic significance. Mineralization, as disseminated carnotite, is often abundant in the calcretes and underlying horizons of the lower terraces. Moderately high grades — exceeding 1 000 ppm — can be found locally, but most occurrences are too small to have economic significance. The most promising deposit is at Minindi Creek [3].

Other Occurrences of Surficial Uranium Mineralization

Traces of secondary uranium mineralization have also been located in other settings.

- (a) An occurrence by Lake Dundas, near Norseman, the most southerly record of carnotite in Western Australia, was probably one of the first discovered [15, 16], and recognized as uranium-vanadium ochre. Electron microprobe and X-ray diffraction data confirm carnotite mineralization occurring as thin films in voids and fractures in weathered granite and overlying pedogenic carbonates. Traces of reduced uranium occur in Lake Dundas itself, at depths of 10 to 15 m in marine sediments of probable Eocene age.
- (b) Uranium minerals resembling carnotite can be found in weathering, exfoliating granitoids, especially in the Gascoyne Province. The minerals are difficult to characterize, but include phosphates and silicates, such as phosphuranylite $(\text{UO}_2)_3\text{P}_2\text{O}_8 \cdot 6\text{H}_2\text{O}$ and weeksite $\text{K}(\text{UO}_2)_2(\text{Si}_2\text{O}_5)_3 \cdot 4\text{H}_2\text{O}$.
- (c) Radiometric anomalies, some with minor uranium enrichments, have been reported in granitic saprolites exposed in breakaways. Briot [17] considered these to be an enriched horizon in the profile, relict from Tertiary deep weathering, and hence to represent a genetically significant preconcentration of uranium. However, they are more probably surficial accumulations of uranium or its daughter products, concentrated by seepage and evaporation on the exposed face of the escarpment. The uranium mineralogy has not been positively identified.

5. GENESIS

In earlier appraisals of the carnotite genesis problem [18, 19], seven ore-genesis models were proposed and investigated. The models considered were:

1. Separate uranium and vanadium groundwater aquifers.
2. Change of carnotite solubility with change in pH.
3. Evaporation of groundwater.
4. Local increase in potassium activity.
5. Change in partial pressure of carbon dioxide.
6. Dissociation of uranyl carbonate complexes.
7. Redox-controlled precipitation.

Several of these factors are likely to be involved in the genesis of any individual deposit, but the importance of redox control of the movement of vanadium and an increase in potassium ion activity (in many cases by evaporation of groundwater), appear to be dominant processes in many of the larger deposits. At Yeelirrie, for example, excavations to date suggest a predominance of dark-green (relatively reduced, with V(IV)) carnotite deep in the calcrete profile, and of yellower (relatively oxidized, with V(V)) carnotite towards the surface. The dependence of these colour variations of carnotite on redox conditions has been described by Mann and Deutscher [19]. The following generalized genetic model is discussed in more detail elsewhere [3, 4, 19, 20, 21, 22].

The distribution of the uranium occurrences strongly suggests granitoids to be the source of uranium, potassium and, probably, vanadium in the carnotite. Fresh granitoids in the Yilgarn usually contain 3 to 8 ppm U, within the range 1 to 80 ppm, and therefore represent an adequate source, since leaching due to weathering may extend to depths as great as 250 m [23]. There is no evidence that the abundance of uranium has significance, and attempts to relate mineralization to specific types of uranium-rich granites (10 to 17 ppm U) have not been successful [24]. Assuming that some of the uranium is accessible, the factors in a weathering environment that control leaching, mobilization and precipitation have more importance. Conversely, in the Gascoyne Province, it is possible that the mineralization is associated with specific gneissic and migmatitic units.

Based on the presence of carnotite in an outlier of Proterozoic conglomerates on the Yilgarn Block, a now-eroded cover of Lower Proterozoic sediments has been suggested as a source for the uranium [25] however, although one small deposit is recorded from a catchment solely underlain by such sediments [3], there is little evidence to support this as a general mechanism. In the Hinkler-Centipede catchment, the uranium content of groundwaters is lower near Proterozoic rocks than over the granites. Additionally, the young age (< 1 million years) of the mineralization [5] applies severe time constraints on the erosion.

Vanadium is probably derived from mafic minerals in the granitoids, possibly via secondary accumulations in clays or iron oxides. Although greenstone belts, with their associated basic rocks, are present in most catchments, there is no evidence that their presence has any control over the location or grade of any uranium mineralization.

Uranium released from weathering granitoids is transported in groundwaters as uranyl carbonate complexes. Vanadium is solubilized as a four-valent cation. Precipitation of carnotite occurs where concentrations of uranium and potassium have been elevated by evaporation and where vanadium is oxidized to the five-valent state. This may be where vanadium has diffused upwards from depth within the saturated zone under a redox gradient, or where a subsurface bar has caused upwelling of such groundwaters to relatively oxidizing conditions, accompanying effects being mounding and lateral spread of calcrete.

Carnotite dissolves incongruently [19, 26], producing solutions with higher concentrations of vanadium than uranium. The measurement of vanadium concentrations in groundwaters of calcreted drainages may in many cases be a reflection of dissolution of carnotite, and hence be useful in exploration, except where the precipitation is at the downstream terminus of the drainages, in chemical deltas and playas. The solubility index (SI)

$$SI = \frac{\log(K^+) (UO_2^{2+} (H_2VO_4^-))}{(H^+)^2 K_{sp}}$$

has proved to be even more useful, because account is taken of the concentrations of potassium, uranium and H⁺ in groundwater [18]. The mineralization at Lake Raeside [27] was located by a hydrogeochemical survey and calculation of solubility indices. The application of this index to the Hinkler Well drainage system, on the southwestern side of Lake Way [19, 28] has produced evidence to suggest that carnotite in the upstream portions of the calcrete may be dissolving and that carnotite may be precipitating on the chemical delta at the edge of Lake Way, under present climatic conditions.

REFERENCES

- [1] OLLIER, C.D., Early landform evolution, In: Australia, A Geography, J.N. Jeans (Ed.), 85–98. Sydney Univ. Press, Sydney (1978).
- [2] MABBUTT, J.A., *Weathering history and landform development*, In: *Conceptual Models in Exploration Geochemistry – Australia*, C.R.M. Butt, R.E. Smith (Eds.), J. Geochem. Explor., **12** (1980) 96–116.
- [3] BUTT, C.R.M., HORWITZ, R.C., MANN, A.W., Uranium occurrences in calcretes and associated sediments in Western Australia, Aust. CSIRO Div. Mineral. Report FP 16 (1977) 67.

- [4] CARLISLE, D., The distribution of calcretes and gypcretes in southwestern United States and their uranium favorability. Based on a study of deposits in Western Australia and Southwest Africa (Namibia), US Dept. Energy Open File Report GJBX 29(78) (1978) 274p.
- [5] DICKSON, B.L., Uranium series disequilibrium in the carnotite deposits of Western Australia, this Volume.
- [6] MULCAHY, M.J., Landscapes, laterites and soils in southwestern Australia, In: Landform Studies from Australia and New Guinea, J.N. Jennings, J.A. Mabbutt (Eds.), ANU Press, Canberra (1967) 211–230.
- [7] BUTT, C.R.M., The nature and origin of the lateritic weathering mantle, with particular reference to Western Australia. In: Geophysical prospecting in deeply weathered terrain, Doyle, A.A., Glover, J.E., Groves, D.I. (Ed.), Geol. Dept. and Extension Service Univ. West. Aust., Publ., No. 6 (1981) 11–29.
- [8] BUTT, C.R.M., Aluminosilicate cementation of saprolites, grits and silcretes in Western Australia, J. Geol. Soc. Aust. **30** (1983) 179–186.
- [9] HINGSTON, F.J., GAILITIS, V., The geographic variation of salt precipitated over Western Australia, Aust. J. Soil. Res. **14** (1976) 319–335.
- [10] MANN, A.W., HORWITZ, R.C., Groundwater calcrete deposits in Australia: some observations from Western Australia, J. Geol. Soc. Aust., **26** (1979) 293–303.
- [11] BETTENAY, E., CHURCHWARD, H.M., Morphology and stratigraphic relationships of the Wiluna Hardpan in arid Western Australia, J. Geol. Soc. Aust., **21** (1974) 73–80.
- [12] APLIN, T.E.H., The Vegetation of Western Australia, Western Australian Yearbook No. 14, W.A. Govt. Printers, Perth (1975) 590.
- [13] JUTSON, J.T., The physiography of Western Australia, West. Aust. Geol. Surv. Bull. **95** (3rd Ed.) (1950) 366.
- [14] BUTT, C.R.M., GRAHAM, J., Sodian potassian hydroxonian meta-autunite: first national occurrence of an intermediate member of a predicted solid solution series, Amer. Min. **66** (1981) 1068–1072.
- [15] de la HUNTY, L.E., Report on radioactivity near Dundas, Dundas Goldfield, Western Australia, West. Aust. Geol. Surv. Ann. Report 1960 (1956) 34–36.
- [16] NOLDART, A.J., Report on radioactivity near Lake Dundas. West. Aust. Geol. Surv. Bull. **109** (1958) 120–130.
- [17] BRIOT, P., Sur la genese de certains gites uraniferes. Mineral Deposita **17** (1982) 151–157.
- [18] MANN, A.W., Chemical ore genesis models for the precipitation of carnotite in calcrete, Aust. CSIRO Div. Mineral. Report FP 7 (1974).
- [19] MANN, A.W., DEUTSCHER, R.L., Genesis principles for the precipitation of carnotite in calcrete drainages in Western Australia, Econ. Geol. **73** (1978) 1724–1737.
- [20] GASKIN, A.J., BUTT, C.R.M., DEUTSCHER, R.L., HORWITZ, R.C., MANN, A.W., "Hydrology of uranium deposits in calcretes of Western Australia", In: Energy Resources of the Pacific Region, M.T. Halbouty (Ed.), Amer. Assoc. Petrol. Geol. Studies in Geology Series **12** (1981) 311–316.
- [21] DEUTSCHER, R.L., MANN, A.W., BUTT, C.R.M., "Model for calcrete uranium mineralisation", In: Conceptual Models in Exploration Geochemistry: Australia, C.R.M. Butt, R.E. Smith (Eds.), J. Geochem. Explor. **12** (1980) 158–161.
- [22] BOYLE, D.R., Genesis of surficial uranium deposits, this Volume.
- [23] OVERSBY, V.M., Lead isotope systematics and ages of Archaean intrusives in the Kalgoorlie-Norseman area, Western Australia, Geochem. Cosmochim. Acta **39** (1975) 1107–1125.
- [24] STUCKLESS, J.S., BUNTING, J.A., NKOMO, I.T., U-Th-Ph systematics of some granitoids from the northeastern Yilgarn Block, Western Australia and implication for uranium source rock potential, J. Geol. Soc. Aust. **28** (1981) 365–375.
- [25] ALLCHURCH, P.D., BUNTING, J.A., The Kaluweerie Conglomerate: a Proterozoic fluvial sediment from the northern Yilgarn Block, Western Australia, West. Aust. Geol. Surv. Ann. Rep. 1975 (1976) 83–87.
- [26] DALL'AGLIO, M., GRAGNANI, R., LOCARDI, E., "Geochemical factors controlling the formation of secondary minerals of uranium". In: Formation of uranium ore deposits, IAEA, Vienna (1974) 33–48.
- [27] GAMBLE, D.S., The Lake Raeside deposit, this Volume.
- [28] CRABB, D., DUDLEY, R., MANN, A.W., Hinkler Well – Centipede deposits, this Volume.

LAKE AUSTIN URANIUM DEPOSIT, WESTERN AUSTRALIA

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ABSTRACT

LAKE AUSTIN URANIUM DEPOSIT, WESTERN AUSTRALIA

The Lake Austin uranium deposit is a calcrete type deposit in the Yilgarn Block, near Cue, in a catchment area of granitoids and greenstones. The uranium is in valley fill and the sediments of the Lake Austin playa. The mineralization occurs over 1 to 6 meter thickness close to the water table in calcrete overlying clays and/or weathered bedrock. The principal uranium mineral is carnotite. Waters in nearby channels have an uranium content of over 30 ppb. The chloride content of the water increases downstream in the nearby drainages, as does the uranium and vanadium content.

1. LOCATION

The Lake Austin uranium deposit is 20 km west-southwest of Cue, Western Australia, at latitude 27°27'S, and longitude 117°57'E.

2. GEOLOGY

The basement rocks of the whole catchment are the granitoids and greenstones of the Archaean Yilgarn Block [1]. The granitoids are of a wide range of compositions, from granite to tonalite, and are the predominant basement rocks of the catchment. The "greenstones" are the metamorphosed acid volcanics and sedimentary rocks of the Cuddingwarra Formation and metamorphosed basic and ultrabasic intrusive and extrusive rocks of the Moyagee Formation. The granitoids are the probable source rocks for the uranium; some adamellites contain up to 70 ppm uranium but the majority of the granites, which do not outcrop, probably contain less than 10 ppm uranium.

Outcrop is generally poor and rocks are mostly deeply weathered to 30 m or more, commonly overlain by Cainozoic alluvium and colluvium. Calcretes have been deposited in the axes of the larger valleys, and a playa, Lake Austin, has formed in the lowest part of the landscape. The calcrete and its enclosing sediments, and the upper sediments of the playa, are the hosts to uranium mineralization.

3. GEOMORPHOLOGY

The mineralization at Lake Austin is mostly in a narrow arm of the playa at the termination of an extensive, calcrete drainage system entering from the northeast (Figure 1). The main tributaries commence some 80 km to the east and 70 km to the north. Relief throughout the drainage is very subdued; the plateau surfaces which form the drainage divide are generally between 455 and 500 m and the playa is at 408 m [1]. The gradient of the valley floor is about 1:3 200. Calcretes are present in the axes of the tributary drainages for much of their length, tending to form mounds 1 to 3 m above the surrounding alluvial-colluvial plains but with local karstic depressions. The calcrete in the main tributary is more or less continuous, 50 km long, up to 5 km wide and 2 to 15 m thick. It widens into a nearly flat platform of over 50 km² adjacent to the playa. The drainages have surface flow only after exceptional rains; however, the calcrete is an important and prolific aquifer, with the water table at 3 to 5 m. Vegetation on the calcrete consists of low shrubs and grasses, with a few open stands of trees (*Acacia* and *Eucalyptus* spp). The playa surface is mostly bare, with fringing halophytic shrubs. The area is semi-arid, with erratic rainfall averaging about 180 mm per annum, falling mainly between January and June. Summers are hot (average daily range in January is 22.7 to 38.8 °C) and winters mild (average daily range in June is 7.4 to 21.3 °C).

4. HOST ROCKS

The host sequence generally consists of calcrete overlying red-brown clays and/or weathered bedrock. A surface cover of sand or alluvium up to 2 m thick may be present locally. The calcrete is mostly white to grey, occasionally brown, ranging in texture from earthy and friable to porcellaneous and hard. In the channel, the calcrete

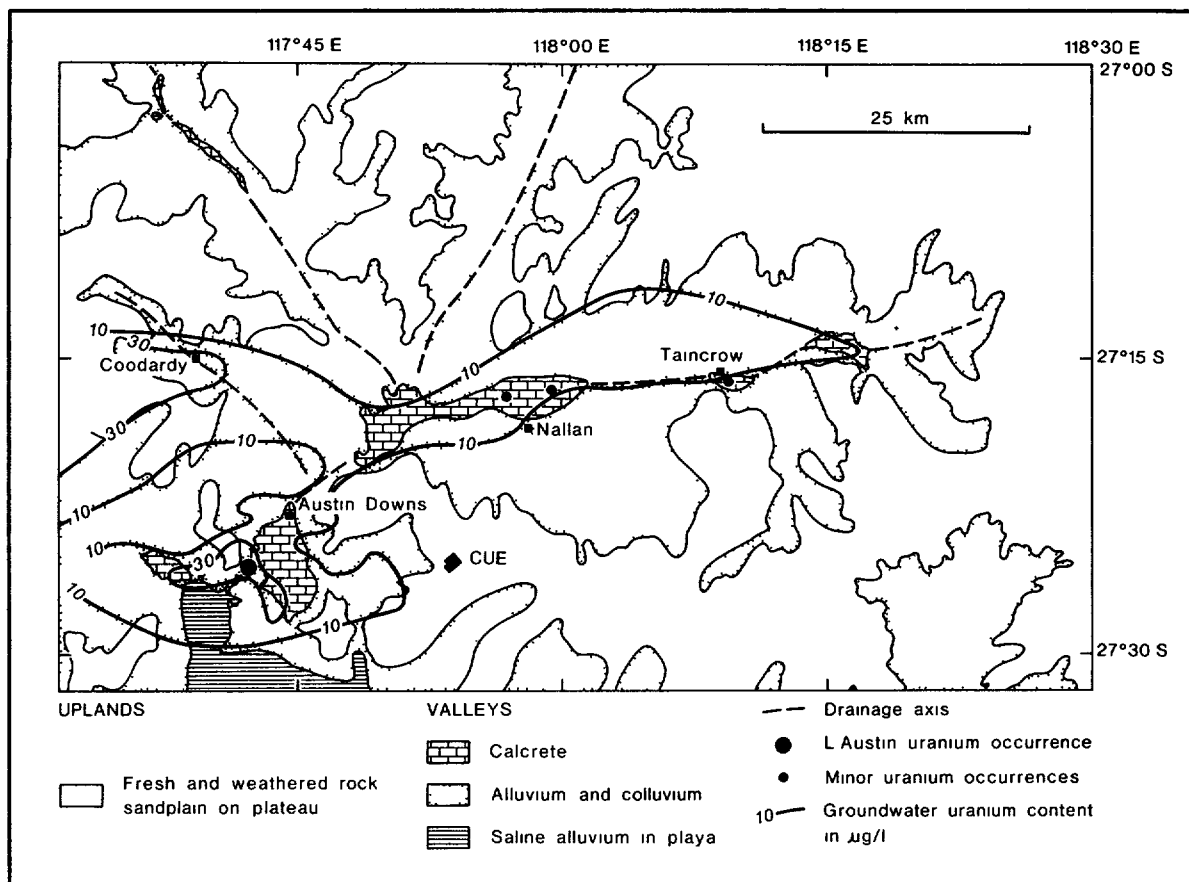


Figure 1

Regional geological setting. Lake Austin uranium occurrence, showing distribution of uranium in groundwaters.

commonly has a lower siliceous horizon, in places up to 8 m thick. On the platform, this silicified zone is present in the north but is absent from the south, toward the plays; the calcrete also thins from 10 to 14 m, to 4 to 5 m near the playa. The calcrete consists of calcite and dolomite, with chalcedony in silicified zones, some gypsum and minor detrital quartz, feldspar, goethite and kaolinite. The underlying orange-brown sandy clays, 3 to 5 m thick, are the usual host to mineralization. They are carbonate-rich and contain quartz and minor magnetite in a kaolinite-smectite matrix. On the platform area, these in turn overlie up to 30 m of red-brown clay and either bedrock or green-grey clays of unknown thickness.

In the playa, 10 to 15 m of saline, gypsiferous orange-brown clays with carbonate nodules overlie up to 20 m of red-brown clay. These two clay units are equated with the similar clays beneath the calcrete.

5. URANIUM MINERALIZATION

Uranium mineralization, as carnotite and minor concentrations of uranium in opaline silica, occurs sporadically throughout the main calcrete channel, centred particularly at Taincrow (50 km updrainage), Nallan (30 km updrainage) and on the platform area [2, 3]. The mineralization occurs as minor enrichments, mostly 30 to 70 ppm uranium (maximum 250 ppm uranium) over thicknesses of 1 to 6 m, usually close to the water table in the silicified lower horizons of the calcrete. On the platform, mineralization is usually in the orange-brown sandy clays below the calcrete. Significant mineralization is found only in the two arms of the playa itself, mostly in the top 1 to 5 m. The carnotite occurs as patches and coating on the clays, with the maximum concentrations close to the water table (0.5 m). It is also disseminated throughout the clay matrix as fine crystallites (30 μ m). The amount of visible carnotite varies periodically, implying chemical activity, although the degree of mobility is probably not great. Uranium contents exceeding 450 ppm (maxima over 2 000 ppm) are found over an area of about 1 500 by 50 m (Figure 2).

6. RADIOMETRICS

Over the calcretes, ground radiometric surveys, initially on lines at 1 km spacings, gave low-contrast anomalies, two to three times above background near Taincrow, Nallan and on parts of the calcrete platform. These anomalies indicate broad areas of uranium enrichment and some, but not all, occurrences of outcropping mineralization. Mineralization at the base of the calcrete or in the underlying sediments has no surface

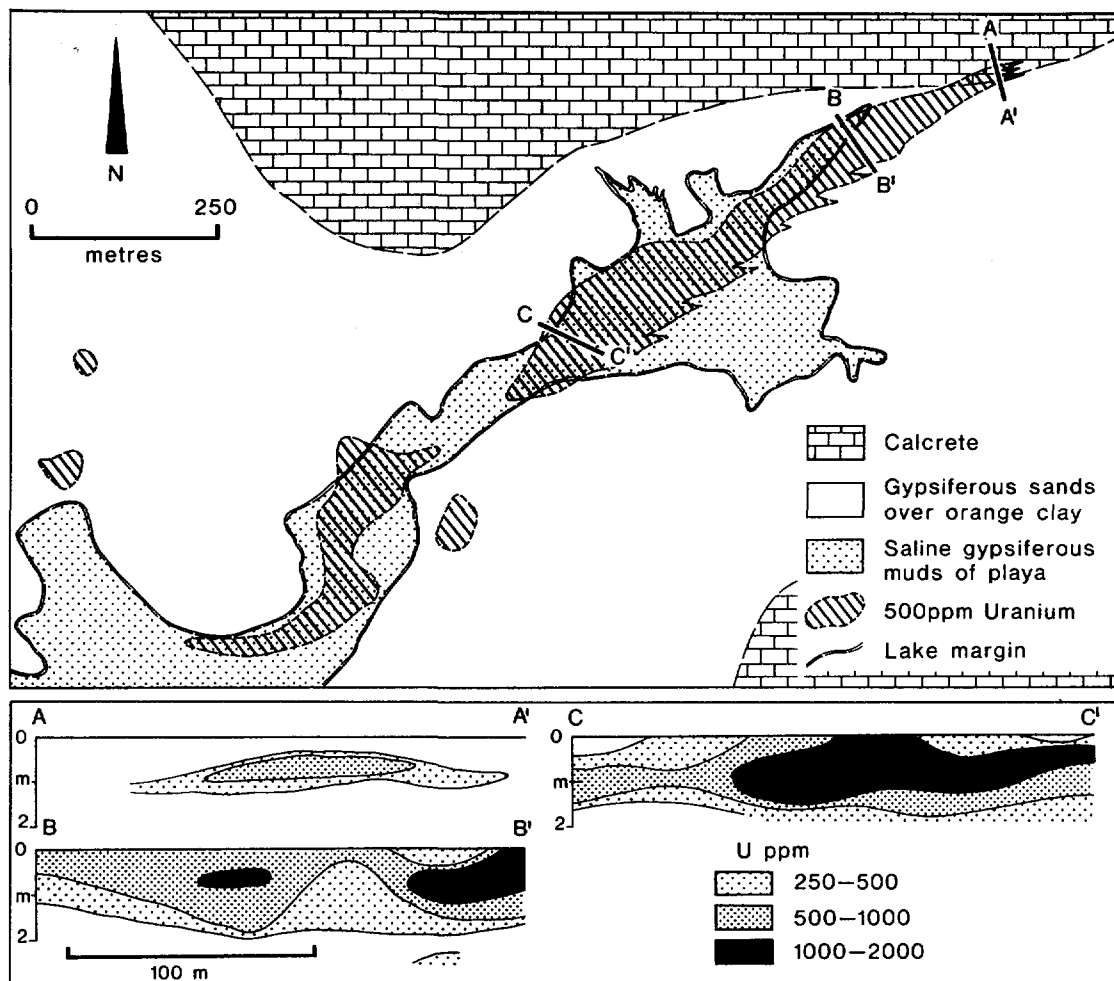


Figure 2

Geological map and uranium distribution, Lake Austin. Sections illustrate distribution of uranium in playa lake sediments, determined by drilling and pitting [3]. (Published by permission of Elsevier Scientific Publishing Co.).

Table 1
Analytical Results and Carnotite Solubility Indices (SI) in Groundwaters,
Lake Austin Drainage, W.A.

		pH	K ppm	U ppb	V ppb	Cl ppm	HCO ₃ ppm	SI
Low salinity	R	5.9-7.9	13 - 90	5 - 90	13 - 90	350 - 1 970	185 - 510	-(1.3 - 2.5)
	M(9)	7.2	30	15	41	1 020	294	-1.8
Moderate salinity	R	6.8-7.5	80 - 130	11 - 58	69 - 153	4 880 - 8 900	245 - 333	-(0.6 - 1.3)
	M(4)	-7.1	94	29	93	6 570	293	-0.90
High salinity	R	6.6-7.1	128 - 350	34 - 132	15 - 155	9 130 - 19 700	230 - 416	-(0.0 - 0.8)
	M(8)	6.9	200	72	200	13 860	304	-0.5
Very high salinity	R	6.8-7.0	800 - 1 200	29 - 170	19 - 74	53 900 - 75 900	93 - 310	-(0.4 - 0.8)
	M(4)	6.9	1 040	70	45	66 775	167	-0.65
Lake waters	R	6.8-7.3	100 - 1 800	8 - 126	28 - 77	56 600 - 93 300	60 - 217	-(0.1 - 1.0)
	M(4)	7.1	1 490	55	53	81 050	127	-0.53

R = Range; M(N) = Mean (no. of samples)

expression. In the playa, an anomaly with a two to five times contrast over an area of 1 900 by 100 m clearly outlined the mineralized zone. Radiometric logging of drill holes gives four to thirty times contrasts over the mineralized intervals.

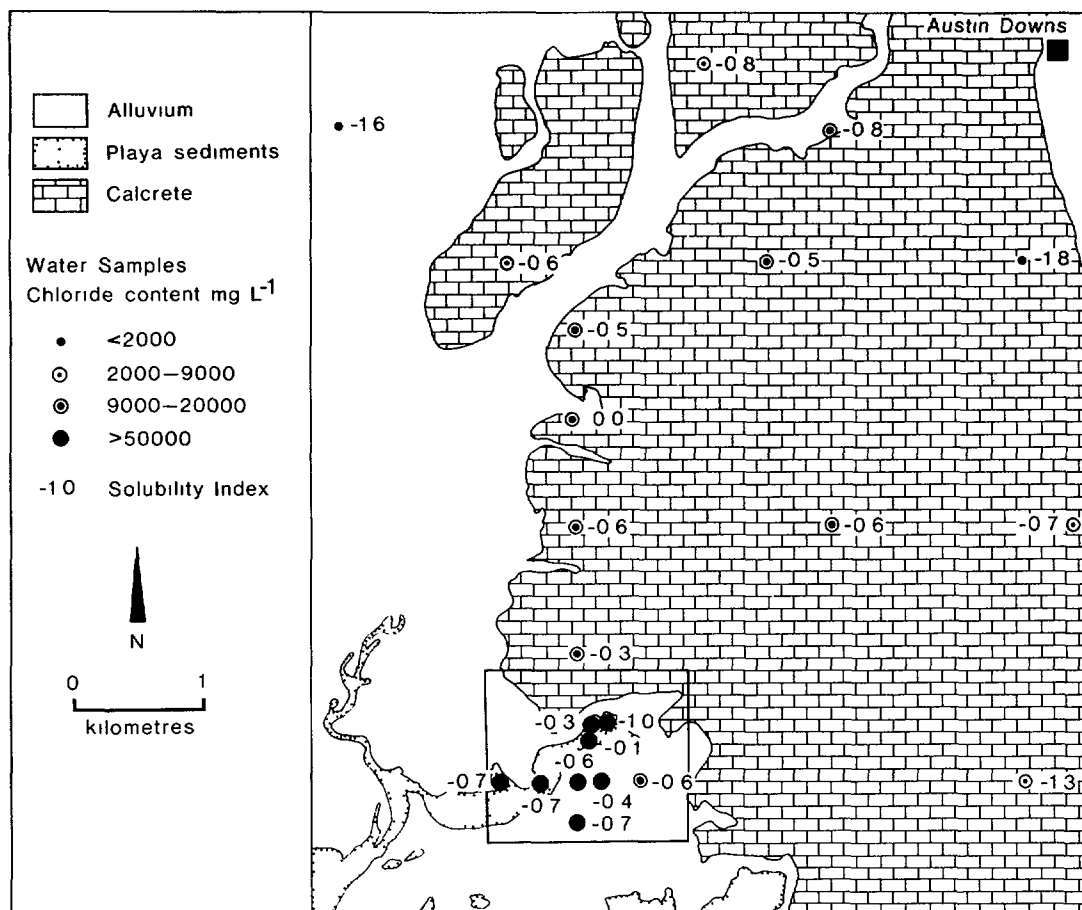


Figure 3
Chloride contents and carnotite solubility indices, Lake Austin [3] (Published by permission of Elsevier Scientific Publishing Co.).

7. HYDROGEOCHEMISTRY

The results of sampling groundwaters in stock wells, exploration drill holes, and in the playa, shallow pits, in the Lake Austin drainage, are summarised in Table 1. On a regional scale (Figure 1), waters in the Taincrow-Nallan and Coodardy channels have elevated uranium contents, exceeding 30 ppb in the area of the calcrete platform and in one possible source area at Coodardy. Detailed sampling [3] showed that chloride contents of calcrete waters increased downdrainage, as a result of evaporation, concentrations ranged from below 1 300 ppm, 50 km from the playa, to nearly 20 000 ppm on the calcrete platform, with a sharp increase to 54 000 to 93 000 ppm close to and in the playa. Potassium increased proportionately with chloride, from below 20 to 1 800 ppm; although some potassium is precipitated as carnotite, this is negligible in comparison with the effect of evaporation. Bicarbonate concentrations were in the range 185 to 510 ppm in the calcrete, but declined where the chloride content exceeded 50 000 ppm, close to the playa, this implies that the concentrations of carbonate and uranium-carbonate complexes had also fallen. Vanadium and uranium concentrations varied markedly, but tended to increase with chloride content, downdrainage. The carnotite solubility indices become less negative closer to the playa, approaching zero in the area of mineralization, implying active precipitation (Figure 3).

ACKNOWLEDGEMENTS

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REFERENCES

- [1] de la HUNTY., Cue, Western Australia. Explanatory notes, Aust. Bur. Mines. Resour. Geol. Geophys. 1:250 000 Geol. Ser. (1973).
- [2] BUTT, C.R.M., HORWITZ, R.C., MANN, A.W., Uranium occurrences in calcrete and associated sediments in Western Australia, Aust. CSIRO Div. Mineral. Report FP 16 (1977) 67.
- [3] HEATH, A.G., DEUTSCHER, R.L., BUTT C.R.M., In: Conceptual Models in Exploration Geochemistry: Australia, C.R.M. Butt, R.E. Smith (Ed.), J. Geochem. Explor. 12 347–349.

HINKLER WELL – CENTIPEDE URANIUM DEPOSITS

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ABSTRACT

HINKLER WELL – CENTIPEDE URANIUM DEPOSITS

The Hinkler Well – Centipede deposits are near the northeastern margin of the Archean Yilgarn Block on a drainage system entering Lake Way. Basement rocks are granitoids and greenstones. The rocks are deeply weathered and overlain by alluvium. Granitoids, the probable uranium source, currently contain up to 25 ppm uranium, in spite of the weathering. The host calcrete body is 33 km long and 2 km wide. Uranium up to 1000 ppm occurs in carnotite over a 15 km by 2.5 km area.

1. LOCATION

The Hinkler Well – Centipede drainage system is located near the northeastern margin of the Yilgarn Block, latitude 20°50' N, and extending from longitude 120 °E to longitude 120°20' °E. The drainage system enters the southwestern side of Lake Way.

2. GEOLOGY

Basement geology comprises granitoid and greenstone of the Archaean Yilgarn Block, with Proterozoic sandstone forming part of the catchment divide to the north. Outcrop is scarce, as the rocks are mostly deeply weathered, and often overlain by alluvium and colluvium.

Within the Hinkler Well – Centipede catchment, four major hydrogeological zones have been recognized [1]. These are granitoid, including alluvium and colluvium overlying granitoid basement, greenstone, calcrete, and playa, including Lake Way and its margin. These zones are shown on the map (Figure 1).

Knowledge of the detailed mineralogy of the granitoid zone is limited. Information from neighbouring drainages and the Yilgarn Block in general suggests that the unweathered granitoid rocks would comprise quartz, microcline, oligoclase, orthoclase, albite, muscovite and biotite, and that the weathered profile in such areas would be principally kaolinite and quartz with minor amounts of montmorillonite, illite, hematite and goethite.

The granitoids of the Yilgarn Block are the probable source of uranium for carnotite formation, and granite samples from within the catchment show a large variation in uranium content, from less than 2 to 25 ppm.

However, it is worth stressing that the measured concentration of uranium in a granite is perhaps not an accurate guide to its past or future potential as a uranium source, because the weathering rate of uranium from a particular granite is probably a more important determinant of the amount of uranium mobilized.

The mineralogy of the greenstones and associated weathered material in this catchment area is not known in detail. By analogy with other greenstones in the vicinity, the unweathered ultramafics would comprise *serpentine, olivine, talc, tremolite-chlorite, magnetite and chromite, and the unweathered amphibolites would contain plagioclase, amphiboles, chlorite, ilmenite and quartz, with some magnetite. Weathered material from these rocks would include hematite, goethite, magnesite, calcite, montmorillonite, kaolinite, saponite, quartz and chalcedony in varying proportions, dependent on the primary composition of the source rock.*

3. GEOMORPHOLOGY

The calcrete hosting the mineralization is a body some 33 km long in the axis of a catchment of approximately 1 200 km². It consists of an elongate calcrete body over 2 km wide in the west that narrows before broadening into a chemical delta where it enters Lake Way. Calcrete within the Hinkler Well – Centipede channel forms a positive relief feature of the order of 1 to 3 m in relation to the surrounding land surface. This topographic feature of the calcrete is mainly due to erosion and incision of the channel margins by the present-day surface runoff. The original calcrete “profile top” is restricted to a few remnants of limited areal extent. The original calcrete surface before erosion is usually identifiable on the basis of its massive to blocky, very fine granular texture and dirty white colour, and by the presence of a sparse veneer of rounded quartz and other bedrock pebbles.

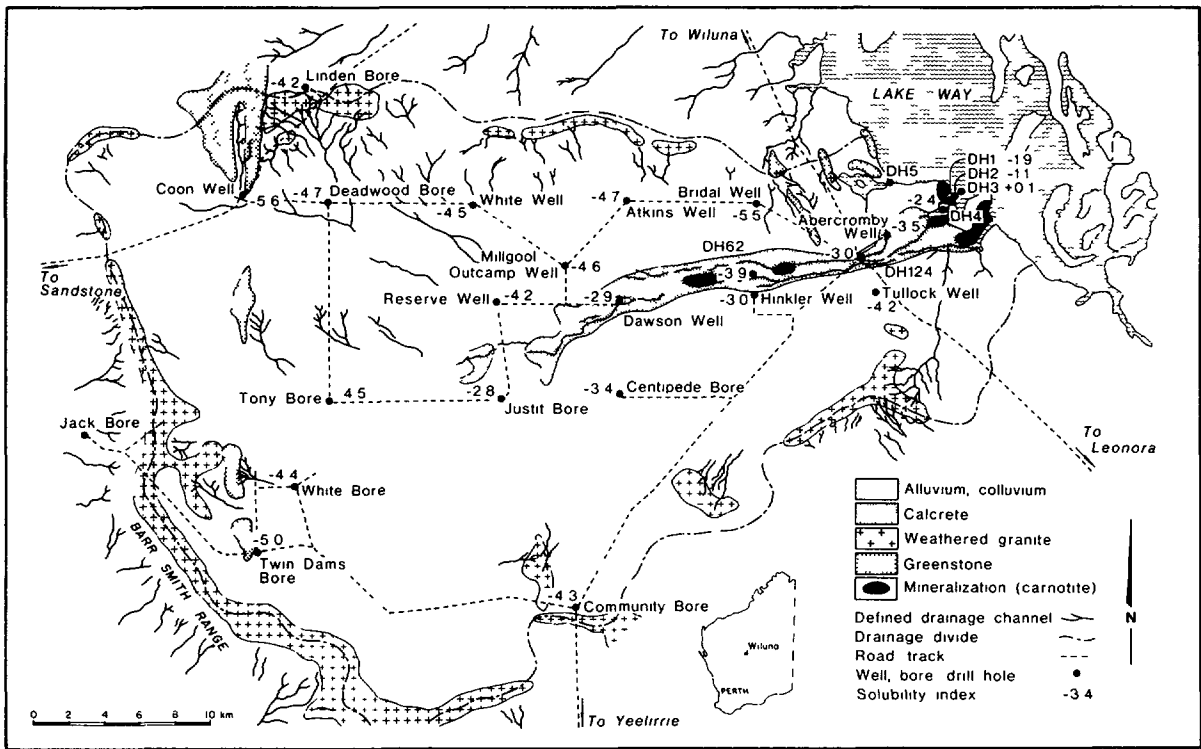


Figure 1
Hydrogeology, water sampling locations and solubility index data for the Hinkler Well — Centipede catchment system.

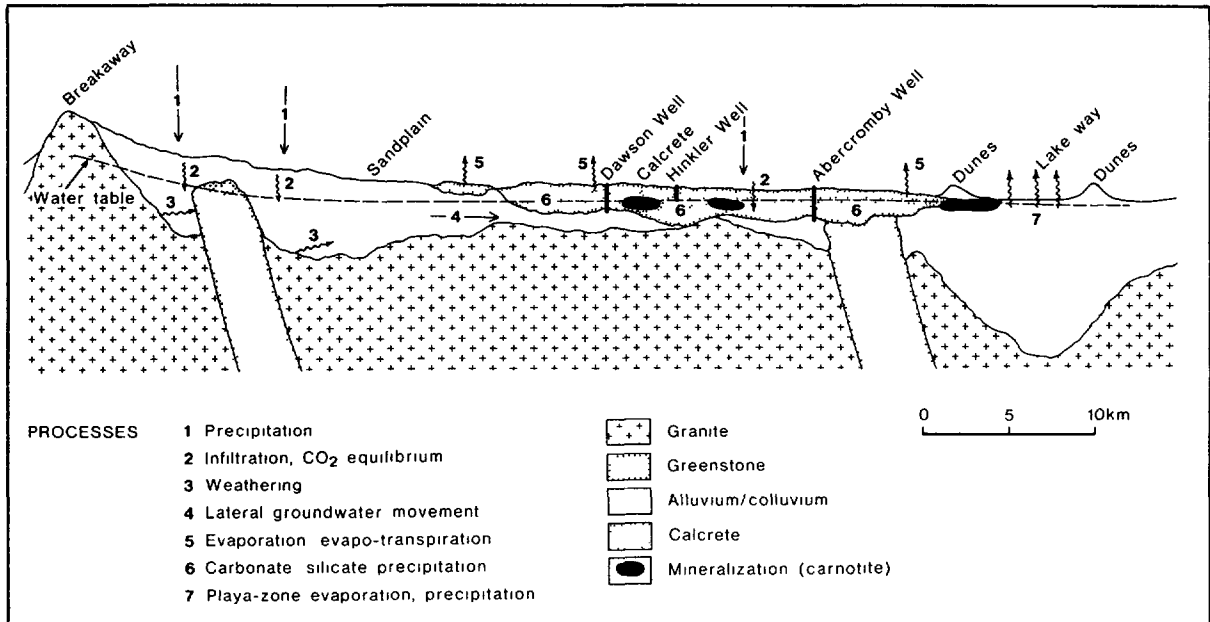


Figure 2
Idealized section along the drainage mid-line of the Hinkler Well — Centipede catchment system.

4. HOST ROCK

The mineralogy of the elongate calcrete body and the calcrete of the chemical delta differ significantly. The elongate calcrete is principally calcite with chalcedony and minor amounts of dolomite, gypsum and sepiolite. It is underlain and sometimes interspersed with kaolinitic and/or smectite-rich clay and in some cases by laterite (hematite and goethite). There is a small area of carbonated weathered granite outcropping and immediately beneath, mineralized calcrete near Hinkler Well. The calcrete of the chemical delta is characterized, in general, by increased proportions of dolomite and sepiolite and by the presence of some aragonite [2].

5. MINERALIZATION

Uranium mineralization, both in an elongate calcrete unit and in the chemical delta section of the drainage system, occurs exclusively as the mineral carnotite.

In the elongate calcrete unit, carnotite, generally as coatings on vugs and fracture surfaces, is distributed in discontinuous sheets or lenses at, above and below the present water table. This uranium mineralization, which at many localities averages less than 10 ppm uranium in grade, occurs over a 15 x 1.5 to 2.5 km area. Some very isolated lenses of mineralization up to 1 000 ppm uranium have been located between Hinkler and Dawson Well (Figure 2).

When mineralized the massive, dark-coloured, dolomitic calcrete of the chemical delta area often contains fine-grained, disseminated carnotite throughout the carbonate matrix. Carnotite also occurs as coatings on fracture surfaces and on the walls of small cavities. Three distinct pods of ore-grade mineralization have been outlined in the chemical delta. (Economic parameters have been used to define edges of pods and these edges are not natural limits of mineralization, which is erratically distributed between all three pods.) The mineralized pods are hosted by soft grey to black manganiferous calcrete, covered by varying amounts of overburden – from near zero to up to 6 m of windblown sands and silts. The thickness of the mineralized zones varies from one to five metres, with the bulk of the mineralization concentrated near or just below the present-day water table; grades are variable, with concentrations of up to 2 000 ppm uranium. The soft grey-black calcrete is transitional into comparatively harder calcrete, typical of the elongate calcrete unit, on the western edge or upstream side of the mineralized pods. Grade and thickness of mineralization fall off rapidly in this transition zone.

6. RADIOMETRICS

Surface traverses with hand-held scintillometers revealed several radiometric spot anomalies, as well as more widely distributed anomalies, generally elongated parallel to the drainage system. The majority of radiometric highs occur over exposed, weakly mineralized calcrete, or in areas of less than one metre of overburden over strongly mineralized calcrete.

Maximum readings with down-hole gamma-ray logging instruments always correlated well with the peak concentration of uranium in drill holes, which varied from 2 to 6 m below surface, depending on the overburden thickness. Similarly, correlation between surface and drill hole radiometric anomalies was observed to be fairly good in locations with shallow (less than 1 m) overburden; but as overburden thickness increased, strong radiometric anomalies observed in drill holes were not detectable on the surface. Very few detectable radiometric anomalies were recorded below an average depth of 10 m throughout both the elongate calcrete zone and chemical delta zone. In a study of disequilibrium in the mineralized Chemical Delta area, Dickson [5, 6] found that the mean disequilibrium ratio (U_3O_8/eU_3O_8) for 311 mineralized samples to be 1.04. The only significant variation in the disequilibrium ratio occurs with depth, when samples from above the water table tended to have a ratio greater than 1, while those from below the water table tended to have a ratio of less than 1.

A large number of isolated radon anomalies of low magnitude were observed in addition to several elongate anomalies coincident with the calcrete. These radon anomalies, together with the anomalous radiometrics, extend for nearly the full length of the calcrete from west of Dawson Well to Lake Way. Radon content of the groundwater was generally less than 10 emans.

7. HYDROGEOCHEMISTRY

Potassium concentrations range from 10 to 20 ppm on the western edge of the catchment to values of over 3 000 ppm near Lake Way; the potassium concentration increases rapidly near the lake margin. Uranium concentrations range from 10 to 30 ppb near the granitoid breakaways to 440 ppb at Justit bore at the western end of the calcrete. On the calcrete, from Justit bore to Lake Way, uranium concentrations are in the range of 50 to 200 ppb and there is no increase in uranium concentration concomitant with increasing salinity near Lake Way [2]. The uranium concentrations are highest in groundwaters on the southwestern side of the catchment, but there appears to be no large uranium contribution from the Proterozoic rocks along its northern boundary.

Vanadium concentration in groundwater does not exceed 20 ppb, except in the calcrete. In the upstream sections of the calcrete, the vanadium concentrations are between 20 and 60 ppb, increasing to higher values (up to 180 ppb) near the lake margin.

From the groundwater analysis results for potassium, uranium and vanadium, a simple solubility index reflecting the saturation status of the groundwater with respect to carnotite has been calculated for each sampling point (Figure 1).

Present-day groundwaters in most parts of the representative drainage are seen to be undersaturated with respect to carnotite (index negative), even near some areas of the calcrete known to be mineralized, for example between the Dawson and Hinkler wells. This implies that the carnotite in this area, if it is in contact with groundwater, should dissolve. High vanadium concentrations in the groundwater are a feature of this area. Toward the margin of Lake Way, the solubility indices increase, and one of the holes on the edge of Lake Way (DH 3) has a positive value implying supersaturation of the groundwater with respect to carnotite.

This is in contradiction to the age of $>10^6$ years suggested by the apparent equilibrium of the Centipede deposit from radiometric data [5]. Dickson [6], however, suggests the likelihood of differential mobility of uranium and its daughter products and has proposed a model to accommodate this. It should also be pointed out that a unique "average age for carnotite deposits may be misleading, since mineralization may have occurred over an extended period of time.

REFERENCES

- [1] MANN, A.W., DEUTSCHER, R.L., Hydrogeochemistry of a calcrete containing aquifer near Lake Way, Western Australia, *J. Hydrol.* **38** (1978) 357–377.
- [2] MANN, A.W., DEUTSCHER, R.L., Genesis principles for the precipitation of carnotite in calcrete drainages in Western Australia, *Econ. Geol.* **73** (1978), 1724–1737.
- [3] CARPENTARIA EXPLORATION COMPANY (PTY) LTD., Final Report Hinkler Well Prospect (1972).
- [4] ESSO AUSTRALIA, LTD. Minerals Department, Company Reports and maps of the Centipede Uranium Deposit (1982).
- [5] DICKSON, B.L., CSIRO, Institute of Earth Resources, Division of Mineral Physics, Restricted Report 1048R (1980).
- [6] DICKSON, B.L., Uranium series disequilibrium in the carnotite deposits of Western Australia, this Volume.

LAKE MAITLAND URANIUM DEPOSIT

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ABSTRACT

LAKE MAITLAND URANIUM DEPOSIT

The Lake Maitland uranium deposit, 105 km southeast of Wiluna is in a playa in an Archean granitic terrain. The area is deeply weathered and of low relief. The deposit, in playa calcrete sediments is 6 km long by 0.3 to 0.5 km wide. Uranium Grades are generally below 700 ppm but some values exceed 1800 ppm. The uranium is in carnotite. Groundwaters in the playa contain 5 to 150 ppb uranium and 30 to 80 ppb vanadium.

1. LOCATION

The Lake Maitland uranium deposit is about 105 km southeast of Wiluna, at 121 ° 05' East, 27 ° 10' South.

2. GEOLOGY

Lake Maitland is a playa containing a sequence of Tertiary to Recent clastic and evaporitic sediments within a predominantly granitic Archean terrain. Approximately 6 km west there is a north-striking greenstone belt of metamorphosed basalts, dolerites and banded iron formations. A fossil drainage system represented by siliceous calcrete extends into the playa, dividing it into two arms (Figure 1) with a selvage of dolomitic calcrete continuing beneath the playa surface at 2 to 4 m depth. The uranium deposit is contained within the sediments of the playa.

3. GEOMORPHOLOGY

The terrain is deeply weathered with a generally subdued relief. The greenstone belt forms a discontinuous line of low hills and the rarely outcropping granite forms sandy plains. The southerly trending palaeodrainage was presumed to have been active during the period of deep weathering. The siliceous calcrete forms a low mound rising a metre or so above the clay pans and fringing sapphire flats. Small gypsum sand dunes occur on the west side of the lake, and larger ones to the east. The landforms of the region have been described by Churchward [1].

4. HOST ROCKS

A typical vertical columnar section through the playa sediments is shown in Figure 2. Mineral compositions are estimated from XRF analyses and some X-ray diffractometry (R.J. Gilkes, R. Brown, written communication). The principal lithological units, from the surface down, are as follows:

Gypsum sand and silt, increasingly clay-rich with depth, form the top 1 m of sediment. Twinned gypsum crystals and rosettes, 50 to 100 mm across, occur in clay-rich sections. The water table is usually within 100 mm of the base of the unit.

Dark brown and black clay and silt, locally very variable in thickness but usually 0.60 to 0.70 m thick, underlie the gypsiferous unit, except in the east and south of the main playa, where they are absent. The unit is very hard and slablike in places, and resembles calcrete, but the carbonate content is only low. The black colouration, which forms a coating to brown and pink clay, may be due to either manganese oxide or organic matter. The unit is a major aquifer.

Red-brown and pale brown dolomitic clay, 0.5 to 1.6 m thick, is the most continuous and widespread unit. The red-brown clay is composed of dolomite, kaolinite and possibly smectite, whereas the light-brown clay is dominantly smectite with lesser dolomite and quartz. Overall, the unit contains 12 to 25 % dolomite. This unit is impervious and probably acts as an aquiclude between the dark clay aquifer and the calcrete aquifer.

Calcrete occurs as discontinuous layers, 0.5 to 2.0 m thick, separated by clays with a calcrete component. The calcrete wedges out on the eastern edge of the playa and south of line 28N, and is discontinuous on the western edge north of line 44N. The calcrete is pale buff to cream coloured, with occasional black flecks, and comprises 60 % dolomite, 15 to 20 % smectite, 20 % quartz and some kaolinite. In comparison, the calcrete in the drainage entering the playa from the northwest contains abundant opaline silica, and some aragonite. The slabby calcrete in the playa is a major aquifer and is host to most of the uranium mineralization.

Red-brown and buff silty sand occurs where the calcrete is absent.

Sandy silt (10 to 20 %, 1 mm quartz sand), grading to, or interbedded with, **mottled silty sand** (> 20 % quartz), generally comprises the interval 1 to 3 m below the calcrete, particularly on the eastern side of the playa.

From limited data, it appears that deeper sediments consist of sandy and silty units, with 1 m thick calcrete horizons at depths of 10 m and 20 m.

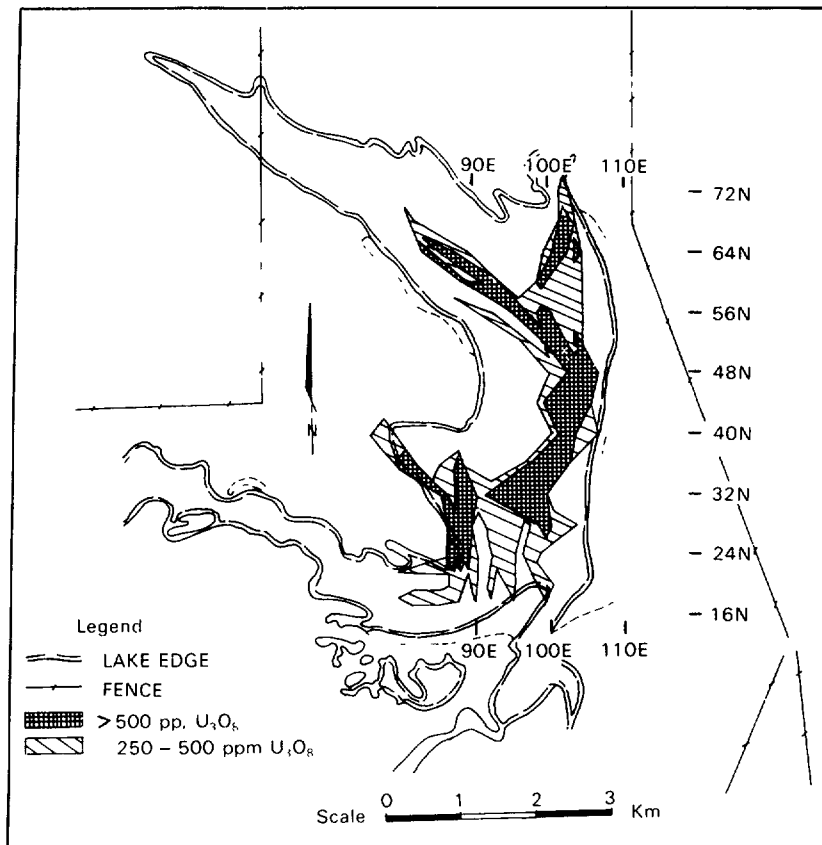


Figure 1
Distribution of uranium mineralization, Lake Maitland.

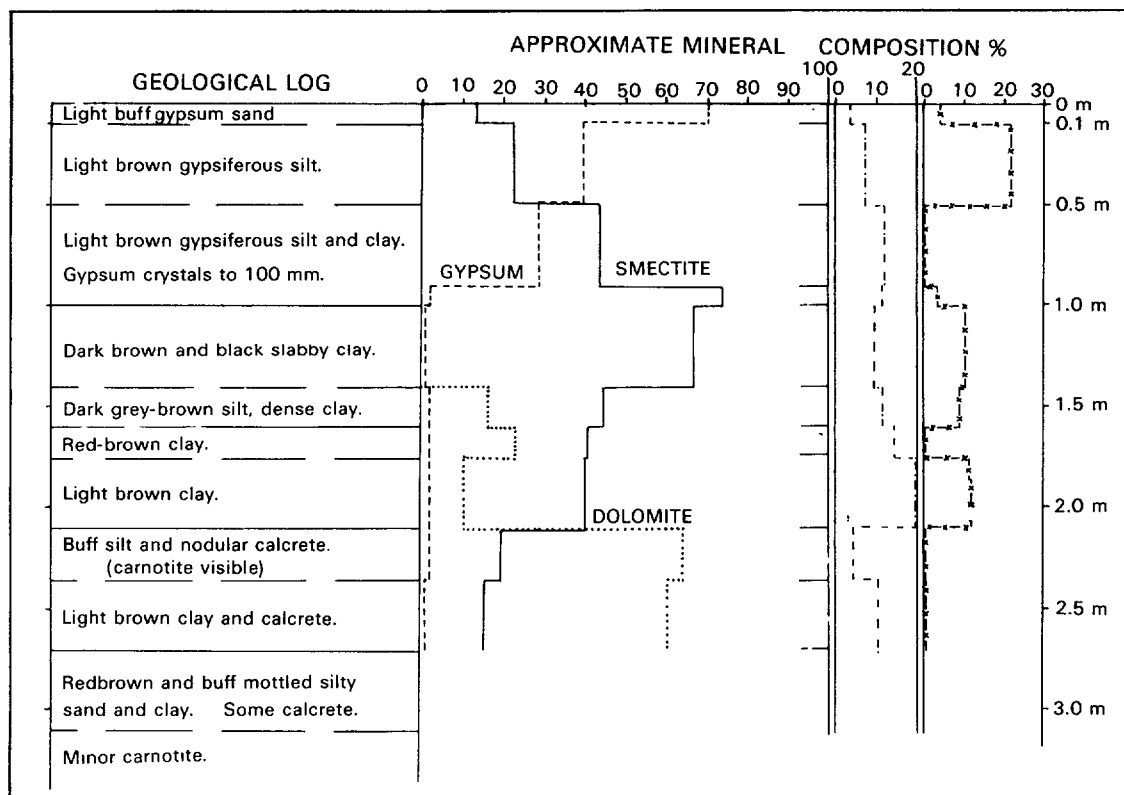


Figure 2
Lithology, mineralogy and uranium distribution in surface sediments, Lake Maitland, in costean at 40N, 103E (for location, see Figure 1).

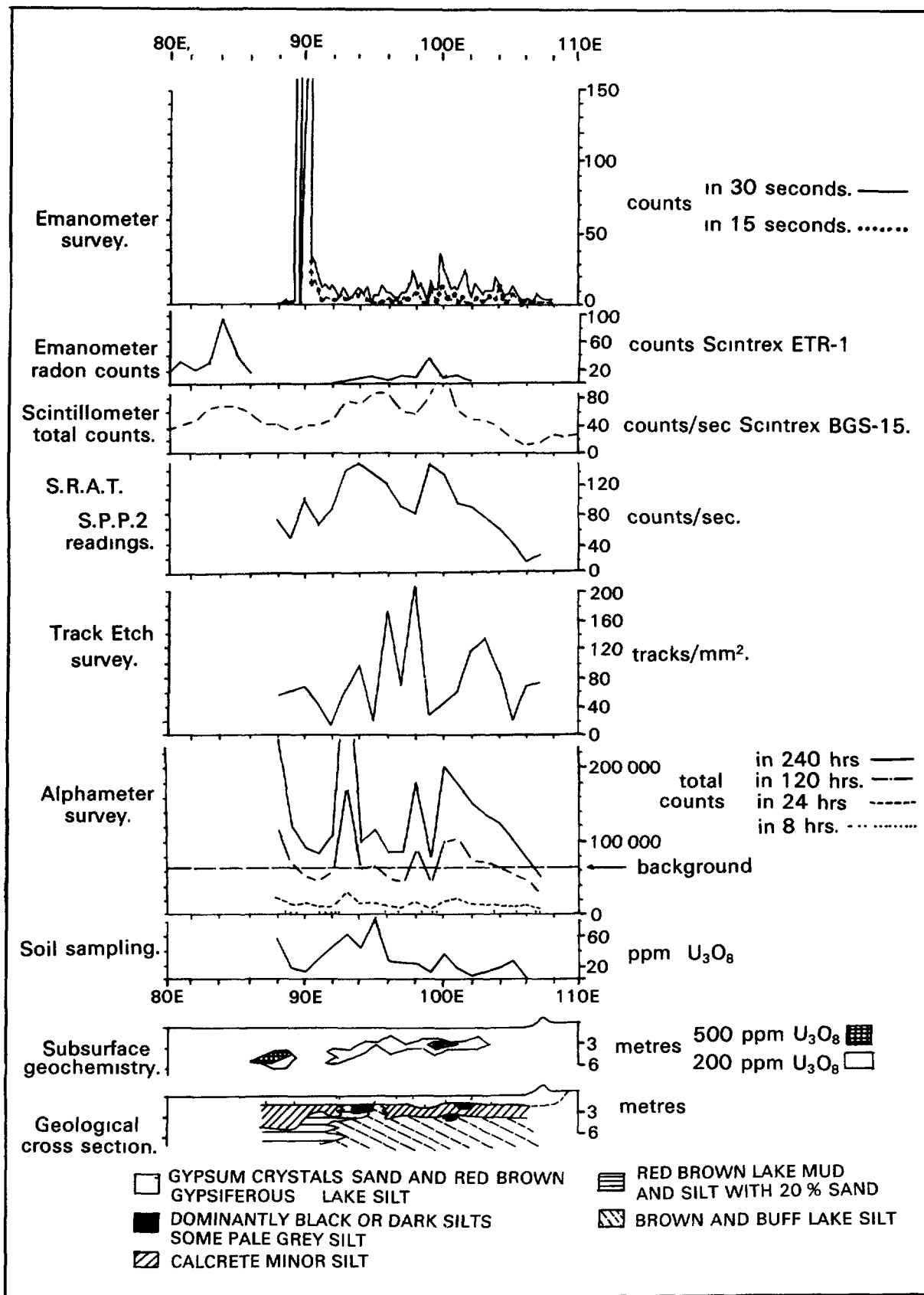


Figure 3

Comparison of geochemical and geophysical exploration techniques, Line 28N (for location, see Figure 1)

In general, there is an antipathetic sulphate/carbonate relationship, with gypsum near the surface and dolomite at depth. Smectites are most common in the aquiclude, where both gypsum and dolomite are absent. Similarly, there is an antipathetic relationship between quartz and dolomite.

5. MINERALIZATION

The mineralization (> 250 ppm uranium) was outlined by drilling on a grid of 100 x 400 m and extends in an arcuate zone some 6 km long by 0.3 to 0.5 km wide through the centre and both arms of the playa (Figure 1). Uranium content is mostly less than 700 ppm, although peak values exceed 1 800 ppm.

Over 80 % of the intersections outlined by the 500 ppm U_3O_8 cut-off are spatially related to calcrete. Of the rest, most are on the same horizon as calcrete in adjacent holes. In some cases, a thin layer of calcrete may not have been recognized during geological logging. However, the mineralization is not confined to the calcrete and in over half of the intersections, the lower boundary is in sand (40N 103E), pale clay (56N 100E), brown silt (28N 99E) or sandy clay (28N 101E).

The uranium is almost certainly always present as carnotite. Within the harder calcrete, the carnotite forms coatings on the outside of slabs. Both carnotite and slabs are commonly striated, probably as a result of volume changes associated with calcrete formation. The carnotite has preferentially deposited in the interslab voids of the aquifer.

Disequilibrium ratios were determined on 46 samples. In samples with U_3O_8 greater than 200 ppm, the mean ratio was 0.97. There is a slight trend to radium enrichment between 1.5 and 1.5 m depth, but deeper samples show very little dispersion (B. Dickson, written communication).

6 RADIOMETRICS

The property was originally explored in 1972 by Asarco (Aust.) (Pty) Ltd, as a follow-up to anomalies shown by an airborne radiometric survey by the Bureau of Mineral Resources. In 1973, Carpentaria Exploration Company (Pty) Ltd carried out a total count scintillometer survey, using a Scintrex BGS-IS instrument. This outlined an anomaly 2 to 3 times background, with peaks up to 10 times background, broadly coincident with the mineralization. Down-hole logging, using Mt Sopris 1 000 and Austral 100 instruments, gave fair agreement with chemical assays. Discrepancies are most probably due to down-hole contamination of drill samples. Thus, logging defined boundaries of mineralized layers more precisely than drilling and indicated thin high-grade bands within the mineralized zone (R. H. Duffin, written communication, 1974, G. M. Sheehan, written communication, 1975).

Uranerz Australia (Pty) Ltd tested a variety of exploration techniques over the southern part of the lake along line 28N (J. Borschhoff, written communication, 1977). The results of these and previous surveys are presented as stacked profiles in Figure 3. The scintillometer survey recorded peaks of 5 and 7 times background over variably mineralized pods and 4 times background between them. An alpha track survey gave several peaks 1.5 to 3 times background but these did not coincide with the mineralization. An emanometer survey gave peaks 2 to 3 times background over a mineralized pod in the middle of the lake and 16 times background in the dryer material near the edge of the lake over another mineralized zone. Alphameter surveys gave peaks of 2.1 and 2.6 times background over mineralization but also one of 3.8 times background over poorly mineralized material. Soil samples gave erratic highs across the lake.

7. HYDROLOGY

Two aquifers are present in the upper 5 m of lake sediments, the upper in the dark slabby clay beneath gypsiferous silt and separated by red-brown dolomitic clay from the lower in calcretes.

Total dissolved solids increase from about 3 000 mg/l in the calcrete 1 km west of the playa to 50 000 to 100 000 mg/l at the playa edge and 160 000 mg/l, 1.6 km into the playa, 400 m from the eastern margin. Groundwaters in the playa contain 5 to 150 ppb uranium and 30 to 80 ppb vanadium.

ACKNOWLEDGEMENTS

This paper is published with the permission of Carpentaria Exploration Company (Pty) Ltd, and Uranerz Australia (Pty) Ltd.

REFERENCES

- [1] CHURCHWARD, H. M., Soils, landforms and regoliths of the Sandstone-Mt. Keith area of Western Australia. Australia CSIRO Land Resources Management Series No. 2 (1977).

THE LAKE RAESIDE URANIUM DEPOSIT

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ABSTRACT

THE LAKE RAESIDE URANIUM DEPOSIT

The Lake Raeside uranium deposit is in the Yilgarn block, 60 km from Leonora in an area of granites with 8 to 10 ppm uranium. Waters near the deposit are nearly saturated with carnotite. The area is a mature peneplain with deep weathering and slow ground water movement. The deposit has an estimated 1700 tonnes of U_3O_8 at an average grade of 0.025% U_3O_8 . Carnotite is the only uranium mineral. The postulated mode of formation has the granite as the source rock and uranium movement as a carbonate. On concentration by evaporation the uranium was released and formed carnotite.

1. INTRODUCTION

The Lake Raeside deposit is located approximately 60 km from Leonora at 120°40'E, 28°45'S. Although the deposit is small in size, the hydrogeochemistry is particularly interesting.

Following the discovery of Yeelirrie, 250 km north, in 1971, considerable attention was paid to the large radiometric anomalies coincident with several playa lakes in the Yilgarn area of Western Australia. Despite extensive exploration by a number of companies, no significant body of mineralization was located to explain adequately the anomalous radiation coincident with Lake Raeside.

In 1974, a regional groundwater sampling program was carried out by Derry, Michener & Booth (Pty) Ltd, in an effort to gain further information on the then poorly understood nature of calcrete uranium mineralization. The water samples were analysed for uranium, vanadium, total alkalinity, pH, and specific gravity, which was estimated using an hydrometer. The results obtained were confusing (Figure 1). In some areas known mineralization was found to be associated with high uranium concentrations, but at Lake Raeside the higher values were associated with granites to the north and only low uranium values occurred in the radiometrically anomalous area.

During 1975, the radioactive anomaly on the lake was tested further by drilling, using a percussion drill mounted on the back of a small tracked vehicle. The work proved to be arduous and unrewarding, except for a trace of carnotite mineralization located by one of the last holes on the northern shore of Lake Raeside.

By early 1976, following a suggestion by Professor P.B. Hostetler (Macquarie University), a procedure for determining the solubility indices for calcite and carnotite was developed by the author (see appendix). The calcite indices indicated that large areas were supersaturated, whereas the carnotite index indicated that the waters were in general undersaturated, but approached saturation in the vicinity of mineralization (Figure 2).

In view of the complexity of the U-V-HCO₃-H₂O system, and the approximations involved in the calculation, this result was particularly pleasing. In the case of Lake Raeside, the regional water sampling of wells indicated that the margins of the lake were prospective, but the granitic areas to the north were not, despite the high uranium content of the waters in that region. Consequently, a detailed drilling program was instigated in the vicinity of the minor mineralization located in 1975. This drilling outlined the deposit described below.

2. DESCRIPTION OF THE DEPOSIT

2.1 Geology and Geomorphology

The basement rocks are predominantly biotite-granite to granodiorite [1], which contain 8 to 10 ppm uranium, with local maxima up to 80 ppm uranium. To both west and east are greenstone belts, which are possible sources of vanadium.

The landscape is a mature peneplain, with deeply weathered soils, and low drainage angles. The drainage axes are choked with sediments which have formed playas. In the headwaters of the catchments, the remnants of an older erosion surface form spectacular cliffs (breakaways) up to 30 m high. Drainage is predominantly by very slow groundwater movement, with sheetwash after occasional heavy rain. In 1974-75, (for the first time in living memory), Lake Raeside was filled with water by a tropical cyclone and connected surface flow took place.

2.2 Host Rocks

The deposit is situated on a low-lying peninsula on the northern shore of the lake. It is possible that this is a delta which has been breached by the moderately sized stream which enters the lake just to the west. Alternatively, the peninsula may be a chemical delta associated with the groundwater, and the stream conducts the occasional surface flow.

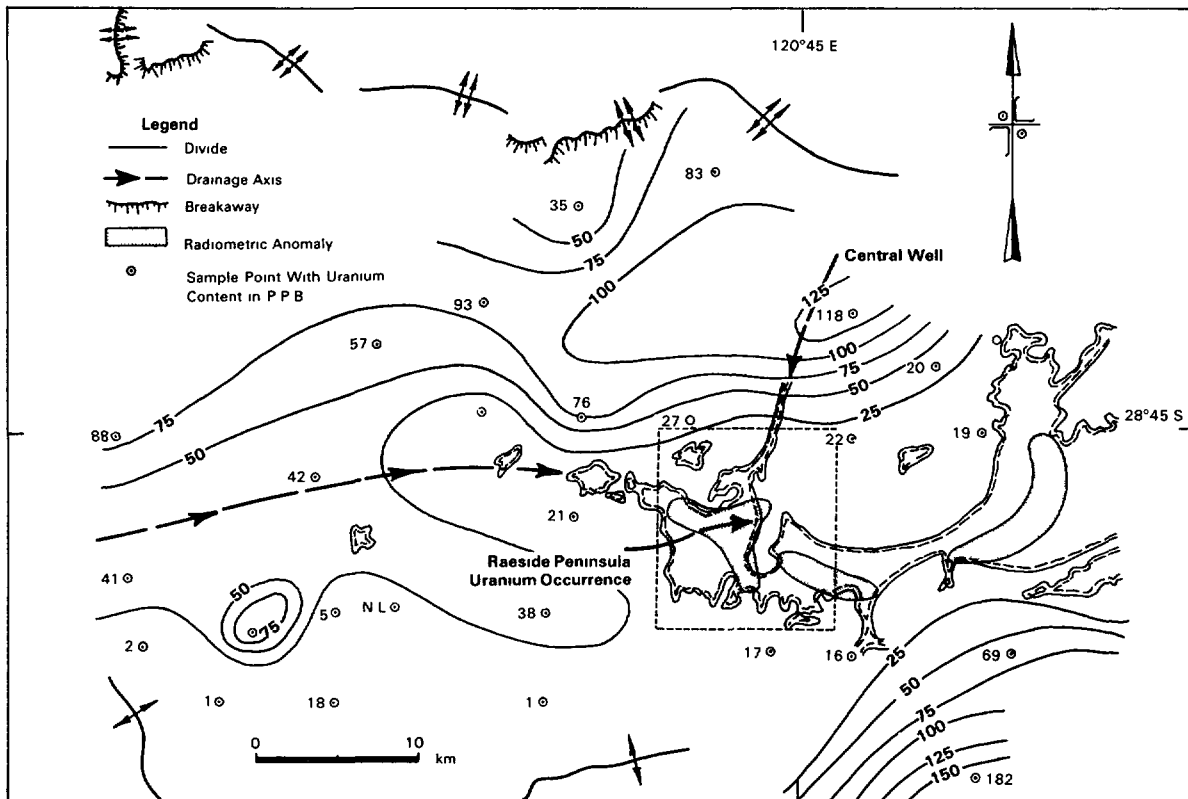


Figure 1
Lake Raeside area regional water sampling – water soluble uranium contours.

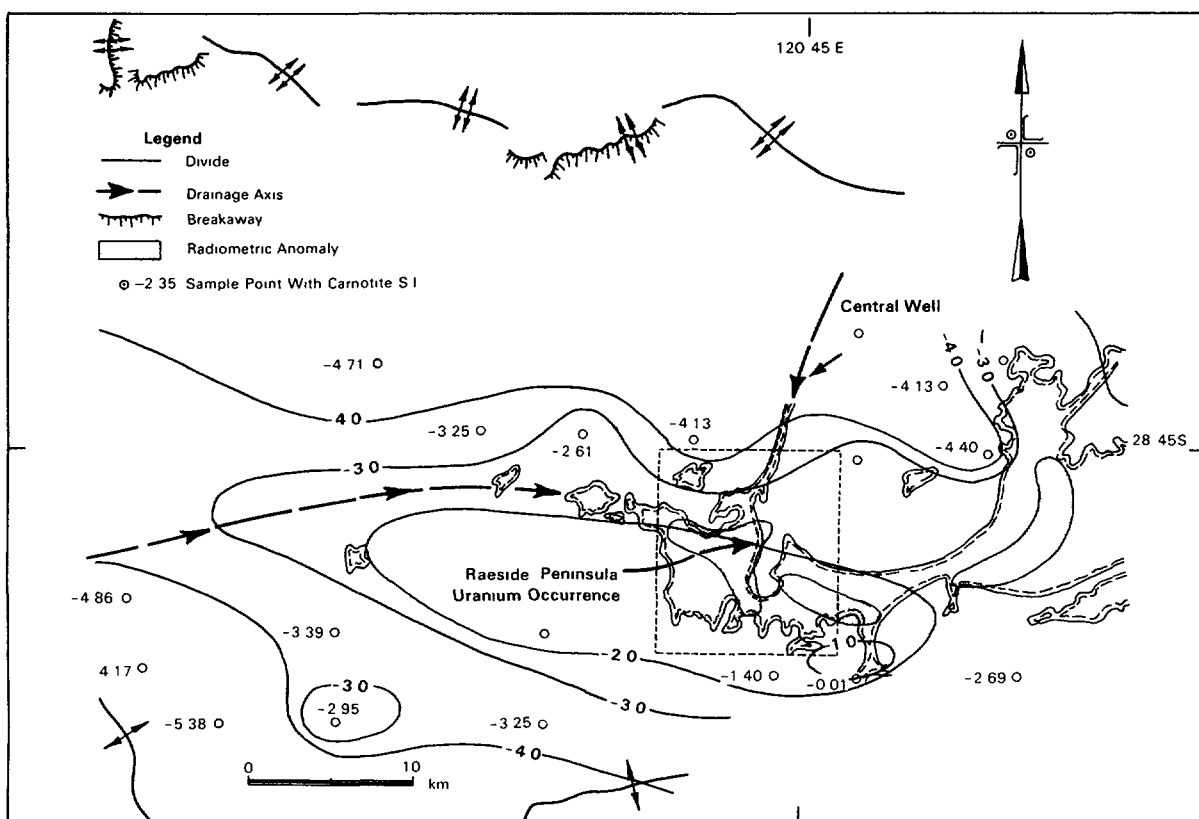


Figure 2
Lake Raeside area regional water sampling – carnotite solubility index (SI) contours (log).

TABLE 1
XRF Analyses of Samples from Lake Raeside Peninsula
(Surficial Host Rock)

	Hole A4			Hole A2	
	0-1 m	1-2 m	2-3 m	3-4 m	4-5 m
U (ppm)	6	175	195	170	80
Th (ppm)	12	8	14	8	16
V (ppm)	50	50	75	75	110
Quartz	D	CD	A	A-SD	D
Kaolinite	SD	SD	A	SD	SD
Calcite	Tr-A	CD	A	A	Tr
Feldspar	Tr	Tr	Tr	Tr	A
Gypsum	—	—	D	D	A-SD
Halite	—	—	—	—	Tr

Key: D = dominant
 CD = co-dominant
 SD = sub-dominant
 A = accessory (roughly between 5 and 20 %)
 Tr = trace (less than 5 %)

The host rocks are predominantly red or brown calcareous clays and clayey grits, overlying indurated ferruginous clays. Gypsum is common, and in places has formed thick "kopi" dunes, which are impervious to gamma radiation. Some mineralogical and chemical analyses are shown in Table 1.

2.3 Mineralization

The mineralization is confined to the peninsula, in a zone approximately 5.6 km long by 100 to 800 m wide and 1 to 2 m thick. The mineralization is shallow, between 1 to 5 m below surface, and is generally slightly above the water table. Using a cut-off grade of 200 g/tonne, the resource potential of the area is estimated at 1 700 tonnes of contained U_3O_8 with an average grade of 0.025 % U_3O_8 . This figure is based principally on radiometric probing of drill holes on a 200 x 800 m grid, and is only a very crude estimate. A typical cross section is shown in Figure 3.

The mineralization is strongly associated with the more calcareous clays. Carnotite is the only uranium mineral observed.

2.4 Radiometrics

Airborne radiometric surveys were carried out by both the Bureau of Mineral Resources (BMR) [2] and Consolidated Goldfields Australia (Pty) Ltd (CGFA) [3]. The BMR survey, published at 1:250 000 scale, indicates a strong total-count anomaly coincident with Lake Raeside. The CGFA survey covered this area in more detail, and showed a strong uranium anomaly over the lake. Values over the peninsula were not regarded as anomalous. However, later ground traverses over the peninsula using a Geometrics DISA 400 gamma-ray spectrometer and a chart recorder detected the mineralization with an anomaly to background ratio of 5:1. A limited regional alpha track survey using "TRACK ETCH" cups indicated a strong anomaly on the lake margins, and it is concluded that the lake anomaly is probably due primarily to radium leaching from the peninsula mineralization. Subsequent breakdown to ^{214}Bi would produce anomalous radiometric readings.

2.5 Hydrogeochemistry

Regional water sampling of wells and boreholes in 1974 had indicated that waters to the north had high uranium contents (greater than 100 ppb), but were undersaturated with respect to carnotite. During the 1976 drilling program, water samples were collected from the holes for analysis (Figure 4).

Eh, pH, salinity, conductivity and temperature were measured on site, and filtered samples were sent to Perth to be analysed for potassium, uranium and vanadium. Bicarbonate was determined both in the field and in Perth with very similar results. Eh and pH were determined using a Titron meter; salinity, conductivity and temperature were measured with a YSI salinity meter with the probe in the hole. Measurements downhole indicated little stratification, although measurements in other areas had shown strong stratification associated with uranium mineralization. Bicarbonate was determined by standard alkalinity titration. Potassium was determined by atomic absorption spectrometry with no preconcentration. Uranium and vanadium were determined down to 1 ppb levels using a proprietary XRF method by Sheen Laboratories. Other techniques, including delayed neutron activation, were tried, but XRF proved the most satisfactory. Typical results are shown in Table 2.

From these samples, and a large number of others collected elsewhere, it is possible to make the following generalizations:

1. Potassium and calcium contents increase linearly with salinity, from less than 20 ppm to more than 100 ppm.
2. pH is relatively constant in the range 6.5 to 7.5.
3. Waters are generally well oxidized compared to a standard calomel electrode (SCE). Hole A42 (Table 2) is a rare exception. This is significant in that under reduced conditions carnotite precipitation is unlikely to occur. The calculated solubility index does not make allowance for oxidation state; however, Mann [4] has suggested that some carnotite may precipitate due to changes in oxidation state.
4. There is a sharp decrease in bicarbonate associated with saline areas from 300 to 500 ppm to about 150 ppm. This is probably due to the precipitation of calcium carbonate as calcite.
5. Vanadium does not conform to any particular pattern, ranging from trace amounts to greater than 200 ppb. There does not appear to be any association with particular rock types.

Table 2
Hydrogeochemical Data of Groundwater

	Eh mV	pH SCE	HCO ₃ ppm	U ppb	K ppm	V ppb	Salinity %	SI (log)
Central Well	N/A	7.8	283	118	20	7	N/A	-4.84
A51	+140	6.3	502	25	323	15	2.47	-2.05
A42	-190	7.4	334	70	610	110	4.90	-1.03
A35	+140	7.6	146	70	945	35	5.42	-0.36
A15	+145	7.4	126	590	825	10	8.00	-0.26

Hole A51 is about 400 m up-drainage from the mineralization, holes A42 and A35 are both at the northern end (updip) of the mineralization, and hole A15 is in the middle. Central Well is located in granitic rocks 8 km north of the mineralization.

Table 2 illustrates these points. The data are arranged roughly in order of location along the drainage. The first sample from Central Well (Figure 1) has quite high uranium and bicarbonate contents but low salinity and potassium contents. The carnotite solubility index (SI) indicates that the sample is very undersaturated. The second sample A51 (Figure 4) is just outside the mineralized area. The uranium content is quite low, but potassium and vanadium contents are higher and, together with the lower pH, give a carnotite SI value much higher than at Central Well, but still undersaturated. Sample A35 is actually in carnotite mineralization. Potassium, vanadium and uranium contents have all increased, and together with the lower bicarbonate, yield a SI very close to zero. This indicates that the solution is saturated and that carnotite should be precipitating, as is observed. Sample A15 continues this trend, and the SI indicates that the water is slightly supersaturated.

From these observations, the following mode of formation is postulated:

1. Weathering of the granites to the north of Lake Raeside provides a source of soluble uranium, potassium, and calcium. The source of the vanadium is not well understood, but may be leached from the laterites.
2. The uranium is strongly complexed by the formation of uranyl dicarbonate complex (UDC) and uranyl tricarbonate complex (UTC), due to the high bicarbonate concentration. This effectively precludes a reaction involving uranium ions in this environment.
3. Groundwaters carry the complexed ions slowly down-gradient. Calcium and potassium ion concentrations increase due to evaporative concentration until calcite and/or dolomite precipitate as calcite, removing calcium and/or magnesium and bicarbonate from the groundwater.
4. Due to the reduction in bicarbonate concentration, the UDC and UTC complexes break down, releasing uranium ions. These combine with the abundant potassium and smaller quantities of vanadium to form potassium uranyl vanadate – i.e. carnotite.

ACKNOWLEDGEMENTS

This work was carried out by the author whilst employed by Derry, Michener and Booth (Pty) Ltd, consultants acting on behalf of BP Minerals Australia (Pty) Ltd. Their assistance is gratefully acknowledged. Numerous discussions with Dr A.W. Mann and Dr R.L. Deutscher were of mutual benefit, and the work of Professor P.B. Hostetler was invaluable.

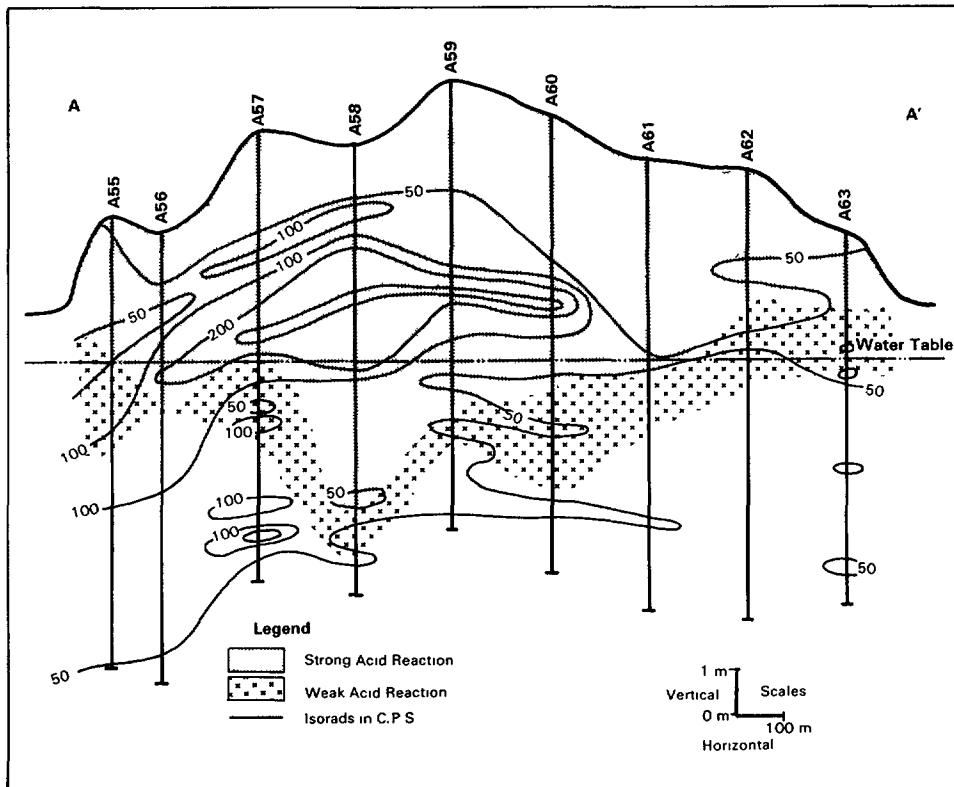


Figure 3
 Lake Raeside Deposit typical cross section (see Figure 4 for orientation).

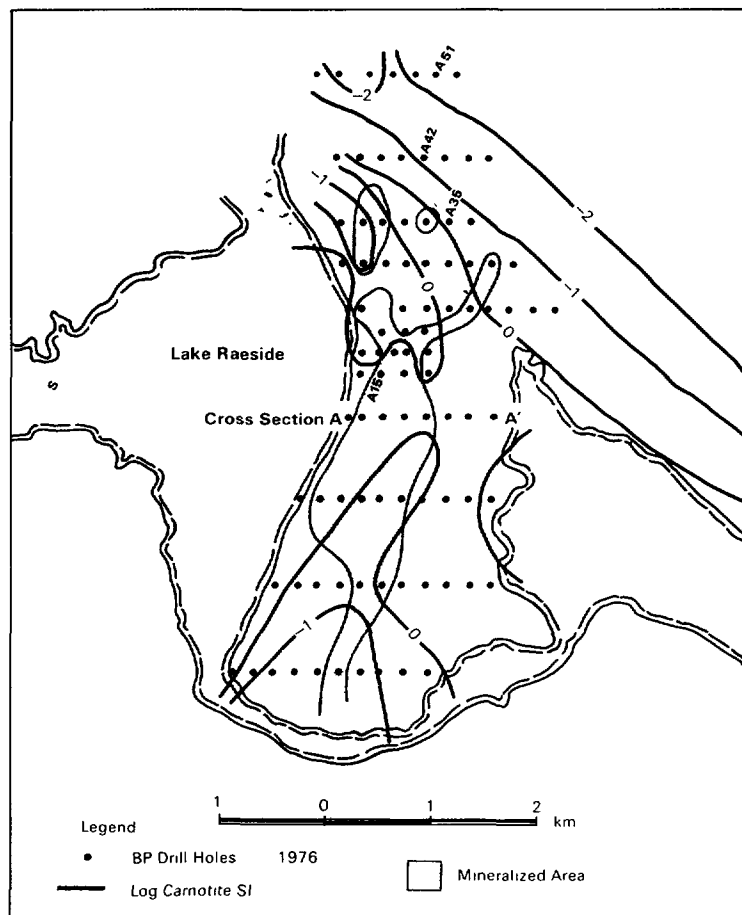


Figure 4
 Lake Raeside Deposit detailed water sampling - carnotite solubility index (SI) contours (log).

APPENDIX

Calculation of Solubility Indices for Calcite and Carnotite

The solubility index (SI) of a particular mineral is a figure which, if greater than unity, indicates that a solution is supersaturated and precipitation can proceed. It is calculated from the product of the molar concentration of the active ionic species, divided by the solubility product.

In the case of calcite,

$$SI = \frac{(Ca^{2+}) (CO_3^{2-})}{10^{-8.5}}$$

Normally, CO_3^{2-} is present in very small quantities compared to HCO_3^- , and must be calculated from the equation

$$\frac{(CO_3^{2-})(H^+)}{(HCO_3^-)} = 10^{10.3}$$

The calculation for carnotite is similar, using the equation

$$CSI = \frac{(K^+) (H_2VO_4^-) (UO_2^{2+})}{(H^+)^2 * 10^{-6.8}}$$

Several complications arise, however, in that the active concentrations of UO_2^{2+} are very much reduced by the formation of the complex ion $UO_2(CO_3)_2 \cdot 2H_2O^{2-}$ (UDC) and $UO_2(CO_3)_3^{4-}$ (UTC). Similarly, the active concentration of K^+ is altered by the very high salinities which occur in the saline areas. The formation of the $H_2VO_4^-$ ion is dependent on Eh.

The formation of UDC and UTC can be estimated using the total dissolved uranium concentration, and dissociation constants given by Hostetler and Garrels [5].

A short program for an HP25 programmable calculator is given in Table 3. This program estimates the carnotite solubility index from pH, bicarbonate (alkalinity), uranium, potassium and vanadium. It gives good results in the calcrete areas of Western Australia, but does not allow for reducing conditions which will affect the concentration of available vanadium. Nor does the program allow for the ionic strength of the solutions.

Table 3
SI Carnotite Program (HP25) Instructions

INSTRUCTIONS	INPUT DATA	KEYS	OUTPUT
1. Switch to PRGM Enter PRGM Switch to Run			
2. Clear PRGM/STK		f PRGM f STK	
3. Enter Constants			
K (carbonate) R0	10.33	CHS STO 0	
K (carnotite) R1	6.8	CHS STO 1	
K (UTC) R2	24.2	CHS STO 2	
MW HCO ₃ R4	61	STO 4	
MW U R5	238	STO 5	
MW V R6	51	STO 6	
MW K R7	39	STO 7	
4. Enter Variables			
pH		R/S	
HCO ₃ (ppm)		R/S	Log (CO ₃ ²⁻)
U (ppm)		R/S	Log (UO ₂ ²⁺)
K (ppm)		R/S	Log (SI)
V (ppm)			
5. Repeat step 4 any number of times			

Table 4
SI Carnotite Program (HP25)

LINE	CODE	KEY	COMMENTS
01	2404	RCL 4	
02	71	÷	
03	33	EEX	
04	32	CHS	
05	03	3	
06	61	x	
07	1408	f log	
08	21	xy	
09	2303	STO 3	
10	51	+	
11	2400	RCL 0	
12	51	+	
13	74	RS	Log CO ₃ ²⁻
14	2405	RCL 5	
15	71	÷	
16	33	EEX	
17	32	CHS	
18	06	6	
19	61	X	
20	1408	f log	
21	21	xy	
22	03	3	
23	61	X	
24	41	-	
25	2402	RCL 2	
26	51	+	
27	74	R/S	Log UO ₂ ²⁻
28	2406	RCL 6	
29	71	÷	
30	21	xy	
31	2407	RCL 7	
32	71	÷	
33	61	X	
34	33	EEX	
35	32	CHS	
36	09	9	
37	61	X	
38	1408	f log	
39	51	+	
40	2403	RCL 3	
41	02	,2	
42	61	X	
43	51	+	
44	2401	RCL 1	
45	41	-	SI Carnotite (Log)

REFERENCES

- [1] THOM, R., BARNES, R.G., Leonora, Western Australia, West. Aust. Geol. Survey 1:250 000 Geol. Series Explan. Notes (1977).
- [2] LEONORA - SW, Total Magnetic Intensity and Radioactivity, Aust. Bur. Min. Res. Geol. Geophys. Sheet H51/B1-91-3.
- [3] CONSOLIDATED GOLDFIELDS AUSTRALIA "Leonora" 1972 West. Australia Geol. Survey, Open File Report, roll 237 M1187.

- [4] MANN, A.W., Calculated solubilities of some uranium and vanadium compounds in pure and carbonated waters as a function of pH, Aust. CSIRO Div. of Mineral. Report FP 6 (1974) 39.
- [5] HOSTETLER, P.B., GARRELS, R.M., Transportation and precipitation of uranium and vanadium at low temperature, with special reference to sandstone-type uranium deposits, Econ. Geol., 57 (1962) 137-167.

LAKE WAY URANIUM DEPOSIT, WILUNA, WESTERN AUSTRALIA

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ABSTRACT

LAKE WAY URANIUM DEPOSIT, WILUNA, WESTERN AUSTRALIA

The Lake Way uranium deposit, 16 km southeast of Wiluna, is in an area of granites with around 12 ppm uranium, and greenstones, near the edge of the playa Lake Way which is the drainage base for a large ancient drainage system. The deposit is carnotite in calcrete and is below or near the water table in areas of high salinity. The deposit has over 5000 tonnes U_3O_8 , averages 1.55 m thick and is at depth of 0–10 meters. The deposit was discovered by an airborne radiometric survey.

1. LOCATION

The Lake Way uranium deposit is located 16 km southeast of Wiluna, Western Australia, at longitude $120^{\circ} 20'E$ and latitude $26^{\circ} 40'S$ (Figure 2).

2. GEOLOGY

Lake Way is a remnant of an extensive ancient drainage system formed on the Precambrian Shield and is now the dominant base level for local intermittent drainage. The lake is normally dry with a surface veneer of sodium and magnesium salts underlain by gypseous clay and silt. Groundwater in the sediments contains more than 10 % TDS and is normally less than 1 m below the surface.

In the area of the deposit, surficial sediments include fluvial and deltaic sand, silt, clay, calcrete valley-fill, aeolian sand, and lacustrine clastics and evaporites (Figure 1). The sediments grade downwards to lacustrine clay of very low permeability. Sandstone, conglomerate, and granite breccia overlie the basement rocks in some areas. The sedimentary section thickens southward towards the lake where it attains a thickness in excess of 90 m.

Lake Way overlies the contact between Archaean granite and gneisses on the east, and older Archaean dolerite, basalt, amphibolite, and minor acid volcanics on the west (Figure 2).

Rocks in the main catchment area consist of adamellite and gneissic biotite granite which outcrop 18 km to 28 km northeast of the deposit and which provide the headwaters for the Uramurdah and Scorpion Creeks (Figure 2). Airborne reconnaissance surveys over the Mt. Cleaver adamellite outcrop show an anomalous radiation level of three to five times that of other granite exposures in the area. The medium-grained adamellite contains an allotriomorphic granular aggregate of quartz (30 %), microcline (30 %), plagioclase (30 %) and biotite (7 % to 10 %). Altered monazite, ilmenite, zircon and magnetite are selectively associated with the biotite. Zircon (> 1 %) is surrounded by metamict alteration envelopes. Trace element analyses of weathered hand samples are given in Table 1.

Table 1
Trace Element Analyses of "Source" Rock (ppm)

U	12	Hf	10
V	50	Ce	300
Th	40	La	150
Zr	120	Y	70

3. GEOMORPHOLOGY

The area lies on the internal plateau of Western Australia and is characterized by remnant salt lakes and extensive tracts of featureless undulating sand plains, interspersed with higher areas of bed rock. Duricrusted granitoid outcrops are commonly bounded by erosional escarpments and deeply weathered mafic rocks are covered by laterite and form low, rounded hills. The maximum relief in the region is generally less than 100 m and within the mineralized area, it is less than 10 m.

Local features consist of calcrete "valley-fill" up to 20 m thick with a surface elevation 5 m above the present surface of Lake Way. Massive calcrete terminates 2 km north of the lake. Silt and fluvial deltaic sediments extend south to a younger "chemical delta". Clay, calcrete, and dolomite in the delta form a distinct elevated platform 1 m above the lake surface. Aeolian dunes separate the surficial fluvial and deltaic mineralized zones and cover the southern edge of the calcrete "valley-fill" (Figures 1 and 3).

Several intermittent creeks drain the eastern and western flanks of the calcrete and others flow onto the calcrete to become part of the groundwater regime.

4. CLIMATE AND VEGETATION

The area is arid, with an average annual rainfall of 249 mm and evaporation in excess of 3 000 mm. Most of the rainfall occurs in periods lasting less than 48 hours between January and June. Dry periods may last from 6 to 9 months and droughts lasting several years have been recorded. Monthly mean maximum temperatures range

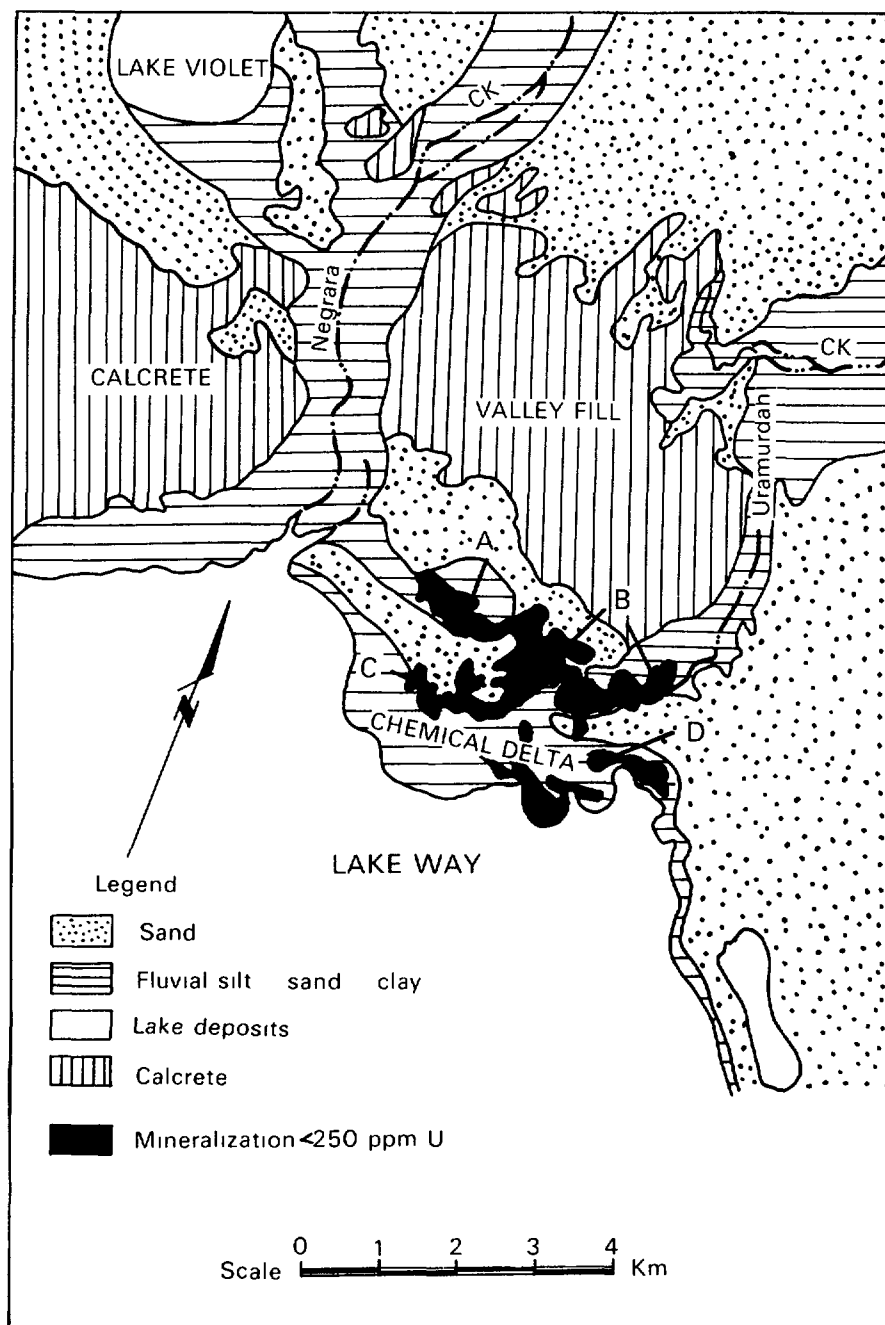


Figure 1
Surficial geology of the Lake Way uranium deposit

from 19 °C in June-July to 37 °C in December-February; mean minimum temperatures range from 7 °C in July to 23 °C in January-February. Summer daytime temperatures commonly exceed 40 °C, but winter days are generally mild and frost may occur at night.

Vegetation in and around the mineralized area varies in accord with the underlying rock type, depth and salinity of the groundwater. Low-lying saline areas near the lake margin support the more salt-tolerant halophytic shrubs and are almost exclusively vegetated by samphires. *Atriplex*, *Maireana*, and *Enchyleana* spp. dominate the chenopod flora of the higher flats and, in areas underlain by fresher water, the shrubs *Lycium*, *Cratystylis*, *Olearia*, and *Muehlenbeckie* are present. Stands of *Acacia* and *Melaleuca* spp. form a distinct border to the halophytic communities and mark the change to sandy, less saline soils.

In the higher calcrete areas there is a predominance of *Acacia* and *Eucalyptus* spp. forming an overstorey to the chenopod (saltbush) flora. Open spinifex grasslands are the feature of the sand plain and dunal areas.

Soils in the area are predominantly coarse-grained red silt sands; they are variously saline and have low phosphorus, nitrogen and organic levels.

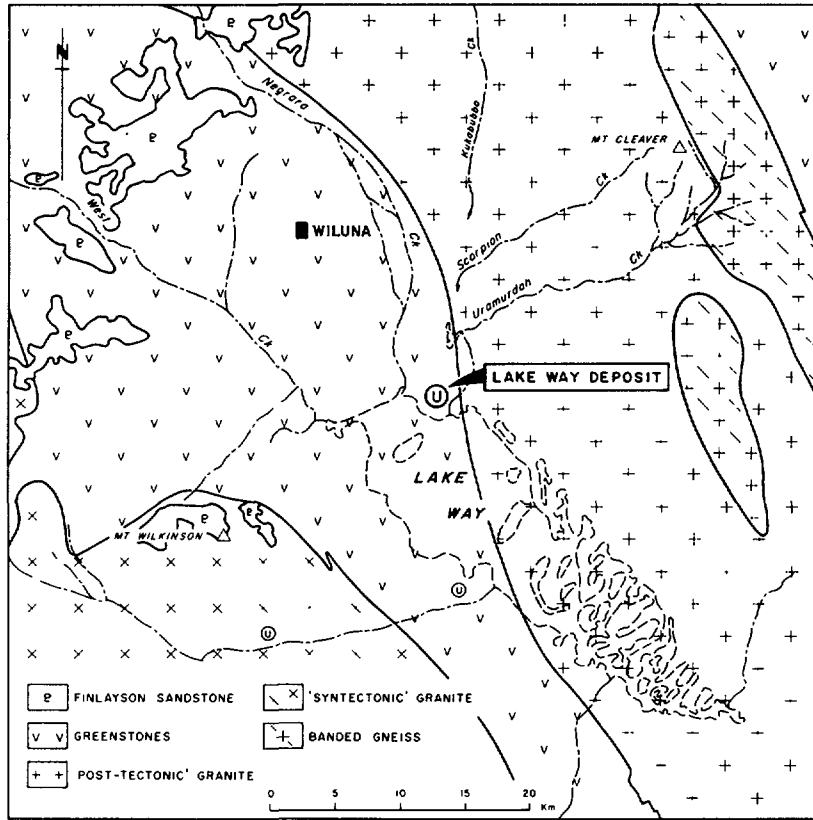


Figure 2
Geology of the basement rocks in the vicinity of Lake Way

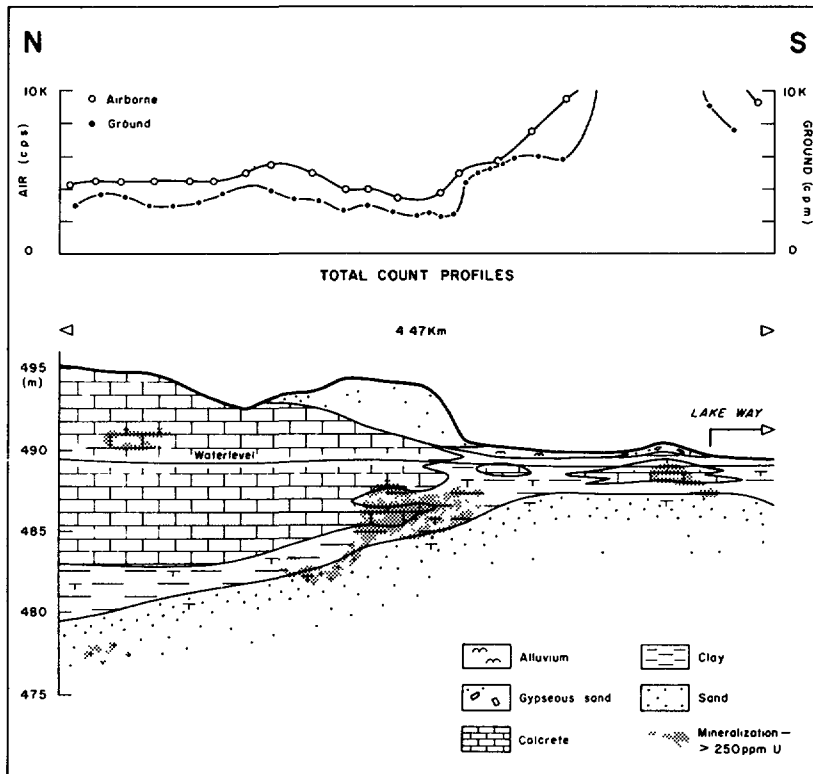


Figure 3
Ground and airborne radiometric responses over the uranium mineralization and cross-section through the ore body. See Figure 6 for locality of NS

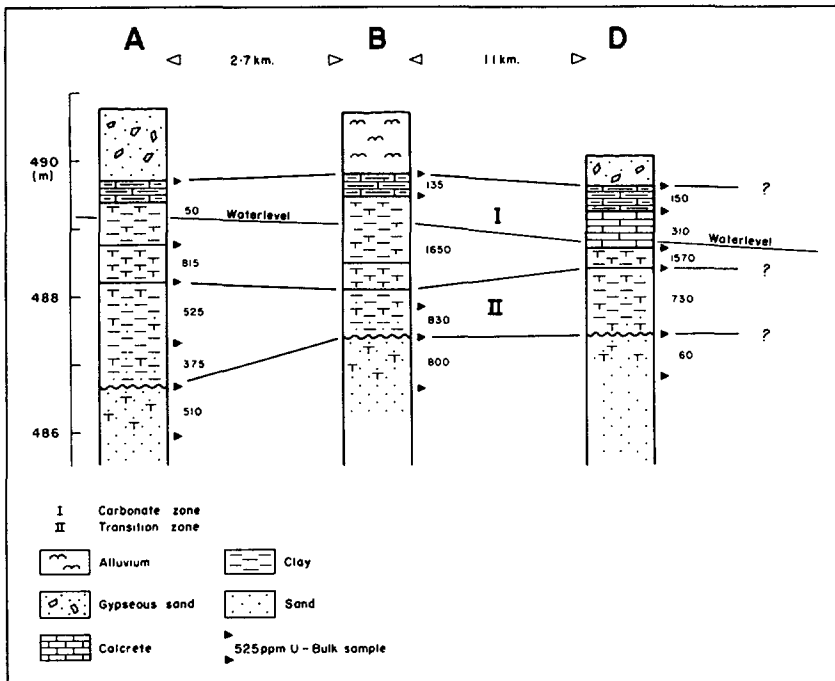


Figure 4
Cross-section costeans A4-B4-D12 through the uranium mineralization

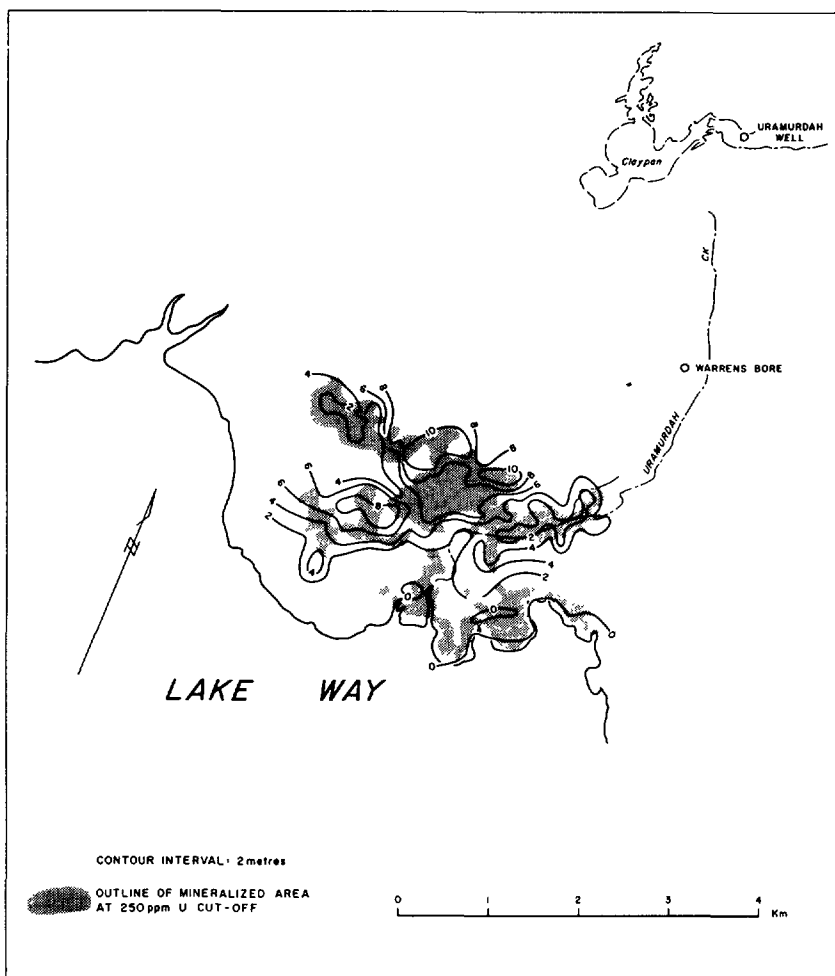


Figure 5
Overburden isopach map

Analyses of plants and associated soils from the area of major uranium mineralization are shown in Table 2.

Table 2
Analyses of Plants and Soils

Vegetation	Plant	Soil	
	U ppm	U ppm	Ra (Bq/g)
Chenopod	0.2–9.2	2.5–45.0	0.07–0.23
Halophyte	0.1–0.3	0.1– 1.3	Below detection
Grasslands	0.1–0.2	0.7– 3.0	0.6
Salt pan	0.2	24.0	0.21

5. HOST ROCK

Most of the carnotite has been deposited within carbonated reworked fluvial clastics which occupy the southern extremity and peripheral areas of the Uramurdah-Negrara drainage, but significant mineralization also occurs in the southern edge of the "valley-fill" calcrete and in the younger "chemical delta" carbonates at the edge of Lake Way (Figures 1 and 3). Mineralization is not lithologically controlled, but is directly related to sediment permeability (primary or secondary), water table depth and rate of groundwater evaporation.

Fluvial deltaic sediments consist of an interfingering and transitional sequence of carbonated sand, silt, clay, and calcrete. Quartz sands are subangular, dark brown to grey and vary in grain size from very fine to grit and become more argillaceous towards the delta area. Reworked carbonate fragments and nodules are common and carbonaceous material is found lining fossil root tubes.

Carbonated silts and clays are typically brown to light grey, thinly bedded and very arenaceous. Thin lenses of sand, grit, and reworked calcrete fragments are present, especially in Area 'B'. Former soil surfaces are in evidence, as shown by fossil root tubes which are filled with calcareous and carbonaceous material.

Dominant minerals in the clay-sized fractions in Areas 'A' and 'B' (Figure 1) are very fine quartz and dolomite. Kaolin is the subordinate clay mineral, but a single horizon in Area 'A' contains smectite and smectite-illite mixed-layer clays. Accessory and trace minerals in Area 'A' are gypsum, kaolin, feldspar, attapulgite, halite, mica, illite and goethite; Area 'B' contains all the above except smectite and attapulgite.

Calcretes are generally light to dark grey, but the younger, more massive and dolomitic calcretes in the "chemical delta" are distinctly brown. Quartz grains are common inclusions and sepiolite is found lining cavities and fractures. Oolitic and spherulitic carbonate forms occur at or near the surface on the lake periphery and are composed of aragonite crystals, often coated with or in a sepiolite matrix.

Some reprecipitation of carbonate is apparent within the calcrete, where clear microcrystalline calcrete is present as growths in voids and on fracture planes. Fluvial and deltaic sediments associated with the calcretes are subject to carbonate replacement, especially those immediately above the water table.

Karst features, dissolution voids, shrinkage cracks and coarse irregular bedding provide for rapid infiltration and movement of groundwater towards local base level.

6. MINERALIZATION

Uranium mineralization commonly occurs below or near the water table, and in areas with little overburden, high evaporation, and high groundwater salinity (Figures 4 and 7). Distribution of the most significant mineralization recognized to date occurs over an area 3.5 km eastwest (around the periphery of the calcretes and in the fluvial detritus) and extending 2.5 km north from the north shore of Lake Way. Additional mineralization has been found to be present in sediments beneath 15 m of calcrete, but has not yet been fully defined. The ore zones average 1.55 m in thickness, with a maximum thickness in excess of 6 m (using a 250 ppm uranium cut-off). Overburden ranges from 0 to 10 m and averages 4 m (Figure 5).

Total reserves drilled on 76 m spacings are 5 200 tonnes U_3O_8 at 250 ppm U cut-off and 3 300 tonnes U_3O_8 at 550 ppm U cut-off. Six additional target areas remain to be drilled.

Most of the visible uranium mineralization occurs in the form of micro- to cryptocrystalline carnotite (less than 0.04 mm) precipitated as coatings along bedding and slippage planes, in interstices between sand grains, in fissures in calcrete and dolomite and in root tubes in buried soil horizons. Some carnotite crystals are present in an argillaceous matrix with micro- to cryptocrystalline calcrete or micro-oolitic and spherulitic carbonate (aragonite). Both the crystalline and the oolitic calcrete are distinctly separate and younger than the massive calcrete valley-fill and are more prevalent in the associated clay/silt horizons. Leaching tests indicate that a small fraction ($\pm 2\%$) of the carnotite may be associated with recent silicification.

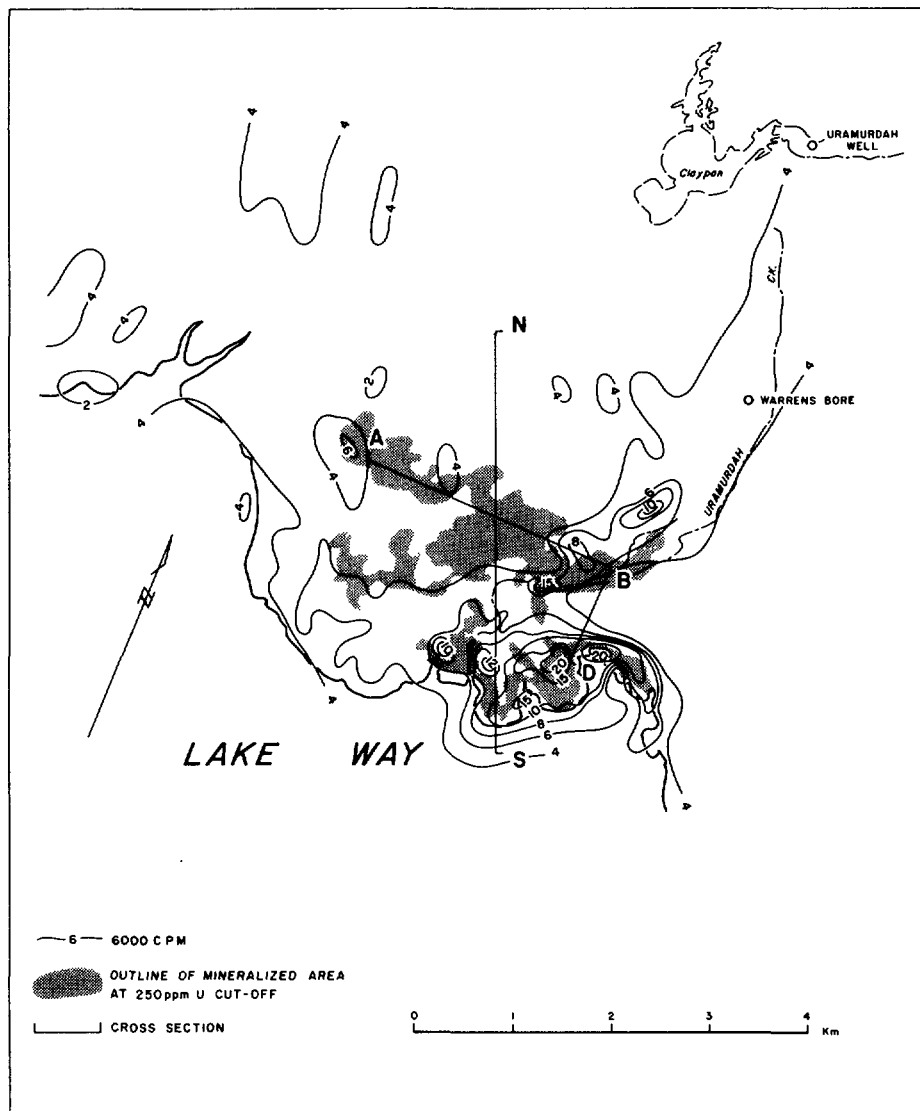


Figure 6
Total count ground radiometric survey contour map

Downhole radiometric surveys were conducted in most of the open drill holes and selected reverse circulation drill cuttings were analysed for uranium by XRF. Overall correlation between the data sets is considered to be within assay limits, but data from a few drill holes show significant variation. Field selection of drill cuttings for XRF analyses was based on the radiation level of the 1 m or 0.33 m sample as measured with a hand-held scintillometer. The relative accuracy of the selection method was confirmed when only 50 additional samples required analyses.

A similar technique was successfully used to select bulk samples from costeans for pilot plant processing. During trial mining studies an area of 1 149 m² was predrilled on 4.6 m centres and mining of the 5 000 tonne block was controlled with a hand-held scintillometer and a beta-gamma analyser coupled to a ratemeter. Each hole was sampled, chemically assayed and radiometrically logged; bulk samples were taken from the excavator bucket, a channel sample was taken from the pit face and each truckload was radiometrically logged. The five crosschecks correlated within chemical assay limits ($\pm 5\%$). Agreement between reserve data calculated from drilling and mining is of the order of 0.5 % grade and 1 % tonnage.

7. RADIOMETRICS

The Lake Way uranium deposit was discovered during an aerial spectrometer survey conducted in 1972. Radiometric data showed anomalies of twice the background to off-scale on the total count, K-U-Th, and U-Th channels, but zero to minor increases on the Th channel. Subsequent drilling and costeaning revealed that the most intense anomalies generally correspond to near-surface accumulations of uranium. Large areas of twice the background radiation are a reflection of a very thin veneer of remobilized uranium that has been widely dispersed by surface water.

Detailed ground radiometric surveys (Figures 3 and 6) confirmed the airborne data and showed anomalies of twice to seven times the background on total count over areas of substantial mineralization. Major anomalies coincide with most of the chemical deltaic deposits and where Uramurdah Creek has eroded most of the overburden. A small anomaly of twice the background coincides with significant mineralization 3 km northwest of the delta area. Two anomalies 2.5 and 3.5 times reflect areas where only minor surface mineralization has been encountered. A large part of the deposit, which is covered by 4 to 10 m of overburden, was not identified by airborne or ground radiometric surveys (Figures 3 and 6).

Disequilibrium studies conducted by the CSIRO [1] showed a range of 1:1.02 to 1:1.16 (average 1:1.09). Maximum disequilibrium was recognized in the "chemical delta" where the mineralization is considered to be slightly younger and probably derived from the higher, more northerly deposits.

8. HYDROLOGY

Uramurdah Creek and Scorpion Creek (Figure 2) drain more than 60 km² of uranium-bearing adamellite and granite gneiss and form part of an intermittent drainage system that flows southwesterly to the north shore of Lake Way. Much of the surface water carried by this system penetrates fluvial and aeolian deposits of loose sand and permeable calcrete valley-fill to become part of the groundwater regime flowing towards the lake. During occasional periods of heavy rainfall, the creeks may overflow their indistinct courses and create sheetflood conditions over large flat areas underlain by calcrete and alluvium. Flooding is also incurred by runoff from the Kukabubba Creek and the Negrara Creek (Figure 2), which flow in a southeasterly direction to the valley-fill area.

Groundwater gradients in the area are low, ranging from 0.001 55 in the north and northeast to 0.000 6 near the lake. Water quality rapidly deteriorates southwards where the water table approaches the surface and is affected by evaporation and transpiration (Figure 7).

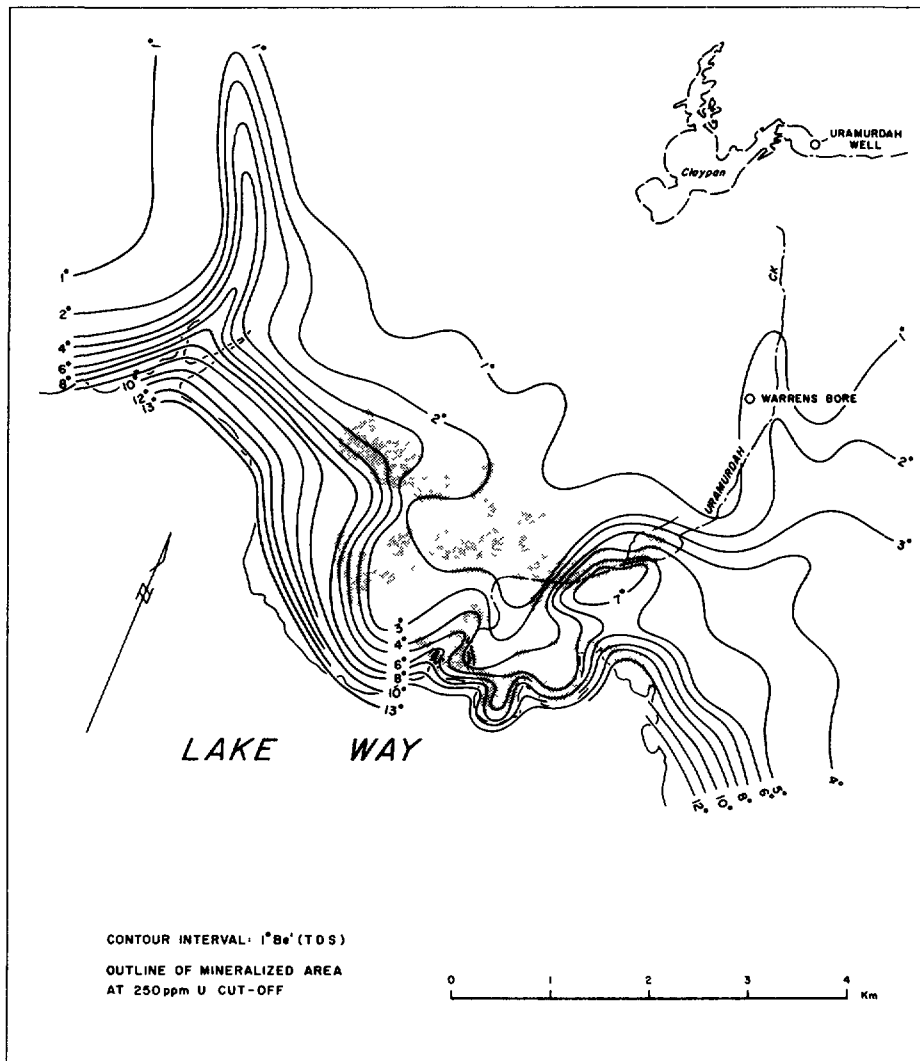


Figure 7
Groundwater salinity contour map

Table 3
Chemical Analyses of Groundwater from the Source Area of the Lake Way Deposit

	Sample No	K ppm	U ppb	V ppb	Cl ppm	HCO ₃ ⁻ ppm	SO ₄ ⁻ ppm	pH	TDS ppm	²²⁶ Ra (pci/l)	SI	
Mt. Cleaver Upstream	1	15	50	10	185	245	115	6.7	787	-	-4.96	
	2	40	45	30	230	240	65	8.2	875	6	-4.16	
	3	47	25	35	900	270	400	7.1	2 360	1	-4.31	
	Downstream	4	130	65	50	2 460	330	740	6.8	5 560	7- 15	-3.47
Kukabubba Drainage Upstream*	1	11 55	11	15	1 700	435	530	6.5	3 900	-	-5.37	
	2	25	6	35	80	285	120	7.7	674	-	-5.28	
	3	35	17	25	330	340	275	7.4	1 382	-	-4.96	
	4	35	19	25	345	270	300	6.7	1 350	-	-4.70	
	Downstream *7 km west of drainage	5	50	40	25	480	315	305	6.8	1 644	-	-4.36
Negrara Drainage Upstream	1	15	3	15	140	310	240	6.7	974	-	-6.21	
	2	11	1	15	135	265	120	6.9	744	-	-6.69	
	3	8	1	25	130	165	105	6.8	588	6.5	-6.19	
	4	20	1	15	510	175	640	6.7	1 945	1.0	-6.07	
	Downstream	5	230	20	210	2 710	245	2 850	7.4	8 828	3.3	-2.86
West Creek Drainage Upstream	1	63	5	8	-	-	-	-	2 030	-	-	
	2	71	40	11	-	-	-	-	3 020	-	-	
	3	53	7	35	-	-	-	-	2 080	-	-	
	4	54	7	16	-	-	-	-	1 860	-	-	
	5	132	20	15	-	-	-	-	5 040	-	-	
	6	-	6	15	815	350	665	6.9	2 665	-	-	
	7	35	13	10	-	-	-	-	1 180	-	-	
	8	101	14	25	-	-	-	-	3 780	-	-	
	Downstream	9	230	20	210	2 710	245	2 850	7.4	8 828	3.3	-2.86
Mineralized Zone	Area 'A'	(6)	1 078	135	680	15 805	300	6 933	8.0	36 027	1-170	-1.08
	Area 'B'	(9)	1 735	109	220	30 916	257	7 308	7.7	66 225	35-200	-1.28
	Area 'D'	(10)	1 116	219	300	21 170	328	5 894	7.7	42 983	17- 45	-1.26

Most of the mineralization occurs in the 1 % to 6 % TDS zone. No commercial mineralization has been found in the lake, where groundwater contains up to 20 % TDS, or in the northern area, where groundwater contains less than 0.5 % TDS.

Analyses of groundwater from the source area, other drainage areas and the mineralized zone, are shown in Table 3. No definitive trends, other than an increase in mineral content with increased evaporation near the lake, have been positively identified.

Subsequently, Mann (CSIRO) has calculated the solubility indices (SI) for carnotite in the groundwaters (Table 3) and the results show a definite increase in saturation (with respect to carnotite) in the downstream direction, towards Lake Way. No corrections for high ion concentrations have been applied; consequently, the SI remains negative for samples from the mineralized area.

REFERENCES

- [1] DICKSON, B.L., Uranium series disequilibrium in the carnotite deposits of Western Australia, this Volume.

THE YEELIRRIE CALCRETE URANIUM DEPOSIT, WESTERN AUSTRALIA

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ABSTRACT

THE YEELIRRIE CALCRETE URANIUM DEPOSIT, WESTERN AUSTRALIA

The Yeelirrie deposit, between Wiluna and Sandstone, lies in the Yilgarn block, in a catchment area of deeply weathered granites and greenstones. The host calcretes are a 1 to 1.5 km wide valley-fill in a long established drainage system, and are developed over a 85 km long distance. The calcretes are either earthy or porcellaneous with voids.

The deposit is sheetlike, some 9 km long and 5 to 1.5 km wide, averaging 3 m thick and is 4 to 8 meters below the surface, and immediately below the water table. The deposit has 52 500 tonnes of U_3O_8 at an average grade of 0.15% U_3O_8 . Carnotite is the only uranium mineral. Water movement in the area is largely subsurface in the calcrete, which is a good aquifer. Uranium concentrations of 100 to 450 ppb are found in the calcrete ground waters compared to background values of 5 to 10 ppb.

1. LOCATION

Yeelirrie is a pastoral property in the East Murchison district of Western Australia, located approximately 650 km northeast of Perth, and more or less midway between the old gold-mining centres of Wiluna and Sandstone. The orebody is centred on the 12 Mile Bore, 20 km north-northwest of the homestead, at 27° 11' S, 119° 55' E (Figure 1).

2. BASEMENT GEOLOGY

The deposit occurs in the Yilgarn Block between the Wiluna-Leonora and Montagu Range greenstone belts. As far as can be determined from the limited outcrops, exposures in the bordering erosion scarps, and from the exploratory drilling, the Yeelirrie catchment area is developed almost entirely on highly decomposed granitic rocks of predominantly biotite-adamellite composition. The only exception is along the extreme western margin where the drainage has just encroached onto the mafic volcanics and intrusives, and sediments of the Montague Range, though these would occupy no more than 3 % of the total catchment area upstream from the orebody.

3. GEOMORPHOLOGY

Yeelirrie is close to the regional watershed, in the headwaters of a major tributary of the palaeodrainage system. Remnants of the high-level "Old Plateau" are still preserved around the margins of the catchment, bounded by inward-facing erosion scarps between 5 and 10 m in height, and providing good exposures of the upper part of the weathering profile. From the escarpment, braided streams traverse the gently sloping alluvial plain of the "New Plateau" surface, falling 80 m at an average gradient of 0.4 % into the central channel containing the orebody. The present-day channel is believed to follow closely the position of the ancestral Tertiary drainage. Longitudinal gradients decrease from approximately 0.12 % upstream to 0.06 % near the orebody. However, the gentle topography of the New Plateau appears to be in sharp contrast with that of the sub-alluvial basement which may drop abruptly by 30 m to the palaeovalley floor. In addition to occupying the well-graded axis of the valley floor, the central channel has a particularly distinctive surface expression, reflecting the lithology, the ephemeral drainage and the locally high water table. A narrow zone, 1 to 1.5 km wide, with calcrete outcrops, light calcareous soils, occasional clay pans and a distinctive flora, contrasts strikingly with the extensive, scrub-covered, red, sandy soils of the bordering alluvial plain.

4. CHANNEL SEDIMENTS

4.1 Mineralized Host Rocks

The principal host rocks of the mineralization are calcretes and highly carbonated modifications of the alluvial sediments which have filled the palaeovalley. In the Yeelirrie area, these carbonate accumulations form highly elongated bodies confined to the main drainage lines. The terms "valley calcrete" [1] and "groundwater calcrete" [2] have been proposed to emphasise the close association with the drainage and water table, and to distinguish them from the extensive pedogenic horizons described from elsewhere [3,4].

Where exposed, the calcrete appears as long, low mounds, separated by shallow, soil-filled depressions and occasional claypans. In depth, however, it forms a more or less continuous sheet, and, though showing considerable variation, the attitude and thickness (4.6 m) remain reasonably consistent (Figure 2). Calcrete lenses are developed over a distance of 85 km along the Yeelirrie channel, the largest of which is approximately 20 km long and from 0.5 to 2.5 km wide, and contains the orebody.

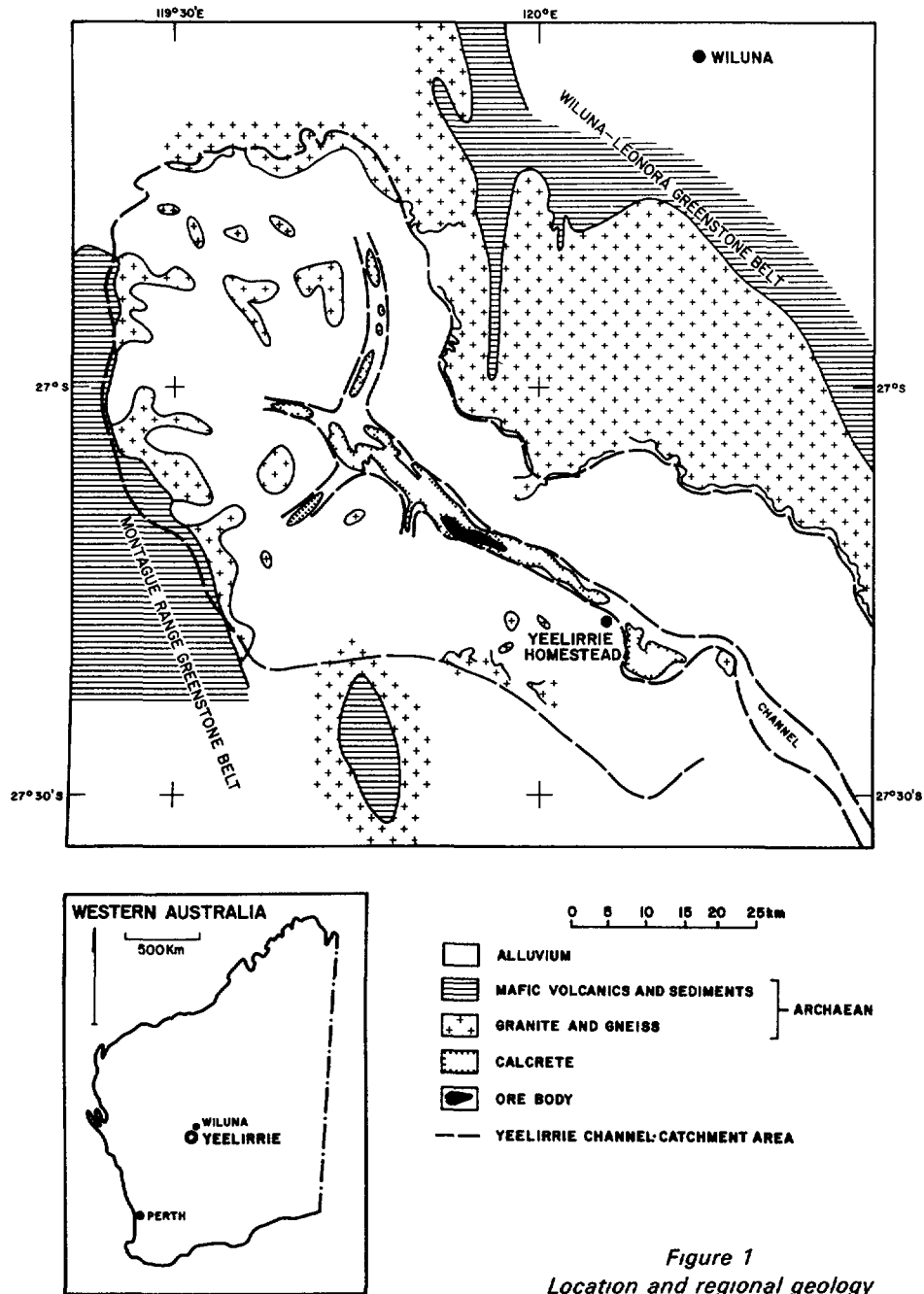


Figure 1
Location and regional geology

The precise age of the calcrete is unresolved, but it is probable that the process has extended over a considerable period in recent geological time, even to the present day when some types are undoubtedly being formed. In outcrop, the calcrete can be seen undergoing surface modification with the development of karst features and the redistribution of the carbonate as a laminar capping.

4.2 Channel Profile

Three principal horizons can be recognised in the drill holes and excavations – viz the overburden, calcrete and clay-quartz (Figure 2). Although the same sequence is present throughout, the horizons nevertheless show considerable variation over short distances and commonly have gradational contacts.

Overburden

The soil is a variable unit, 1 to 2 m in thickness, commonly consisting of a red-brown, sandy loam with a thin, indurated hardpan layer at a depth of 10 to 15 cm. However, on the saline claypans, the surface horizon is a brown, gypseous clay. A local variant of the soil unit is the carbonated loam, marking the transition to the underlying calcrete. Of particular interest in this part of the profile is a thin calcrete gravel, or rubble, composed of either carbonate pisoliths showing a prominent concentric growth pattern, or hardpan peds coated with carbonate. This layer closely resembles the pedogenic calcretes which are widely developed in other parts of the State.

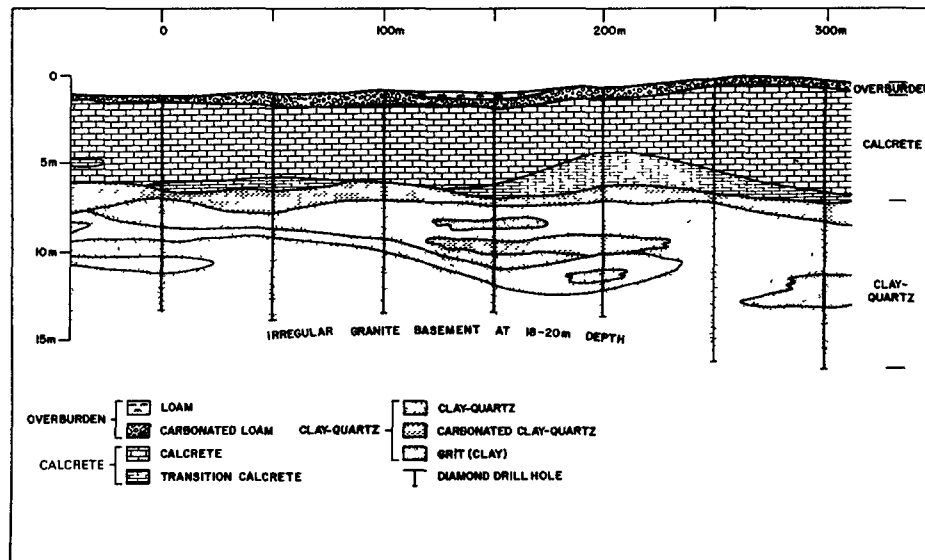


Figure 2
Lithological cross-section

Calcrete

The calcrete at Yeelirrie is of two predominant types with contrasting physical, chemical, mineralogical and genetic characteristics; one is a buff, friable, "earthy" variety, and the other white, hard, nodular "porcellaneous" and commonly riddled with voids.

Carbonate first appears in the lower part of the overburden as thin, widely-spaced, horizontal seams, becoming more numerous with depth and isolating rafts of soil or hardpan which are progressively reduced in size until they are no more than small inclusions. Thus, the emphasis changes from carbonate seams in soil to soil relics in a soft carbonate matrix. Every stage in the elimination of these inclusions can be seen, from recognisable soil material to the point where their former presence is marked only by slightly darker ghosts, giving the calcrete a mottled texture. With the increase in carbonate downwards, the process eventually leads to the formation of a more or less continuous sheet of earthy calcrete.

In contrast, the porcellaneous calcrete originates in the lower part of the soil horizon as small, discrete spheres covered with a network of contraction cracks (possibly due to dehydration), and in the case of the larger examples, often with an internal cavity. When broken, they show no megascopic evidence of any included soil material. As the spheres become more abundant, either laterally or downwards, they coalesce to form increasingly larger, bulbous masses with the typical porcellaneous character. Further emphasizing the contrast in lithology and structure, the larger bodies commonly truncate the horizontal layering of the earthy calcrete and may be bounded by low-angle, slickensided slip planes. Indurated bands in the overburden can sometimes be seen draped over the upper, convex surface of these porcellaneous calcrete bodies, in extreme cases forming a tight syncline between adjacent masses, or passing down between them as a disrupted septum. The basal zone of the porcellaneous calcrete lenses may be extensively silicified, and may contain large caverns measuring a metre or more in length.

Where the two calcrete types can be seen in excavations, they demonstrate contrasting modes of formation. The earthy variety appears to develop by an essentially passive process, infiltrating the soil along horizontal planes or transgressive fractures, and gradually incorporating the soil material into a carbonate-rich matrix. On the other hand, the porcellaneous calcrete gives the strong impression of dynamic growth at a number of discrete sites without the assimilation of soil material into the developing carbonate spheres. With the continued precipitation of carbonate, the process can be envisaged as leading ultimately to the formation of upward-moving growth mounds which pierce the overlying carbonated sediment, and probably giving rise to the elongated ridges now seen at the surface along the channel. If it is a dehydration effect, the network of cracks on the surfaces of the porcellaneous calcrete spheres would indicate a decrease in the water content of the surrounding medium, due either to a descending water table, to the upwards movement of the growth mounds above the phreatic zone, or to a combination of the two. Similar anticlinal structures have been observed in calcretes elsewhere in Western Australia [2].

Clay-quartz

The calcrete is underlain by alluvium which continues down to the basement granite. It consists essentially of a red clay containing disseminated detrital quartz grains, and shows little variation other than the presence of occasional quartz-rich bands, thin seams of celestite, or a thin arkosic layer overlying the decomposed granite. The transition from calcrete to clay-quartz is normally gradational, exhibiting similar carbonate seams to those in

the upper part of the profile, but becoming less well developed and more widely spaced as the carbonate content progressively decreases with depth

The principal constituents of the profile are quartz, carbonates (dolomite and calcite), clays (smectite, specifically saponite, illite, kaolinite; and occasional sepiolite [5]), and feldspar; gypsum and celestite may be locally abundant in restricted sections.

The clay-quartz is a mixture of kaolinite and quartz in varying amounts—typically 45 % kaolinite and 33 % quartz—together with minor saponite, illite and feldspar. In the calcrete, carbonates and saponite become dominant at the expense of quartz and kaolinite, with the proportions of each tending to reflect the different physical characters of the two types—e.g. 75 % total carbonate in the porcellaneous calcrete, but with a higher saponite content in the earthy variety. Calcite is normally subordinate to dolomite, but it may become important, or even the sole carbonate species, in the transition zones and in the overburden. The distinctive nature of these valley (groundwater) calcretes is further emphasized by their appreciable dolomite content, which contrasts with the high calcite content of most pedogenic calcretes. Limited chemical analyses indicate an average of 18.8 % MgO in the main part of the calcrete, but samples of near-surface calcrete gravel with only 3.9 % MgO are more comparable with the world average of 3.1 % [3].

5. URANIUM MINERALIZATION

The main body of ore-grade mineralization is restricted to a zone approximately 9 km long and between 0.5 and 1.5 km wide, elongated along the centre of the channel. It extends from the surface to a depth of 14 m, but is exposed in only one small outcrop, and is mainly concentrated in the interval between 4 and 8 m below the surface. The overall form is therefore, of a flat-lying, shallow sheet, averaging approximately 3 m in thickness, and for the most part situated immediately below the present water table (at 4.5 m). Although the mineralization occurs in both the calcrete and clay-quartz, the strongest development is in the transition zone beneath the calcrete. Throughout the orebody, the mineralization maintains a general continuity but is highly irregular in detail (Figure 3), as yet, there are insufficient exposures to permit the recognition of any local control on this distribution.

The revised estimate of the ore reserves at June 1982 is as follows:

Table 1
Revised Estimate of the Ore Reserves at June 1982

Ore	Ore Tonnes (million)	Contained U ₃ O ₈ Tonnes (000's)	Grade U ₃ O ₈
Prime ore (0.15 %)	13	32.0	0.24
Intermediate ore (0.05 % – 0.15 %)	22	20.5	0.09
TOTAL	35	52.5	0.15

X-ray diffraction analysis has so far failed to identify any uranium mineral other than carnotite. At no stage during the exploration or evaluation of the deposit has there been any evidence that it represents either the redistribution of primary mineralization in the basement, or an in-situ alteration product. In addition to the normal, canary-yellow colour, the carnotite is not uncommonly light-brown or olive green. The possible effect of composition on the colour has not been investigated, but the variations may be due either to a thin film of microcrystalline quartz that commonly coats the carnotite, or to the reduction of vanadium [6].

The carnotite is clearly one of the last stages in the development of the calcrete, only minor quantities of silica or amorphous clays are demonstrably later, usually lining the voids in the porcellaneous calcrete. It normally occurs as seams or disseminations in the earthy calcrete, as a grain coating in the clay-quartz, or as a fracture paint—for example, on the slip planes round the margins of the porcellaneous calcrete mounds. Disseminated carnotite has not been observed in the porcellaneous calcrete, where it normally forms a thin film lining the voids.

No systematic determination of uranium in the soils overlying the orebody has been attempted. Sporadic sampling during orientation surveys has shown wide variations (1 to 890 ppm U) in soils taken at depths of between 0.1 and 0.8 m, with mean values along three traverses ranging from 5 to 40 ppm U [7].

6. RADIOACTIVITY

Although there is only one outcrop of ore-grade mineralization, the Yeelirrie orebody nevertheless has a strong radiometric signature. During the 1960s the Federal Bureau of Mineral Resources (Geology and Geophysics) (the BMR) conducted an extensive airborne magnetic and radiometric survey over the eastern part of the Yilgarn Block.

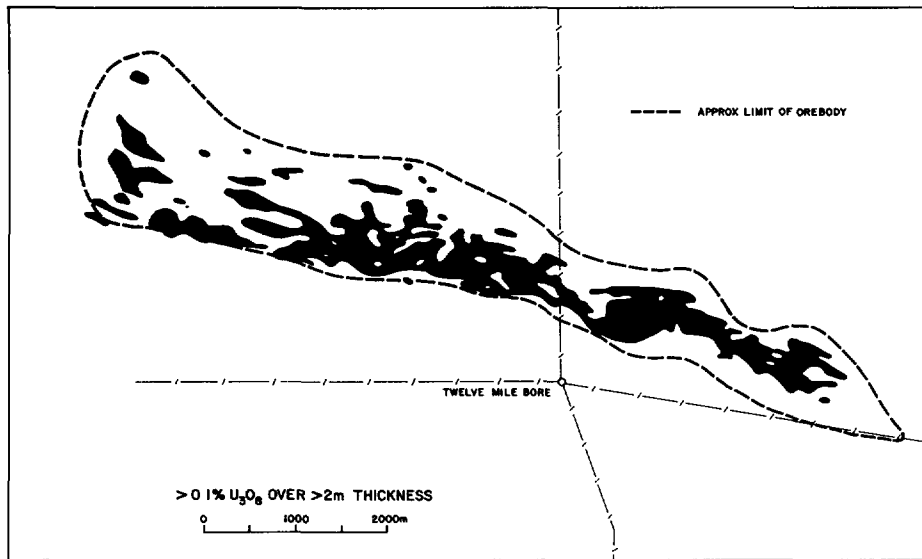


Figure 3
Grade distribution

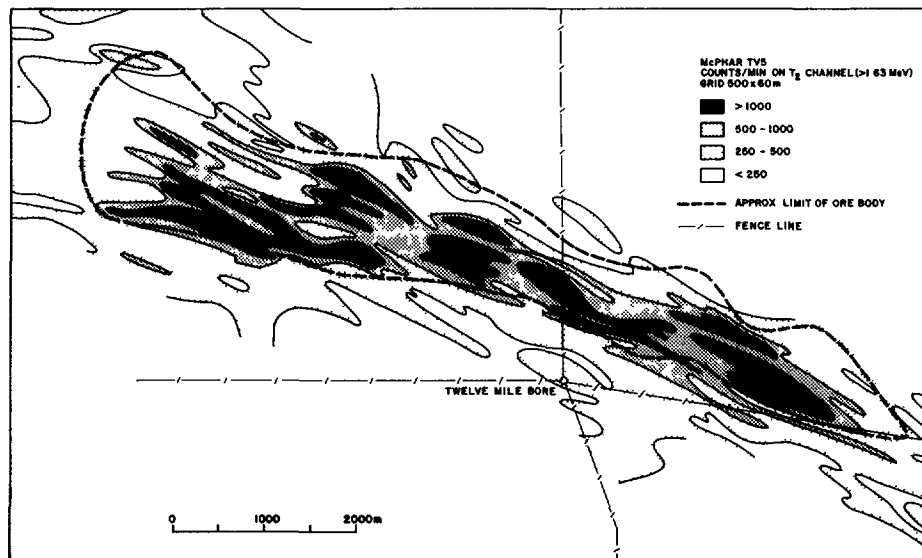


Figure 4
Ground radiometric survey

at a 1 mile (1.6 km) line spacing and 500 ft (150 m) mean terrain clearance. The radioactivity was recorded by two scintillometers, one with a ten-second time constant mounted inboard to measure the regional level, and the other with a one-second time constant trailed 260 ft (80 m) below the aircraft to locate point-source anomalies. The results released in 1970 [8] showed an extensive regional anomaly measuring approximately 10 x 2 km, elongated along the channel and located directly over the mineralization. Peak values on the final published map are 450 cps, compared with the general background level of 50 to 100 cps over the catchment area. In addition, two significant point-source anomalies were identified up-drainage from the orebody and believed to be over claypans. As this was a total-count system, the radioelement characteristics of the source could not be determined.

A ground radiometric survey using a McPhar TV5 intergrating spectrometer on a 500 x 60 m grid showed this to be a strong uranium, but weak thorium, source; the low thorium content was later confirmed by limited chemical analyses during the drilling stage. This ground survey reproduced the airborne regional anomaly, though in greater detail. The orebody is now defined by the twice background contour, corresponding approximately to 400 cpm on the T_2 channel (> 1.63 MeV), with several small zones above 10 times background, and a peak in excess of 5 000 cpm (approximately 25 times background) over the only mineralized outcrop (Figure 4). The close agreement between the airborne and ground surveys emphasizes the value of a rapid airborne survey as an exploration technique in this particular environment.

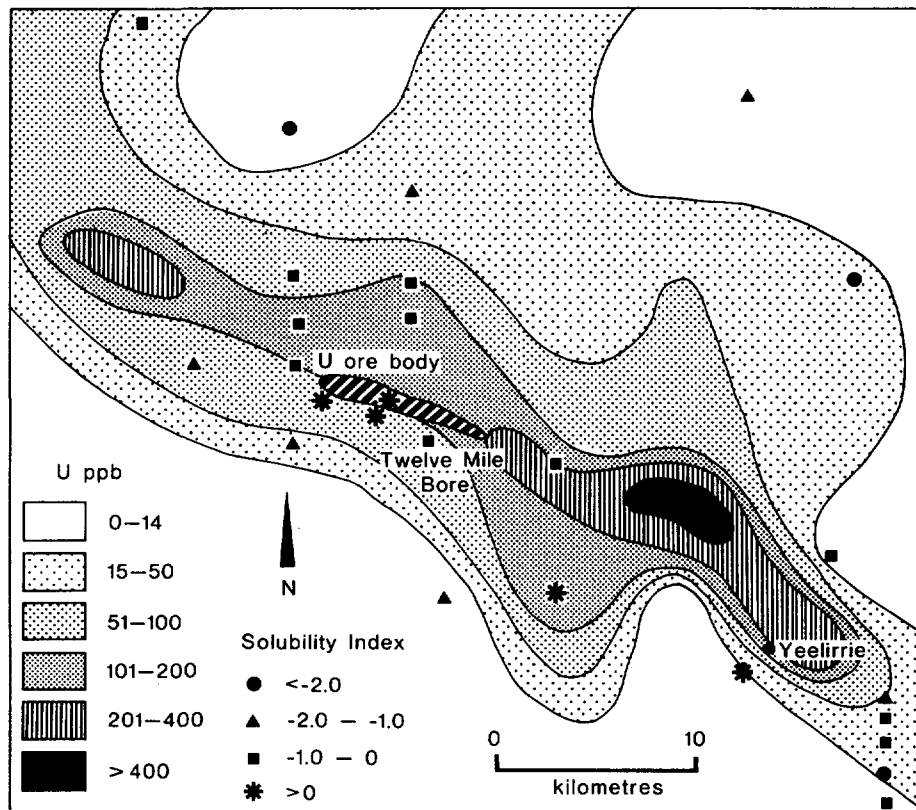


Figure 5
Uranium in groundwater (From : Cameron et al. [13])

The low thorium content of the ore makes the deposit potentially amenable to assessment by γ -logging. Detailed studies have shown that although the ore is not in equilibrium, neither the extent nor distribution is sufficiently serious to preclude the application of gamma spectrometry to grade estimation and control [9, 10, 11, 12].

7. RADON

Because of the nature of the mineralization and the local conditions – e.g. near surface position, permeable host rocks; a thin and generally porous soil cover; and a stable, arid climate – radon measurement appeared to be potentially useful as an exploration technique. However, events pre-empted its use at Yeelirrie other than in orientation surveys.

An early scintillation-detector survey, sampling soil-gas drawn from a depth of 1.3 m, demonstrated a strong radon flux over the ore, ranging from 10 to 50 times the background level. However, in a study of the comparative merits of scintillation detectors and α -sensitive films, Severne [7] attributed the surface response to the uranium content of the soils immediately around the sampling point, rather than reflecting the underlying mineralization. Because of the definitive radiometric signature, radon measurement offered no exploration benefit over a more rapid radiometric survey.

8. HYDROLOGY

In the Murchison region the permeable calcrete are important aquifers, providing abundant water for stock purposes and occasional potable supplies; as an example, pumping tests at Yeelirrie produced a yield of approximately 4.5 million litres a day (1 million imperial gallons) from an exploratory excavation measuring 450 x 40 x 9 m.

Except for the rare occasions when unusually heavy rainfall will produce a short-lived surface flow, the water movement is entirely subsurface. Groundwater recharge is predominantly by infiltration and runoff at the catchment margins and flows through the alluvial plain into the central channel where the water table is at a depth of between 4 and 5 m. Stock bores in the catchment area and some drill holes in the orebody were sampled to provide orientation data for a regional hydrogeochemical survey [13] and for environmental studies [14]. This sampling demonstrated the progressive increase in salinity downstream, from an average of less than 750 ppm TDS around the margins of the catchment area to 5 000 ppm on the edge of the channel, and reaching a maximum of over 25 000 ppm in the calcrete near the orebody, though there are variations, depending on the extent of the lateral recharge. Whilst the concentrations of the major ions (Na^+ , K^+ , Mg^{2+} , U, Ca^{2+} , Cl^- , SO_4^{2-}

and HCO_3^-) show a sympathetic relationship to salinity, the proportions relative to TDS follow two contrasting trends, with Cl^- , SO_4^{2-} , Na^+ , K^+ and U increasing into the channel, whereas Ca^{2+} , Mg^{2+} and HCO_3^- decrease.

The regional hydrogeochemical survey, which ultimately covered approximately 60 000 km², clearly highlighted the strongly anomalous concentration of uranium in the Yeelirrie groundwater. From a background of 5 to 10 ppb uranium on the alluvial plain, the concentration rises to between 100 and 450 ppb along the channel, and up to 1 200 ppb in water taken from a drill hole into the orebody [13]. Both the uranium content and the concentration relative to TDS are highest immediately upstream from the deposit. Calculated carnotite solubility indices increase progressively downstream, ultimately becoming positive close to the orebody [15].

9. DATA SOURCES

Detailed evaluation of the deposit covered a brief, but intense period of activity between 1972 and 1973, consisting of diamond, and rotary reverse-circulation drilling, metallurgical feasibility studies, and the excavation of two exploratory pits from which 165 000 tonnes of material were taken. For a number of reasons activity on the project was suspended in 1973 at the completion of the initial evaluation, except for the statutory environmental monitoring program [14], limited drilling in 1980 to define the grade distribution more closely in a restricted area, and the continuation of metallurgical testing.

No detailed geological documentation or research has been possible other than small-scale studies to resolve problems relevant to the feasibility program. All data available at the present time have been derived from logging drill core, pit mapping, and from limited petrographic examination and X-ray diffraction analysis to complement the metallurgical investigation. As there are no natural sections through the profile, the excavations provide the only exposures, yet represent no more than 0.5 % of the total orebody.

ACKNOWLEDGEMENTS

This summary is published with the permission of Western Mining Corporation. It represents the collective efforts of a large number of individuals engaged on the project at various times and whose invaluable contributions are gratefully acknowledged. In particular, this account serves as a mark of respect to the late John Haycraft who was deeply involved with Yeelirrie over many years.

REFERENCES

- [1] BUTT C.R.M., HORWITZ R.C., MANN A.W., Uranium occurrences in calcrete and associated sediments in Western Australia. Aust. CSIRO Div. Mineral. Report FP 16 (1977) 67.
- [2] MANN A.W., HORWITZ R.C., Groundwater calcrete deposits in Australia; some observations from Western Australia. J. Geol. Soc. Aust. 26 (1979) 293–303.
- [3] GOUDIE A., The chemistry of world calcrete deposits. J. Geol., 80 19 (1972) 449–463.
- [4] CARLISLE D., The distribution of calcrete and gypcretes in southwestern United States and their uranium favourability; based on a study of deposits in Western Australia and South West Africa (Namibia). US Dept Energy. Open File Report GJBX 29(78) (1978) 274.
- [5] GIKES R.J., Clay minerals from Yeelirrie. University of Western Australia (Dept. of Soil Science and Plant Nutrition). Confidential report to Western Mining Corporation (1973).
- [6] MANN A.W., DEUTSCHER R.L., Genesis principles for the precipitation of carnotite in calcrete drainages in Western Australia. Econ. Geol. 73 (1978) 1724–1737.
- [7] GERDES R.A., YOUNG G.A., CAMERON B.F., BEATTIE R.D., Sandstone and Youanmi airborne magnetic and radiometric survey, Western Australia. Bur. Min. Res. (Aust.) Record 1970/2 (1968) 34.
- [8] DICKSON B.L., FISHER N.I., Radiometric disequilibrium analysis of the carnotite uranium deposit at Yeelirrie, Western Australia. Proc. Aust. Inst. Min. Metal. 273 (1981) 13–20.
- [9] AIREY P.L., ROMAN D., Uranium series disequilibrium in the sedimentary deposit at Yeelirrie, Western Australia, J. Geol. Soc. Aust. 28 (1981) 357–363.
- [10] CLARK G.J., DICKSON B.L., MEAKINS R.L., HAYCRAFT J.A., KENNY D., TALASKA A., An instrument for the rapid delineation of grade boundaries in selective mining uranium ore, Proc. Aust. Inst. Min. Metal. 282 (1982) 57–62.
- [11] DICKSON B.L., Uranium series disequilibrium in the carnotite deposits of Western Australia, this Volume.
- [12] SEVERNE B.C., Evaluation of radon systems at Yeelirrie, Western Australia, J. Geochem. Explor. 9 (1978) 1–22.
- [13] CAMERON E., MAZZUCHELLI R.H., ROBBINS T.W., Yeelirrie calcrete uranium deposit, Murchison Region, Western Australia, J. Geochem. Explor. 12 (1980) 350–353.

- [14] WESTERN MINING CORPORATION LTD., Draft environmental statement and environmental review and management program (1978).
- [15] DEUTSCHER R.L., Personal Communication (1979).

URANIUM SERIES DISEQUILIBRIUM IN THE CARNOTITE DEPOSITS OF WESTERN AUSTRALIA

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ABSTRACT

URANIUM SERIES DISEQUILIBRIUM IN THE CARNOTITE DEPOSITS OF WESTERN AUSTRALIA

Studies have been made on the radioactive equilibrium conditions at four calcrete type uranium deposits in Western Australia: Yeelirrie, Centipede, Lake Way and Lake Maitland. The comparatively young apparent age of such deposits and their near surface oxidizing environment has raised concerns about their radioactive equilibrium and the applicability of radiation measurement techniques. However, only the Yeelirrie deposit exhibited a high radiation disequilibrium condition that could effect the usefulness of gamma measuring instruments. The deposit has some 9 per cent excess Radium 226 attributed to an excess of ^{234}U in the deposit. Yeelirrie appears to be the youngest of the four deposits but reliable age determinations are difficult. Uranium may have been flushed from the other deposits increasing their apparent age.

1. INTRODUCTION

The radioactive decay of ^{238}U via a series of radionuclides to ^{206}Pb has special significance to surficial carnotite deposits. The decay series of ^{238}U reaches secular equilibrium, i.e. when the decay rate of each member is equal to that of the parent, after approximately 1 Ma. The short period over which some of the Western Australian carnotite deposits are believed to have formed would have been insufficient for secular equilibrium to have been reached. Further, the contact of present-day oxidizing groundwaters with the deposits and the differing chemical and physical properties of the members of the ^{238}U decay series, could result in disequilibrium between ^{238}U and its daughter radionuclides.

Disequilibrium can cause difficulties in the application of gamma-measuring instruments such as downhole gamma probes and scintillometers, as they require the gamma radiation, predominantly from ^{214}Pb and ^{214}Bi , to be proportional to the uranium content of the ore [1, 2]. Overcoming the disequilibrium problem requires studies of the relationship between radiometric and chemical grade [3] or of the spatial variations of disequilibrium to determine correction factors to apply, for example, to detectors used for grade control in selective mining [4]. However, the relative amounts of the long-lived radionuclides in the ^{238}U and ^{235}U decay series may be used to determine the age of recent deposits [5].

There have been several studies on disequilibrium at Yeelirrie [6, 7, 8]. This report summarizes the earlier results and includes newer data on the Yeelirrie, Centipede, Lake Way and Lake Maitland deposits.

2. YEELIRRIE DEPOSIT

The Yeelirrie deposit has been shown to have an overall excess of 9 % ^{226}Ra , though the extent of the excess varies throughout the deposit [6]. The disequilibrium can be expressed by the disequilibrium ratio (DR), the ratio of chemical uranium to gamma-equivalent uranium. A DR value of 1.00 represents equilibrium, a lower value indicates excess radium and a higher value excess uranium.

The DR results for Yeelirrie have been contoured to show the disequilibrium variation both vertically and along the strike (E-W) of the orebody (Figure 1). Data were grouped in 1 000 m blocks, 1 m deep, for the full width (N-S) of the deposit. The depths of blocks were related to the present-day water table. The contours show a zone near the surface, at the centre of the orebody, where near-equilibrium exists. Underlying this is an eastward-dipping zone with DR values between 1.00 and 0.90. At the eastern and western extremities of the deposit the DR values decrease further.

This pattern could reflect to some extent, a correlation between grade and DR value. For uranium grades above 1 000 ppm, the DR values showed little variation with grade, but below 1 000 ppm the DR values decreased with grade. Samples with uranium below 200 ppm averaged around 40 % excess radium. Thus, on the contour map, low-grade zones are distinguished by low DR values. The maximum radium excess, found to occur at the western end of the deposit, however, could be due to the remobilization of uranium along the channel in the direction of the present-day groundwater flow.

The grade of the mineralization at Yeelirrie is highly variable, as illustrated for a set of samples removed from a horizontal channel at the water table near the centre of the deposit (Figure 2A) and for a set of samples from a vertical drill hole (Figure 2B). On the other hand, the DR values show a more gradual variation. It is generally accepted that there has been considerable leaching and redeposition of both uranium and radium within the deposit [7, 8, 9]. The gradual variation in DR suggests that either the daughter radionuclides move with thorium

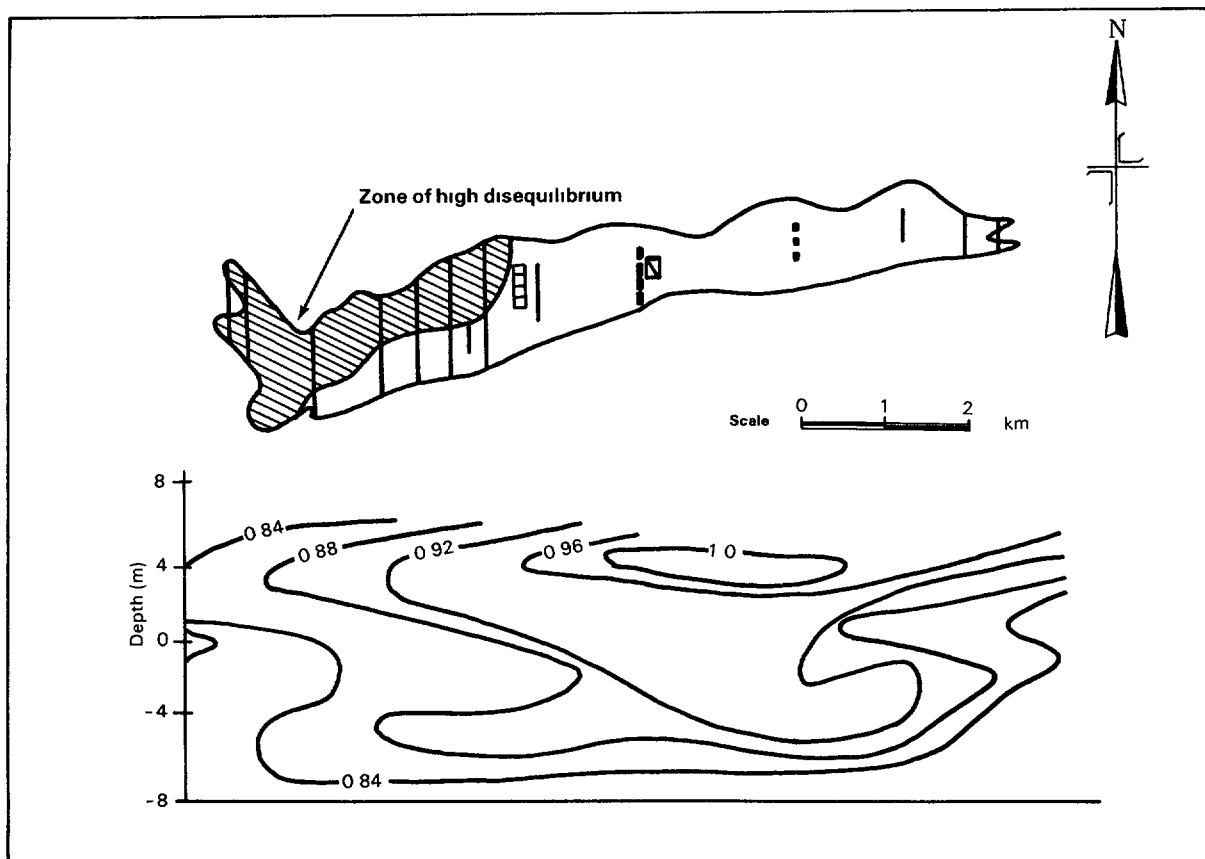


Figure 1
Contour of disequilibrium ratio (U/eU) for the Yeelirrie uranium deposit

and uranium, or remobilization takes place over a very long period of time. The DR results do not support rapid mobilization of uranium.

The excess radium in the Yeelirrie deposit has been shown to be the result of a large excess of ^{234}U [6, 7, 8]. Most studies agree that the excess averages 38 %, but some results (G H. Riley, personal communication) suggest that there is a trend from $^{234}\text{U}/^{238}\text{U}$ equilibrium at the base of the ore zone to a 60 % excess of ^{234}U in near-surface samples. As ^{234}U has a half-life of 245 000 years, the excess of ^{234}U in the Yeelirrie deposit confirms that the deposit is geologically recent.

An age for the Yeelirrie deposit may be estimated using activity ratios of ^{238}U , ^{234}U , ^{230}Th or ^{226}Ra , though, unfortunately, the available data are insufficient to obtain an unequivocal age. The experimental data relate only to the present-day situation, whereas an age estimation requires knowledge of the $^{234}\text{U}/^{238}\text{U}$ activity ratio in the depositing solution, the length of the depositing period, the extent of periods of loss of uranium from the deposit and also the rates at which deposition and leaching took place. Consequently, the data can only form a basis for evaluating hypotheses developed from other information and cannot be used to give an age of deposition by itself. For example, Airey and Roman [8] used an "open system model" to demonstrate that the suggestion by Carlisle [10] of an age of 25 000 years would only be consistent with substantial leaching after the deposition. For the present, the data appear consistent with the Yeelirrie deposit having formed within the period 100 000 to 700 000 BP, but a more precise age cannot be determined.

3. CENTIPEDE DEPOSIT

For the Centipede deposit, on the western margin of Lake Way, the mean DR value of nearly 460 samples was found to be 1.01 ± 0.02 . As at Yeelirrie, samples with low grades were generally radium-rich and the overall mean DR for samples with uranium over 200 ppm was 1.03.

Statistical analysis of the data revealed considerable differences in the variation of the results for samples from around the water table compared to samples below it. The sample set was split into two groups, depending on whether the samples came from above or below a level 1 m below the water table. Cubic trend surfaces were fitted to the DR results for the upper (Figure 3A) and lower (Figure 3B) groups. The upper section has a mean DR of

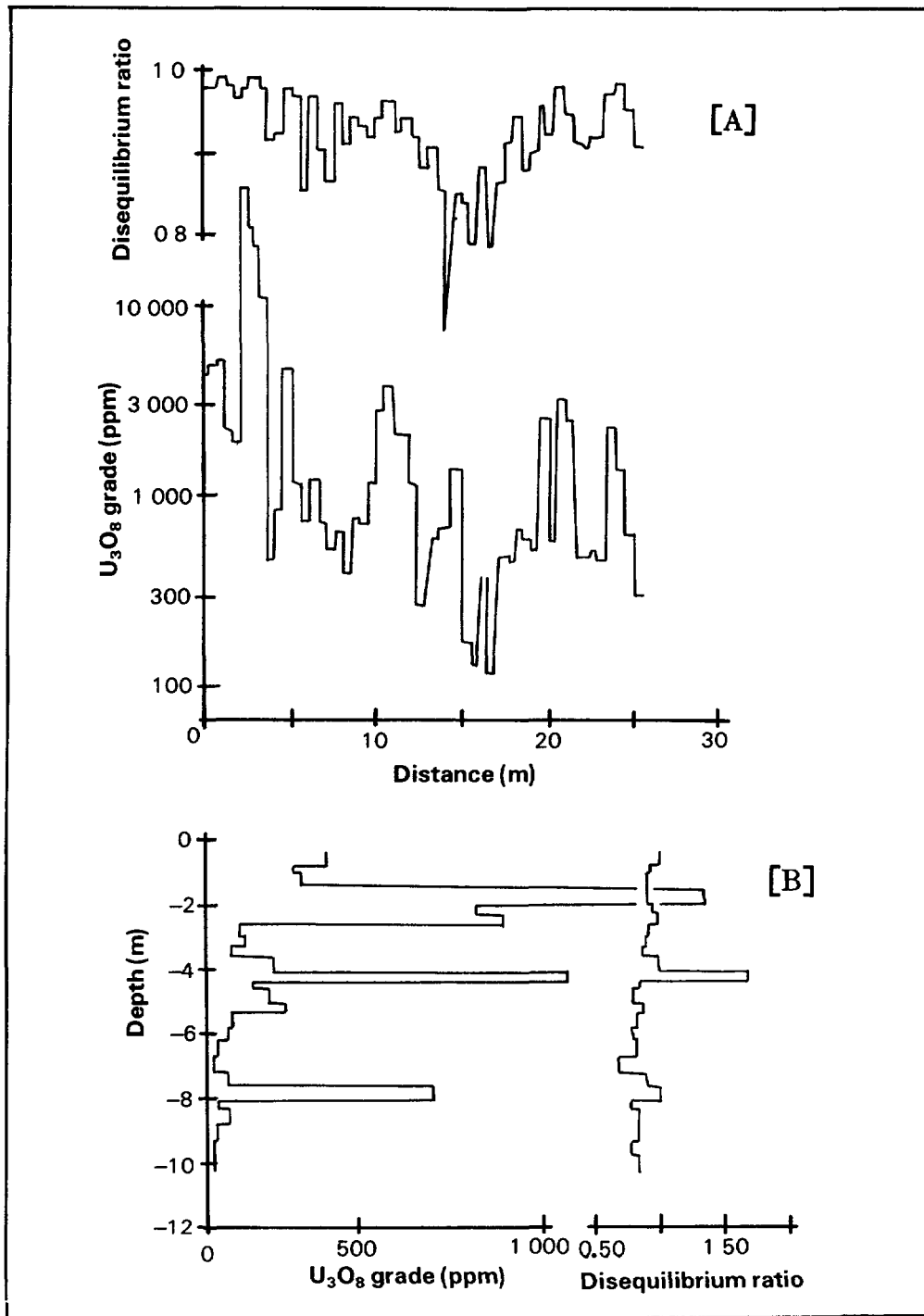


Figure 2
Comparison of grade and disequilibrium variability both horizontally [A] and vertically [B]
in the Yeelirrie uranium deposit

1 06 and shows a trend to uranium-rich disequilibrium towards the lake, whereas the lower section has a mean of 0.99. The high DR values at the lake edge suggest this is an area of recent uranium deposition, possibly as a result of leaching of older uranium from the northwest.

Results of ^{238}U , ^{234}U , ^{230}Th and ^{226}Ra measurements in 10 samples from the lake margin section of the Centipede deposit are shown in Figure 4. Unlike Yeelirrie, these samples average only 3% excess ^{234}U . A trend in the $^{234}\text{U}/^{238}\text{U}$ activity ratios to equilibrium at depth is evident. Both the $^{230}\text{Th}/^{238}\text{U}$ and $^{226}\text{Ra}/^{238}\text{U}$ activity ratios show a strong correlation with depth with ^{230}Th in excess at depth but depleted near the water table. There is excess uranium relative to ^{226}Ra for samples near the water table, but below this the $^{226}\text{Ra}/^{238}\text{U}$ ratios are scattered about the equilibrium value. These results suggest that the Centipede mineralization was deposited much earlier than that at Yeelirrie.

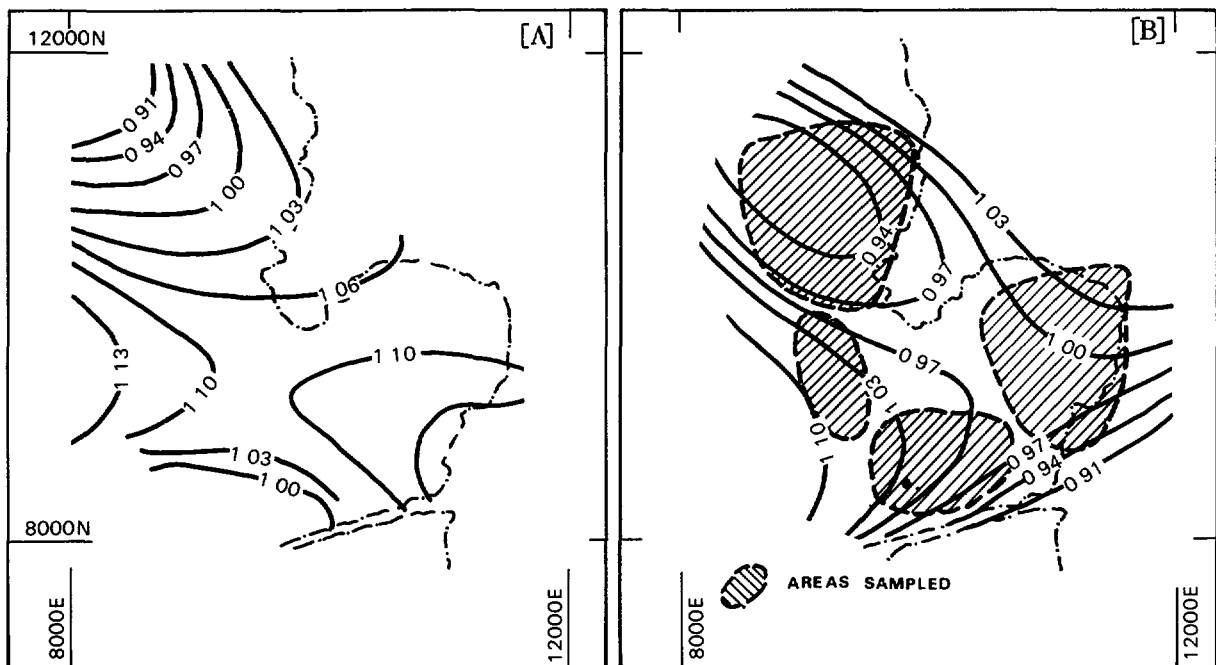


Figure 3
Cubic trend surfaces fitted to disequilibrium ratio data in the Centipede uranium deposit [A] samples taken from near the present day water table [B] samples taken about 1 m below water table

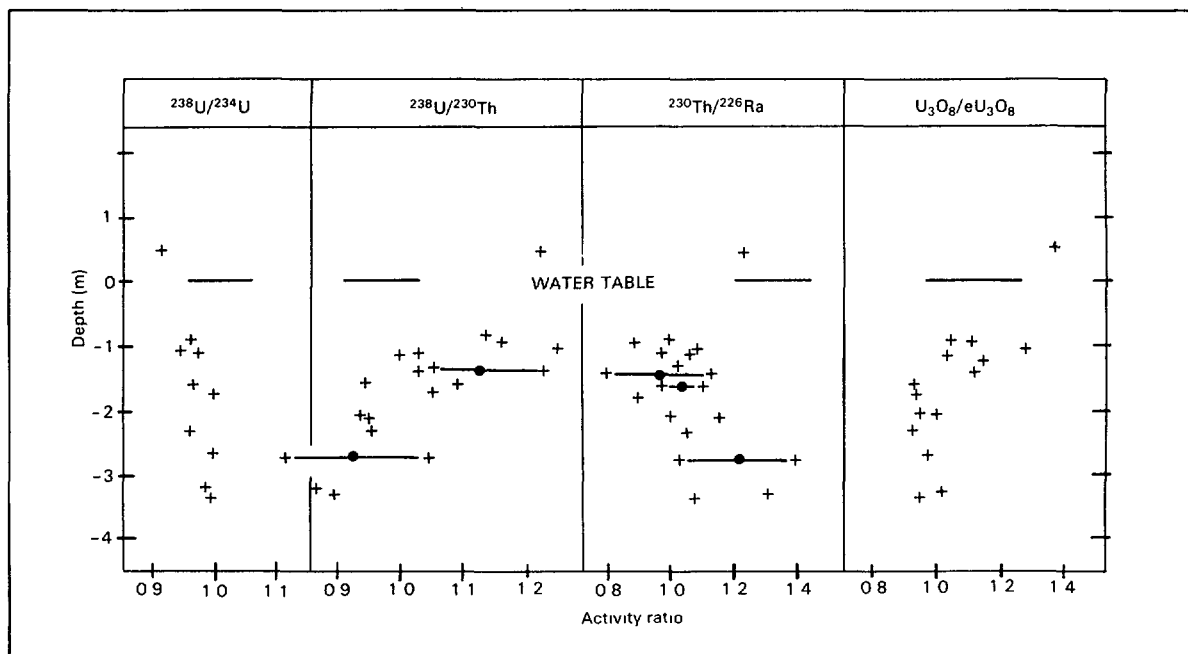


Figure 4
 $^{238}\text{U}/^{234}\text{U}$, $^{238}\text{U}/^{230}\text{Th}$, $^{230}\text{Th}/^{226}\text{Ra}$ and $\text{U}_3\text{O}_8/\text{eU}_3\text{O}_8$ disequilibrium ratios as a function of depth below surface in the Centipede uranium deposit
+, ratios of individual samples; •, means of repeat measurements on same sample

4. LAKE WAY DEPOSIT

In a brief survey of the Lake Way deposit, 57 samples were obtained from four areas. Samples from the areas described as "mature deltaic" or "valley calccrete" with uranium above 200 ppm appear to be in approximate radiometric equilibrium, with a mean DR of 0.99 ± 0.09 and a range of 0.79 to 1.12. Similar samples from the younger deltaic calccrete have a mean DR of 1.16 ± 0.27 with a range from 0.84 to 1.82. The high ratio of the samples from this area suggests it is an area of active deposition and remobilization of uranium, in accord with the

precipitation experiments described by Mann and Deutscher [11]. Examination of six samples from this area by high-resolution gamma spectrometry indicated that uranium loss or gain relative to ^{230}Th or ^{226}Ra was the predominant mechanism of disequilibrium. However, in one low-grade sample (93 ppm uranium) from the lake margin, a 500 % gain of radium was observed. Similar radium-rich samples have also been obtained from the lake surface at the edge of the Centipede deposit, indicating that radium can be mobile in the saline, carbonate-rich groundwaters of the area.

5. LAKE MAITLAND DEPOSIT

A suite of 46 samples from the Lake Maitland deposit, described as clays, silts and calcretes, from depths ranging between 1 and 4 m below the surface, was studied. Samples with grades of less than 200 ppm uranium had a wide range of DR values ranging from 0.76 and 1.14 and had a mean value of 0.97 ± 0.09 .

6. DISCUSSION

The studies described above have shown that of the four deposits examined, only Yeelirrie exhibits an overall radiometric disequilibrium that could affect the use of gamma-measuring instruments. Yeelirrie, in contrast to Centipede, has a large excess of ^{234}U , implying that it was deposited more recently. On the basis of disequilibrium ratio measurements, the three lakeside deposits (Centipede, Lake Way, and Lake Maitland), would appear to be older uranium accumulations. However, such an interpretation may not be correct since, as discussed above, a set of measured uranium series activity ratios cannot give an unequivocal age.

A young age for the lakeside deposits could be obtained if they were formed by continuous addition of uranium from solution with uranium losses occurring at frequent intervals. Such losses could result from the pattern of irregular but intense rainfalls in the area [11] which are known to cause dissolution of calcrete [12]. This periodic rainfall and recharging of the aquifer were suggested to be important factors in the growth and the surface reworking of the calcrete. These episodic water flows could reverse the precipitation conditions for uranium and lead to the dissolution of carnotite and removal of uranium. Carlisle [10] related textural features of the carnotite to continual dissolution and redeposition as a result of seasonally changing groundwater chemistry. Thorium and radium are much less soluble than uranium in oxidizing groundwaters [13], so that any loss of uranium would not be expected to be accompanied by similar losses of thorium or radium. Thus both ^{230}Th and ^{226}Ra would increase relative to uranium over time.

Calculations based on this model demonstrate that frequent losses of uranium from the deposit due to episodic "flushing" could lead to a situation where the ^{230}Th and ^{238}U appear to be near equilibrium even though the period of ^{238}U deposition is no more than 40 000 years. These calculations demonstrated that the lakeside deposits could have begun accumulating uranium more recently than indicated by their apparent closeness to radiometric equilibrium. However, the estimated activity ratios generally had wider ranges (depending on which part of the cycle of uranium loss or gain was examined) than the measured values, implying that a more precise mechanism operated in nature.

Accordingly, determining whether lakeside deposits are "old" or "young" must await further study. The uranium series disequilibrium data cannot give an unequivocal result for a system which is open to large disturbances.

REFERENCES

- [1] HAMBLETON-JONES, B B , Theory and practice of geochemical prospecting for uranium, *Min Sci Engng* **10** (1978) 182-196
- [2] LEVINSON, A A , COETZEE, G , Implications of disequilibrium in the exploration for uranium ores in the surficial environment using radiometric techniques – A review, *Min Sci Engng* **10** (1978) 19-27
- [3] DAVID, M , DAGBERT, M , Case studies in geostatistical ore reserve estimation of uranium deposits, In *Uranium Evaluation and Mining Techniques* (1980)
- [4] CLARK, G J , DICKSON, B L , MEAKINS, R L , HAYCRAFT, J A , KENNY, D , TALASKA, A , An instrument for rapid delineation of grade boundaries in selective mining of uranium ore, *Proc Austr Inst Min Metall* **282** (1982) 57-61
- [5] IVANOVICH, M , HARMON, R S , *Uranium Series Disequilibrium Application to Environmental Problems*, Oxford Univ Press , Oxford (1982)
- [6] DICKSON, B L , FISHER, N J , Radiometric disequilibrium analysis of the carnotite uranium deposit at Yeelirrie Western Australia *Proc Austr Inst Min Metall* **273** (1980) 13 – 19
- [7] LIVELY R S , HARMON R S , LEVINSON, A A , BLAND, C J , Disequilibrium in the ^{238}U uranium series in samples from Yeelirrie, Western Australia, *J Geochem Explor* **12** (1979) 57 – 65

- [8] AIREY, P.L., ROMAN, D., Uranium series disequilibria in the sedimentary uranium deposit at Yeelirrie, Western Australia, *J. Geol. Soc. Aust.* **28** (1981) 357 – 363.
- [9] SEVERNE, B.C., Evaluation of radon systems at Yeelirrie, Western Australia, *J. Geochem. Explor.* **9** (1978) 1 – 22.
- [10] CARLISLE, D., MERIFIELD, P.M., ORME, A.R., KOHL, M.S., KOLKER, O., The distribution of calcretes and gypcretes in southwestern United States and their uranium favourability based on a study of deposits in Western Australia and South West Africa (Namibia), U.S. Dept. of Energy, Open File Report GJBX-29(78) (1978) 274.
- [11] MANN, A.W., DEUTSCHER, R.L., Genesis principles for the precipitation of carnotite in calcrete drainages in Western Australia, *Econ. Geol.* **73** (1978) 1724 – 1737.
- [12] MANN, A.W., HORWITZ, R.C., Groundwater calcrete deposits in Australia: some observations from Western Australia, *J. Geol. Soc. Aust.* **26** (1979) 293 – 304.
- [13] DYCK, W., The mobility of uranium and its decay products in temperate surficial environments, In: *Short Course in Uranium Deposits: Their Mineralogy and Origins.* M.M. Kimberley (Ed.) Mineral Assoc. Canada (1978) 57 – 100.

SURFICIAL URANIUM DEPOSITS IN BOTSWANA

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ABSTRACT

SURFICIAL URANIUM DEPOSITS IN BOTSWANA

The known surficial uranium deposits in Botswana are supergene concentrations either in soils above lower Karoo sediments, or in peat and calcified alluvium of dry stream courses in the Kalahari Desert. A number of uranium occurrences lie above Karoo sedimentary rocks and of these Mokobaesi No. 1 is the best explored. It is a tabular body of disseminated uranium ochre occurring immediately below surface in calcrete and calcified mudstone. The uranium is believed to have migrated upwards from the Karoo rocks. Reconnaissance investigations show that moderately anomalous uranium occurs at a number of localities in peat and calcified sediments that have been deposited in ephemeral water courses. None of these deposits are economic, but the known occurrences are encouraging indications that such deposits may exist in the thick Tertiary to Recent "Kalahari beds", that were deposited in diverse palaeoenvironments.

1. INTRODUCTION

1.1 Physiography and Climate of Botswana

Botswana is mostly a high plateau, about 1 000 m above sea level, that rises to a maximum elevation of just over 1 300 m above sea level in the southeast. The Kalahari Desert, predominantly an undulating sandy plain, occupies the greater part of the plateau. Relief is very low across most of the country (Figure 1).

The drainage lines in the east are shallow washes trending generally eastward, separated by broad low divides. In the west, there are a few dry channels, formed in earlier periods of high rainfall, that for the most part trend eastwards towards the Okavango Delta, or northeastwards towards the Makgadikgadi Depression. There are numerous pans that are the centres of local centripetal drainage basins, irregularly distributed throughout the country.

The Okavango Delta is a unique, seasonally inundated, fan deposit at the mouth of the Okavango River. The river water percolates into the ground or evaporates, dropping sediment as a progressively spreading and deepening fan contained within a neotectonic depression. The Makgadikgadi Depression, east-southeast of the delta, is a basin of lacustrine sediments and is also a major geomorphological feature.

Rainfall in Botswana varies from an average of 250 mm per annum in the southwest to 650 mm per annum in the northeast; it is highly variable in quantity from year to year. Evaporation from open water surfaces varies between 1.7 and 1.9 m per annum [6]. Botswana therefore is semi-arid, but the absorbing Kalahari sands inhibit runoff.

1.2 General Geology

The greater part of Botswana is covered by the "Kalahari beds", an early Tertiary to Recent accumulation of aeolian sand, lake and pan deposits and fluvial sediments, that may be locally and extensively cemented and replaced by calcite, silica, and limonite. This succession of diverse lithologies ranges in thickness up to about 200 m; possibly greater thicknesses exist in the region of the Okavango Delta.

Borehole data indicate that the "Kalahari beds" have marked local variations in both vertical and lateral succession. Natural sections through the beds are scarce, because they form an undissected terrain with only rare shallow washes. Duricrusts are common at or near the surface, and also deeper in the section. Several episodes of cementation are thought to have led to the formation of the duricrusts, and several types have been recognised. Most of these are in the "Kalahari beds", because of their widespread occurrence, but other rocks have also been affected. The Karoo basalts and sandstones are particularly susceptible to such alteration. Geomorphological evidence, such as *abandoned beach deposits, static sand dunes, differing dune orientation and terracing*, seems to indicate frequent Quaternary climatic changes, which produced alternately arid, semi-arid and pluvial conditions. This in turn probably had a significant influence on the development of the cemented horizons. Neotectonic influences may also have had a local effect [3].

The small part of the country in which bedrock can be seen is mostly in the east, along the border with South Africa and Zimbabwe. The bedrock consists of metamorphosed Archaean rocks of the Kaapvaal and Zimbabwean cratons and the Limpopo Mobile Belt, succeeded by relatively undisturbed Proterozoic strata overlain by sedimentary and volcanic rocks of the Karoo Sequence of Upper Carboniferous to Jurassic age. The Karoo rocks underlie much of the Kalahari, although in the west, outcrops of Archaean basement and metamorphosed Damaran sediments of Late Precambrian age occur in several areas, particularly around Ghanzi and adjacent to the border of Namibia (Figure 1). Intrusive bodies range widely in age and type, varying from Archaean granites to dykes of post-Karoo age and kimberlite pipes of probable Cretaceous age.

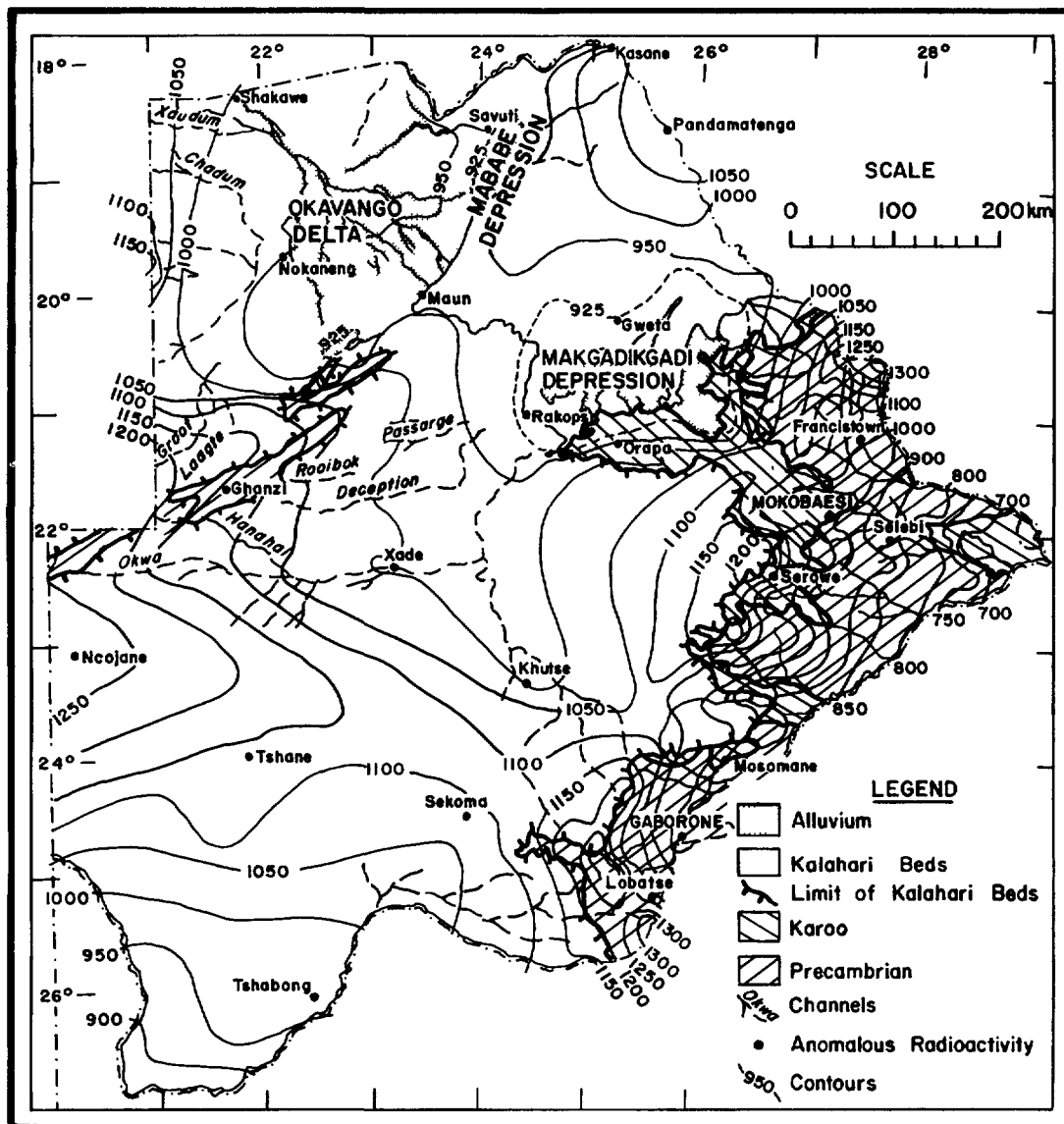


Figure 1

General geology and physiography of Botswana with the location of the radioactive anomalies described.

There is a wide variety of base and precious metal deposits. Large quantities of coal are present in the Karoo succession and some of the kimberlites are diamondiferous.

1.3 History of Exploration for Uranium

Prior to 1970, interest in Botswana as a possible producer of uranium was limited. Increased activity in exploration occurred during the 1970's; the initial targets were potential uranium deposits in intrusive bodies within the Archaean rocks outcropping in the east. Only small radioactive anomalies were discovered in the ancient basement, but airborne radiometric surveys conducted over the adjacent Karoo rocks showed the presence of anomalies in a number of localities. Ground follow-up work revealed several areas of radioactivity where uranium minerals impregnate the superficial "Kalahari beds" that overlie the Karoo sedimentary rocks. In the late seventies, exploration was extended to include the shallow dry drainage channels of central and western Botswana. This reconnaissance work found several small anomalous areas associated with concentrations of uranium in some of the channels.

The above two types of uranium occurrence, namely supra-Karoo deposits and channel deposits, are the only surficial occurrences of uranium known in Botswana. Since their discovery, detailed work has taken place locally on some supra-Karoo occurrences and, to a lesser extent, on anomalies in the channels. To date, no economic prospect has been encountered.

Mokobaesi No. 1, the best studied uranium occurrence in Botswana, is described in detail as an example of the supra-Karoo deposits, and the channel anomalies are described more generally. The described areas are located in Figure 1.

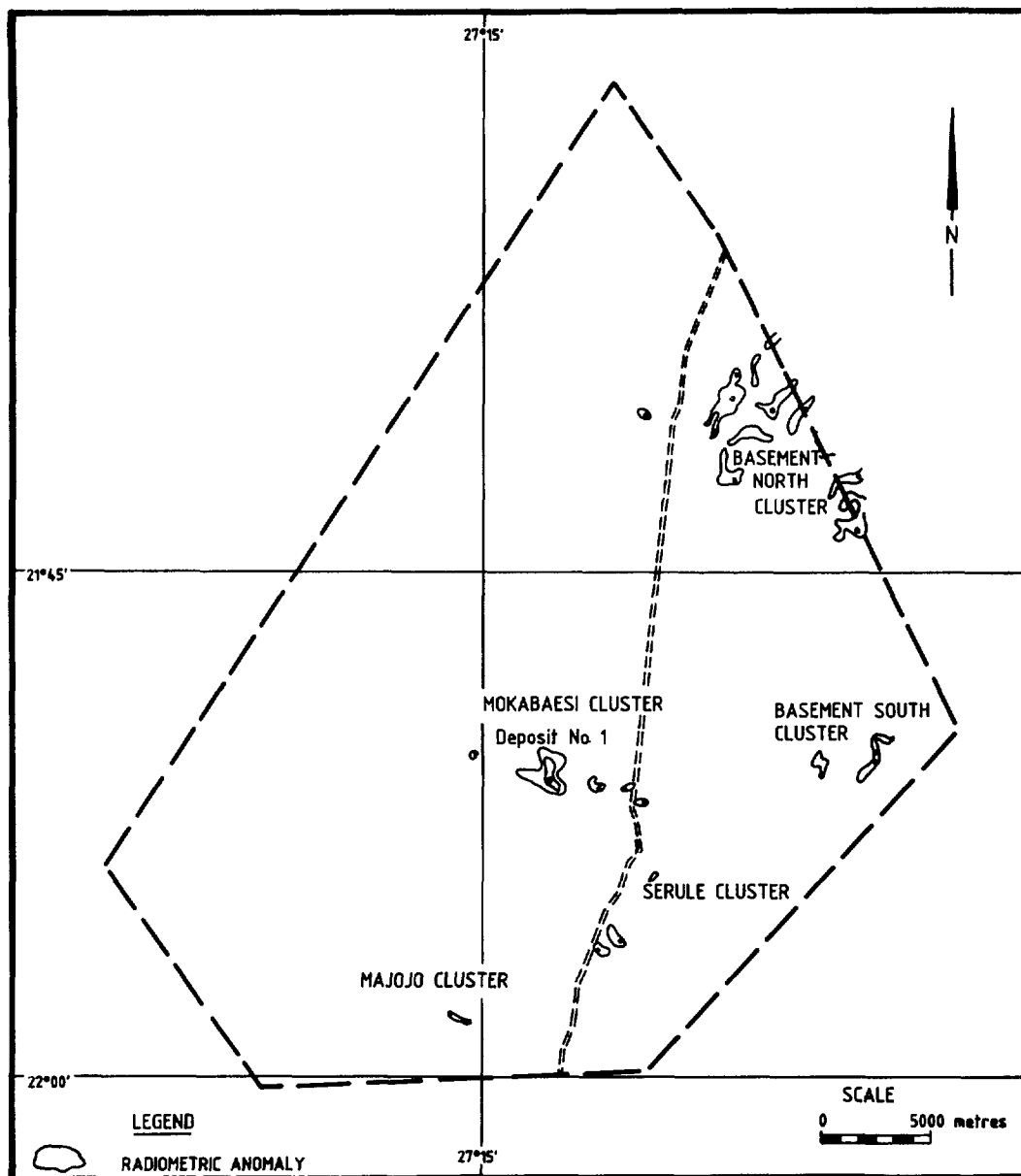


Figure 2
Airborne radiometric anomaly plan of the region adjacent to Mokobaesi.

2. SUPRA-KAROO DEPOSITS, MOKOBAESI NO. 1

Bamangwato Concessions Ltd. (Quarterly Reports to Geological Survey) discovered several uranium occurrences along the eastern limit of exposure of the central Botswana basin of Karoo rocks. The Mokobaesi Cluster, a group of seven anomalous areas, was considered from the aerial survey to be the region with the greatest potential for the discovery of an economic uranium deposit (Figure 2). Further investigations caused the principal exploration effort to be centred on the Mokobaesi No. 1 anomaly. Bamangwato Concessions Ltd. surrendered their interest in the deposit at a preliminary stage, and Falconbridge Explorations Ltd. continued exploration.

A comprehensive surface and subsurface evaluation of the anomaly established the presence of a tabular, horizontal, subeconomic deposit 1 m below the surface within a calcrete and calcified mudstone host. An estimate of the ore reserves of the Mokobaesi No. 1 deposit is given below:

	Proved Ore Reserves (tonnes)	Grade (ppm U ₃ O ₈)	Ave. Width (m)
Assay cut-off method	1 192 000	373	0.93
Block cut-off method	1 683 000	315	1.34

The source of the ground radiometric anomaly is an irregular tabular body of uraniferous calcrete and calcified mudstone, as much as 3.1 m thick, but in general between 0.9 m and 1.3 m in thickness. The mineralized layer is overlain by a more or less constant thickness of semi-transported soil, between 1.0 m and 1.5 m thick.

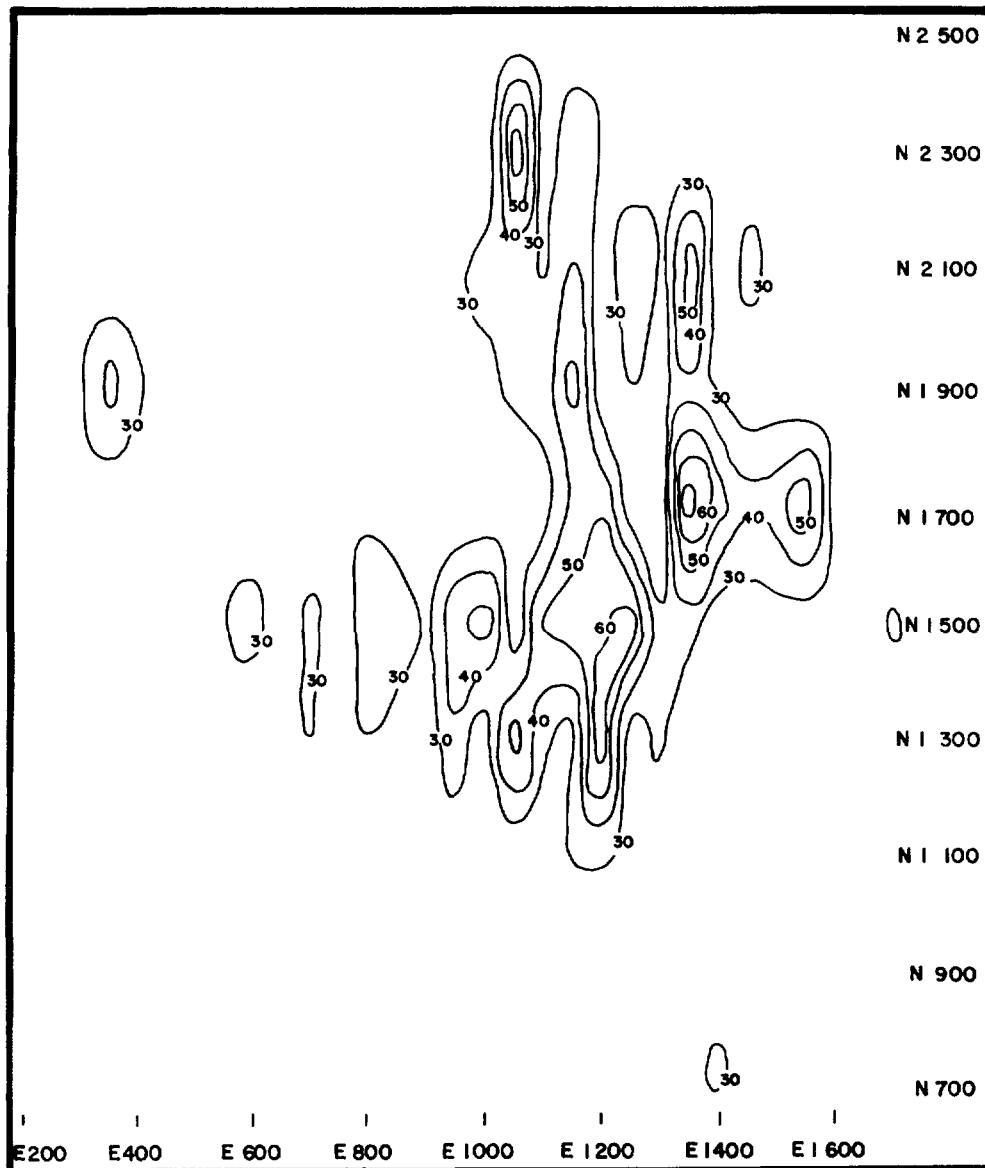


Figure 3
Mokobaesi deposit No.1. approximate uranium content.

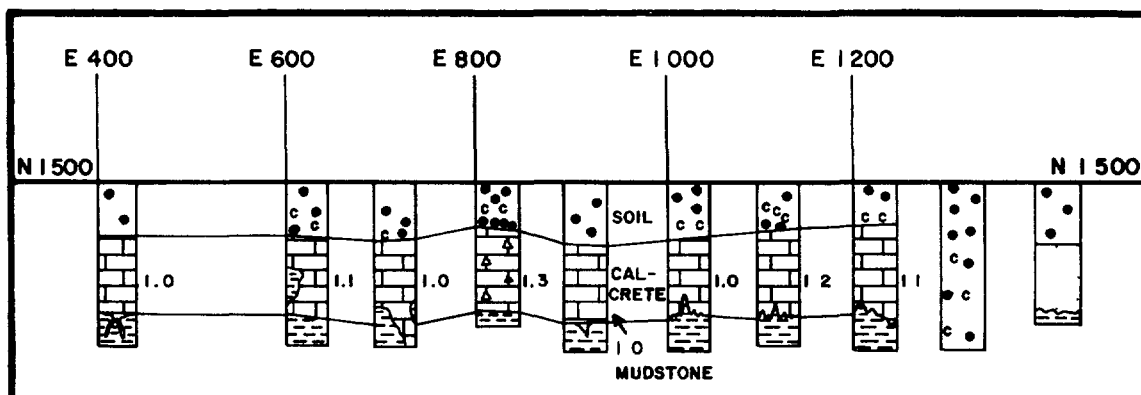


Figure 4
East-west pit profile through central Mokobaesi No 1 (thicknesses in metres)

2.1 Methods of Investigation

Falconbridge Explorations used a multitool approach in follow-up work. An airborne geophysical survey was succeeded by ground spectrometer investigations and seismic and resistivity surveys. Conventional pitting and soil geochemistry (Figure 3) were complemented by radon and biogeochemical studies.

2.2 Description of the Area and Geological Relationships

The area has very low relief, with the ground rising gently from east to west. To the north and south of the area metaquartzites and gneiss outcrop in low ridges and hills. Dry stream courses cross the region from west to east. Two major drainages lie to the north and south of the area and are separated by wide interfluvial ridges rising from 30 to 60 m above stream level. Most of the area is covered by open scrub woodland, and large termite mounds are common.

The western part of the region is underlain by Karoo sediments with an irregular, thin cover of "Kalahari beds". Rocks of the Archaean basement outcrop in the eastern part and consist of metaquartzite, schist, amphibolite, marble and calc-silicates infolded into gneissic units.

Underlying several metres of surficial deposits at Mokobaesi, geophysical investigations have shown the Karoo rocks to be about 70 m thick and overlie Archaean basement.

The stratigraphy of the uraniferous deposit at Mokobaesi No. 1 was investigated by pitting and was found to consist of three different layers (Figure 4) namely an upper soil layer, calcrete and mudstone.

The upper layer comprises dark-grey, grey-brown and less common red-brown silty soil containing abundant decomposed vegetable matter, roots, calcareous patches and nodules, rounded and angular quartz pebbles, hematitic siltstone, chert and quartzite. The pebbles are generally less than 200 mm in diameter, and are found dispersed or concentrated as a pebble zone at the base of the soil profile. Many pebbles display "dreikanter" faceting. The gravels most commonly form a thin (20 to 40 mm) layer directly over the underlying calcrete, but in some instances are 500 mm thick. The thickness of the upper soil layer in most places ranges from 0.75 to 1.25 m, with a maximum of 3 m. This soil, known locally as black turf or cotton soil, gradually changes to sandy alluvial soil near the eastward-directed dry river channels.

The contact between the soil and the underlying calcrete is normally sharp, especially where the basal pebble zone occurs, which suggests an erosional contact. In some pits, however, the contact is gradational across about 100 to 200 mm, but because the soils are similar to those showing a sharp contact, they are considered to be somewhat younger than the calcrete.

The central layer is composed of nodular calcrete coated with irregular coatings of secondary uranium ochre. The calcrete layer has a matrix of friable, partially compacted, grey-white unbedded calcium carbonate surrounding irregularly shaped, coalesced calcitic nodules. Nodules vary in size from 5 to 100 mm in diameter and are generally hard and coherent. Rounded quartz pebbles and rock fragments occur in the matrix. The most common of these are discoidal to plate-like, hematitic siltstone clasts. Both angular and rounded clasts occur, and in some places the round particles appear as pebble bands. Coalesced calcitic nodules are more prominent lower in the central horizon. Patches of upper soils are common in the calcified matrix and have penetrated into decayed root holes. Limonite commonly coats the calcrete nodules. The calcrete layer varies between 0.2 and 1.7 m in thickness, averaging 1 m over mudstone bedrock. Calcrete is poorly developed over sandstone bedrock in the eastern portion of the prospect.

The base of the calcrete layer is irregular and gradational into mudstone, the third unit of the surficial sequence. Grey, partially calcified, mudstone patches occur throughout the calcrete layer, and increase in abundance downwards until mudstone is prominent. In several of the exploration pits no distinct calcrete layer was seen and the upper layer of soil is in direct contact with irregularly calcified mudstone.

The mudstone is dark to light grey and purple-grey. It is homogeneous, broken by an irregular network of short tension cracks, giving a poorly defined sub-horizontal local fissility. There is rare, ill-defined, sub-horizontal banding.

Uranium ochre is present as small grains and films in the mudstone and is usually associated with black staining. The mineralization tends to decrease with depth below the calcrete horizon. Downward projecting "veins" of calcrete in the mudstone are usually more uraniferous than the adjacent host mudstone.

2.3 Mineralogy

The uranium mineralization occurs as ill-defined horizontal bands at various levels within the calcified layer and is commonly associated with a black filmy deposit of manganese or carbon. The uranium ochre is a bright canary-yellow mineral with a weak resinous lustre, which occurs as granular aggregates in the calcrete matrix, as friable coatings on the calcitic nodules and within coalesced nodules and internal fracture surfaces. An X-ray diffraction study revealed the yellow ochre to be an unnamed lead-vanadium-uranium hydroxide.

2.4 Uranium Distribution

Within the upper soil layer, the uranium content is consistently low (Figure 5). Some 95 % of the channel soil samples from 70 pits contain of 20 to 30 ppm U_3O_8 ; only a few exceed 35 ppm, with a maximum value of 106 ppm U_3O_8 .

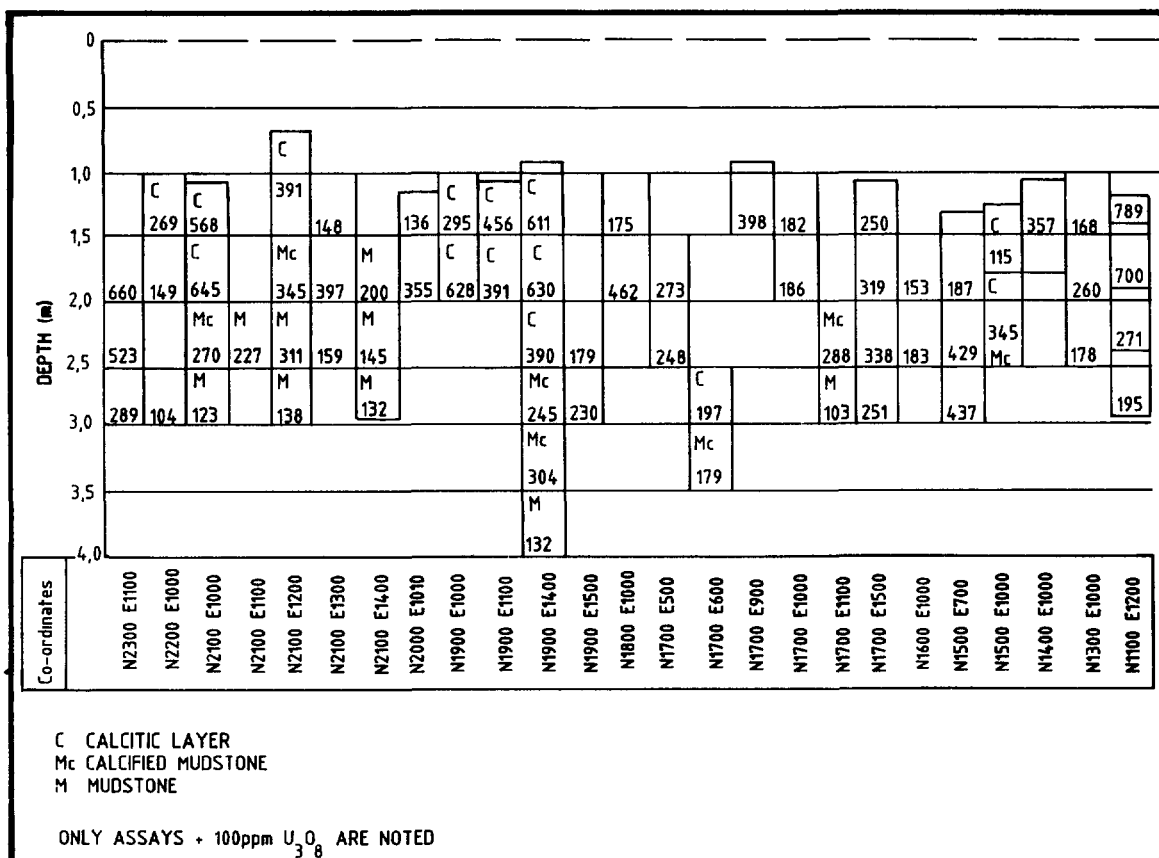


Figure 5
Mokobaesi deposit No. 1: vertical distribution of uranium in pits.

There is no consistent relationship between calcrete thickness and the presence of obvious uranium ochre, although in general there is a fairly sharp decline in grade downwards into partially calcified mudstone. Within the calcrete, 0.5 m channel samples contain 20 to 970 ppm U₃O₈. Values of 300 ppm U₃O₈ and above are almost entirely restricted to the depth between 1.0 and 2.5 m.

Mudstone, which always underlies calcrete, can contain more than 200 ppm U₃O₈. Calcrete veins locally penetrate as much as 4 m into the mudstone and contain associated uranium ochre. Uranium occurring within the mudstone is usually associated with visible ochre and the filmy black material. A grade of 113 ppm U₃O₈ was calculated from pit channel samples of the footwall mudstone exposed in the ore reserve blocks (including marginal blocks with U₃O₈ values in excess of 100 ppm but less than 200 ppm). The highest value of 1 710 ppm U₃O₈ was obtained from a 0.5 m channel sample of mudstone. The distribution of uranium below 4 m is not well established, but seems to disappear below about 8 m.

In channel samples, vanadium concentrations vary from 27 to 210 ppm. Channel samples of the soil layer range in value from 40 to 116 ppm with an average of 71 ppm. Within the calcrete layer, samples with uranium in excess of 200 ppm have between 50 and 210 ppm vanadium, with an average of 126 ppm. Vanadium generally displays a moderately good correlation with uranium values in the calcrete layer.

Thorium assays on selected samples indicate that the concentrations are low in the uraniumiferous calcrete.

2.5 Genesis of the Supra-Karoo Deposits

Calcification at the Mokobaesi deposit was a process whereby the clay component of mudstone was replaced by calcite precipitated from saline-alkaline solutions reacting with the mudstone. On a small scale, solutions moved upward from depth during transpiration and evaporation or, on a larger scale, as a result of seasonal water table adjustments. Associated with this process was the transfer of some elements in the bedrock into the lower soil horizons.

The deposition of uranium is considered to have been dominated by vertical rather than horizontal processes. Under oxidizing conditions that probably extended to below 20 m at Mokobaesi, soluble di- or tri-carbonate uranyl ions could have formed, leading to the precipitation of uranium in the mudstone and surficial deposits at the time of calcrete formation and the deposition of calcium carbonate, phosphate and lead-vanadium [1].

Granites and gneisses of the Archaean basement are an adequate primary source of the uranium, which was deposited in a reducing environment in the Karoo sediments at the time of their deposition.

Mineralization of Tertiary age at the Mokobaesi No. 1 deposit represents a final stage in the upgrading process from granitic parent through derived sediment to deposition in the supergene zone.

3. VALLEY DEPOSITS IN CENTRAL AND WESTERN BOTSWANA

A number of dry shallow drainage channels, occurring principally in the western and central parts of Botswana, are considered to have formed during a more pluvial period than at present. Because of the possibility that they host surficial uranium deposits, an airborne radiometric survey was undertaken by Union Carbide Exploration Corporation between 1976 and 1979 along the more obvious of these features. Ground radiometric and resistivity surveys were conducted and hand augering, water sampling and helium-in-soil surveys were carried out locally until exploration was terminated in 1980.

3.1 Geomorphology and Geological Relationships

The channels represent a late phase in the complex and imperfectly understood geomorphological history, during which successive episodes of landform development were associated with progressive deposition of the "Kalahari beds". Massive calcretes developed during the Late Tertiary in the upper portions of the Kalahari succession [2]. Calcification was followed by surficial sand deposition and dune development. The visible drainage channels are thought to have originated in the Late Tertiary, after the major calcification of the Kalahari beds, but before the deposition of the surficial sand facies [2]. A subsequent episode of incision of the drainage is considered to have occurred in Late Tertiary-Early Pleistocene times, predating a later episode of dune formation that locally modified the channels but did not obstruct them. The most recently active channels occur in the northwest [4].

Calcification of the sands in, and adjacent to, the channels, has taken place in phases since the inception of incision of the drainages. Terrace and valley calcification is associated with sediment in the shallow valleys.

Jack [4] divided the investigated drainages into three groups as follows:

Xaudum	— youngest group, most recently active
Chadum	
Okwa	— intermediate group
Hanahai	
Groote Laagte	— oldest group
Deception	
Passarge	
Rooibok	

The axes of the Rooibok, Passarge and Deception palaeodrainages of the oldest group have about 250 mm of powdery calcified sand with minor chalcedonic lenticles as a surface accumulation above uncemented sand. Calcification of the Groote Laagte drainage is less; it is irregularly distributed, and the calcitic crust is considered to have suffered some erosion.

Silification has occurred at the base of the deep sand layer in all the drainages of the oldest group. Beneath the Groote Laagte Valley the Kalahari succession is thin locally, and basement Damara Sequence occurs at less than 20 m in depth at places. In the Rooibok channel, the deep sand layer rests directly on green Karoo sandstone at some 60 m depth.

In the second group of channels, of intermediate age, there is no surface axial calcitic cement, although both the Okwa and Hanahai have calcified marginal terraces.

The two major drainages of northwest Botswana, the Xaudum and Chadum, constitute the third and youngest group of channels. Evidence from cross-cutting relationships suggests they formed later than local stabilized dunes. Both drainages contain extensive, but local, surface peat deposits that are as much as 10 m thick in the Chadum valley, but much thinner in the Xaudum channel.

The total thickness of the surficial deposits is controlled by the palaeotopography of the basement, which was affected by neotectonic events during deposition of the overlying "Kalahari beds". Drilling has revealed up to 60 m in the Chadum valley. In the Chadum channel, adjacent to the Namibian border, unmetamorphosed siltstones and minor quartzite lie beneath the "Kalahari beds". Some 35 km further east spotted slate with andalusite porphyroblasts was encountered at less than 10 m below surface; granite was intersected about 40 m below surface approximately 45 km east of the border. The western part of the Chadum channel is underlain by dolomites and limestones in a graben-like structure. Further east mica schists occur, and basement granitic gneiss was encountered about 60 km from Namibia.

3.2 Uranium Mineralization

Valley axes were considered to be the main target for uranium deposits, although samples taken from anomalies found during the airborne surveys were consistently low. The highest uranium concentration in calcified valley sediments was 102 ppm in the surface of the Groote Laagte channel. Other surface samples had maximum uranium concentrations of 42 ppm in the Rooibok-Passarge drainage and 34 ppm in the Deception Valley.

Concentrations of uranium in uncalcified soil are insignificant, except in the peat of the two northern drainages, in which the maximum was 336 ppm U_3O_8 in over 1.0 m. Maximum uranium deposition in the peat of both drainages has taken place where a north-northwest trending lineation crosses the valleys. This reflects faulting which has disturbed the surficial sediments and controls tributary disposition. The slight change in channel characteristics has favoured precipitation of uranium in the surficial peat of both drainages at this point.

Although uranium has been, and is being, transported in meteoric waters along the investigated drainages of northwest and central Botswana, an economic deposit has yet to be identified. Source areas currently available to the drainages in the west of the country are not particularly favourable for uranium and the time available for uranium precipitation under stable climate and tectonic conditions may have been relatively short. Furthermore, bedrock constrictions are rare and the permeability of the cemented valley sediment is low, thus impeding reconcentrations; in some places organic matter may compete for uranium in solution [2]. The drainages of central northeast Botswana, although mostly inactive, are probably not fossil but ephemeral, and flow at least locally during heavy rainfalls; they may be younger than is generally thought.

In Gordonia, South Africa, which lies immediately south of the Molopo River international boundary with Botswana, several anomalous areas of surface radioactivity have been shown to be the result of high surface concentrations of uranium, thought to be derived from the underlying basement gneisses [5].

4. CONCLUSION

Sediments of the Upper Carboniferous-Permian Lower Karoo Sequence are uraniferous locally and have an enormous area of suboutcrop beneath thick Kalahari sediments. Elsewhere, basement igneous rocks are a potential source. The basal parts of the "Kalahari beds" may be as old as Early Tertiary. They are largely uninvestigated and exhibit diverse palaeoenvironments. The possibility of older channels at depth or even at surface cannot be ignored. The complex depositional history of the "Kalahari beds" reflects a juxtaposition of shallow water and subaerial deposition in which suitable environments for the precipitation of uranium may well have been widespread throughout the Tertiary. That such conditions existed locally has now been demonstrated.

It is considered that exploration in surficial deposits in Botswana is at an early stage, and that the anomalies so far revealed and investigated are an encouraging indication of a potential for radioactive minerals which has still to be extensively explored.

5. ACKNOWLEDGEMENT

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REFERENCES

- [1] CAIN, A.C., Terminal report on the radioactive minerals exploration program in the Serule area, northeast Botswana, SG 7/76 Bull. 2064, Falconbridge Explorations (Botswana) (Pty) Ltd. (1978).
- [2] CARLISLE, D., Review of Union Carbide Exploration, Central Electricity Generating Board Calcrete Uranium Project, Botswana, UCEX-CEGB Botswana, Uranium in Calcrete Project. Final Report on Prospecting Licence Nos. 26/78, 23/79, 6/79, 7/79, 8/79, 9/79, 4/79, 5/79, 3/80, 4/80 and 5/80 (1980).
- [3] COATES, et al., The Kalatraverse One Report. Bull. 21 Geol. Surv. Dept., Republic of Botswana (1979).
- [4] JACK, D.J., Union Carbide Exploration Corporation Final report on prospecting Licence Nos. 23/78, 24/78 and 25/78 (1979).
- [5] LEVIN, M., Uranium Occurrences in the Gordonia and Kuruman Districts. A report on fieldwork conducted during June 1978, PER-37, Atomic Energy Board, Pelindaba (1978).
- [6] PIKE, J.C., Rainfall and evaporation in Botswana. Surveys and training for development of water resources and agricultural production, Tech. Doc. No. 1, Republic of Botswana (1971).

SURFICIAL URANIUM DEPOSITS IN CANADA

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ABSTRACT

SURFICIAL URANIUM DEPOSITS IN CANADA

Surficial ("young") uranium deposits in Canada occur in such diverse regions as semi-arid, alpine and permafrost terrains. Two broad classes of deposits are recognized, namely lacustrine/playa and fluvial types. Subclasses are based largely on specific environments of deposition. Deposits of this type are formed at or within a few metres of the surface by the interaction of ground or surface waters with various components of soils and sediments. These deposits contain few, if any, daughter products and the uranium is loosely bonded and hence easily remobilized. Molybdenum is a common companion to uranium and vanadium is characteristically absent. Virtually all deposits occur in areas underlain by intrusive rocks varying from intermediate to felsic in composition.

Detection of these deposits is dependent upon the recognition of 1) potential source lithologies; 2) suitable climatic conditions for formation and 3) geomorphic features capable of trapping uranium.

1. INTRODUCTION

At present, the only viable surficial uranium deposits in Canadian environments are those that have been termed "young" uranium deposits. The term "young" uranium deposit is used to denote concentrations of uranium which are still forming today and which have few or no gamma-active daughter products and thus do not produce significant radioactive anomalies. In some places this is due to the fact that uranium has been deposited within the last few thousand years, and hence has not had time to reach equilibrium; in other places it may be the result of uranium being loosely held by ion adsorption or by oxidation-reduction processes and, unless fixed by precipitation as a vanadate or phosphate, will usually migrate within the deposit to remain non-radioactive.

Young uranium deposits have been found in such diverse regions as semi-arid, alpine and permafrost terrains (Table 1). Although they vary widely in their setting and modes of accumulation, those discovered to date have the following unifying characteristics:

1. They are surficial, forming at or within a few metres of the surface by the interaction of ground or surface waters with various components of soils or sediments. The type of water involved, modes of water-sediment interaction and environment of accumulation determine the style or nature of a deposit.
2. Almost no daughter products are emplaced with the uranium, and hence no anomalous radioactivity is associated with the deposits. Exceptions occur in cases of extreme surficial enrichment involving desiccation and in cases that directly involve fresh water springs.
3. The uranium is loosely bonded by processes of sorption and ion exchange to sedimentary material and is hence easily remobilized.
4. Molybdenum is a common companion to uranium. Vanadium is characteristically absent.
5. Virtually all deposits always occur in areas underlain by intrusive rocks varying from intermediate to felsic in composition.

A classification of surficial uranium deposits in Canada, with appropriate examples, is given in Table 1. Two broad classes of deposits are recognized, namely lacustrine/playa and fluvial. Subclasses are based largely on specific environments of deposition.

To date, the area with the greatest proven potential for young uranium deposits in Canada is the south-central dry belt of British Columbia (Figure 1). The Okanagan Valley region, in which nearly all known deposits have been found, occupies the southernmost portion of this belt.

Table 1
Classification of surficial uranium deposits in Canada

Type of Deposit	Environment of Deposition	Principal Depositional Controls	Characteristics	Deposit Examples*
LACUSTRINE/PLAYA	Closed Basin – oxidizing	topography and evaporation	generally alkaline saline waters, shallow basin, uranium concentrated at surface	Wow Flats, Vicars Lake (Oliver Area)
	– reducing	topography, evaporation and bacterial reduction	sulphate brines, deeper basin, uranium concentration at bottom	Purple Lake (Oliver Area)
	Cyclically Closed Basin	topography and evaporation	alkaline conditions, interlayered clays and organics, occasionally reducing (H ₂ S gas)	Stinkhole Lake, (Summerland area); Ranchhouse Lake, Powerline Flats, Sawmill Lake, Sinking Basin Cornerpost Pool (Oliver area); Shinglebend (Penticton area)
FLUVIATILE	Valley Fill – collector basin	groundwater upwelling and evaporation discharge	deposits often large and complex	Prairie Flats (Summerland area)
	– swamp	groundwater flow and organic sequestration	often role or tongue shaped; U concentration generally at bottom of organic profile, groundwaters may be fresh or alkaline	Nkwala, Brent (Penticton area); Sinking Basin, Meyers Flats, Burnell (Oliver area); Whooper Swamp (New Brunswick); Kasmere Lake (Manitoba); T A. Bog (Nova Scotia)
	– channel	groundwater flow and organic sequestration	organic rich	Eneas Canyon (Summerland area);
	Flood Plain – meadow	groundwater infiltration and reduction	sand and gravel sediments mixed with organic material	Meadow Valley (Summerland area)
	– oxbow, levee	groundwater infiltration and reduction	sandy-silt channels containing organic material, alkaline groundwaters	Hunter Basin (Oliver area)
	Deltaic	surface drainage, organic sequestration, cation exchange	sandy organic sediments	Oromocto Lake (New Brunswick)
	Spring Deposits	groundwater discharge, organic sequestration, cation exchange	small fresh water orifices discharging into organic rich and/or clay rich catchments, commonly radioactive	Partridge Lake (Yukon) Mir Springs (Northern B.C.)

*Note: All locations are in British Columbia except where noted

2. OKANAGAN VALLEY REGION

2.1 Regional Geology

The main physiographic components of the area are the Shuswap-Okanagan Highlands, representing the area east of the dry belt boundary shown on Figure 2 and the Okanagan Valley region, which occupies most of the area to the west of this boundary.

The Shuswap metamorphic terrane contains the oldest rocks in the area. Rock types include gneisses, quartzites, schists and limestones within the Monashee and Mount Ida Groups. Metavolcanic-metasedimentary sequences of Palaeozoic-Mesozoic age, consisting of greenstone-quartzite-argillite-limestone assemblages, occur as isolated roof pendants on the Shuswap metamorphic and Mesozoic intrusive complexes.

Major intrusive activity probably began in Early to Middle Jurassic times with the emplacement of the West Okanagan intrusions consisting of the Okanagan, Oliver, Shorts Creek and Vernon bodies in the Okanagan Valley region. The activity continued into Late Cretaceous times with the emplacement of the Okanagan Highlands intrusive complex, apophyses of which also occur in the Okanagan Valley region. These intrusives consist mainly of porphyritic granite and quartz monzonite, with lesser amounts of granodiorite.

Volcanic-sedimentary rocks of Eocene age formed in isolated basins in the southwestern half of the region. These rocks consist mainly of basal sediments and intermediate (alkalic) and acid volcanics. The Coryell alkaline intrusions are coeval with the Tertiary volcanics.

The structural pattern observed in Figure 2 is largely the result of Tertiary tectonics. Subsequent to emplacement of the main intrusive phases, the period between Late Cretaceous and Early Eocene appears to mark a transition between waning compressional tectonics on a NE-SW axis (Laramide Orogeny) and the development of

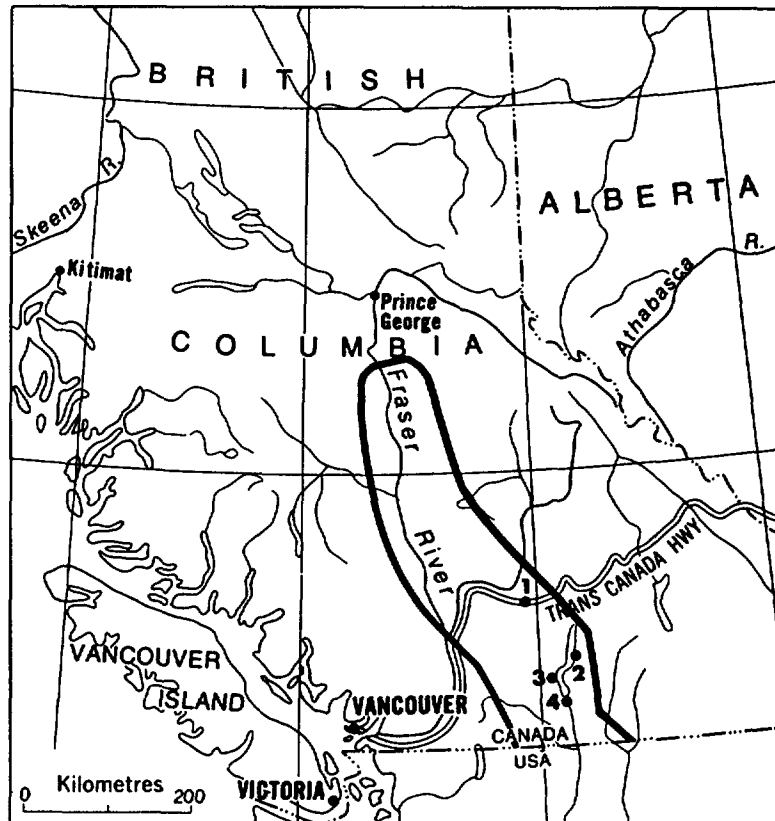


Figure 1

Location of south central dry belt region (solid line), British Columbia. Numbers refer to major urban centres mentioned in text. 1. Kamloop, 2. Kelowna, 3. Summerland, 4. Penticton. Dashed line represents Okanagan Valley and Highlands Region outlined in Figures 2, 3, and 4.

extensional tectonism on a probable E-W axis. The peak intensity in extensional tectonism is marked by the extrusion of the Eocene volcanics and emplacement of coeval Coryell intrusives. The tectonic processes that accompanied and followed the Eocene volcanism (late Pliocene uplift) were probably responsible for extensive block faulting and the development of major N-S fault lineaments such as the Okanagan Valley Lineament.

2.2 Glaciation and Geomorphology

At least two glacial advances have been recorded for the Okanagan region [1], both apparently covering the entire region with continental-type ice sheets. Stratified drift and varved glaciolacustrine deposits with thicknesses of up to 1 200 m occur in lowland areas such as the Okanagan valley.

The dry belt region in Figure 2 consists of a valley floor occupied largely by Okanagan Lake and to the east, a "midlands-type" of topography, characterized mainly by benches along the major valley, rolling hills and by small isolated basins perched above the valley.

2.3 Climate and Vegetation

The weathering history of this region, as it pertains to the formation of surficial uranium deposits, is related largely to postglacial climatic conditions. Glacial activity ceased about 10 000 years ago [1]. Significantly different climatic conditions exist for many areas of the Okanagan. Annual precipitation in the uplands region is generally in the order of 400 to 700 mm, most falling in the winter months, leading to considerable spring runoff. The dry belt region is characterized by mild winters and hot summers, giving rise to a sparsely vegetated semi-arid landscape. Annual precipitation trends over a 30 year period for the dry belt region are relatively uniform and range from about 250 mm (Kamloops) to 380 mm (Princeton). In the Oliver area, the annual precipitation is about 300 mm. Unlike most semi-arid regions, winter precipitation falls mainly as snow and there is, therefore, an important meltwater period during the spring. Much of this meltwater enters a groundwater regime severely depressed by the semi-arid conditions of the previous summer. The spring period thus marks an important influx of labile uranium into the depositional sites containing surficial uranium deposits.

Temperatures in the dry belt may vary from a low of -20 °C in the winter months to a high of 40 °C in the summer period (June to September). During the summer, the rate of evaporation easily exceeds the rate of precipitation.

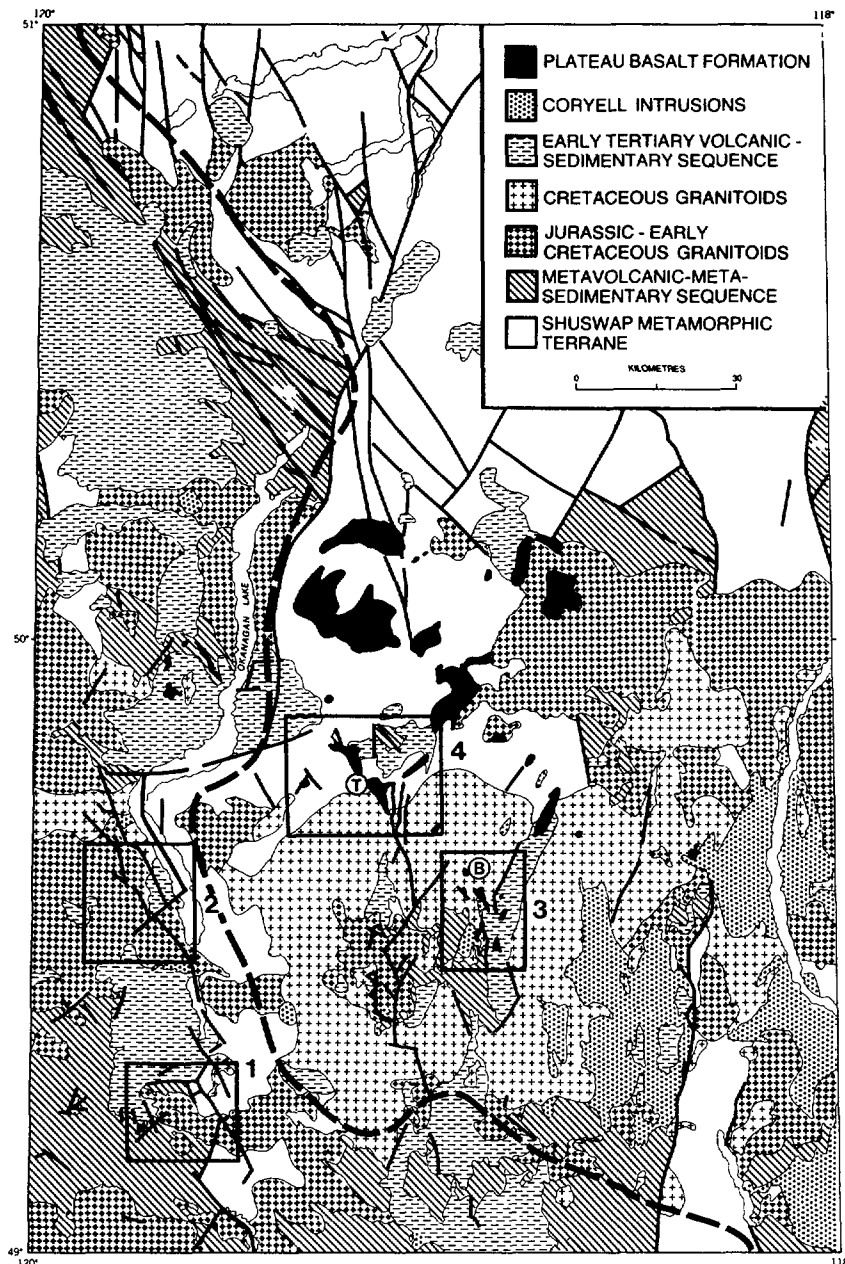


Figure 2

Generalized geology of the Okanagan Valley and Highlands Region. Heavy dashed line represents eastern boundary of the south-central dry belt. 1. Oliver area; 2. Summerland area; Regions 3 (Lassie Lake area) and 4 (Hydraulic Lake area) outline areas containing basal type uranium deposits (B-Blizzard, T-Tyee deposits; see Boyle (8)). Geology after Little (10, 11) and Jones (12).

2.4 Regional Geochemistry

The entire Okanagan region has been covered by a hydrogeochemical survey with a sampling density of one sample per 12 square kilometres [2]. An interpretation of the uranium data from this survey may be found in Boyle and Ballantyne [3]. In addition, detailed studies in various parts of the region have helped in explaining the various environmental factors affecting dispersion and concentration of uranium in the surficial environment [3, 4, 5].

A contour plot of pH (Figure 3) outlines those areas in the Okanagan region with highly alkaline stream waters. The dry belt region is characterized by stream waters having a pH generally in excess of 7.5 and as high as 9.0. Bicarbonate contents of these waters are generally of the order of 50 to 600 ppm. These conditions have been shown to severely affect the ability of the sediments along the valleys to concentrate uranium [3, 4], thus allowing greater amounts of the element to reach the closed basins and other types of traps in which surficial uranium deposits will form.

The regional distribution of uranium in stream waters is shown in Figure 4. The dry belt region is characterized by highly anomalous concentrations of the element in stream waters; in particular, the region south of Summerland

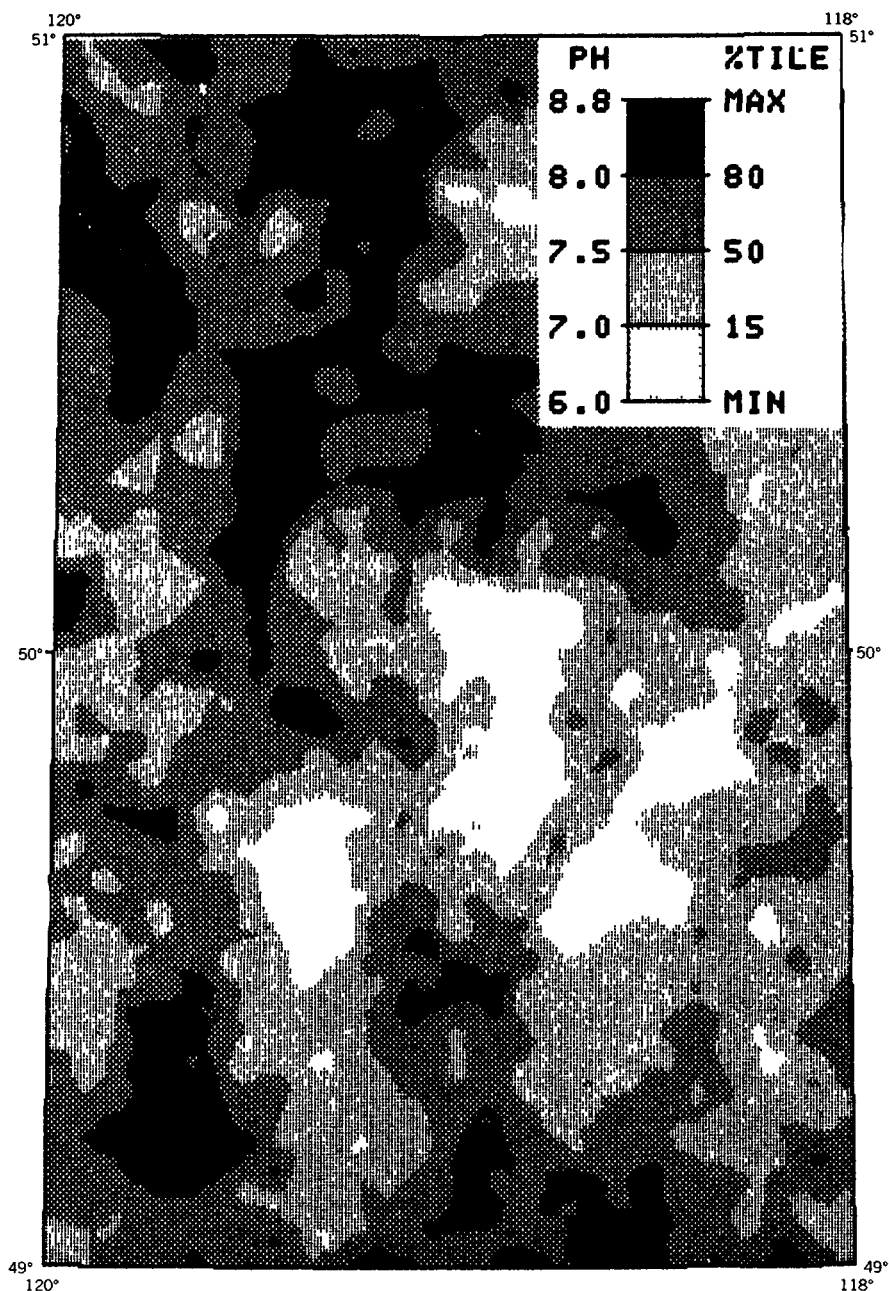


Figure 3
Aplicon contour plot of the pH of stream waters in the Okanagan Region, Data from Geological Survey Canada, 1977.

is typified by surface waters generally containing uranium in excess of 5 ppb. Values as high as 300 ppb in stream waters and 2 000 ppb in alkaline lake waters have been reported [4].

3. YOUNG URANIUM DEPOSITS

With the exception of deltaic and spring deposits, all of the types of surficial deposits shown in Table 1 occur in the Okanagan Valley region. Sampling of these deposits has been carried out at half-metre intervals using an extendable hand auger. Calculation of the concentration of U_3O_8 per square metre for the Prairie Flats, Hunter Basin and Stinkhole Lake deposits were carried out using appropriate bulk densities and a depth in each case down to the bottom of the uraniferous layer (generally 3 to 5 m). Uranium assays were made using low-energy gamma spectrometry [6], with checks by delayed neutron activation and fluorimetry.

3.1 Lacustrine/Playa Deposits

Numerous small saline lakes occur throughout the central dry belt of British Columbia and some of these have been commercially exploited in the past for their salts. Saline lakes in the dry belt rarely exceed 1 to 2 km in their greatest dimension. They occur on all of the major lithologies shown in Figure 2 as well as on some volcanic units

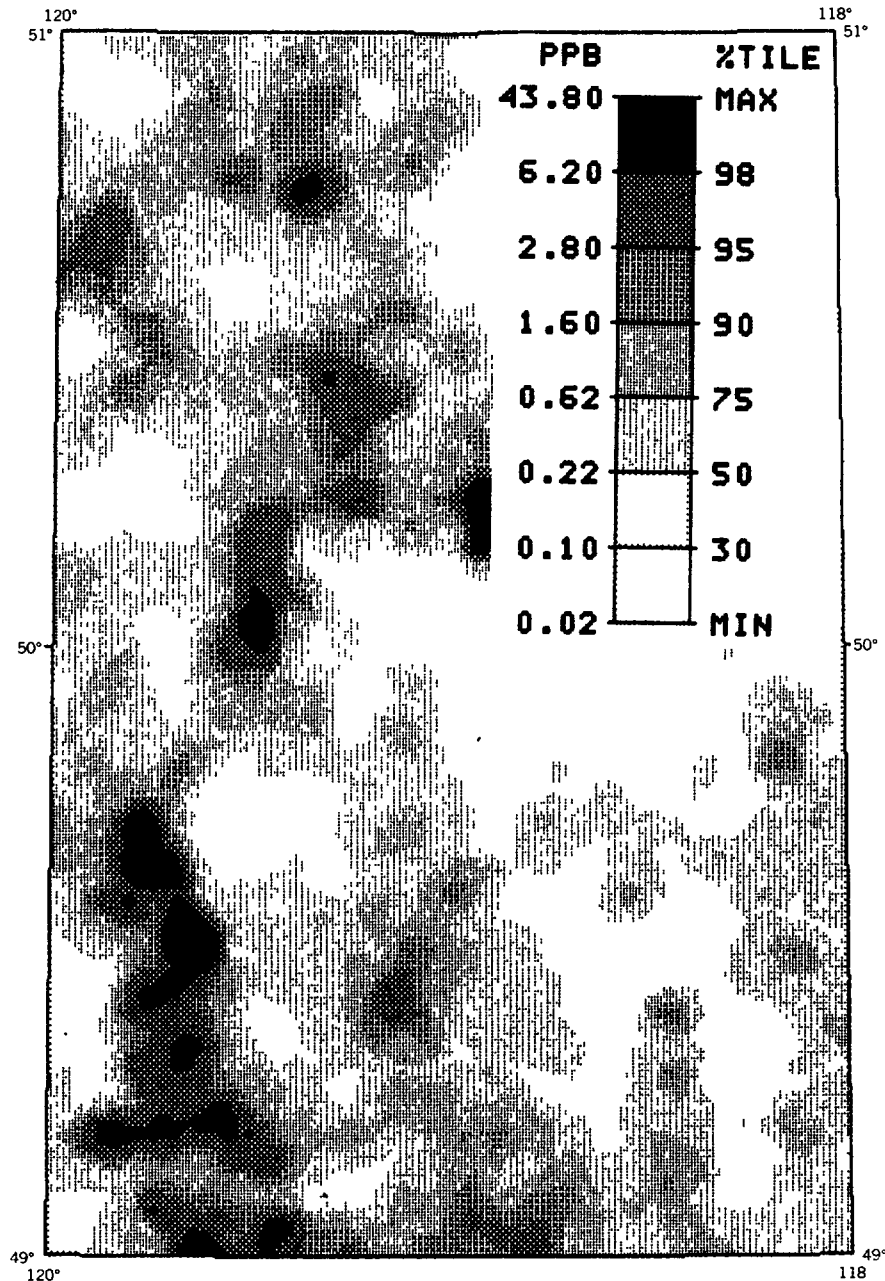


Figure 4

Aplicon contour plot of U in stream waters in the Okanagan region, Data from Geological Survey of Canada, 1977.

that do not occur in the Okanagan region. With rare exceptions, only those located on intrusive rocks are uraniferous.

The lacustrine/playa deposits can be subdivided into closed basin (oxidizing and reducing) and cyclically closed basin types. For both types, the principal depositional controls are topography and evaporation, although in some basins bacterial reduction may also play a role in precipitation of uranium. Hydrologically closed basins tend to become hypersaline, with minimal plant growth. Uranium is transported to and concentrated at the surface by evaporative processes without reduction taking place. The oxidizing profile shown in Figure 5 for the Wow Lake deposit on the Oliver granite is typical of this type of occurrence. Surface enrichment of uranium reaches 2 000 ppm and, although the daughter product equilibrium is less than 2 %, this still allows the deposit to be detected by scintillometer. Because the deposits in alkaline flats generally dry up in the summer, they are subject to deflation.

Not all closed basins have surface concentrations. Larger basins have dominantly lateral groundwater flow (rather than vertical) and a deeper depth of brine. Purple Lake (hypersaline profile, Figure 5), located on the Oliver granite, has gypsum-rich sediments and a layer of purple sulphur-fixing bacteria at the sediment-brine interface. Groundwaters containing uranyl carbonate complexes are rapidly decomplexed under acid and/or bacterial reducing conditions, resulting in a relatively homogeneous concentration of uranium in the sedimentary sequence.

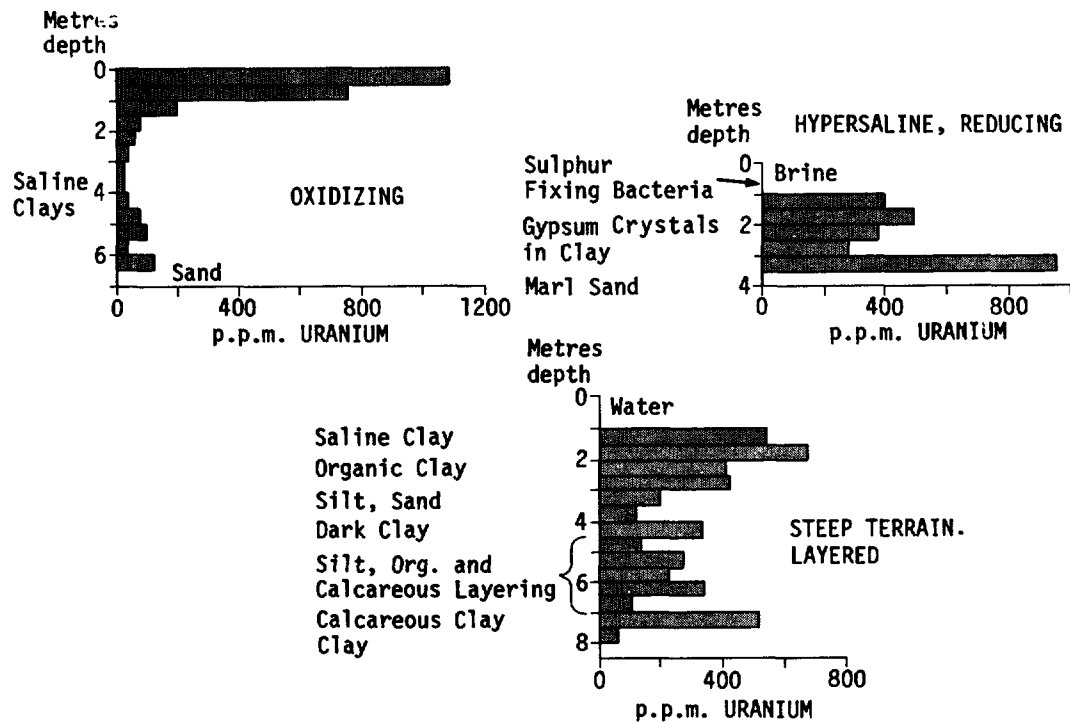


Figure 5

Distribution of uranium in sediment profiles from the three main types of lacustrine/playa deposits represented by Wow Flats (oxidizing), Purple Lake (hypersaline, reducing) and Cornerpost Pool (steep terrain, layered).

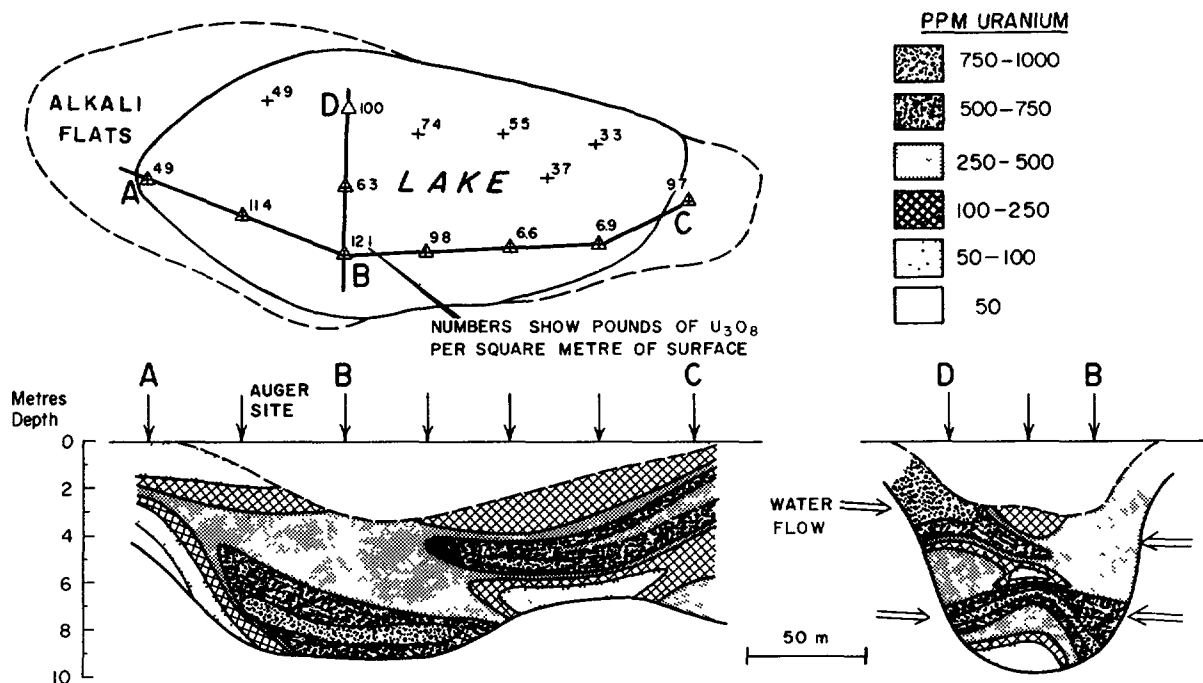


Figure 6

Distribution of uranium in a cyclically closed basin deposit, Stinkhole Lake, Summerland area.

For basins in areas of steeper topography, such as Cornerpost Pool (steep terrain profile, Figure 5), periodic surface runoff causes interlayering of organic-, clay- and sandy-rich sediments. Uranium in these deposits tends to be erratically distributed within the sedimentary layers.

Many saline and alkaline basins are only marginally closed (e.g. Stinkhole Lake, Figure 6) and periodic flushing by fresher waters may produce organic-rich layers in clays and marls. Uranium is not always concentrated in the organic layers and may be controlled more by reduction of interstitial waters during maturation of organic matter. Some of the deposits of this type, such as Sawmill Lake (an 800 m long slough) and the upflow portion of Sinking Basin (Figure 7) have a component of groundwater flow which moves laterally through the trap.

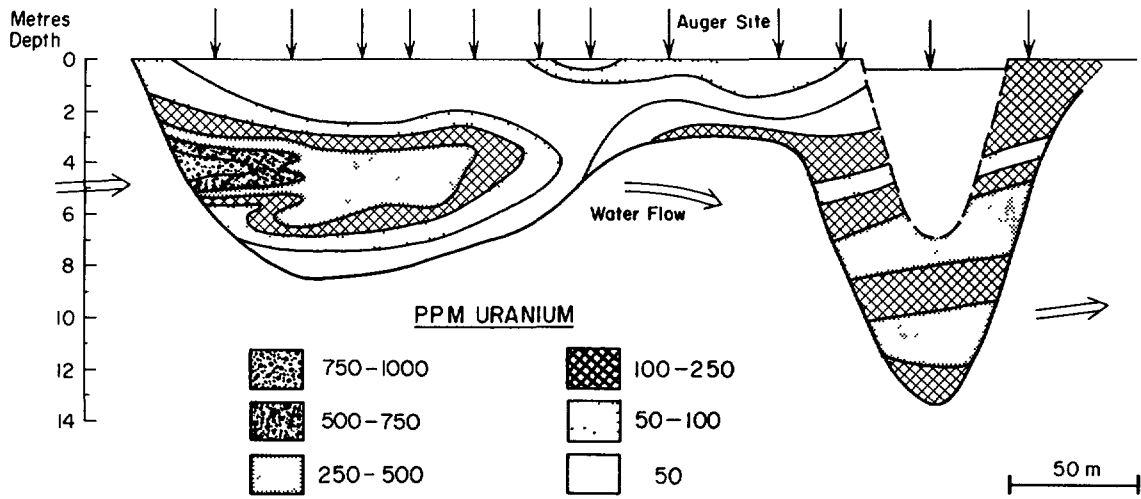


Figure 7
Distribution of uranium in a cyclically closed basin and fluvial swamp deposit, Sinking Basin, Oliver area.

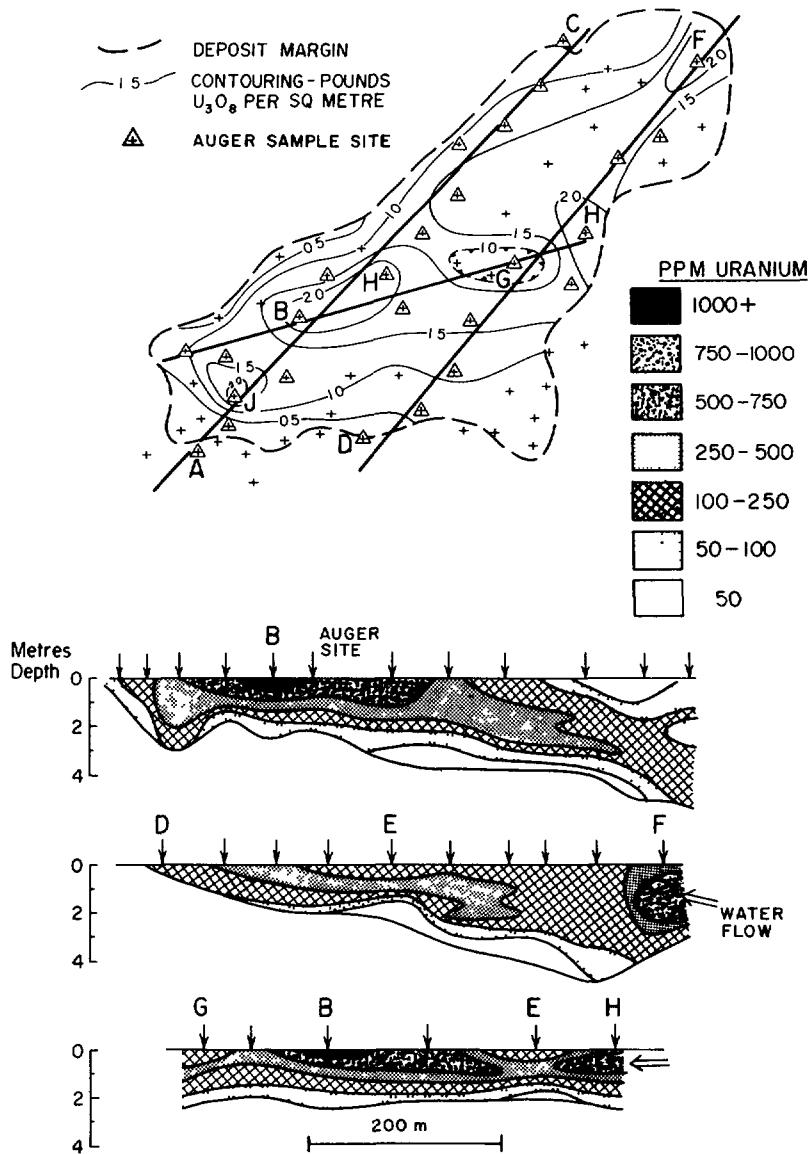
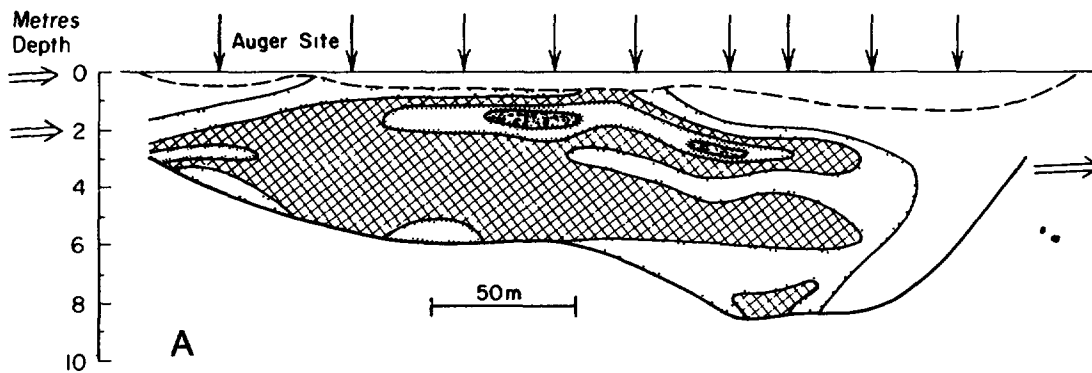
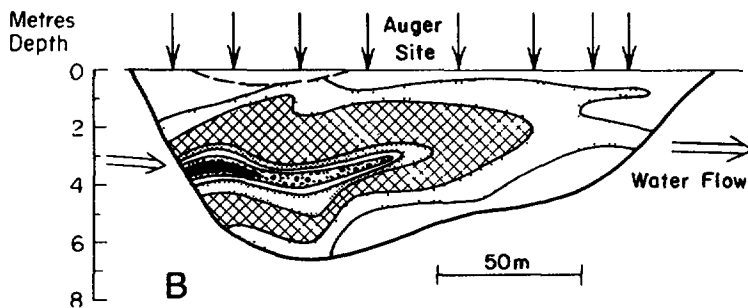


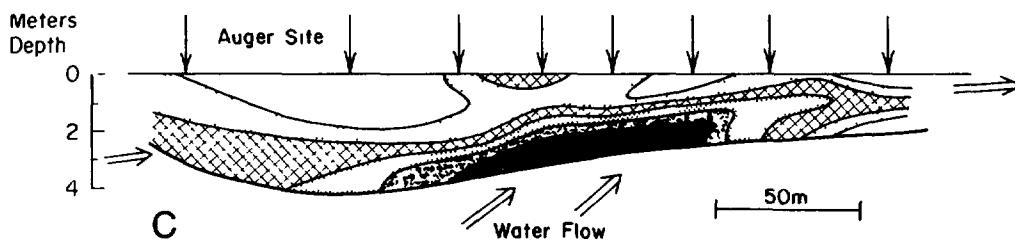
Figure 8
Distribution of uranium in a valley fill collector basin deposit, Prairie Flats, Summerland area.



A



B



C

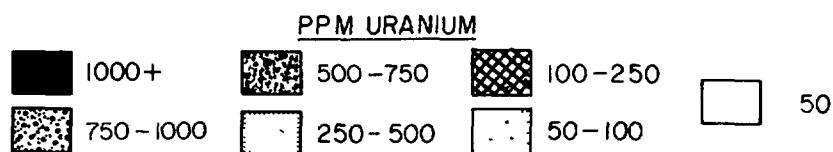


Figure 9

Distribution of uranium in various fluvial swamp environments, A. Nkwala Marsh; B. Burnell Swamp; C. Meyers Flats.

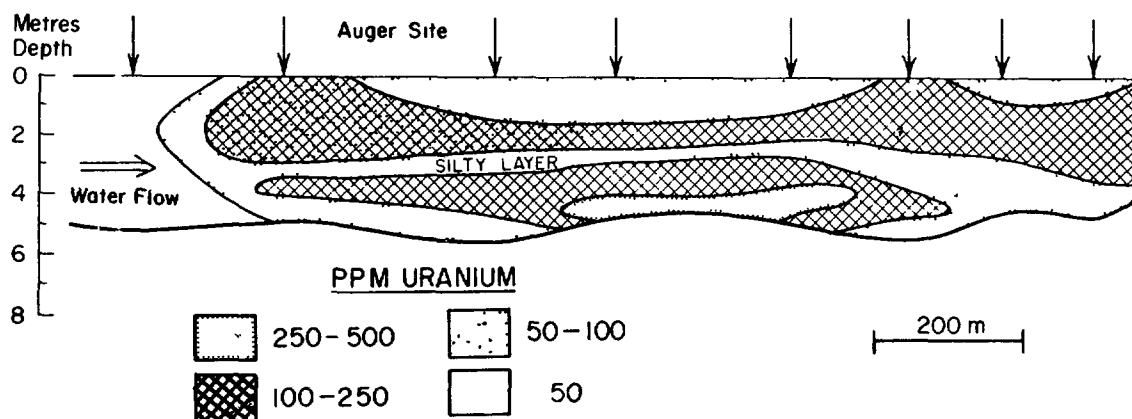


Figure 10

Distribution of uranium in a fluvial channel deposit, Eneas Canyon, Summerland area.

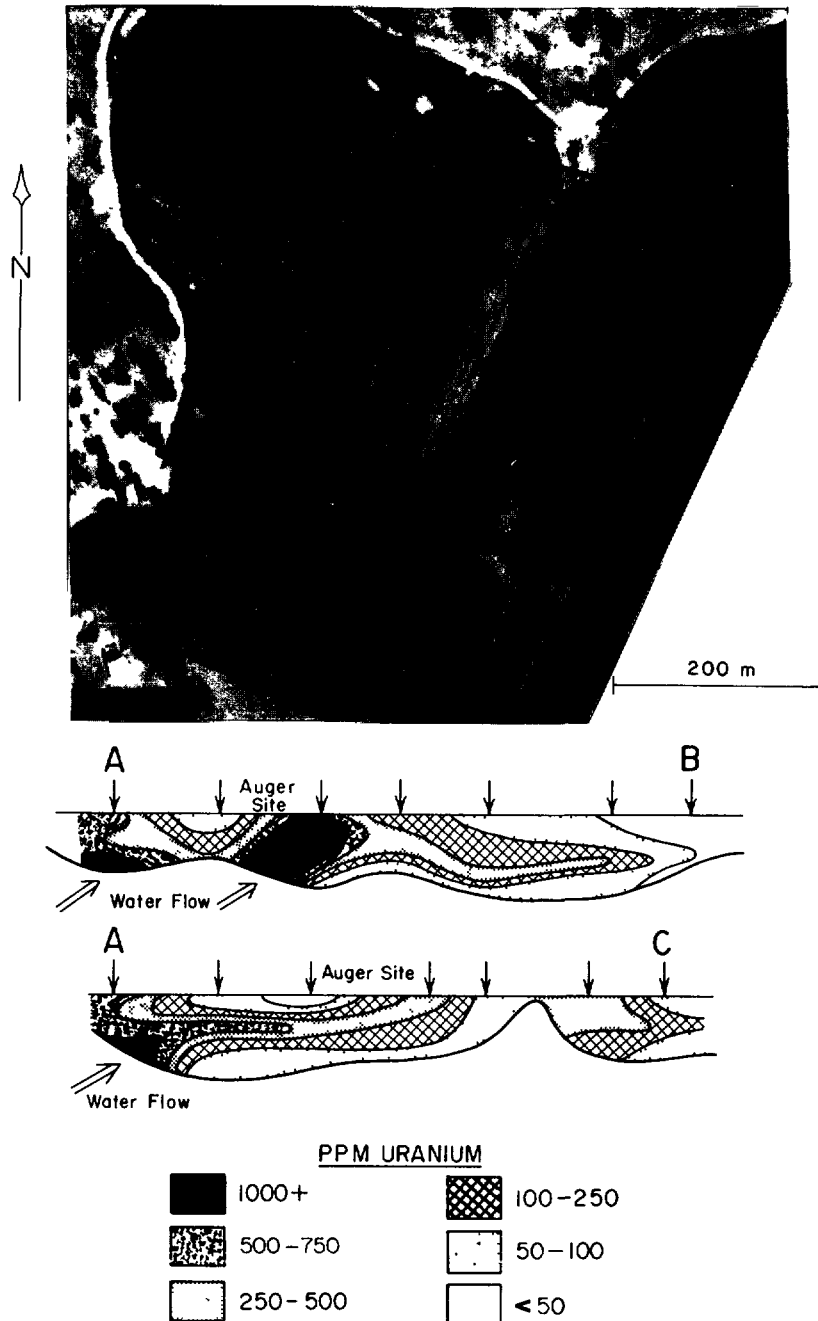


Figure 11
Distribution of uranium in a flood plain deposit, Hunter Basin, Oliver area.

3.2 Fluvatile Deposits

Uraniferous fluvatile deposits may be classed as valley-fill or flood-plain types (Table 1). For the valley-fill deposits, three main subclasses are recognized. Collector basin deposits, that occur near a valley head or valley junction, appear to be the most important of this group. Upwelling of groundwaters into these broad organic-rich soil flats, topographic control, and concentration of uranium by evaporative discharge and cation adsorption are the principal depositional controls. The Prairie Flats deposit near Summerland is an excellent example of this type of deposit (Figure 8); ore reserves to a depth of 3 m are about 230 t U_3O_8 , and it is estimated that since glacial retreat, uranium has accumulated at a rate of about 23 kg per year. The greatest concentrations of uranium, which locally exceed 1 000 ppm, occur in the surface layer.

Numerous valley-fill deposits in the Okanagan Valley region occur within swamps formed as the result of partial damming or glacial excavation of a valley. These areas lack well-defined drainage channels and uranium is introduced chiefly by groundwaters to form tongue- or roll-shaped deposits (Figures 7 and 9). Organic sequestration is the principal process of fixation.

Landslides in steep-sided valleys often result in alluvial damming of an aquifer system [1]. In some places organic-rich sediments, such as those in Eneas Canyon (Figure 10), developed in blocked valleys and were later covered over by sands and gravels. Uranium continues to precipitate in both the original sediments and the cover layer of the Eneas Canyon occurrence.

Significant, but rather diffuse, concentrations of uranium may occur in flood plains of large valleys. Two types of deposits may form in this environment. Those occurring in flood-plain meadows are generally associated with small meandering streams whose groundwaters enter a profile of organic materials mixed with silt, sand and old channel-filling of coarser clastics. Such deposits have proved difficult to evaluate. In flood plains involving large mature rivers, groundwaters from recharge areas adjacent to oxbows and levees may infiltrate such features with a resultant reduction and precipitation of uranium as has taken place in the Hunter Basin (Figure 11).

3.3 Mineralogy and Associated Elements

To date no uranium minerals have been identified in these deposits. Rather, the element appears to be loosely bonded to organic material and clays. Depending upon material composition, 48 to 73 % of the total uranium in these deposits can be extracted using a weak $\text{NH}_4\text{CHO}_3\text{-H}_2\text{O}_2$ solution [7].

Most of the young uranium deposits evaluated to date contain molybdenum in concentrations of the same order of magnitude as uranium. Enrichments of selenium have been noted in some deposits but vanadium is characteristically absent.

3.4 Source of Uranium

With rare exceptions, these deposits overlie intrusive basement rocks varying in composition from granodiorite to porphyritic granite. The mean uranium contents of these intrusive rocks vary from 2.3 to 7.3 ppm [8].

Deposits in the Oliver area (area 1, Figure 2) are underlain by the Oliver intrusion of medium to coarse-grained biotite-muscovite, porphyritic granite and quartz monzonite cut by later pegmatites, aplites, lamprophyre dykes and small gold-bearing quartz veins. The mean uranium content of the Oliver intrusion is 7.3 ppm but it also has small zones containing uranium in excess of a few hundred ppm.

Deposits in the Summerland area (area 2, Figure 2) are underlain by rocks of the Okanagan Highlands intrusive complex, varying in composition from granodiorite (mean = 2.3 ppm U) to quartz monzonite (mean = 4.8 ppm U). Rocks of this complex have been described in detail by Boyle [8]. Their most important feature is a higher than normal content of CO_2 , which correlates mineralogically with concentrations of carbonates along tectonic elements of the complex. This gives rise to structurally-controlled groundwaters having anomalous contents of bicarbonate and uranium.

The labile uranium content of various intrusive bodies in the Canadian Cordillera, including those of the Okanagan, is presented in Table 2. Rock powders were leached for 20 hours using a solution similar in composition to present-day groundwaters in the Okanagan. Details of the method are described by Boyle [8]. The labile uranium content varies greatly with rock type as well as with intrusions of the same rock type. Apart from minor pegmatites, the Oliver granite and the quartz monzonite of the Okanagan Highlands intrusive complex, which are the dominant rock types of the Summerland area, have the highest labile uranium content of all the intrusive rocks in the Okanagan region.

Fabric loosening by repeated tectonic and multiphase intrusive activity is a notable feature of the intrusive rocks in the Okanagan area [8]. This has given rise to deep-seated circulation of uraniferous groundwaters that eventually infiltrate the surficial sediments. Groundwaters, such as those draining the Darke Creek-Eneas Creek-Nkwala fault structures in the Summerland area, display a marked increase in uranium content with increasing tritium ages [8]. In addition, older groundwaters tend to be more depleted in dissolved oxygen, making them more susceptible to reduction when entering environments favourable for uranium deposition. Structurally-controlled groundwaters draining the Oliver granite generally exceed 10 ppb U and values as high as 125 ppb U have been observed for those draining the Okanagan Highlands intrusive complex [3].

It should be noted that although significant deposits of young uranium are associated with intrusive bodies having a high labile uranium content, they have also been found overlying rocks of both low total and labile uranium content (i.e. granodiorites and quartz diorites). The most important factors governing source fertility, therefore, seem to be 1) the degree of fabric loosening of the body; 2) the presence of a deep-seated, well-connected groundwater regime and 3) the presence of carbonate alteration to produce bicarbonate-rich groundwaters. In addition to these factors, high labile uranium contents would add importance to, but would not be a determinant to, the source potential of a particular intrusive body.

4. OTHER SURFICIAL URANIUM DEPOSITS

The surficial uranium deposits found outside the Okanagan region are fluvial in nature and comprise accumulations in swamps (valley- and lake-fill), lake deltas and surficial sediments associated with fresh-water springs.

Deltaic deposits, such as the Oromocto Lake occurrence in New Brunswick (Table 1), consist of diffuse concentrations of uranium in organic-rich silts and clays. Fresh-water spring deposits are radioactive because of

Table 2
Total and labile uranium concentrations in intrusive rocks from Canadian Cordilleran intrusive complexes
(Data from Boyle [8])

Rock Type ⁺	Mean Uranium* in Rock (ppm)	Mean Concentration of Labile Uranium (ppb)
Adanac Granite	18.8 (7)	451
Surprise Lake Alaskite	14.6 (48)	277
Okanagan Pegmatite	5.2 (3)	192
Tombstone Syenite	18.0 (25)	162
Fourth of July Granite	5.6 (14)	134
Oliver Granite	7.3 (15)	133
Okanagan Qtz. Monzonite	4.8 (79)	86
Shorts Cr. Monzonite	4.0 (13)	84
Raft Qtz. Monzonite	4.6 (25)	64
Okanagan Granite	5.4 (20)	59
McClure Granite	2.2 (6)	57
Cantung Granodiorite	6.7 (5)	47
Coryell Monzonite	6.7 (76)	43
Meselinka Monzo-diorite	9.4 (11)	38
Raft Granodiorite	2.4 (4)	36
Antimony Hill Granite	8.6 (3)	34
Katsberg Qtz. Monzonite	4.7 (4)	33
Goldway Tonalite	2.7 (2)	30
Thane Tonalite	3.4 (4)	24
Vernon Qtz. Monzonite	5.5 (34)	22
Nicola Granodiorite	2.6 (3)	18
Quilchena Granodiorite	1.0 (9)	15
Nicola Qtz. Monzonite	1.6 (13)	13
Wildhorse Qtz. Monzonite	1.5 (5)	11
Wildhorse Granodiorite	1.9 (10)	11
Frederickson Tonalite	3.8 (3)	11
Quilchena Qtz. Monzonite	1.4 (6)	10
Asitka Tonalite	1.6 (3)	10
Meselinka Granodiorite	9.0 (5)	9
Okanagan Granodiorite	2.3 (43)	9
Douglas Granodiorite	0.6 (4)	8
Douglas Qtz. Monzonite	0.4 (2)	4
Duckling Syenite	1.1 (12)	4
Lay Monzo-diorite	2.2 (3)	4
Wildhorse Diorite	1.7 (3)	3
Jensen Tonalite	1.0 (12)	3
Fleet Diorite	1.8 (7)	3
Ingenika Tonalite	2.7 (2)	3

* No. of samples in brackets

+ Rock types from Okanagan region underlined

the build-up of radium, and attain significance only in areas where uraniferous springs are located within or bordering organic-rich and/or clay-rich sedimentary basins.

Numerous enrichments of uranium have been documented for bog deposits occurring in a variety of geological environments in Canada, in particular the Canadian Shield. These bogs consist almost entirely of sphagnum peat. Coker and DiLabio [9] have described uraniferous bogs in northern Manitoba that are in the discontinuous permafrost zone of the Wollaston metasedimentary belt. Concentrations of as much as 0.5 % uranium occur in well-humified peat having a thickness of up to 3 m. Interstitial waters in the peats contain up to 400 ppb uranium, possibly indicating the presence of a state of equilibrium between waters and organic material and a loose bonding of uranium on the peat. Local groundwaters in the area contain up to 50 ppb uranium. The type of underlying bedrock is not known due to a heavy cover of glacial till.

5. PROSPECTING TECHNIQUES

Detection of these deposits is dependent upon: 1) recognition of potential source lithologies, using the factors mentioned above; 2) the recognition, particularly relating to lacustrine/playa deposits, of suitable climatic conditions for formation and 3) the determination of geomorphic and tectonic features capable of trapping uranium.

Topographic maps are adequate to choose sufficient traps for reconnaissance sampling but aerial photographs are recommended for follow-up work. Sampling can be carried out with the aid of an extendable hand auger because deposits rarely exceed 5 to 10 m in depth. Sampling should be done at the inflow point of the trap.

Hydrogeochemical surveys have been found to be useful only in detecting source lithologies. Particular emphasis should be placed on the analysis of structurally-controlled groundwaters to see whether a particular source lithology is capable of releasing large quantities of labile uranium.

Scintillometers, which detect high energy gamma-radiation, are not applicable to exploration for most types of young uranium deposits. Adaptation of a low-energy gamma spectrometric technique (40 to 100 KeV, [6]) with a plastic encased NaI crystal lowered down auger holes, has demonstrated good correlation with assay results. This should greatly increase the efficacy of site evaluation.

REFERENCES

- [1] FULTON, R.J., Quaternary geology and geomorphology, Nicola-Vernon area, British Columbia, Geol. Surv. of Canada Mem. 380 (1975).
- [2] GEOLOGICAL SURVEY OF CANADA, Regional stream sediment and water geochemical reconnaissance data, southeastern British Columbia, Geol. Surv. of Canada Open Files 409, 410, 411 (1977).
- [3] BOYLE, D.R., BALLANTYNE, S.B., Geochemical studies of uranium dispersion in south-central British Columbia, Canadian Inst. Min. Metall. 73 No. 820 (1980).
- [4] CULBERT, R.R., LEIGHTON, D.G., Uranium in alkaline waters — Okanagan Area, B.C., Canadian Inst. Min. Metall. Bull. 71 No. 793 (1978).
- [5] BOYLE, D.R., The dispersion of uranium around Miocene "basal type" uranium occurrences in the Lassie Lake area, south-central British Columbia, Geol. Surv. of Canada Paper 79-1A (1978).
- [6] CULBERT, R.R., LEIGHTON, D.G., Low-energy gamma spectrometry in the geochemical exploration for uranium, J. Geochem. Explor. 14 1 (1981).
- [7] HUNKIN ENGINEERING INC., Preliminary metallurgical test results and conceptual production processes for young uranium deposits, unpublished Report (1979).
- [8] BOYLE, D.R., The formation of basal-type uranium deposits in south-central British Columbia, Econ. Geol. 77 (1982).
- [9] COKER, W.B., DiLABIO, R.N.W., Initial geochemical results and exploration significance of two uraniferous peat bogs, Kasmere Lake, Manitoba, Geol. Surv. of Canada Paper 79-1B (1979).
- [10] LITTLE, H.W., Geology of the Kettle River (east half) area, British Columbia, Geol. Surv. of Canada Map 6-1957 (1957).
- [11] LITTLE, H.W., Geology of the Kettle River (west half) Area, British Columbia, Geol. Surv. of Canada Map 15-1961 (1961).
- [12] JONES, A.G., Vernon map area, British Columbia, Geol. Surv. of Canada Mem. 296 (1959).

DEPOSITOS SUPERFICIALES DE URANIO EN EL NORTE DE CHILE

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ABSTRACT — RESUMEN

SURFICIAL URANIUM DEPOSITS OF NORTHERN CHILE

Uranium deposits have recently been discovered in Upper Cenozoic clastic sediments and salt deposits of the Tarapaca and Antofagasta regions of northern Chile. At the southeast edge of the Salar Grande, which is a saline playa within the coastal mountain range, carnotite is associated with clay and blue halite that form epigenetic cements in Pleistocene and Holocene fluvial and deltaic sands and gravels. The uranium anomalies are related to east-west fractures and shear zones in Cretaceous granodiorites. The granodiorites may be the source of the uranium; however, Tertiary ignimbrites and tuffs in the Cordillera of the Andes cannot be excluded. Other uranium occurrences are associated with chert and carbonaceous diatomaceous earth that occur in Pliocene and Pleistocene sedimentary rocks deposited in a semi-arid fluvial-lacustrine environment.

DEPOSITOS SUPERFICIALES DE URANIO EN EL NORTE DE CHILE

Recientes exploraciones efectuadas en las regiones de Tarapacá y Antofagasta del norte de Chile, evidenciaron la existencia de mineralización de uranio asociada a rocas sedimentarias y depósitos salinos del Cenozoico Superior.

En el borde suroriental del Salar Grande, la mineralización uranífera, principalmente carnotita, está asociada a arcillas ocluidas en halita azul, la que ha cementado epigenéticamente a gravas y arenas, principalmente fluviales y deltaicas asignadas al Pleistoceno-Holoceno. Las anomalías uraníferas se relacionan directamente con zonas de falla y/o de fuerte fracturamiento EW que afectan a granodioritas del Cretácico, las cuales podrían constituir la fuente del uranio. No se excluye la posibilidad que el uranio provenga de la lixiviación de ignimbritas y tobas terciarias de la Cordillera de Los Andes.

Otras ocurrencias de uranio están relacionadas a capas de chert y diatomitas con escasa materia orgánica, interestratificadas con rocas sedimentarias del Plioceno-Pleistoceno. Estas rocas representan un ambiente de depositación fluvio-lacustre en condiciones semidesérticas.

1. INTRODUCCION

Entre 1977 y 1981, diversas exploraciones realizadas por Essex Minerals Company y la Comisión Chilena de Energía Nuclear (CCHEN) en las regiones de Tarapacá y Antofagasta del norte de Chile, constataron la existencia de mineralización de uranio en rocas sedimentarias del Cenozoico Superior.

Fisiográficamente el área mencionada corresponde a una depresión tectónica rellena por sedimentos aluviales y fluvio-lacustres, llamada Pampa Central (altitud media de 1 500 m), que se emplaza entre la Cordillera de la Costa (altitud máxima de 1 500 m) por el W, ascendiendo gradualmente hacia la Cordillera de los Andes (altitud máxima de 6 000 m) por el E. El sector norte de esta Pampa Central está disectada por profundas quebradas de dirección EW (Figura 1).

El clima es desértico normal variando desde "normal con nublados abundantes" en la zona costera a "normal marginal de altura" en la cordillera de los Andes [1] En la costa y Pampa Central las precipitaciones son desde muy reducidas (<1 mm) a nulas [1].

En el área, las rocas preterciarias corresponden a unidades sedimentarias marinas, continentales y volcánicas de carácter andesítico, cuyo rango de edad varía entre el Devónico y el Neocomiano. Las rocas más antiguas están afectadas por metamorfismo de bajo grado, reconociéndose metaareniscas y metaconglomerados cuarcíferos. En las rocas jurásicas se reconocen andesitas con intercalaciones de areniscas, lutitas y calizas fosilíferas marinas. Brechas, conglomerados, grauvacas y lutitas continentales, son características de las unidades neocomianas [2, 3].

Los ciclos intrusivos Carbonífero, Jurásico y Cretácico están representados por granitos de grano grueso, dioritas-tonalitas y granodioritas a granitos respectivamente [2, 3].

Durante el Terciario Medio a Superior, se depositaron secuencias continentales de ambiente aluvial, constituidas por conglomerados, areniscas y limolitas con intercalaciones de yeso. El Terciario Superior culmina con un ambiente fluvio-lacustre, depositándose calizas, diatomitas y niveles de sílice. En estas últimas secuencias, se encuentran ocurrencias uraníferas de pequeña envergadura [2, 4, 5].

El Cuaternario está constituido por depósitos de yeso, anhidrita y halita, en parte uranífera [3], que rellenan cuencas y depresiones. Depósitos eólicos, coluviales y rególiticos cubren y/o se intercalan localmente entre las evaporitas.

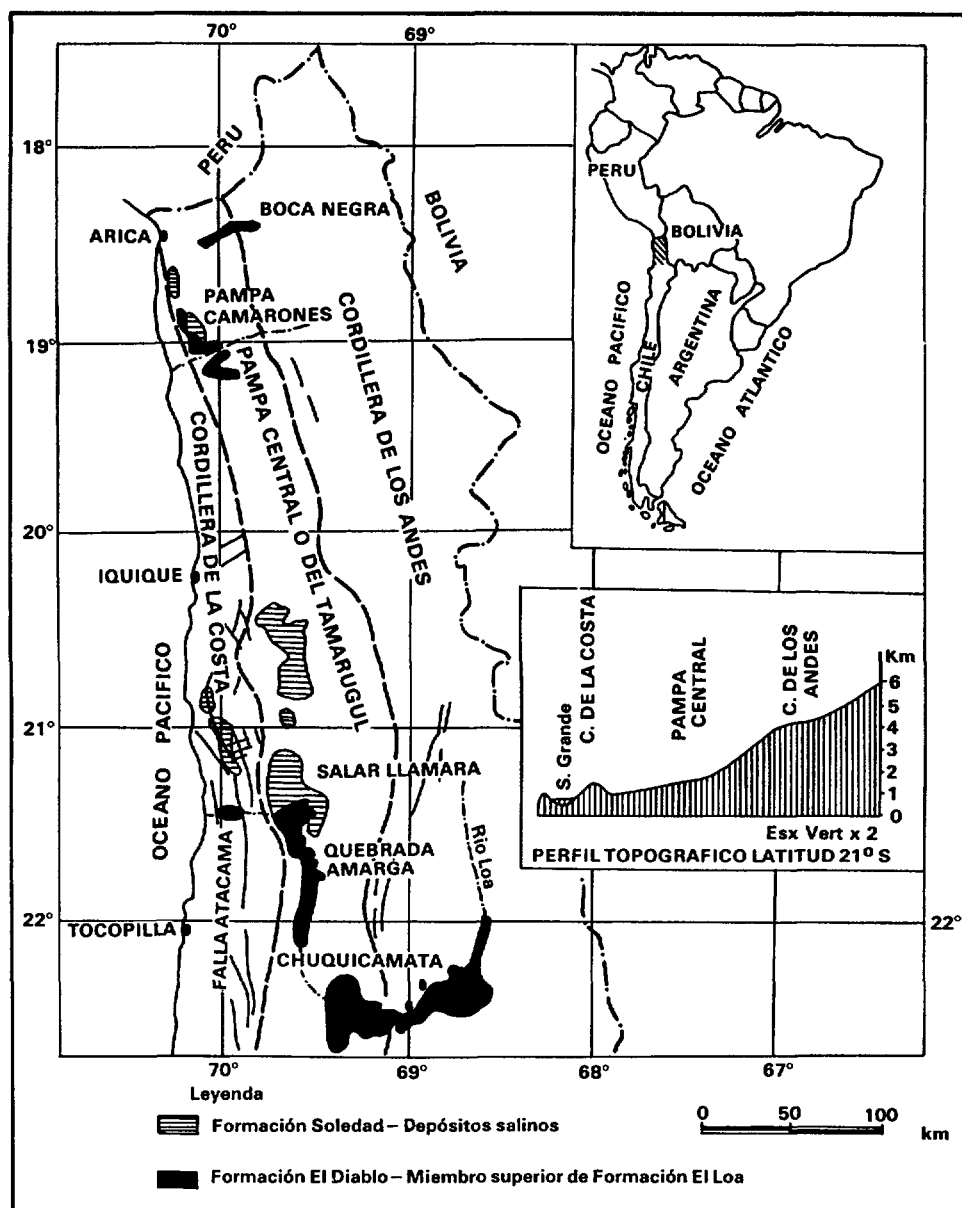


Figure 1

Distribucion de las formaciones fluvio-lacustres y depositos salinos del Terciario superior — Cuaternario en el Norte de Chile.

Distribution of the fluvio-lacustrine formations and saline deposits of the Upper Tertiary and Quaternary in northern Chile.

2. DEPOSITOS URANIFEROS DE TIPO FLUVIAL

Algunas ocurrencias halitíferas de uranio se detectaron en formaciones evaporíticas del Pleistoceno-Holoceno del norte de Chile. De ellas, las más importantes ocurren en los bordes del Salar Grande.

Este consiste en una cuenca tectónica intermontana ubicada en la Cordillera de la Costa, 80 km al Se de Iquique. Durante el Terciario Superior, esta depresión drenó hacia el océano [3] cerrándose posteriormente debido al continuo solevantamiento tectónico del bloque costero [6, 7, 8].

La cuenca, unida por el sur a otra denominada Salar de Llanara, está rellena por depósitos evaporíticos cuaternarios (formación Soledad) constituidos por yeso, anhidrita y halita con potencias superiores a los 12 m. En el centro del Salar Grande la halita alcanza un espesor continuo de 200 m [8, 9]. Aparte de la costra salina, se han diferenciado depósitos de playa (arenas, guijarros y cascajos cementados por halita y yeso); regolitos modernos (limos, yeso pulverulento y arenas cementado por halita) de origen eólico, coluvial y descomposición in situ; terrazas (linos, arenas, clastos redondeados y angulosos) y depósitos aluviales de origen fluvial (conglomerados, areniscas con estratificación cruzada, cementados por arcillas, yeso y halita) que, al menos en un sector,

constituyen evidencia de un paleocanal de desague parcial del Salar [3, 8]. Circundan la cuenca, andesitas con intercalaciones de calizas fosíferas marinas del Jurásico, sedimentos continentales (limos, areniscas, conglomerados) neocomianos y rocas intrusivas representadas por granodioritas y granitos de grano medio de probable edad cretácica

Las rocas mesozoicas presentan estructura monoclinal de rumbo NW. Las rocas terciarias presentan estructura subhorizontal, en tanto que los depósitos cuaternarios están horizontales. La falla Atacama (NS) atraviesa la cuenca, afectando incluso a los depósitos recientes con un salto de 15 m. Fallas paralelas EW en la zona sureste y este del Salar, han producido desplazamientos verticales y horizontales de cierta importancia. La mayoría de las anomalías y ocurrencias uraníferas se encuentran en la zona del borde suroriental del Salar, distribuyéndose como puntos aislados en una extensión de 17 km de largo por 0.3 a 1.5 km de ancho. Ellas se relacionan con gravas y arenas de origen fluvial que se han depositado en paleocauces controlados por las zonas de fractura EW [3, 10]. Los sedimentos que presentan estructuras de canales y niveles de minerales pesados, han sido cementados epigenéticamente por halita, la que ha producido una corrosión y separación de los clastos detríticos [11]. En superficie la halita se muestra masiva, con espesores que varían de 0.2 a 1 m, a mayor profundidad, la halita se hace menos abundante y con carácter granular fino.

2.1 Mineralización y recursos

La mineralización de uranio, carnotita, está directamente relacionada a capas de halita, en parte arcillosa y/o limosa. La halita presenta una marcada coloración azul, desde claro a muy intenso, causada por una alteración de su red cristalográfica al ser modificada la estructura atómica del sodio por radiación, aunque no se descarta la posibilidad de una coloración adicional producida por algunos elementos traza contaminantes como manganeso, molibdeno y sodio coloidal [3, 10].

La carnotita se presenta en fracturas, en bandas paralelas a la estratificación y deseminada, asociada a arcillas (serpentinitas, illita y montmorillonita) ocluidas en la sal azul y en partes a yeso y anhídrita. En la superficie salina se la ha observado como una delgada pátina amarilla sin una relación directa con halita azul, probablemente constituyendo una mineralización más joven que la ya descrita, producto de una removilización de la misma [11]. En casos aislados se ha detectado un mineral amarillo verdoso que podría corresponder a schroekingerita [10].

En zanjas de reconocimiento, se encontraron valores comprendidos entre 0.2 y 1 kg, y puntualmente hasta 9 kg de U_3O_8 /ton. Los trabajos exploratorios indican la existencia de recursos razonablemente asegurados de 11.7 ton de uranio [3]. Especulativamente se ha indicado la posibilidad de unas 100 ton de U_3O_8 [12].

Algunas muestras extraídas del Salar, fueron sometidas a una lixiviación con agua y posteriormente los residuos fueron tratados a) con una solución de carbonato de sodio y b) con ácido sulfúrico, recuperándose el 90 y 97 % del uranio total respectivamente [10].

2.2 Génesis

Se ha postulado que el uranio contenido en ignimbritas y tobas terciarias de la Cordillera de Los Andes se habría lixiviado, para posteriormente ser transportado como ión uranilo por aguas subterráneas, principalmente a través de fracturas EW, y en forma superficial a través de ríos y lagos desarrollados entre el Plioceno y Holoceno, en ambientes semi-desérticos. El uranio habría precipitado al llegar al ambiente hipersalino del Salar Grande y Llamara, indicándose como principal control de la mineralización la intersección de una antigua línea de costa del Salar con el sistema de fallas EW.

Hambleton-Jones [11] ha indicado que la fuente de uranio y vanadio sería la granodiorita que circunda el Salar, restringiéndose eso sí a aquella que está afectada por el intenso fracturamiento EW. La carnotita, que ocurre en gravas fluviales, habría precipitado bajo condiciones evaporíticas (capilaridad) como también por fenómenos de adsorción en arcillas y óxidos de hierro, donde la hipersalinidad habría jugado un rol poco importante. Incluso indica que la carnotita podría haber precipitado antes que se hubiesen desarrollado las condiciones hipersalinas.

De acuerdo a la clasificación propuesta por Toens y Hambleton-Jones [13] estas ocurrencias se definen como depósitos fluviales de valle y/o de tipo deltaico.

3 DEPOSITOS URANIFEROS DE TIPO LACUSTRE

Una serie de ocurrencias de uranio se encuentran asociadas a rocas sedimentarias del Plio-Pleistoceno denominadas formación El Diablo [2] y miembro superior de la formación El Loa [3, 4], ambos cronoestratigráficamente equivalentes. Estas unidades que se ubican de preferencia en la Pampa Central, están integradas por diatomitas, chert, cenizas reabajadas, conglomerados, calizas y limolitas calcáreas, presentándose intercalaciones de yeso y anhídrita, lo cual representa un ambiente de deposición fluvio lacustre en condiciones semidesérticas. Estos sedimentos rellenan paleocuevas someras y paleodrenajes (Pampa Camarones, Quebrada Amarga, Boca Negra).

En general la mineralización de uranio, en forma de carnotita y escasa schroekingerita, se encuentra asociada a diatomitas blancas a gris claro con restos de plantas, las que se encuentran interestratificadas con chert y cenizas.

[3, 4, 11]. Se han encontrado valores que fluctúan entre 100 y 1 000 ppm de U_3O_8 , pero el tamaño y extensión de los cuerpos mineralizados los hacen subeconómicos.

De acuerdo con [13] estas ocurrencias se clasifican como depósitos lacustres.

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REFERENCIAS

- [1] INSTITUTO GEOGRAFICO MILITAR, Atlas Regionalizado de Chile, Inst. Geográf. Mil. (1981).
- [2] BOBENRIETH, L., Geología y potencial por uranio de las formaciones terciarias y cuaternarias ubicadas entre Iquique y Arica. Informe inédito preparado para CCHEN (1982).
- [3] ESSEX MINERALS COMPANY (CHILE), Investigaciones preliminares sobre mineralización de uranio en ambientes evaporíticos en el norte de Chile. Informe interno (1982).
- [4] VILA, T., Descripción de anomalías radiométricas y geoquímicas en rocas de la formación El Loa, II Región. CCHEN (1982).
- [5] FELLEMBERG, E., Comprobación de anomalías aeroradiométricas en la I Región, CCHEN (1983).
- [6] MORTIMER, C., SARIC, N., Landform evolution in the coastal region of Tarapacá Province, Chile Rev. de Geom. Dynam., Vol. 21, No. 4, (1972) 162–170.
- [7] MORTIMER, C., SARIC, N., Cenozoic studies in northernmost Chile, Geologische Rundschau (1975) 395–420.
- [8] VILLEMUR, J.R., Geological structural and mining survey of the coastal range south of Iquique (Tarapacá Province), UNDP program (1962).
- [9] ERICKSEN, G E., Geology and origin of chilean nitrate deposits, US Geol Surv. Prof. Pap. 1188, Washington (1981).
- [10] EGERT, E., VIEIRA, C , BOBENRIETH, L., Mineralización de uranio asociada a halita en Salar Grande, I Región de Tarapacá, Chile Revista Minerale, Santiago (en prensa).
- [11] HAMBLETON-JONES, B B., A review of the uranium potential in the Upper Cenozoic formations of northern Chile, PIN-639 (B/R), Nuclear Dev. Corp. of South Africa (Pty) Ltd , Pretoria (1982) 20.
- [12] ROJO, M., Nuevos antecedentes acerca de mineralización de uranio en Chile, Nucleotécnica, CCHEN (en prep).
- [13] TOENS, P.D., HAMBLETON-JONES B.B , Definition and classification of surficial uranium deposits, this Volume.

URANIUM ENRICHMENT IN EUROPEAN PEAT BOGS

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ABSTRACT

URANIUM ENRICHMENT IN EUROPEAN PEAT BOGS

In Europe peat bogs are extensively developed but high uranium concentrations have been reported from only a relatively few in Sweden, Finland and the United Kingdom. Because of the limited tonnage of uranium ore it is unlikely that they would ever become economically viable. The distribution of uraniumiferous peat bogs is governed by enrichments of labile uranium in the source rocks.

1. INTRODUCTION

The only surficial occurrences of uranium in Europe are concentrations in dead organic matter in peat bogs. Uranium deposits in coal and brown coal are not described here.

Peat bogs are extensive in Ireland, Sweden and Finland and some data are available from the latter two countries and from the United Kingdom.

2. SWEDEN

Sweden has an extensive coverage of post-glacial peat bogs, developed over the last 8 to 17 000 yr's. Organic material is an excellent medium for geochemical exploration and therefore some 127 000 samples have been taken over an area of 200 000 km². It is now well-established that some contain considerable enrichments of uranium and other metals. The best documented occurrence is at Masugnsbyn, about 90 km southeast of Kiruna in northern Sweden (Figure 1), where a deposit of some 24 tonnes uranium in peat with an average grade of 0.2 % uranium in ashed material are known. While these occurrences are not economic, considered purely as uranium resources, their exploitation for fossil fuel raises two considerations:

- a) That the uranium and other metals might be recovered from the ash, adding to the value of the product, or
- b) That the content of metals may constitute an environmental threat

Content of heavy metals is now one of the factors considered in the evaluation of peat bogs, but it appears that the bogs with the highest uranium contents are not so suitable for peat production because of their high ash content and configuration.

The Masugnsbyn uraniumiferous peat bog is described by Armands [1]. It was discovered in 1958 during car-borne uranium exploration operated by AB Atomenergi (now Studsvik Energiteknik AB). The peat bog, which lies about 4.5 km northwest of the village of Masugnsbyn was extensively sampled, an area of about 600 by 200 m being sampled on a 20 x 20 m grid. Uranium content in the ashed material ranged from 0.04 to 3.1 %, with an average of 0.2 %. The peat bog has extremely low gamma radioactivity and samples studied indicated a high degree of disequilibrium. The highest contents of uranium and radon are connected with the occurrence of radioactive springs in the region. The source of the uranium appears to be the Precambrian (Svecokarelian) bedrock in the area which is slightly enriched in labile uranium and is extensively fractured. Spring waters contain several ppb uranium and water derived from fractures contains 200 to 300 ppb uranium (max 1 800 ppb uranium). Minor uranium mineralizations are also recorded in skarn iron ores in the vicinity.

High uranium contents are also recorded in the county of Jämtland, as a result of uranium prospecting by Swedish Geological, financed by the Swedish Nuclear Fuel Supply Company (SKBF). Uranium contents of up to 3.4 % are recorded from peat bogs near the village of Stugun. Springs in the area are highly radioactive and the bedrock is slightly enriched in labile uranium, there also being some minor uranium mineralizations in the vicinity.

Another region with high uranium contents in peat bogs is situated within the area of the uranium-enriched Jarre granite, about 50 km west of Jokkmokk. Within this area practically all springs are radioactive, indicating that the uranium in the granite is easily leached. A large number of peat bogs with maximum uranium contents varying from 1.1 to 3.2 % have been recorded as a result of a state-financed uranium prospecting campaign. All anomalous peat bogs are related to radioactive springs. Systematic sampling from vertical and horizontal profiles [2], has shown that the uranium is very unevenly distributed in the peat material (Figure 2). The strongest uranium enrichment is always found along the drainage route of uranium-enriched spring water through the bogs. It is estimated that the most anomalous part of the bog (11 900 m²) contains 5 64 tonnes of uranium.

The above studies, together with investigations of peat bogs carried out in connection with their evaluation for fossil fuel, indicate that the uranium concentration is usually very heterogeneously distributed. High uranium contents in peat bogs is almost always associated with radioactive springs, which in their turn are usually

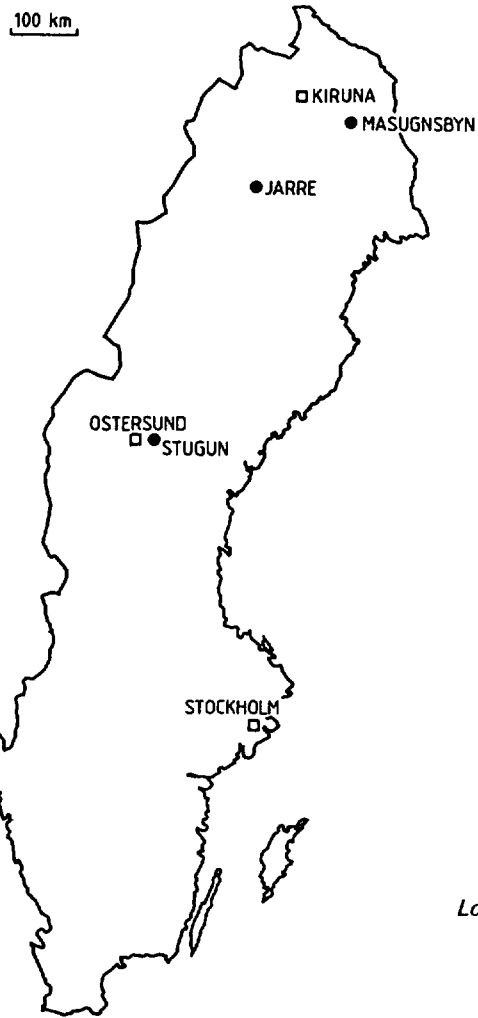


Figure 1
Localities of uraniumiferous peat bogs in Sweden.

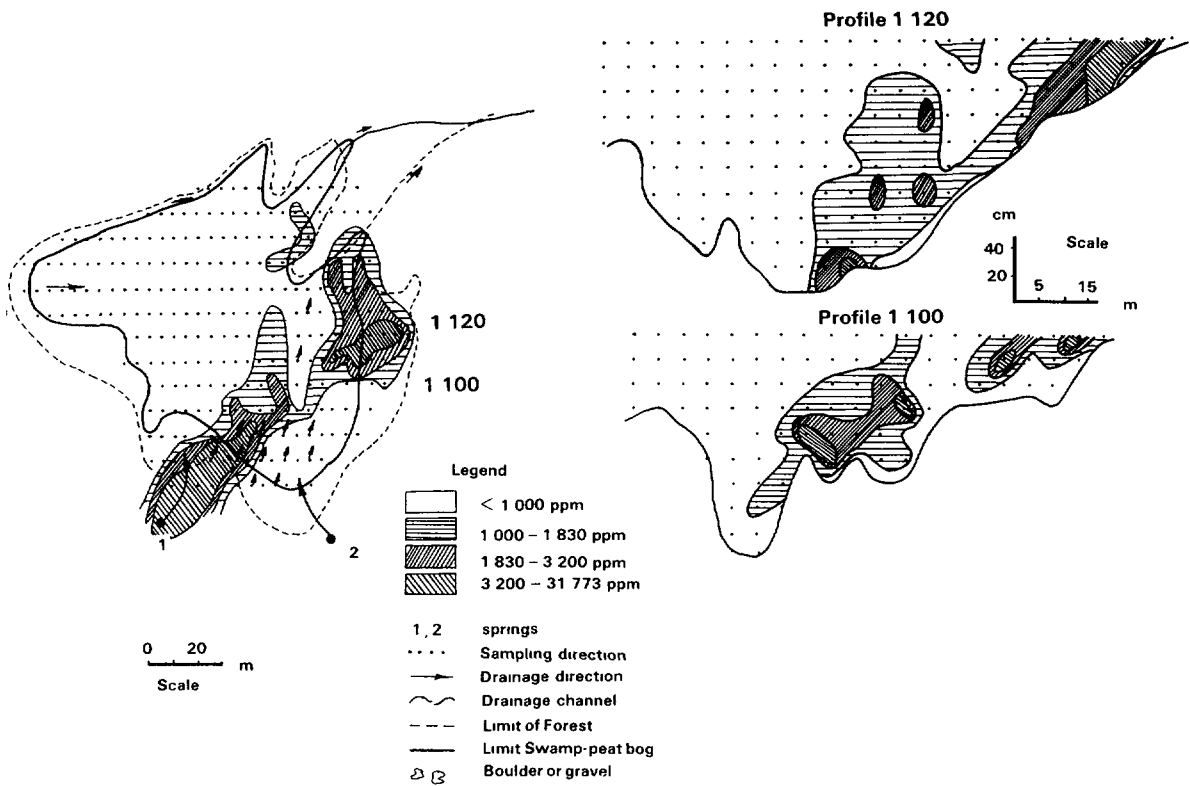


Figure 2
Contour map showing surface and vertical distribution of uranium in a peat bog near Jarre in Sweden.

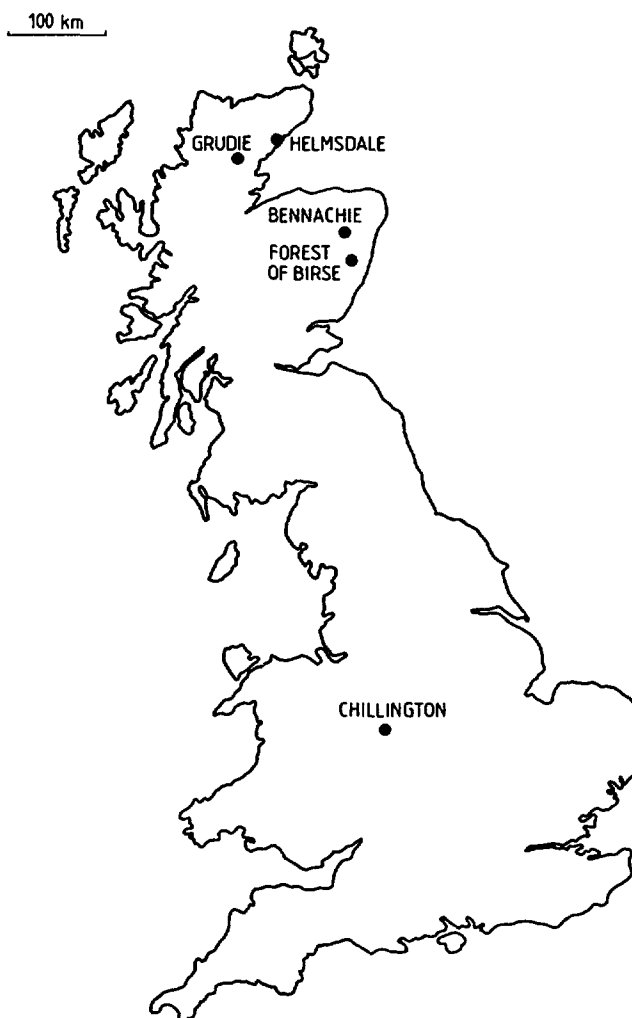


Figure 3
Localities of uraniumiferous peat bogs in the United Kingdom.

associated with uranium-enriched granites with labile uranium and fracture zones. Springs associated with the uraniumiferous black shales of Cambrian age, containing up to 330 ppm uranium, are not conspicuously radioactive, because the uranium in these shales is not labile.

The relationship between uranium and radium concentrations in bedrock, organic material, soils, and surface and groundwaters has been studied [3, 4, 5] as part of a wider investigation of radioelement geochemistry sponsored by the Radioactive Waste Program of SKBF (Swedish Nuclear Waste Supply Co.).

3. FINLAND

Uranium concentrations in peat bogs in Finland are described by Yliruokanen [6]. About 1 700 peat samples from 131 peat bogs in various parts of Finland were collected and analysed; 21 of these bogs were used for fossil fuel production and had low uranium contents. The uranium content in peat-ash exceeded 1 000 ppm in samples from seven bogs, all of which were on granitic bedrock, and the highest value recorded was 2.4 %. The distribution of uranium is irregular; high uranium contents are found only in a limited area in each case and are restricted to basal peat layers.

4. UNITED KINGDOM

4.1 English Midlands

Within the East Shropshire syncline, overlying the Triassic Keuper Marl, a marshy area adjacent to Chillington Brook (SJ 875 073) contains a shallow peat deposit enriched in uranium [7, 8]. A maximum value of 162 ppm uranium was measured in dry peat, corresponding to about 580 ppm uranium in the ashed sample. High concentrations of several other elements, notably vanadium (up to 8 500 ppm) and also including Ni, Co, Ba, Cu and Zn are present in the peat. Radiometric readings throughout the uraniumiferous zone (some 1 300 x 70 m) are generally low (7 to 10 R/h) indicating that the uranium is young in its present environment. The underlying Keuper Marl contains only 3 ppm uranium, while groundwaters in this region contain up to 30 ppb uranium.

4.2 Scottish Highlands

In the Lairg district of Sutherland, areas of high uranium in peat and glacial overburden occur near the southeast margin of the Grudie granite [7, 9, 10]. Enhanced uranium concentrations (200 ppm) were measured in samples of dried peat derived from an area (about 500 x 160 m) in the outer margins of the granite and over the adjacent Moine schists. The highest uranium value (24 ppm) in rock was recorded from this sector of the stock. Attendant cross-cutting galena-fluorite veins in the granite and adjacent schists contribute to associated enrichments of lead (2 000 ppm), molybdenum (100 ppm), copper and zinc in the peaty soils of this zone

High uranium concentrations have also been determined in peat and peaty soils from several other Caledonian granites of northern Scotland.

Uranium levels greater than 3 000 ppm have been measured over parts of the Helmsdale pluton and the Durriss (northeast) part of the Forest of Birse granite mass. High uranium contents have also been found in peaty soils overlying the Bennachie granite. No systematic studies to elucidate the extent and origin of these enrichments have been undertaken.

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REFERENCES

- [1] ARMANDS, G., Geochemical prospecting of a uraniumiferous bog deposit at Masugnsbyn, northern Sweden, In, *Geochemical Prospecting in Fennoscandia*, A. Kvalheim (Ed.), Interscience Pub, New York (1976) 127–154
- [2] DUGERDIL, Y. Prospection géochimique dans la région de Lovos, Univ. of Geneva, Dep of Minerology (1976)
- [3] EK, J., Bearbetning av uranhaltmätningar i vatten och backtorv från backer i Sverige (Interpretation of uranium concentration determination in water and organic stream sediment samples from streams in Sweden), SKBF-KBS Technical Report 1981–11 Stockholm, KBS (1981).
- [4] EK, J., EVANS, S., BERGMAN, R, Variations in radioactivity, uranium and radium 226 contents in three radioactive springs and along their outflows, northern Sweden, Studsvik report NW-82/177, Studsvik Energiteknik AB, (1982).
- [5] EVANS, S, BERGMAN, R, Uranium and radium in Finnsjön — an experimental approach for calculation of transfer factors, SKBF-KBS Technical Report 1981–04 Stockholm, KBS (1981).
- [6] YLIRUOKANEN, I., The occurrence of uranium in some Finnish peat bogs, *Kemia-Kemi*, 4 (1980) 213–217.
- [7] BOWIE, S.H.U., OSTLE, D., CAMPBELL, C.B., Uranium mineralization in northern Scotland, Wales, the Midlands and southwest England, *Trans. IMM Sect. 82* (1973) 177–179.
- [8] BOWIE, S.H.U, BALL, T K, OSTLE, D, Geochemical methods in the detection of hidden uranium deposits, In, *Proc 3rd Int. Geochemical Exploration Symposium*, Toronto, CIM Special Vol. II (1971) 103–111
- [9] MICHIE, U. McL, GALLAGHER, M.J., SIMPSON, A., Detection of concealed mineralization in northern Scotland, In, *Proc. 4th Int Geochemical Exploration Symposium* (1973) 117–130.
- [10] GALLAGHER, M J., MICHIE, U McL, SMITH, R.T., HAYNES, L., New evidence of uranium and other mineralization in Scotland, *Trans. IMM Sect. B 80* (1971) 150–173.

DEPOTS SUPERFICIELS D'URANIUM EN MAURITANIE

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ABSTRACT-RESUME

SURFICIAL URANIUM DEPOSITS IN MAURITANIA

In the Ain Ben Tili region of northern Mauritania, uraniumiferous calcareous clastic sediments have been discovered at the base of the flat hammada surfaces overlooking the Saharan Reg. The groundwaters are phreatic, neutral to slightly alkaline, and have a high content of total dissolved solids, particularly sodium and chloride. The source of the uranium in the hammadas is the calc-alkaline granite of the Reguibat basement which contains between 20 and 30 ppm uranium. Precipitation of the epigenetic uranium minerals and calcium carbonate is due to oscillations in the groundwater table and occurred behind local structural barriers.

DEPOTS SUPERFICIELS D'URANIUM EN MAURITANIE

Dans la région de Ain Ben Tili au nord de la Mauritanie, des pédiments clastiques calcaires uranifères ont été découverts à la base des surfaces plates d'hammada dominant le Reg saharien. Les nappes souterraines sont phréatiques, l'eau est neutre ou légèrement alcaline, et a une grande teneur en solides totalement dissous, en particulier du sodium et des chlorures. La source d'uranium dans les hammadas est le granit calco-alcalin de la roche de base du Reguibat. Ce granit a une teneur en uranium comprise entre 20 et 30 ppm. La précipitation des minéraux d'uranium épigénétiques et du carbonate de calcium est due aux oscillations dans la table des nappes et a eu lieu derrière des barrières structurales locales.

Des concentrations uranifères de type calcrete ont été découvertes dans le Nord de la Mauritanie à proximité de la frontière avec le Sahara Occidental et l'Algérie. Elles se localisent dans les hamadas, surfaces tabulaires dominant le reg saharien de quelques mètres à quelques dizaines de mètres. Cette région fait partie de la dorsale Reguibat, une des composantes du craton ouest africain. Pour l'essentiel, la dorsale est constituée de granite calco-alcalin (type Ain Ben Tili) associé à des granites gris, des microgranites, des rhyolites et des filons de quartz, pegmatites et dolérites [1]. Le climat actuel de la région est aride et chaud avec des précipitations moyennes annuelles comprises entre 20 et 50 mm [2] et des températures moyennes annuelles très élevées. Le réseau hydrographique est constitué d'oueds aboutissant à des zones dépressionnaires ou sebkhas, nom local des lacs salés. L'écoulement de ces cours d'eau intermittents s'effectue vers le Sud, conséquence du basculement tertiaire de la dorsale Reguibat.

Les hamadas se présentent comme des plateaux tabulaires à bords pentus qui dominent le reg avoisinant d'une hauteur dépassant rarement 15 m [1]. Ce sont les plus anciennes des formations récentes déposées sur le vieux craton ouest africain. Il existe deux dépôts hamadiens successifs reposant sur une formation de base conglomératique, appelés hamada basse et hamada haute ou blanche. La formation conglomératique basale est complexe (formation d'Iguetti) et repose sur le socle granitique arénisé (Figure 1).

L'altération des granites est peu poussée, c'est une isaltérite à structure grenue reconnaissable et à feldspaths conservés [3]. Les granites gris sont beaucoup plus altérés que les granites roses du type Ain Ben Tili [1]. La présence de fragments de tailles variées provenant probablement d'une croûte ferrugineuse antérieure [4], de galets détritiques siliceux à produits ferrugineux [3] et de traces d'anciens sols ferrallitiques [5] laisse supposer le développement sur ce socle d'une histoire pédologique complexe. Les formations détritiques les plus récentes auraient pour origine le remaniement d'un puissant manteau d'altération [1]. Sur le socle altéré s'est déposée la formation d'Iguetti, conglomérat dont le matériel détritique constitutif proviendrait de sources proches voire de remaniements in situ [3]. Les dépôts hamadiens proprement dit forment un ensemble gréseux mal trié dont une partie seulement a subi un transport. 5 % des grains sont façonnés par l'eau, 35 % sont des grains éoliens et 60 % sont des grains non usés [6]. Les deux formations détritiques successives ont été, par la suite, affectées de phénomènes appelés hamadisations. Celles-ci comportent des carbonatations, des gypsifications et des silicifications [1]. L'argilisation des dépôts est soit primaire, soit secondaire [1]. La fraction argileuse est composée d'un mélange de montmorillonite et d'attapulgite, le pourcentage de montmorillonite diminue avec la présence des carbonates et de la silice et disparaît quand les carbonatations et les silicifications sont massives (barre calcaire et silcrete terminal). La sépiolite fait alors son apparition [1]. Les carbonatations sont des cimentations épigénétiques de formations détritiques et semblent liées à la circulation des nappes. Une phase terminale de silicification épigénétique certains de ces dépôts carbonatés. Du gypse et de la célestite ont été également observés. La minéralisation exprimée sous forme de carnotite est pour l'essentiel localisée dans la hamada basse mais elle se retrouve aussi dans les autres formations, arène granitique comprise.

Les nappes circulantes dans les hamadas ont des caractéristiques géochimiques similaires à celles des eaux des chenaux de l'Ouest australien [7,8,9] (Figure 2). Les eaux de trois sondages et d'un puits ont été analysées. Elles

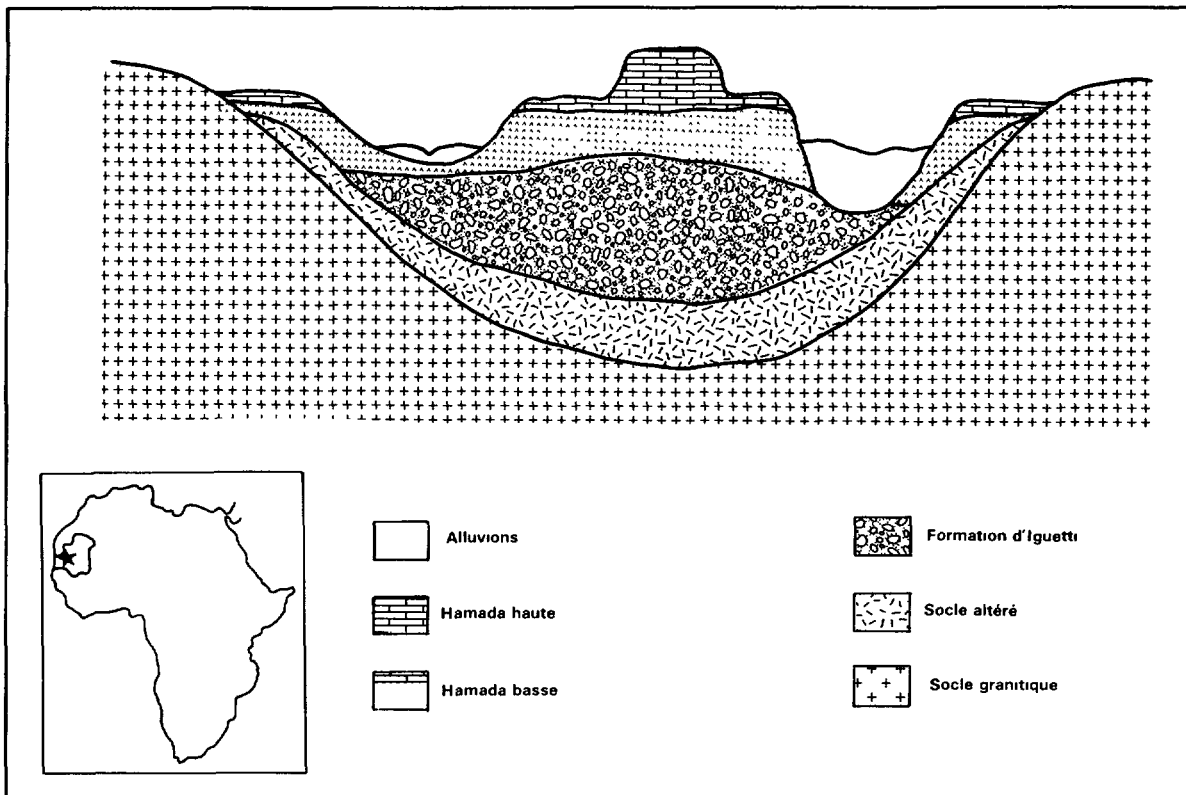


Figure 1
 Coupe schématique géomorphologique et géologique des hammadas de Mauritanie septentrionale (d'après Minatome SA).

Schematic geomorphological and geological section of the northern Mauritanian hammadas (after Minatome SA).

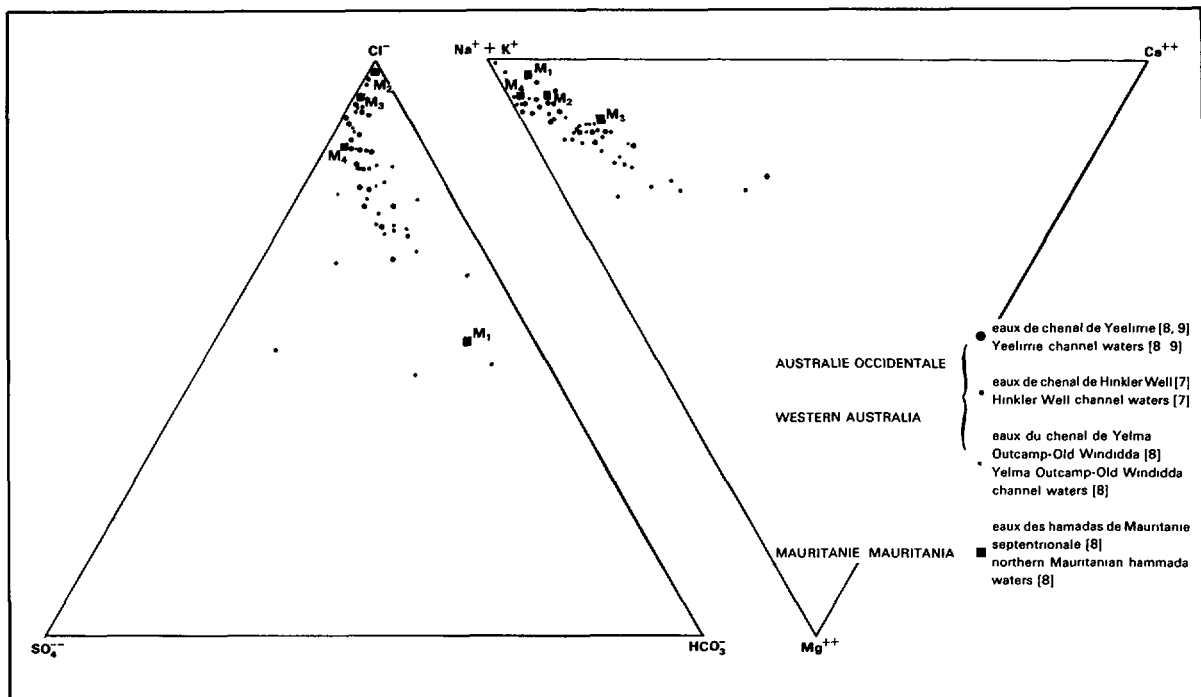


Figure 2
 Le chimisme des eaux des chenaux d'Australie Occidentale et des hammadas de Mauritanie septentrionale : représentation en diagramme triangulaire.

Triangular diagram representing the chemical composition of groundwaters in channels of Western Australia and the hammadas of northern Mauritania.

sont chlorurées sodiques à l'exception de l'eau du puits (M₁) qui tend à être bicarbonatée sodique. Cette caractéristique chlorurée sodique est commune à de nombreuses eaux superficielles et de nappes de l'Ouest africain, en particulier au Maroc et en Algérie [10,11,12,13]. Elle est liée à la recharge des nappes qui sont essentiellement alimentées par les eaux de précipitations. Leur pH est compris entre 7.0 et 8.1, leur salinité est élevée (entre 32 et 106 g/l) à l'exception de l'eau du puits (1.2 g/l), leur teneur en silice dissoute est forte (30 à 95 mg/l) [8].

Les caractéristiques hydrogéochimiques et minéralogiques des hamadas à occurrences uranifères tendent à montrer qu'il existe une grande similitude entre leurs processus de mise en place et celui qui est à l'origine du gisement de Yeelirrie (Australie Occidentale). Un mûrissement des eaux des nappes sous un climat aride et chaud amène les conditions nécessaires à la précipitation des carbonates et de la carnotite. L'installation des minéralisations uranifères est également favorisée en Mauritanie par l'existence de structures verrouses jouant en piège. La source de l'uranium est locale et à rechercher dans les granites qui ont des teneurs élevées comprises entre 20 et 30 ppm [5]. La libération de cet élément pourrait être en relation avec l'histoire complexe de l'altération du socle. L'histoire géochimique de cet élément avant son arrivée dans les eaux des nappes serait alors peu différente de celle mise en évidence en Australie Occidentale [14,15].

Ainsi la formation des gîtes uranifères de type calcrete dans les hamadas de Mauritanie septentrionale semble pour l'essentiel guidée par des facteurs climatiques et morphologiques. Par ailleurs, la localisation géographique de ces occurrences laisse à penser qu'il puisse en exister dans les pays avoisinants.

REFERENCES

- [1] BRAUN, R., Etudes des hamadas de la dorsale Reguibat, région d'Aïn Ben Tili (Rép. Isl. Mauritanie), Rapport DEA, Marseille, France (1974) 67.
- [2] FURON, R., Le Sahara, géologie, ressources minérales, Payot, Paris (1964) 313.
- [3] BRIOT, P., Phénomènes de concentration de l'uranium dans les environnements évaporitiques intracontinentaux : les calcretes de l'Ylgarn australien. Essai de comparaison avec les calcretes de Mauritanie et de Namibie, Thèse 3^e cycle, Orsay, France (1978) 167.
- [4] BARRERE, J., SLANSKY, M., Note explicative de la carte géologique au 1/2 000 000^e de l'Afrique Occidentale, Mém. Bur. Rech. Géol. Min. 29 (1965) 120.
- [5] MINATOME SA, Communication orale.
- [6] FURON, R., Minéraux de l'Afrique Occidentale, Mém. Mus. Nat. Hist. Nat., (C), IV, 2 (1954) 177–192.
- [7] MANN, A.W., DEUTSCHER, R.L., Hydrogeochemistry of a calcrete containing aquifer near Lake Way, Australia, J. Hydrol., 38 (1978) 357–377.
- [8] BRIOT, P., Géologie et géochimie des gisements d'uranium liés aux milieux pré-évaporitiques intracontinentaux : les calcretes uranifères, Thèse d'Etat, Paris, France (1983) 216.
- [9] BRIOT, P., L'environnement hydrogéochimique du calcrete uranifère de Yeelirrie (Australie Occidentale), Mineralium Dep. (1983) (sous presse).
- [10] MARGAT, J., Les eaux salées au Maroc. Hydrogéologie et hydrochimie, Notes Mém. Serv. Géol. Maroc (1967) 137.
- [11] BLANC, P., CONRAD, G., Evolution géochimique des eaux de l'oued Saoura (Sahara Nord Occidental), Rev. Géogr. Phys. Géol. Dyn., X, 5 (1968) 415–428.
- [12] CONRAD, G., L'évolution continentale post-Hercynienne du Sahara algérien, CNRS, Paris (1969) 527.
- [13] CONRAD, G., Modèles de sédimentation évaporitique continentale actuelle, en zone aride nord-saharienne (Algérie) ; comparaison avec le Quaternaire, 9^e Congr. Intern. Sédim., Nice, France (1975) 29–34.
- [14] BRIOT, P., Sur la genèse de certains gîtes uranifères, Mineralium Dep., 17 (1982) 151–157.
- [15] BRIOT, P., FUCHS, Y., A contribution on morphology and geochemistry of some uranium-bearing calcretes, Même ouvrage (1984).

SURFICIAL URANIUM DEPOSITS IN NAMIBIA

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ABSTRACT

SURFICIAL URANIUM DEPOSITS IN NAMIBIA

Uranium resources of the surficial uranium deposits in the < \$130/kg U cost category of Namibia amount to 33 300 t uranium, which constitute about 24 % of the uranium inventory for that country. There are six relatively large, fluvialite surficial uranium deposits — Aussinanis, Tubas, Tumas, Langer Heinrich, Trekkopje and Spitskoppe — none of which are being mined at this time. In addition, there are a number of uneconomic pedogenic occurrences of which the biggest is Mile 72. The deposits occur in the central Namib Desert between the Great Escarpment in the east and the “western cutoff line” in the west, which is an area situated to the east of Walvis Bay. Uraniferous fluvialite sediments occur in the Namib Group, but mainly in the Langer Heinrich and Tumas Formations, which were deposited by high-energy, flash-flood conditions in deep palaeochannels formed during the Upper Cretaceous. The uranium occurs largely as carnotite in the Langer Heinrich Formation and is associated with calcite and dolomite, but in the Tubas deposit it is found in the gypsum-rich sediments of the Tumas Formation. The age of the uranium mineralization is probably Upper Tertiary. Precipitation of carnotite in the large thick fluvialite deposits was controlled mainly by redox reactions, the adsorption of vanadium on active surfaces and soil suction.

1. INTRODUCTION

The discovery of the surficial uranium deposits of Namibia in the early 1970's is credited to airborne radiometric surveys, made by both sophisticated equipment and a portable scintillometer mounted in a low-flying small aircraft. After subsequent ground exploration, the nature of the orebodies became better known and became the basis for adopting new target selection methods and new prospecting techniques.

In Namibia, surficial uranium deposits occur in fluvialite and in pedogenic environments on the coastal plain of the Namib Desert, mainly between the escarpment in the east and the “western cutoff line” in the west (Figure 1).

Climatically, the Namib Desert is extremely dry, and all of the major surficial uranium deposits occur within the 100 mm isohyet; the eastern boundary of this area corresponds to the escarpment. The arid environment has preserved these uranium deposits.

The uranium resources recoverable at cost categories less than \$130/kg uranium and \$130 to \$260/kg uranium are given in Table 1 [1]. Within the Reasonably Assured Resources and Estimated Additional Resources in the \$130/kg uranium category, the uranium in the surficial sediments constitutes approximately 24 % of the total uranium inventory. The uranium deposits in the Karoo sediments are included in these figures, but they may be regarded as negligible. This indicates that the Namibian surficial uranium deposits could become of considerable economic importance if the price of uranium were to increase. An important feature of these uranium deposits is that they are within the upper 15 to 25 m, and could make opencast mining an attractive proposition.

Resource evaluation is difficult because of the patchy nature of the ore and the problem of disequilibrium where the ratio, chemical uranium/spectrometric uranium, is between 0.5 and 2.0. At times this hampers accurate radiometric borehole logging and grade control [2].

2. GENERAL GEOLOGY OF THE CENTRAL NAMIB DESERT

The surficial uranium deposits in Namibia are on the coastal plain of the Namib Desert in palaeovalleys of ancient river systems that flowed westwards from the Great Escarpment (Figure 1) during the Upper Cretaceous and Lower Tertiary, about 88 to 25 Ma, and in decomposed basement rocks. They occur in the Namib Group (Figure 1), but are largely confined to the Tumas and Langer Heinrich Formations [3]. The Namib Group occurs between the “western cutoff line” (Figure 1) in the west, a line possibly marking the highest wave-cut platform during an earlier marine transgression, and the Great Escarpment in the east. It unconformably overlies the basement rocks of the Damara Sequence and the Abbabis Complex that are composed of metasedimentary, gneissic, and granitic units. The lithological relationship of the Namib Group and the Damara Sequence is given in Table 2. Granitic rocks of various ages occur throughout the basement, and their spatial distribution is important from the point of view of the occurrence of surficial uranium deposits. The larger granitic bodies, such as the syntectonic granite gneiss and Salem Granite, and the post-tectonic intrusions, are in some localities enriched in uranium. They probably constituted the source rocks for the uranium mineralization of the Namib Group.

The Langer Heinrich Formation is largely of fluvialite origin, having been deposited during sporadic, high-energy regimes — e.g. heavy rains, flash floods — typical of desert climates. Sedimentary structures, such as scour channels and erosion surfaces, are common. In general, the sedimentary units appear to be upward-fining, with conglomerates developed near the base of the respective channels; occasionally, downward-fining sequences

Table 1
Recoverable uranium resources in tonnes U as at 1 January 1981,
FOR NAMIBIA IN THE < \$130/kg U COST CATEGORY

ROCK TYPE	REASONABLY ASSURED RESOURCES (RAR)		ESTIMATED ADDITIONAL (EAR)	
	Recoverable at < \$80/kg U	Recoverable at < \$80-130/kg U	Recoverable at < \$80/kg U	Recoverable at < \$80-130/kg U
Granitic rocks	93 000	9 000	15 000	21 000
Karoo strata and younger surficial sediments	26 000	7 000	15 000	2 000
TOTAL	119 000	16 000	30 000	23 000

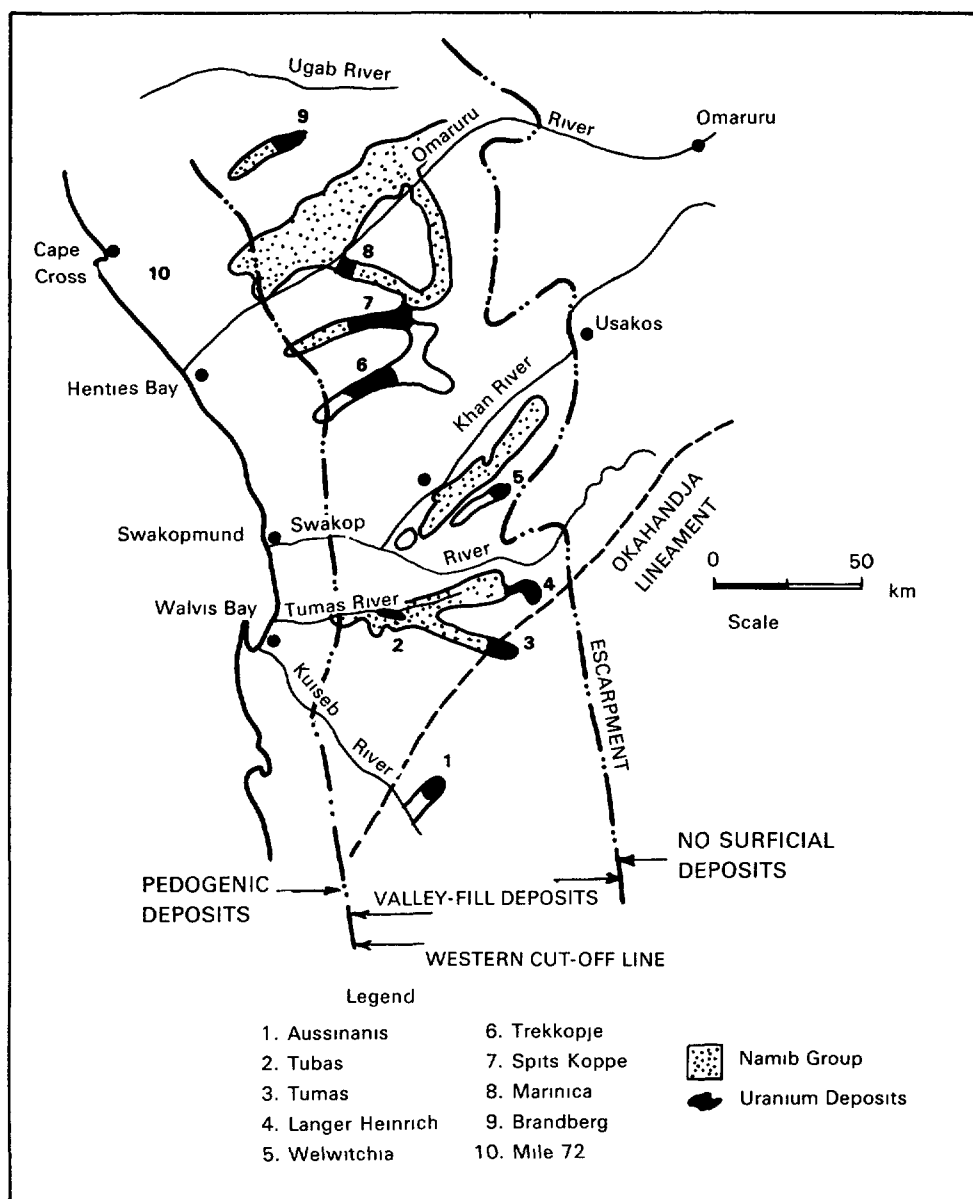


Figure 1
The distribution of the surficial uranium deposits in the Namib Group.

Table 2
Stratigraphic column of the Central Namib Desert

Group	Subgroup	Formation	Epoch
Namib	Gawib	Sossus Sand Bloedkoppie (in east) Tumas (in west)	Recent to Pliocene
	Unconformity		
	Gobabeb	Langer Heinrich Tsondab	Miocene
Unconformity			
Damara Sequence	Swakop	Kuiseb Karibib Chuos	Late Precambrian
		Unconformity	
	Ugab	Rössing	
	Unconformity		
	Nossib	Khan Etusis	Precambrian
Unconformity			
Abbabis Complex			Proterozoic

have been noted. Thicknesses as much as 200 m have been found during drilling, occurring in what were probably gorges formed during the Upper Cretaceous and early Tertiary. The sediments consist mainly of angular basement debris, in variable and alternating bands of conglomerate, grit, sand, clay-grit and clay. There are more coarser fractions, such as sand and boulders, than of silt and clay.

The Tumas Formation occurs mainly in the Tumas River valley and unconformably overlies the Langer Heinrich Formation. It consists of poorly consolidated gypsiferous red sands that occur as continuous bodies several square kilometres long. Rounding, and the fineness of the sand grains, suggest an aeolian origin, but the presence of occasional pebbles and the lack of internal bedding planes has led to the suggestion that these sands form part of a series of mass flow deposits (L.E. Minter, personal communication). The colour of the sands changes gradually with depth from yellow-brown to pale grey.

The sediments of the Namib Group and overlying pedogenic material have been cemented by authigenic calcite, dolomite, gypsum, and occasionally carnotite. These matrix minerals were introduced during several stages of precipitation, the oldest probably being of mid-Tertiary age.

Uranium in the Namib Desert occurs chiefly as the mineral carnotite, but soddyite has also been reported from the small Welwitchia occurrence [5]. Carnotite occurs interstitially along grain boundaries, filling cavities and has maximum development in zones of high porosity. To date, no reduced surficial uranium occurrences have been found.

The age of the uranium mineralization is difficult to establish, but determinations using the disequilibrium technique indicate that it is greater than 0.5 Ma. However, geological relationships suggest that an Upper Tertiary age (2 to 5 Ma) is more likely.

3. GEOLOGY OF SELECTED URANIUM OCCURRENCES

In Namibia, there are at least six major surficial uranium deposits that have a potential for production under a more favourable economic climate. These include Aussinanis, Tubas, Tumas, Langer Heinrich, Trekkopje and Spitskoppe. These are all very similar fluvial deposits and only some will be described to illustrate the essential features of their formation. Another occurrence, Mile 72, though not economic, is of pedogenic origin, formed by surficial enrichment of weathered basement rocks.

3.1 Tubas

The Tubas* uranium deposit (Figure 2) is about 40 km east of Walvis Bay within the middle portion of the Tumas* River (Figure 1). During the early Tertiary, the Tumas River was part of a large drainage system and probably

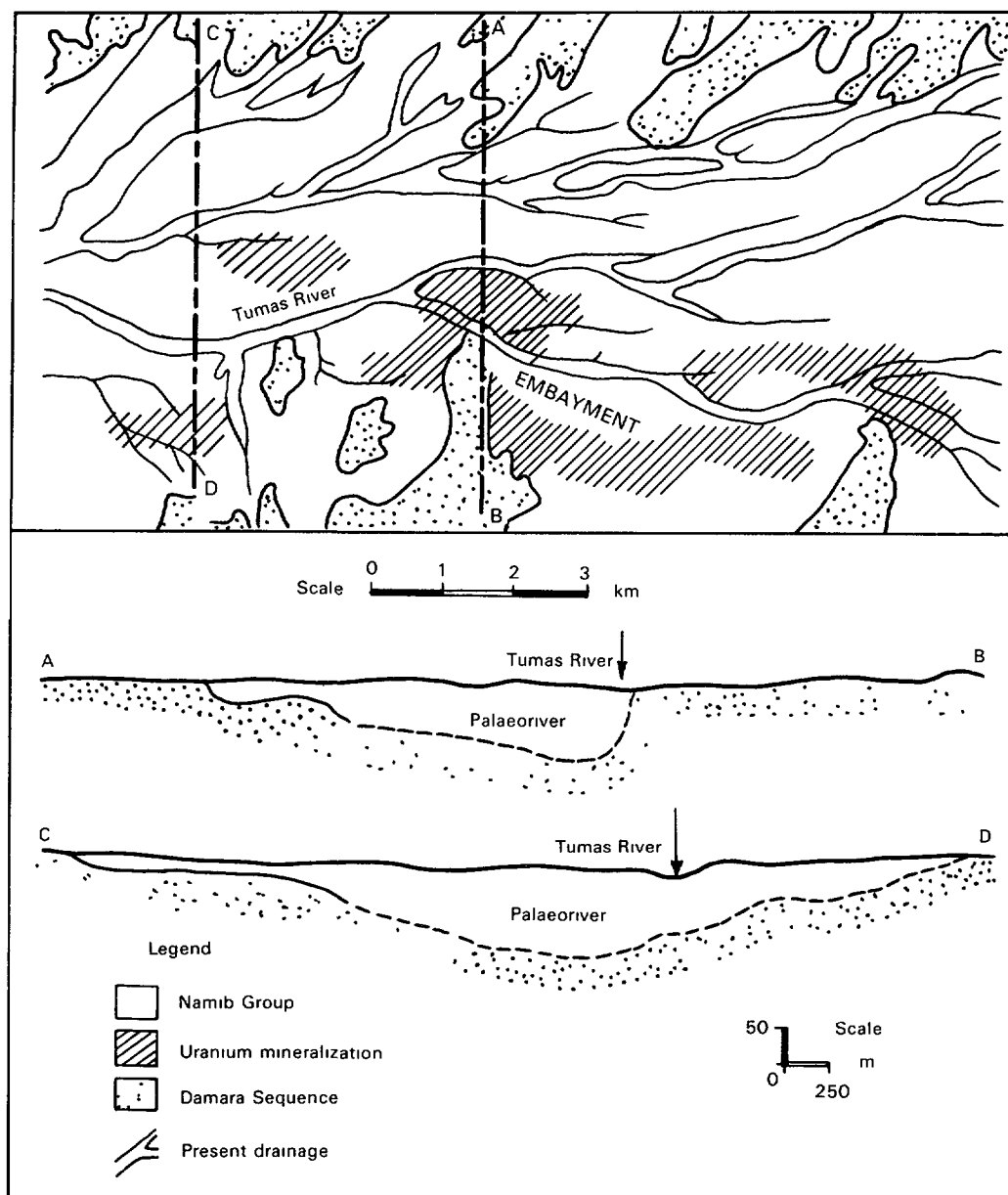


Figure 2
Geology of the Tubas uranium deposit (Anglo American Corp of SA Ltd)

* The terms Tubas and Tumas should not be confused. The Tubas deposit occurs in the central portion of the Tumas River. The Tumas uranium deposit occurs in the same river but to the east (Figure 1)

formed the southwestern extension of the modern Swakop River. Prominent northeasterly trending ridges of the Khomas Subgroup have been cut by the Tumas River and it appears that they played an important constricting role in the deposition of the uranium.

The Namib Group at Tubas is in excess of 100 m thick in places and consists of the Tumas Formation, 5 to 15 m thick and the unconformably overlying Langer Heinrich Formation. Generalized lithological descriptions of the succession are given in Figure 3 and the relative mineralogical proportions in Figure 4.

Bright yellow carnotite is the only uranium mineral that has been recognized in this area. It occurs between the sand grains and forms part of the interstitial cement that consists mainly of gypsum and, to a lesser extent, calcite and hematite. In a zone near the surface, carnotite occurs between the "petals" of small gypsum desert roses and also as coatings in worm burrows or shrinkage cracks and around the larger clasts.

Concentrations of uranium minerals occur at various depths, those of ore grade are in tabular bodies, mostly in the upper 20 m of the red sands of the Tumas Formation. A major concentration of uranium occurs within an embayment created by a wedge of marble of the Karibib Formation jutting out into the south bank of the main channel of the Tumas River (Figure 2).

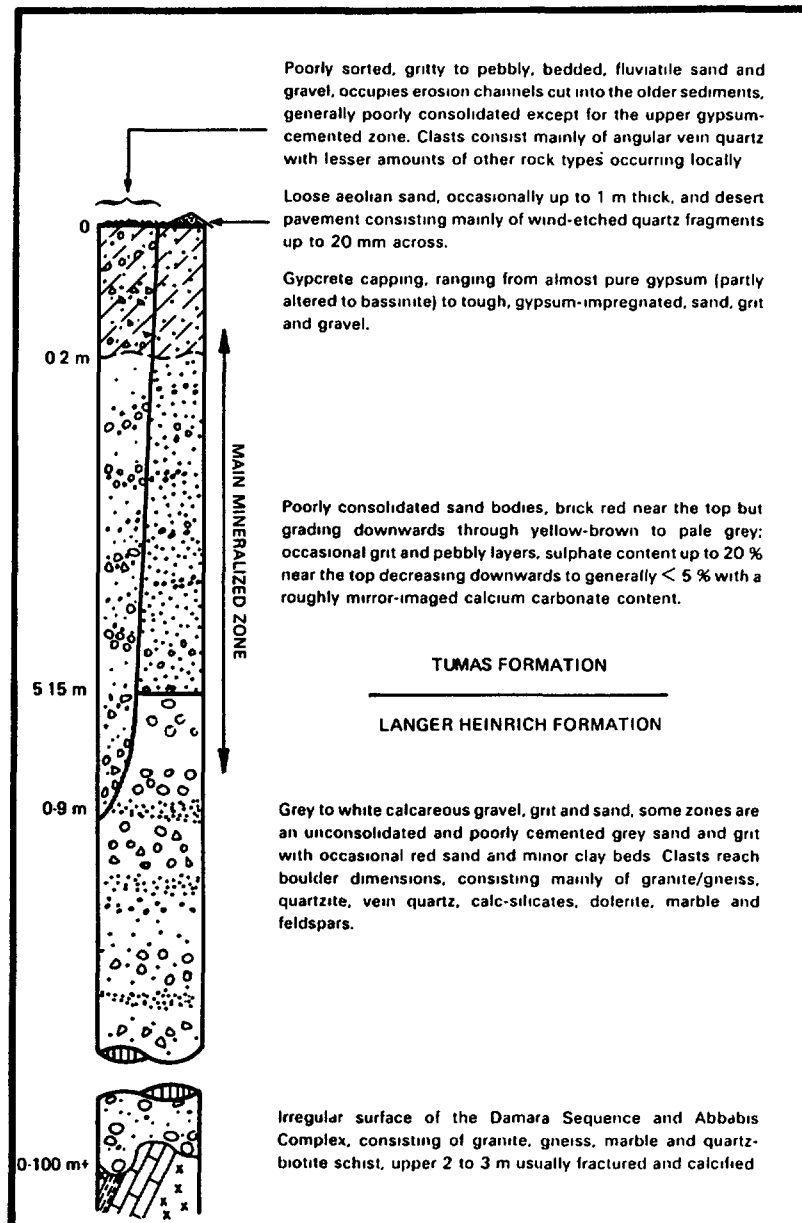


Figure 3
Generalized stratigraphic column for the Tubas uranium deposit (Anglo American Corp. of SA Ltd.).

3.2 Langer Heinrich

The Langer Heinrich uranium deposit is in the Gawib River valley, between the Langer Heinrich Mountain and the Schieferberge, approximately 100 km east of Walvis Bay (Figure 1). The geology of the deposit has been described elsewhere [4, 5, 6, 7]. A geological map of the area is shown in Figure 5 and the relative mineralogical proportions of the Langer Heinrich Formation are given in Figure 6. The basement rocks of the Langer Heinrich area comprise the Nosib and Swakop Groups (Table 2), which are mainly metaquartzite and schist respectively, into which the late-syntectonic to post-tectonic Bloedkoppie Granite pluton and numerous pegmatites have been intruded.

The Bloedkoppie Granite has importance as it is the probable source of the uranium in the Langer Heinrich Formation. It is a medium-grained, but locally coarse-grained leucogranite with quartz, microcline, plagioclase, and biotite as the main constituents. It has a mean uranium content of 18 ppm and Th/U ratio between 0.9 and 2.6 which gives it a weak radiometric signature [5].

The surficial sediments in the Gawib River valley comprise the Langer Heinrich and Bloedkoppie Formations (Table 2). Headward erosion by the Gawib River initiated by uplift during the Pleistocene, resulted in exposure of the Langer Heinrich Formation. Geophysical investigations, and percussion drilling on the Gawib Flats at the western end of the Gawib River, have shown that the channel narrowed considerably and, at this point, probably

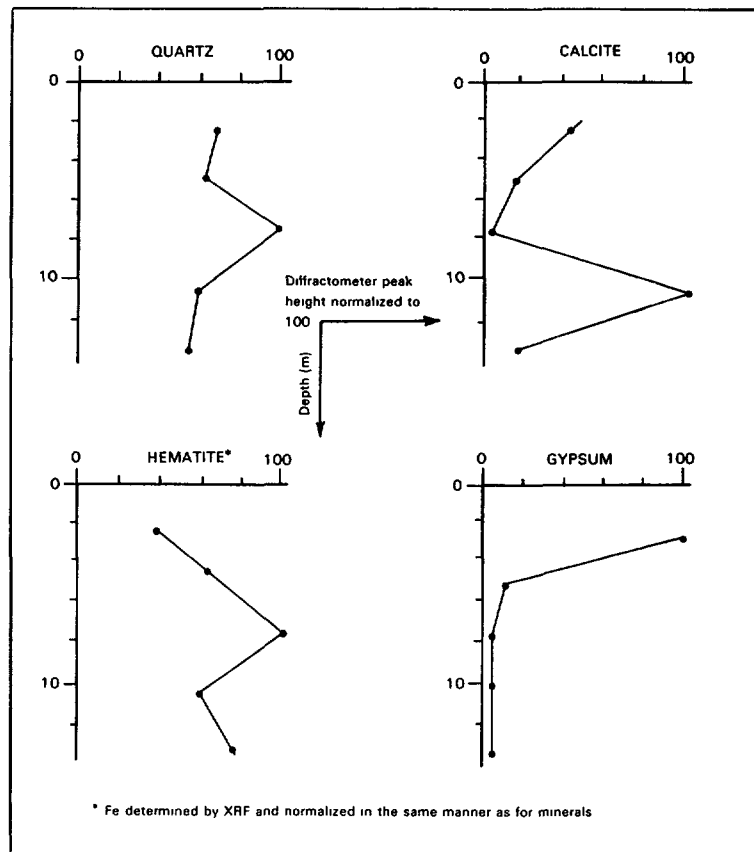


Figure 4
Relative mineralogical proportions of the Tumas Formation.

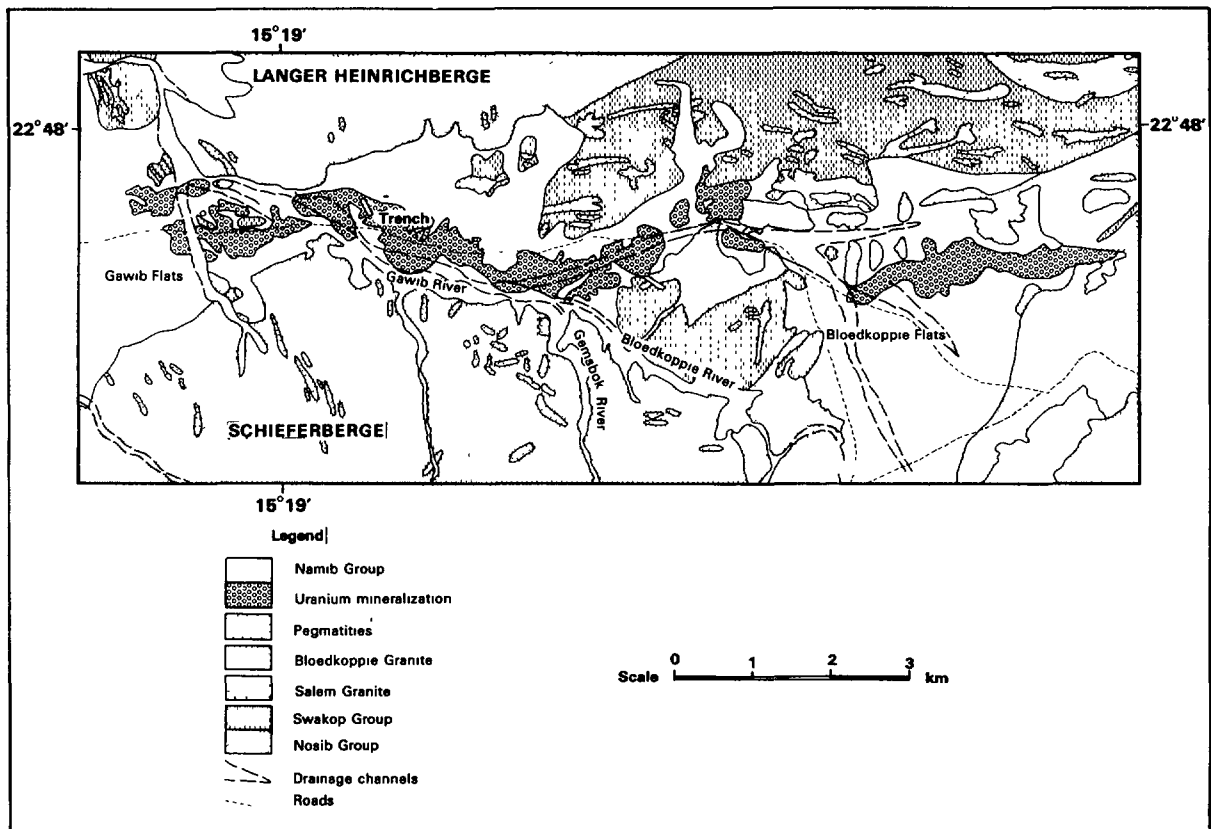


Figure 5
Geology of the Langer Heinrich uranium deposit (Gencor).

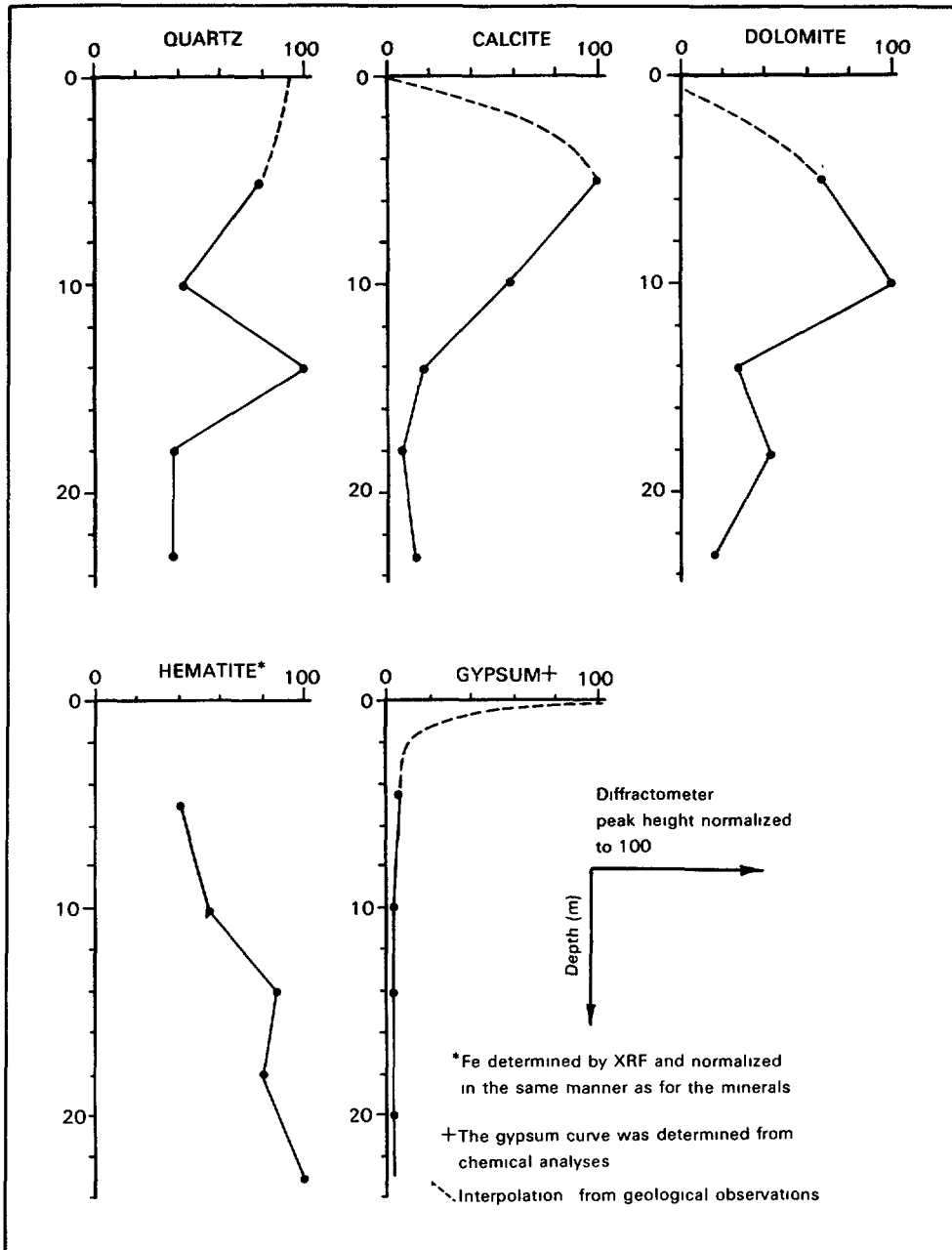


Figure 6
Relative mineralogical proportions of the Langer Heinrich Formation.

first became choked with surficial sediments of the Langer Heinrich Formation. Prior to this event, the Gawib River was probably a tributary of the Tumas River.

The uranium deposit has been almost fully delineated and the distribution of the uranium is shown in Figure 5. Depths to the base of the palaeochannel are variable and sedimentary thicknesses up to 45 m have been recorded. In general, the uranium mineralization is confined to the Langer Heinrich Formation, with only a small amount in the Bloedkoppie Formation (B. Fletcher, personal communication), and is probably the result of a later, minor redistribution of uranium from the Langer Heinrich Formation. The uranium deposit extends from the Bloedkoppie Flats in the east, westwards along the Gawib River palaeovalley and continues under the Gawib Flats.

The generalized distribution of the uranium is shown in a cross-section (Figure 7) through the Langer Heinrich Formation. The grades tend to be highest in a central core zone, which does not necessarily correspond to the present water table.

Detailed mapping of the eastern wall of a large trench and radiometric total count logs of the centre-line boreholes are shown in Figures 8 and 9. Comparing both sections, it is observed that there are numerous lithological units in the Langer Heinrich Formation and that there is almost no correlation between the uranium

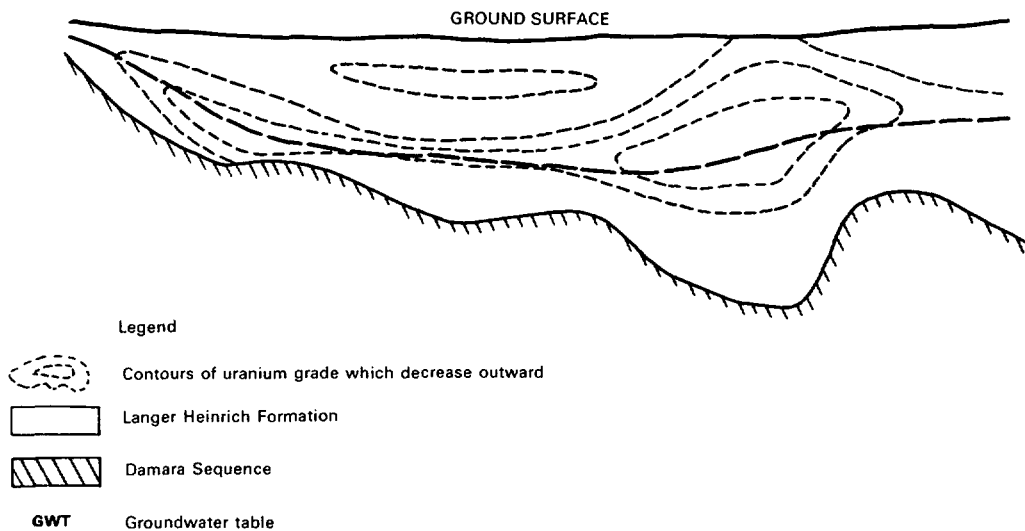


Figure 7
Generalized distribution of the uranium grade in a cross section through the Langer Heinrich.

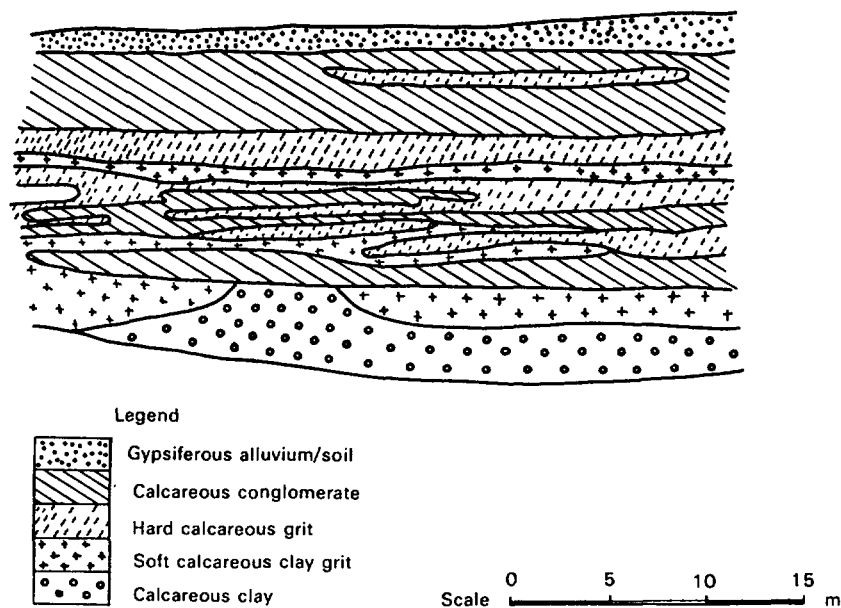


Figure 8
Lithology of the Langer Heinrich Formation in the eastern side-wall of a trench at the Langer Heinrich (Gencor).

content and the lithology of the sediments. Furthermore, the uranium distribution is totally irregular and discontinuous. Boreholes within a metre or less of each other have completely different radiometric grades, demonstrating the patchy nature of the ore, which was formed in pods, veins, lenses and particularly as cavity fillings. The highest uranium grades are in those parts that are least consolidated, i.e. zones low in carbonate cement and which therefore possess the highest porosity. Within the clay portions of the sediments, calcium carbonate-rich nodules and tubules frequently contain high-grade uranium mineralization.

The colour of the sediments exposed in the trench varies from greyish to reddish-brown; intermediate yellowish-brown tones are most common. The clay tends to be slightly greenish-blue, being, in part, the original colour of the micaceous material derived from the schist of the Kuiseb Formation. Within the upper Langer Heinrich Formation, there is no direct evidence from the colour of the sediments of redox control. Determination of iron (II)/iron (III) ratios shows that the more reduced sections tend to be nearer the surface and that the degree of oxidation increases with depth down to 20 m. This agrees with the observation that when bright yellow carnotite is exposed at the surface, it sometimes tends to become slightly green, probably as a result of the reduction of vanadium (V) to vanadium (IV), the latter having a green colour. Newly excavated carnotite has not been found to be greenish in colour.

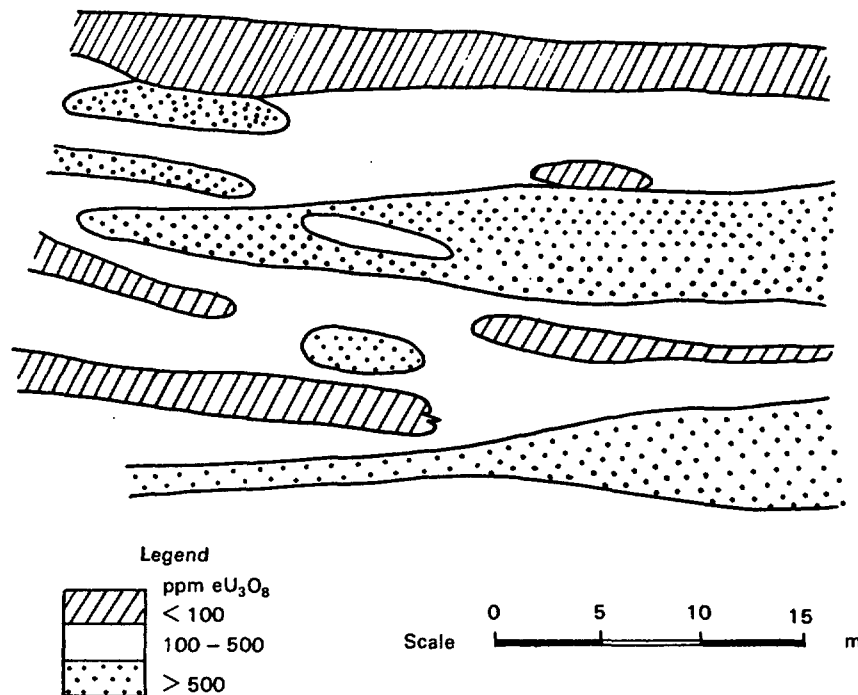


Figure 9

Equivalent uranium distribution in the Langer Heinrich Formation as determined in the centre — line boreholes in a trench at the Langer Heinrich (Gencor).

The paragenetic carnotite/calcite relationships in the Langer Heinrich Formation indicate that several ages of calcite precipitation took place, probably starting in the Upper Tertiary [4, 5]. Carnotite is associated with one of the earlier, coarse-grained, calcite fractions. Geomorphologically, the carnotite seems to predate the Pleistocene uplift that caused the incising of the Gawib and Swakop Rivers. The last two empirical relationships indicate, therefore, that precipitation of the carnotite took place during Upper Tertiary times.

3.3 Mile 72

Pedogenic uranium occurrences are common in Namibia, the most important being Mile 72. Many calcrete and gypcrete cappings and outcrops contain small amounts of carnotite, which implies that uranium is still mobile. Occurrences of this nature may constitute the proto-ore for future uranium occurrences within fluvial regimes.

Mile 72 comprises a cluster of uranium occurrences situated along the coast between Henties Bay and Cape Cross (Figure 1), 72 miles (95 km) north of Swakopmund. It lies on the coastal plain of the Namib Desert in the weathered and decomposed basement rocks.

The basement metasedimentary rocks belong mainly to the Khomas Subgroup and consist of marbles, metaquartzites, calc-silicates, and schists, into which various granites such as the syntectonic Salem Granite and post-tectonic pegmatites and alaskites were intruded. Primary uranium minerals such as uraninite, betafite, monazite and apatite occur mainly in the alaskite. The thin veneer of Tertiary to Recent surficial material overlying the basement rocks consists of aeolian sand, isolated remnants of fluvial gravel and desert soil, all of which have been cemented by gypsum and, to a lesser extent, by halite and calcite. These secondary cementing minerals extend down into the basement rocks, filling joints, fissures, and cleavage planes.

During the marine transgression of the late Pleistocene and early Quaternary, most of the surficial sediments, and probably the Langer Heinrich Formation, were eroded west of the "western cutoff line" (Figure 1). Basement rocks were exposed and only remnants of the Langer Heinrich Formation remained in depressions.

The uranium is patchy, and occurs in several pockets associated with metasediments, granite and dolerite. Secondary minerals, such as carnotite (the dominant phase), and minor amounts of phosphuranylite, occur principally above the water table. Phosphuranylite is closely associated with apatite.

One occurrence in metasediments varies from 1 to 30 m in width and extends to 18 m in depth. From trenching operations, it was found that the main uranium deposit occurs near the contact between calc-silicates and schist in association with quartz veins and alaskites. The metasediments are, in places, deeply weathered and replaced by crystalline and powdery gypsum and carnotite. Alaskites within this zone tend to be more radioactive than those occurring in less weathered material. However, this could be caused by either primary or secondary enrichments.

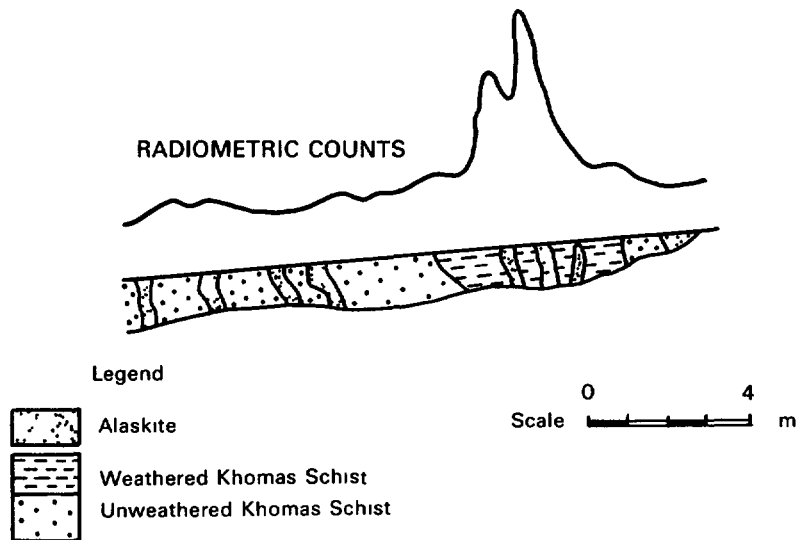


Figure 10
Trench section and radiometric profile through the uranium mineralization at Mile 72

A typical geological profile of a trench and the associated uranium distribution is shown in Figure 10. From the nature of the occurrences, it appears that the weathered zones and the joints in the basement rocks acted as sumps for the precipitation of carnotite, with the uranium largely having been derived in-situ from the various granites.

4. GENESIS OF THE CARNOTITE

Seven mechanisms for the precipitation of carnotite have been proposed [8, 9], of which three appear to be the most important in this context, viz., evaporation of groundwater, dissociation and decomplexing of the uranyl carbonates, and oxidation-reduction (redox) effects. An additional mechanism is the effect of adsorption of vanadium ions onto clay or hydroxide surfaces [5].

In considering the origin of the carnotite, the Namibian deposits can be divided into two main categories, (1) thick fluvial types in sedimentary piles, such as Langer Heinrich, have high economic potential, and (2) shallow or thin pedogenic types, such as Mile 72, having low economic potential.

In the fluvial type of deposit where sedimentary thicknesses exceed 5 m, it appears that the most important mechanism for the precipitation of carnotite is a redox control similar to that described by Mann and Deutscher [9]. The colour of the carnotite may vary from bright yellow to greenish-yellow, which suggests such a redox effect and the occurrence of vanadium (IV).

A plot of oxidation potentials versus pH values for groundwaters from the Namib Desert on a vanadium phase diagram is shown in Figure 11. Those points indicated by dots have vanadium concentrations less than 5 ppb and all fall into the H_2VO_4^- field where vanadium (V) is stable. Circled dots have vanadium concentrations greater than 5 ppb and fall within the paramontroseite stability field (vanadium IV) as defined by the solid phase boundaries for various vanadium concentrations. It is suggested that part of the vanadium in the groundwater is quadrivalent and can be absorbed onto reactive surfaces such as clay particles or hydroxides. In some unmineralized parts of the surficial sediments, there is an excess of vanadium over the uranium that is required for the precipitation of carnotite. Oxidation of the absorbed vanadium (IV) and decomplexing of the uranyl carbonate by partial evaporation or soil suction [5] in the presence of potassium, are the final steps in the formation of carnotite. Carnotite solubility indices (CSI) for the Langer Heinrich and Tumas regions vary between -0.5 and -5.5, suggesting that carnotite is at present dissolving.

The surficial material in shallow types of deposits is usually only a few metres thick and it appears that evaporation and subsequent decomplexing of the uranyl carbonate ions are the major precipitating mechanisms. Generally, the uranium and vanadium seem to have been derived mainly in-situ from an underlying source or from one in close proximity.

5. CONCLUSION

In Namibia the fluvial surficial deposits, for example Tubas and Langer Heinrich, contain major uranium resources, whereas the pedogenic type, such as at Mile 72, is unimportant.

The uraniumiferous fluvial sediments in the Namib Group, especially in the Langer Heinrich and Tumas Formations, were deposited under flash-flood conditions in deep palaeochannels. The sediments of the Langer

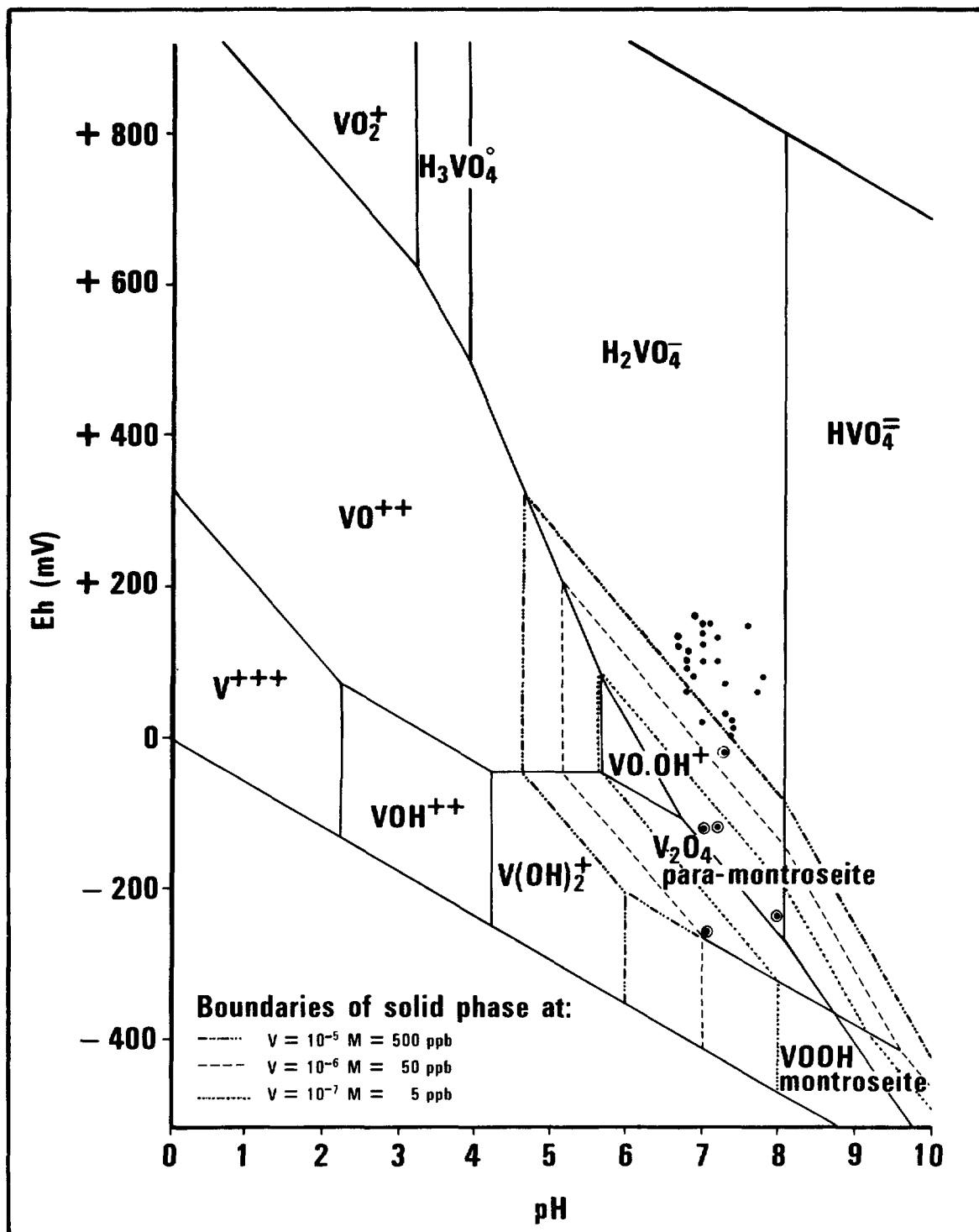


Figure 11

Vanadium phase diagram showing the plots of oxidation potentials of natural waters from the Namib Desert.

Heinrich Formation consist mainly of angular clastic basement debris forming alternating bands of conglomerate, gravel, and clay, the coarser fractions predominating. The Tumas Formation is composed of reworked aeolian sand with occasional pebble bands. Authigenic calcite, dolomite, gypsum, and carnotite have precipitated in the surficial material. Carnotite is the main uranium mineral, occurring interstitially along detrital grain boundaries. The age of the mineralization was probably Upper Tertiary.

The precipitation of carnotite in the thick fluviatile uranium deposits, such as the Langer Heinrich, has been controlled primarily by redox effects, adsorption of vanadium on to active surfaces, and soil suction. In smaller deposits, where the uranium is near the surface, evaporation is the most important mechanism.

REFERENCES

- [1] OECD, Uranium: Resources, production and demand, Report OECD/NEA/IAEA (1983).
- [2] HAMBLETON-JONES, B.B., ANDERSEN, N.J.B., Natural and induced disequilibrium, this Volume.
- [3] HAMBLETON-JONES, B.B., LEVIN, M., WAGENER, G.F., Surficial uranium deposits of Southern Africa, in press, Geol. Soc. S. Afr.
- [4] CARLISLE, D., MERIFIELD, P.M., ORME, A.R., KOHL, M.S., KOLKER, O., The distribution of calcretes and gypcretes in the southwestern United States and their favourability based on a study of deposits in Western Australia and South West Africa (Namibia), US Dept. of Energy GJBX-29(78) (1978) 274.
- [5] HAMBLETON-JONES, B.B., The geology and geochemistry of some epigenetic uranium deposits near the Swakop River, South West Africa, University of Pretoria, D.Sc. Thesis (unpubl.) (1976) 306.
- [6] HAMBLETON-JONES, B.B., TOENS, P.D., Preliminary report on the geology of a calcrete occurrence in South West Africa, Pelindaba, Atomic Energy Board, Report No. PER-52 (1980) 8.
- [7] HARTLEB, J.W.O., The Langer Heinrich uranium deposit, South West Africa/Namibia, in press.
- [8] MANN, A.W., Calculated solubilities of some uranium and vanadium compounds in pure carbonated waters as a function of pH, Aust. CSIRO Div. Mineral Report No. FP6 (1974) 39.
- [9] MANN, A.W., DEUTSCHER, R.L., Hydrogeochemistry of a calcrete-containing aquifer near Lake Way, Western Australia, J. Hydrol. 38 (1978) 357-377.

SURFICIAL URANIUM DEPOSITS IN SOMALIA

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ABSTRACT

SURFICIAL URANIUM DEPOSITS IN SOMALIA

Surficial uranium deposits in Somalia are of the valley-fill calcrete type and occur in the arid Mudugh Province of the Dusa Mareb-El Bur region. They are located in a belt about 240 km in length which is orientated parallel to the north-south regional tectonic framework. The uranium resources of the region amount to about 5 000 t U_3O_8 at an average grade of 0.1 % U_3O_8 . Basement rocks constitute a 7 000 m thick succession of Jurassic to Quaternary sediments of the Somalian Basin. Uranium mineralization in the form of carnotite occurs in the uppermost Mercia Series. The origin of the uranium and vanadium is unclear due to a shortage of the favourable source rocks.

1. INTRODUCTION

In Somalia, uraniferous calcrete-type deposits are located in the Mudugh Province of the Dusa Mareb-El Bur region about 400 km north-northeast of Mogadiscio between latitudes 4°30' and 6°30' north and longitudes 46°26' east (Figure 1). The uranium occurrences and radiometric anomalies occur in a north-south zone, having a length of 240 km and a width of 15 km which conforms to the general structural fabric and drainage patterns of central Somalia. The main resources of this region are estimated as 5 000 tons U_3O_8 at an average grade of 0.1 % of U_3O_8 [1].

Climatically, the area is arid to semi-arid, having high daytime temperatures; there is a brief season of heavy rainfall, with an average annual rainfall of 250 mm (Figure 1). Flooding may occur, with the water accumulating in shallow depressions or playas [2], but due to the high rate of evaporation, surface water disappears rapidly [2, 3].

The groundwaters are alkaline and highly saline [2, 3] with the water table occurring at depths between 6 and 10 m.

2. GENERAL GEOLOGY

In East Africa, the regional geology consists of a Precambrian basement overlain by a thick succession of Jurassic to Quaternary sediments which attains a thickness of about 7 000 m in the Somalian Basin in the Mudugh Province [1].

3. URANIUM MINERALIZATION

There are many uranium occurrences and radiometric anomalies in the Dusa Mareb-El Bur region (Figure 2). They occur in the Mercia Series of Miocene age which consists of two lithological units:

1. The **basal unit** is composed of continental fluvial and flood-plain sediments consisting of clay-rich sandstones, marls, and isolated lenses of limestone and gypsum overlying weathered basalts, having a thickness of 25 to 30 m [1, 2, 4]. Typically these sediments are characteristic of shallow seasonal basins and lagoons [1].
2. The **upper unit** is a light grey calcrete [2] having a cryptocrystalline texture and is interbedded with breccia and sand [1], and attains a maximum thickness of 20 m. In the Mirig zone, calcite is the dominant mineral and has structures similar to some of the calcretes at the Yeelirrie uranium deposit in Western Australia. Minor amounts of celestite and fluorite are also known to occur.

The channel containing the uranium occurrences has cut through the calcrete of the Mercia Series, remnants of which are now only found in the channel-fill material which contains substantial amounts of gypsum.

Carnotite is the only uranium mineral and occurs in cracks, voids and as surface coatings. The main zone of mineralization occurs beneath a 2.5 m thick layer of weakly mineralized soil, marl, clay, and limestone and extends down to the water table at about 6 m, below which it disappears [1, 2].

From the available evidence the genesis of the uranium mineralization is similar to that postulated for the Yeelirrie deposit in Australia [5, 6]. However, the source of the uranium and vanadium still remains unresolved, but there are four hypotheses [1, 2]:

1. Granitic rocks are situated several hundred kilometres away in north and northwest Ethiopia [1, 2], implying exceptionally long distances of transport.

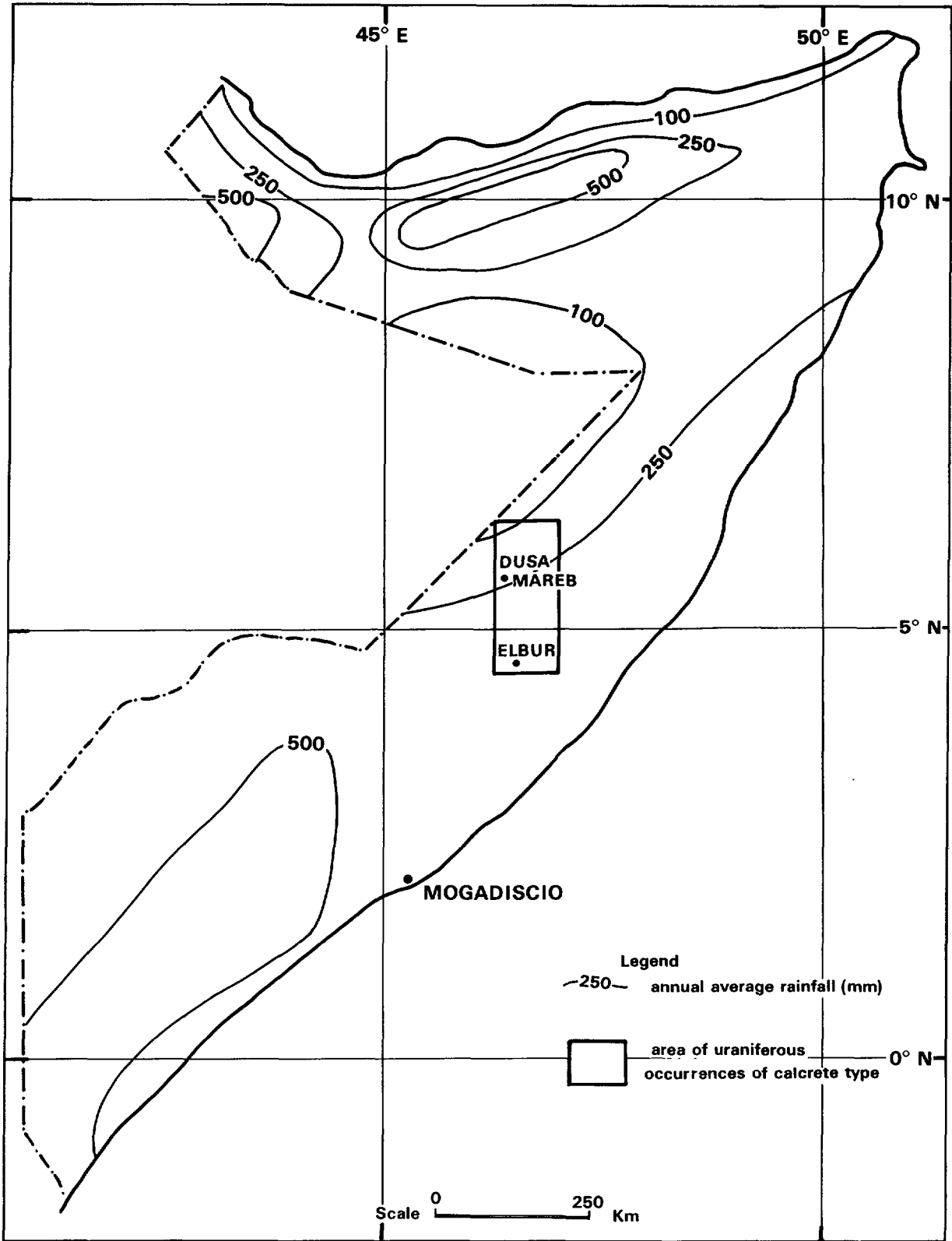


Figure 1
 Locality of the Dusa Mareb - El Bur surficial uranium province in Somalia.

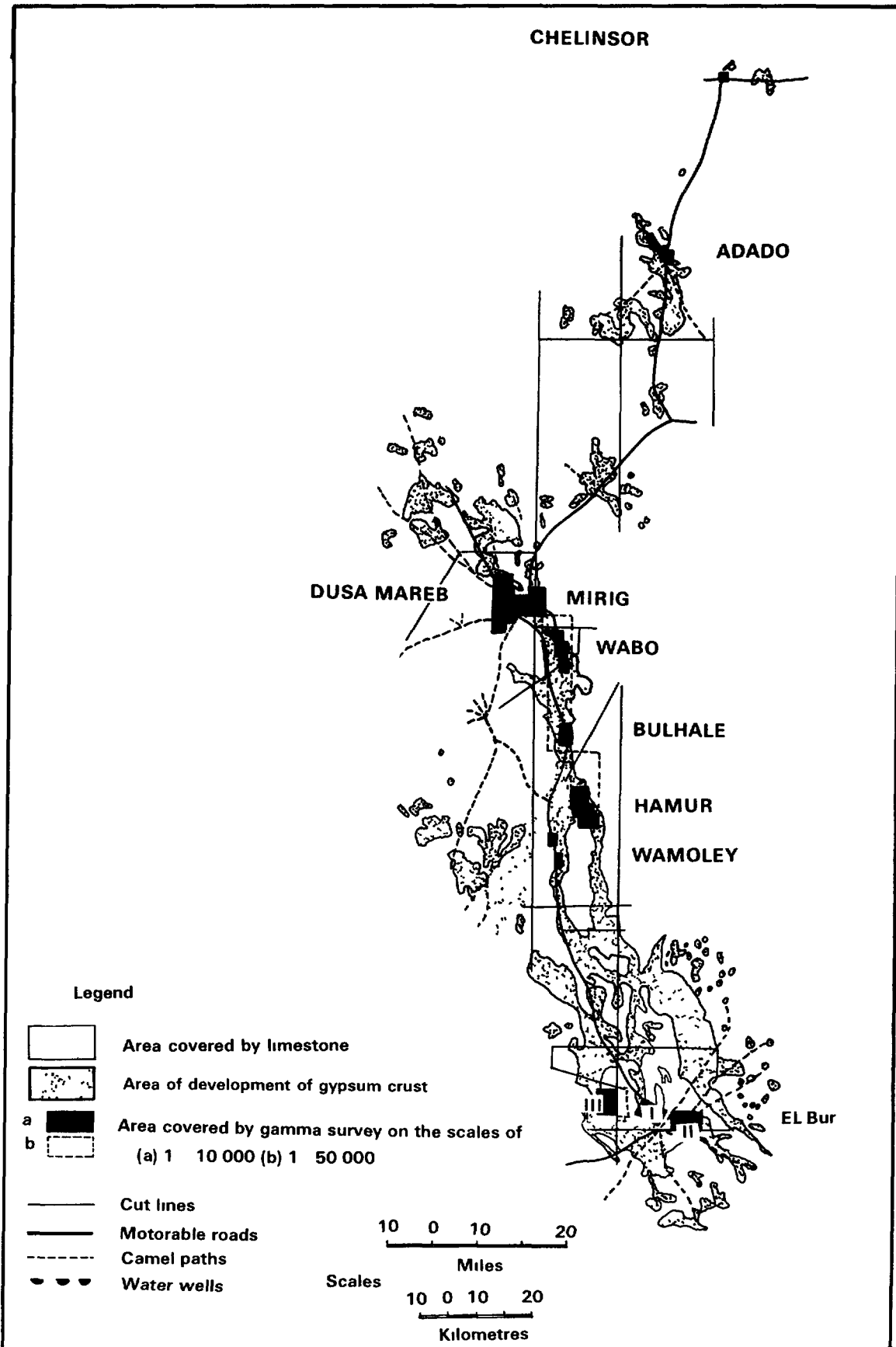


Figure 2
 General Geology of the Dusa Mareb – El Bur surficial uranium province

2. Fragments of volcanic origin occurring in the sandstone at Wabo suggest that volcanic tuffs could have been the source.
3. A north-south fault system paralleling the channel may have provided a hydrothermal source.
4. The source of the vanadium could have been in the clay fraction of the sediments of the Mudugh Province, in which anomalous concentrations have been noted [2].

4. CONCLUSION

The valley-fill calcretes of the Dusa Mareb-EI Bur region have formed in the Mercia Series of Miocene age. Collectively, the uranium resources are about 5 000 t at a grade of 0.1 % U_3O_8 . Carnotite is the only uranium mineral present but the sources of both uranium and vanadium are largely speculative because accessible granite source rocks are situated several hundred kilometres to the north in Ethiopia. The geochemistry of the groundwater and the arid climate favours the precipitation of the carnotite in a manner similar to these fluvial surficial uranium deposits in Namibia and Western Australia.

REFERENCES

- [1] WORLD URANIUM: GEOLOGY AND RESOURCE POTENTIAL, Somalia, OECD/NEA/IAEA, IUREP Report on Phase 1 (1980) 170–176.
- [2] CAMERON, J., The occurrence and mode of formation of the Mudugh uranium deposits in Somalia, unpubl. Report, IAEA, Vienna (1974).
- [3] UNITED NATIONS, Mineral and groundwater survey – Somalia, United Nations development programme (1970) 133.
- [4] BARBIER, J., BAUBRON, J.C., BOSCH, B., BRIOT, P., JACOB, C., Données préliminaires sur les isotopes du soufre dans les calcretes uranifères; un cas dans la province de Mudugh (Somalia). C.R. Acad. Sc. Paris, (D) 290 (1980) 1047–1050.
- [5] BRIOT, P., Géologie et géochimie des gisements d'uranium liés aux milieux pré-évaporitiques intra-continentaux: les calcretes uranifères. Thèse d'Etat, Paris, France (1983) 216.
- [6] MANN, A.W., DEUTSCHER, R.L., Genesis principles for the precipitation of carnotite in calcrete drainages in Western Australia, Econ. Geol. 73 8 (1978) 1724–1737.

SURFICIAL URANIUM DEPOSITS IN SOUTH AFRICA

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ABSTRACT

SURFICIAL URANIUM DEPOSITS IN SOUTH AFRICA

Surficial uranium deposits in South Africa contain 1000 metric tons U in the Reasonably Assured Resources \$80-\$130/kg U cost category, which constitutes only a minor proportion of the total uranium inventory. Currently, no deposits are being mined because of the depressed state of the world uranium market. Most deposits have been found on the Bushmanland Plateau, but there are a few below the escarpment and on the coastal plain. The fluvial type, such as Brulkolk, and the lacustrine type, such as Abikwaskolk, Geelvloer, Dirkskop, Kannikwa and Henkries, are predominant. No significant uranium pedogenic occurrences have been found. Generally, the uranium mineralization occurs as carnotite in the oxidized sediments and is frequently associated with gypsum and calcite. In the reduced diatomaceous earth/peat environments such as Henkries and Kannikwa, uranium occurs probably as an urano-organic complex. The age of the uranium is Upper Tertiary to Recent.

1. INTRODUCTION

Following the discovery of surficial uranium in South West Africa/Namibia during the early 1970's, exploration effort moved southwards to the Republic of South Africa, where the prospecting activity for these types of deposits reached its peak during the mid-1970's. Radiometric airborne surveys along palaeodrainage channels, such as the Koa River, were conducted, and many anomalies were detected.

The region that has the greatest potential for surficial uranium deposits is the semi-arid Bushmanland Plateau (Figure 1) that, unlike the Namib Desert in Namibia, does not form part of the coastal plain. The climate of the Bushmanland Plateau is less arid than that of the Namib Desert and receives an average annual rainfall of between 80 and 100 mm. Only a few deposits were found below the escarpment, the most notable being Henkries and Kannikwa.

The uranium resources in surficial uranium deposits of the Republic of South Africa are given in Table 1 [1]. In terms of the in-situ tonnage and the overall percentage proportion (0.2 %) within the total Reasonably Assured Resources + Estimated Additional Resources groups, the surficial uranium deposits are virtually insignificant.

2. GENERAL GEOLOGY OF BUSHMANLAND

Tertiary to Recent surficial material overlies basement metasedimentary, gneissic and granitic rocks of the Namaqualand Metamorphic Complex in the northwestern Cape Province. The surficial sediments are less well-known than those of the central Namib Desert of Namibia and insufficient data are available on which to base regional stratigraphic subdivisions. They are generally of fluvial and aeolian origin and fill palaeodrainage channels of the main river courses (Figure 1). The valley-fill material in the interior differs from that described for the Namib Group in Namibia in that it was deposited under much lower gradients and, consequently, the thicknesses of the sediments are seldom greater than a few metres. During the Early Tertiary, deep gorges developed, with the gradients becoming steeper towards the Orange River to the north, which were filled with sediments that have thicknesses in excess of 300 m in some localities.

The upper reaches of the Koa River valley attain widths of as much as 8 km. During the Mid- to Upper Tertiary, the water flowed rapidly, as is indicated by the well-rounded cobbles and boulders found in certain alluvial diamond diggings. Stratigraphically higher in the succession, much of the sediment is probably of aeolian origin. Dunes of Pleistocene age, generally orientated parallel to the river, cover most of the eastern portion of the drainage. Drilling has indicated that the present drainage channel is displaced up to 2 km to the west of the deepest central portion of the valley and that the uranium occurrences are situated within the upper layers of this valley-fill material.

Warping along the Griqualand-Transvaal Axis reduced the gradients to zero or even reversed certain drainages, causing ponding and the formation of pans. Typical examples in the context of the uranium distribution are Abikwaskolk and Geelvloer. Cross-cutting dunes have blocked the rivers in places, behind which pans have formed, for example Dirkskop and Kamasoas in the Koa River Valley (Figure 1).

None of the uranium deposits so far discovered attain the size of their counterparts in Namibia. Most of the smaller occurrences are in river gravels associated with gypsum, but the largest occurs in peat-rich diatomaceous earth.

Table 1
Recoverable uranium resources in tonnes U as at 1 January 1983,
for the republic of South Africa in the < \$130/kg U cost category

ROCK TYPE	REASONABLY ASSURED RESOURCES (RAR)		ESTIMATED ADDITIONAL (EAR)	
	Recoverable at < \$80/kg U	Recoverable at < \$80-130/kg U	Recoverable at < \$80/kg U	Recoverable at < \$80-130/kg U
Witwatersrand Basin Conglomerates	163 000	50 000	98 000	43 000
Witwatersrand Basin Tailings	22 000	21 000	-	-
Carbonatite	2 000	-	-	-
Karoo Sequence	4 000	50 000	1 000	5 000
Younger Surficial Sediments	-	1 000	-	-
TOTAL	191 000	122 000	99 000	48 000

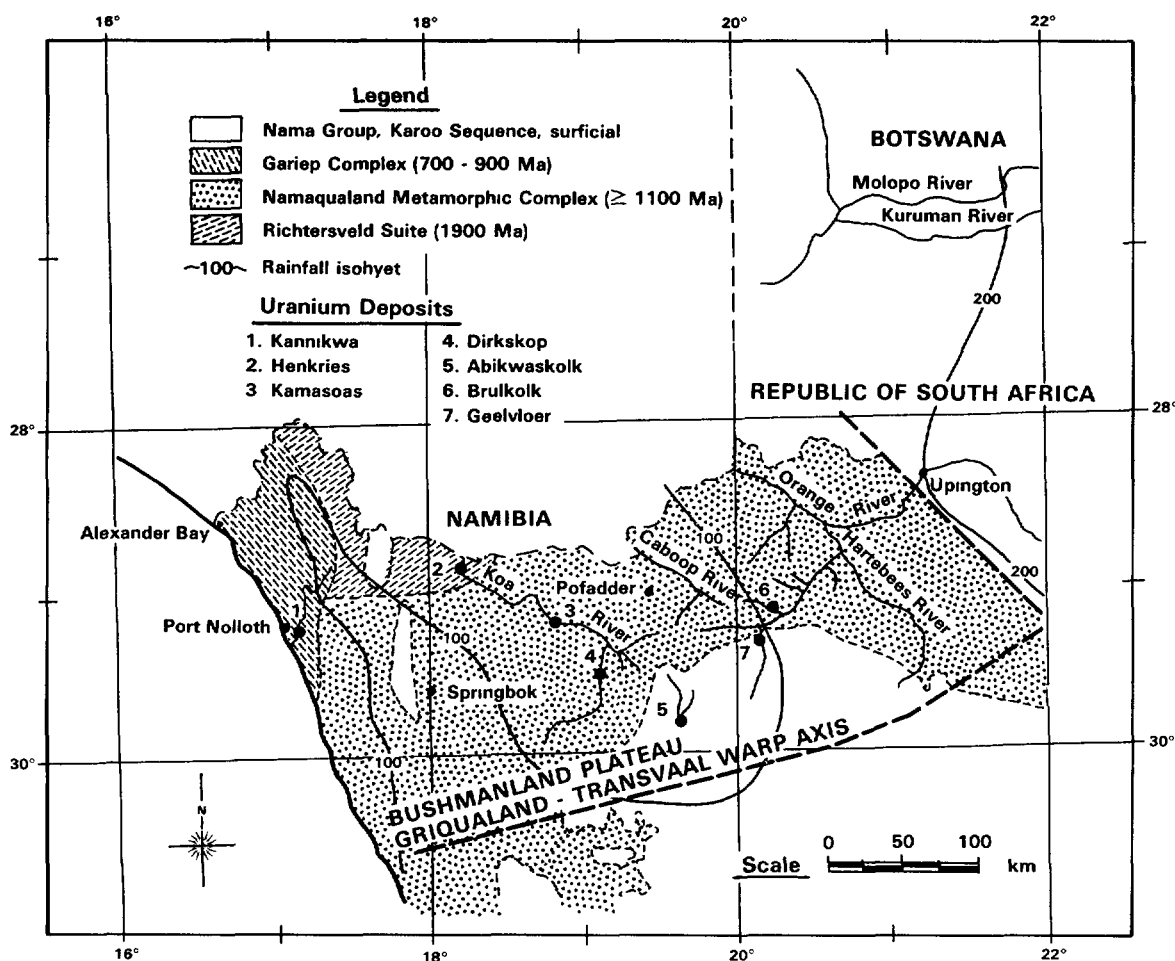


Figure 1
Tectonic provinces and sedimentary cover rocks of the Namaqualand and Bushmanland regions.

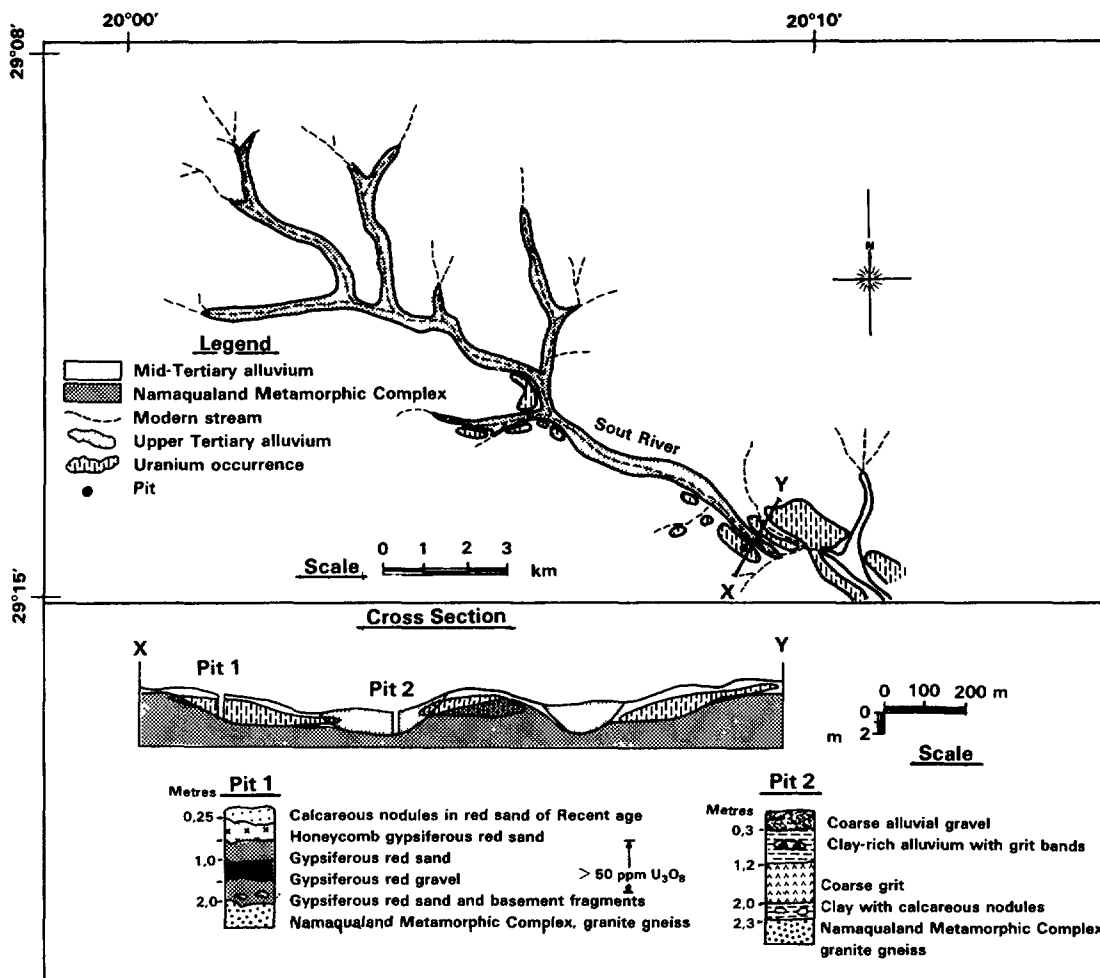


Figure 2
Geology of the Brulkolk uranium occurrence (Gencor).

3. GEOLOGY OF SELECTED URANIUM OCCURRENCES

The surficial uranium occurrences in South Africa fall into the fluvatile, lacustrine and pedogenic categories. Most were formed in an oxidizing environment, the exceptions being the reduced diatomaceous earth/peat ores which formed in lacustrine conditions.

3.1 Fluvatile Deposits

Fluvatile occurrences contain only a small portion of the surficial uranium resources in South Africa, the most important one being Brulkolk, which is of the valley-fill type.

Brulkolk

The Brulkolk uranium deposit is located about 80 km east of Pofadder (Figure 1) and is situated in the drainage of the Sout River.

The basement rocks of pink paragneiss, grey-gneiss metaquartzite, calc-silicate and marble, all belong to the Namaqualand Metamorphic Complex. Generally, the gneisses weather easily and form the areas of low relief, whereas the resistant metasediments form the inselbergs.

The geology of Brulkolk is shown in Figure 2. During the Mid-Tertiary the Sout River had a shallow channel and seldom attained depths greater than a few metres. Subsequently, it was filled with alluvium, cemented with calcite, gypsum and in places fluorite. The geological log of pit 1 illustrates the nature of the fluvatile sedimentary accumulations that are typical of the Mid-Tertiary environment in this area. During the Upper Tertiary, river rejuvenation gave rise to the partial erosion of these sediments and remnants now form minor elevated topographic features that are found on the flanks or shoulders of the younger aggrading drainages. Sediments filling these drainage channels are primarily of Kalahari age, the nature of which is shown in the geological log of pit 2. Overlying the whole area is a 0.1 to 0.3 m veneer of calcrete, aeolian sand and alluvium containing calcrete nodules.

The uranium mineralization is patchy. The main depositional area is in the southeast, where the Upper Tertiary erosion did not cut through the Mid-Tertiary alluvium. The cross section, X - Y, shows the attitude of the deposit within the drainage channels, and that the uranium is almost entirely associated with the older alluvium. It has subsequently been locally redistributed in the younger sediments. Apparently, erosion removed the central portions of the valley-fill material which probably contained a large proportion of the uranium.

Carnotite is restricted to a narrow 0.1 to 2 m zone 0.75 m below the present surface, which is composed of red fluviatile sands and gravels. A limited amount of mineralization extends into weathered basement rock, particularly where it forms topographic highs within the drainage.

3.2 Lacustrine/Pan Deposits

There are many pans in Southern Africa, but only a few contain uranium. Some have an internal drainage with only an inlet, e.g. Abikwaskolk, whereas others are situated within drainages, and have both an inlet and an outlet. Only under exceptionally wet conditions will water also flow into the adjoining river. Otherwise it will collect and dissipate within the pan sediments or by surface evaporation, as at Geelvloer. The reason for the lack of significant uranium accumulation is the limited recharge and the small catchment area surrounding the pans. Had the recharge been much greater, however, the pans would probably not now exist.

Pan sediments in the northwestern Cape range widely in composition. There are the salt pans with hypersaline conditions, where the salt crust overlies a gypsum-rich clay. Others contain massive gypsum (Geelvloer), clay and sand with some gypsum (Abikwaskolk, Dirkskop) and peat with diatomaceous earth (Henkries, Kannikwa). The latter type is not well-known in Southern Africa and constitutes a newly discovered environment for this region.

Abikwaskolk

Abikwaskolk, located approximately 90 km south of Pofadder (Figure 1), is a small pan having an elliptical shape and an areal extent of about 2 km². The drainage system is essentially internal, with its inlet in the northeast through a breached dam wall.

Geological and geochemical maps of Abikwaskolk are shown in Figure 3. The main rock type in the area is the Dwyka shale, which overlies the basement granitic rocks of the Namaqualand Metamorphic Complex. Granite gneiss, which outcrops about 1 km northeast of the pan, has been intruded by alaskitic-type leucogranite and quartz porphyry (Figure 3A). The radioactivity of the alaskites is slightly higher than the granite gneiss, and they contain 45 ppm and 35 ppm U₃O₈ respectively, which suggest that the alaskite was probably one of the sources of the uranium mineralization in the pan.

The pan surface is covered with silt that has been cemented with salt, forming the characteristic tubular mounds and crusts. In the northeast there is a slightly elevated portion that has been described as a delta by Carlisle [1], but which could also be regarded as an alluvial fan. This is overlain by recent alluvium carried in as a result of the breaching of the dam wall (Figure 3A). The following generalized sedimentary log was established by a study of percussion drilling cuttings:

Depth (m)	Description
0 — 1	Surficial silt
1 — 2	Beige gypsiferous sand and silt
2 — 3	Beige gypsiferous sand and silt — slightly radioactive
3 — 5	Gypsiferous silt becoming darker brown, probably due to highly saline conditions
5 — 6	Dwyka shale

In all the drill sections, the Dwyka shale formed the floor of the pan and the overlying sediments averaged about 5 m in thickness.

Uranium, as carnotite, was initially located by the Geological Survey in airborne radiometric surveys [3], which indicated that the major anomaly was situated in the Dwyka shale on the eastern margin of the pan. A subsequent ground radiometric survey [4] confirmed this finding but, in addition, found that the anomaly extended into the pan (Figure 3D). Mineralization within the Dwyka shale is found in cracks and fissures near the surface and occurs in association with gypsum.

The grade of uranium mineralization in the pan was found in most places to be less than 100 ppm U₃O₈, and has an average thickness of about 0.1 m. Borehole radiometric values, uranium concentrations in the groundwater and ground radiometric contours (Figures 3 B,C,D) correspond to the position of the alluvial fan. The exceptionally high uranium concentrations in the groundwater, of as much as 3 500 ppb U₃O₈ in places, indicate that the groundwater is virtually static and that there is probably insufficient vanadium for the precipitation of carnotite.

Geelvloer

Geelvloer is located about 80 km southeast of Pofadder (Figure 1) in the choked Sout River drainage and has a surface area of approximately 50 km². The inlet is from the south and only during periods of very heavy rainfall

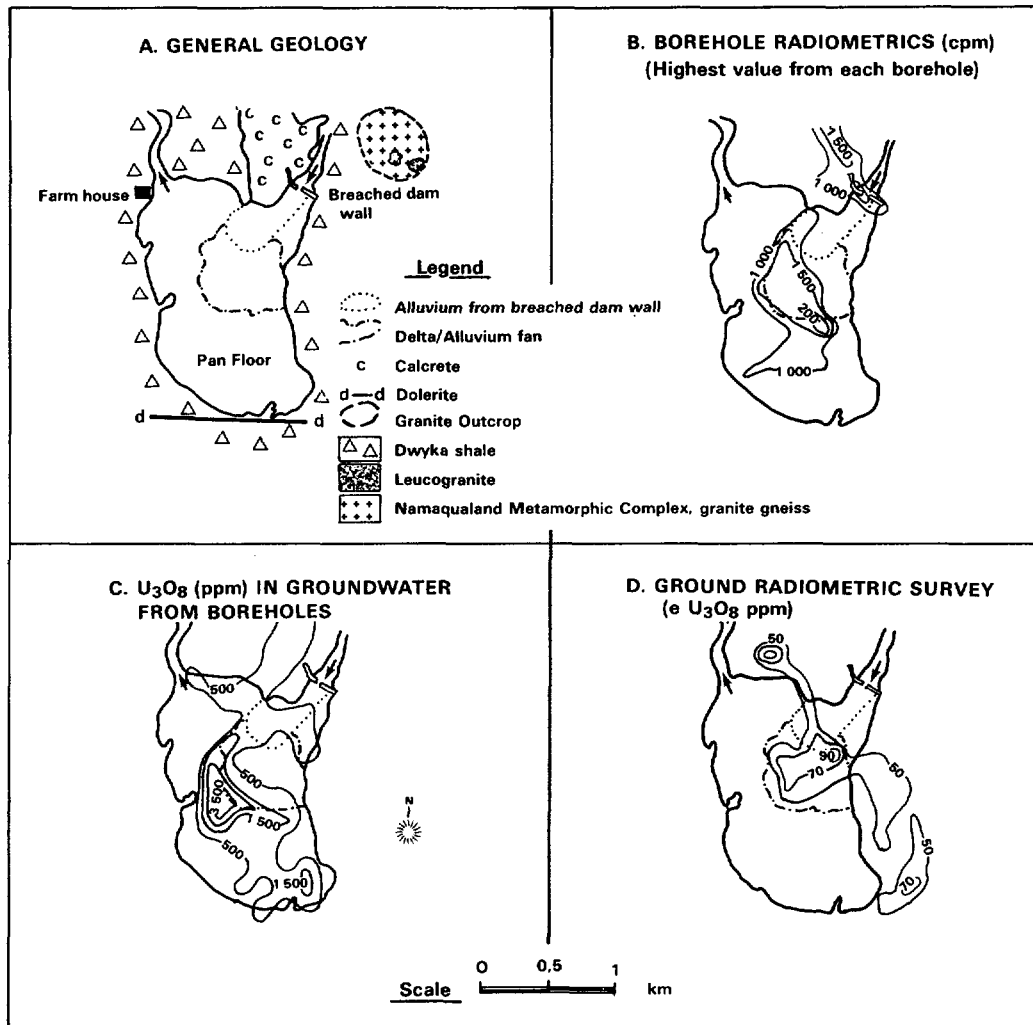


Figure 3

Geology of the Abikwaskolk uranium occurrence (Phelps Dodge of Africa Ltd., for maps A, B, C: Schutte [4] for map D: modified after Carlisle [2].

does water in the pan flow northwards into the Sout River. The outlet of the pan forms part of a fluvatile system but, in general, it has typical pan characteristics.

The basement rocks outcrop locally and consist of grey, white and pink granites, gneisses, pegmatites and metasediments of the Namaqualand Metamorphic Complex (Figure 4). The pan sediments consist mainly of clay, silt, alluvium and reworked aeolian sand, which have been cemented by chemical precipitates such as gypsum, calcite and salt. The surface material tends to be silt and clay, having a high salt content. Groundwater in most places in the pan is within at least one metre of the surface and has an extremely high salinity.

Uranium, as carnotite, occurs in three localities and in all instances it is closely associated with the contact between the granites, the overlying Dwyka shale and surficial material. Only in the two northernmost anomalies is the uranium found in the pan sediments, whereas in the western part the mineralization occurs on the flanks of the pan in a desert soil. The latter consists of weathered Dwyka, granitic material and red aeolian sand. Frequently it contains calcareous nodules which, in the upper layers, have been cemented with calcium carbonate. The uranium has precipitated mainly in the most porous portions, such as the sands overlying fractures in the granite that provided the necessary source and solution channels.

The distribution of the uranium in the groundwater of the pan shows a good correspondence to the uranium mineralization. In places, the uranium concentrations in the groundwater are as high as 6 000 ppb, which indicates that under the existing hypersaline conditions, uranium is readily soluble, i.e. conditions are thus similar to those at Abikwaskolk.

Dirkskop

The Dirkskop uranium deposit is located in the Koa River valley (Figure 1). The area is characterised by two prominent metaquartzite inselbergs, Dirk se Kop in the west and Klein Dirk se Kop in the east, having an

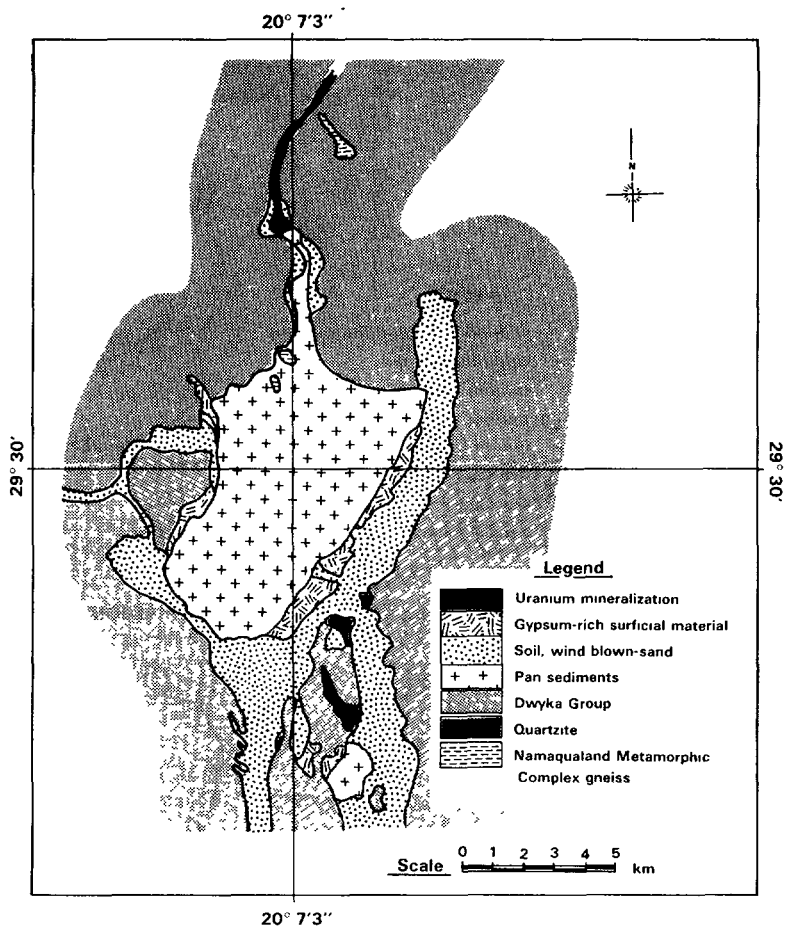


Figure 4
Geology of the Geelvloer uranium occurrence (Phelps Dodge of Africa Ltd.).

unexposed interconnecting metaquartzite ridge which is covered by Kalahari sand dunes. Pans and depressions are important geomorphological features, which are located south of this ridge (Figure 5).

Owing to the westerly prevailing winds, the sand dune belt is situated on the eastern side of the present-day Koa River drainage. West of the sand dunes, the surface geology consists generally of a metre of windblown sand and calcrete overlying basement rocks, comprising metasediments and granite gneiss of the Namaqualand Metamorphic Complex.

The typical lithological sequence for the northernmost pan in the area consists of 20 m of reddish aeolian sand underlain by about 4 m of whitish porcellanous and massive, fine-grained, lacustrine calcareous sediment. This is underlain by 5 to 30 m of calcareous and gypsiferous, red, fluviatile and lacustrine material which extends down to the basement (Figure 6). Locally, lenses of clay and sandy clay are present within this sediment. The thickness of the lacustrine clay increases towards the northeastern portion of the area, where 20 m have been recorded.

The uranium is associated with two pan features, Dirkskop North and Dirkskop South (Figure 5), that of the former occurring slightly offset to the west of the present-day pan. Carnotite is the uranium-bearing mineral and appears to have a siliceous coating. There is no strict relationship between the uranium mineralization and lithotype but the highest grades are found mostly in the red sands below the lacustrine material. Locally, carnotite has precipitated in the upper calcareous sediment but is of a lower grade (Figure 6).

In pit sections, the distribution of the carnotite is erratic, and extreme variations occur within short distances. This is due to the nature of the mineralization, which occurs as narrow steeply dipping stringers. The uranium mineralization is predominantly concentrated over an elevated portion of the granitic basement that was probably the source of the uranium.

Kannikwa

The Kannikwa uranium occurrence is situated approximately 15 km east of Port Nolloth (Figure 1) and is located in the choked drainage of the Kamma River. It could be classed within the fluviatile group since it is located within a river channel. However, as marshy or bog conditions developed in some channels due to reduced flow caused by ponding, Kannikwa has been classified as lacustrine. There are other uranium occurrences of this nature, for

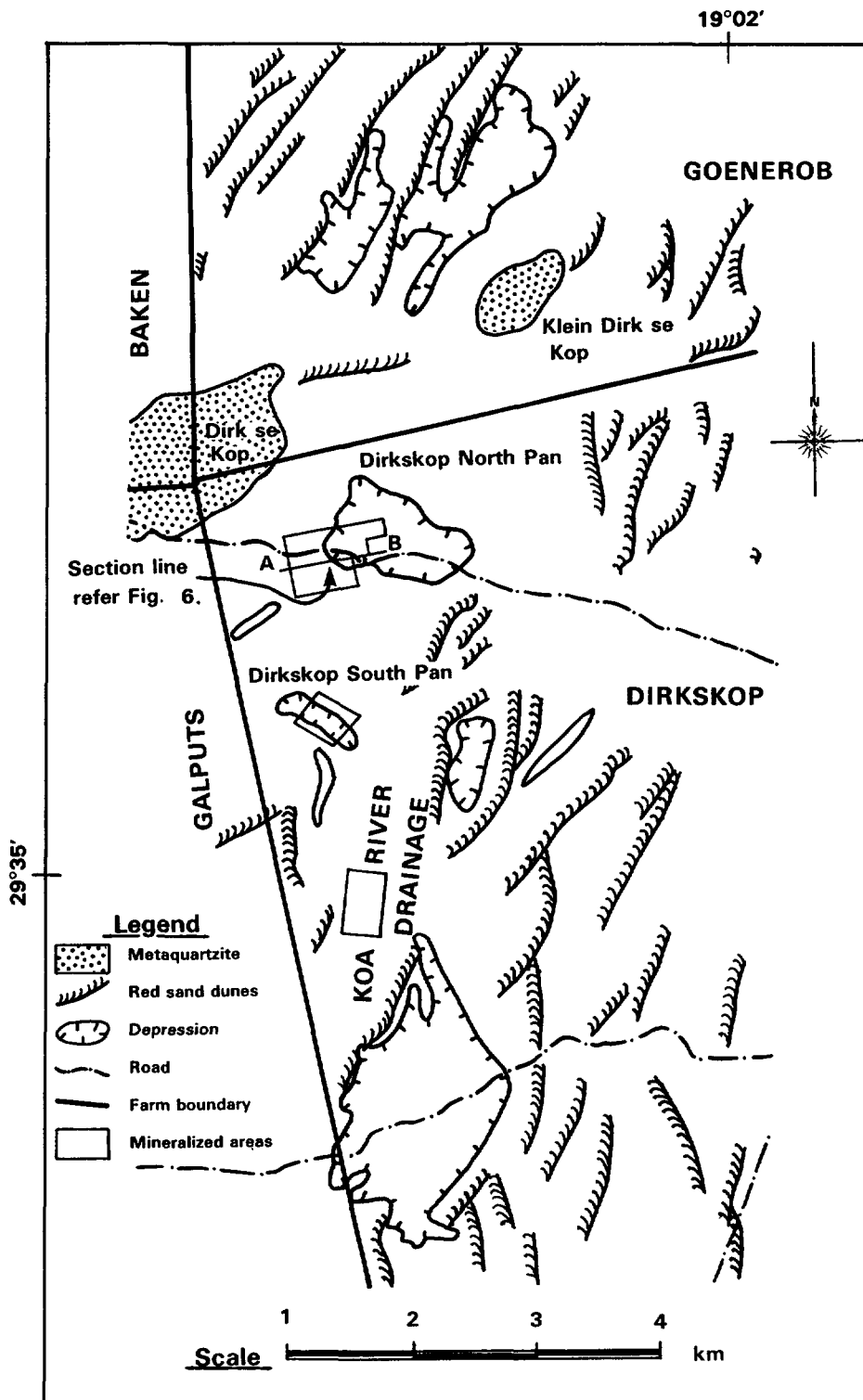


Figure 5
 Geomorphology of the Koa River valley in the vicinity of the Dirkskop uranium occurrence.

example Rus-en-Vrede in the northern Cape [5] and Henkries (Figure 1) in the lower reaches of the Koa River valley near the junction with the Orange River.

The basement rocks around Kannikwa are metaquartzites of the Gariiep metamorphic belt. About 70 km to the east, the headwaters of the Kamma River drain a granitic area and the Steenbok Shear zone, which is known to contain uranium. The low resource potential of this occurrence may therefore be attributed to a poor source area in the immediate vicinity.

The Kannikwa uranium occurrence is situated in a basin feature, the western portion of which has been choked off by sand. The surface of the channel is covered by Recent calcified alluvial gravel and aeolian sand overlying an

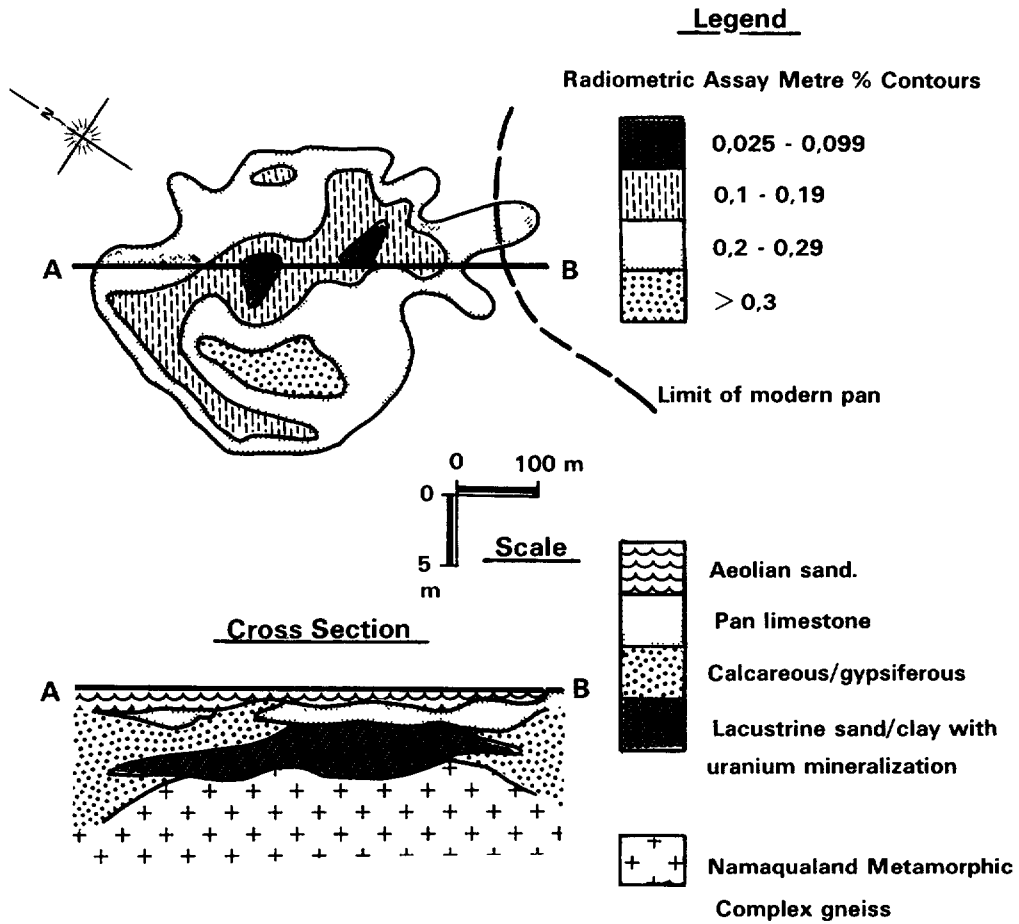


Figure 6
Geology of the Dirkskop uranium occurrence (Anglo America Corp. of SA Ltd.).

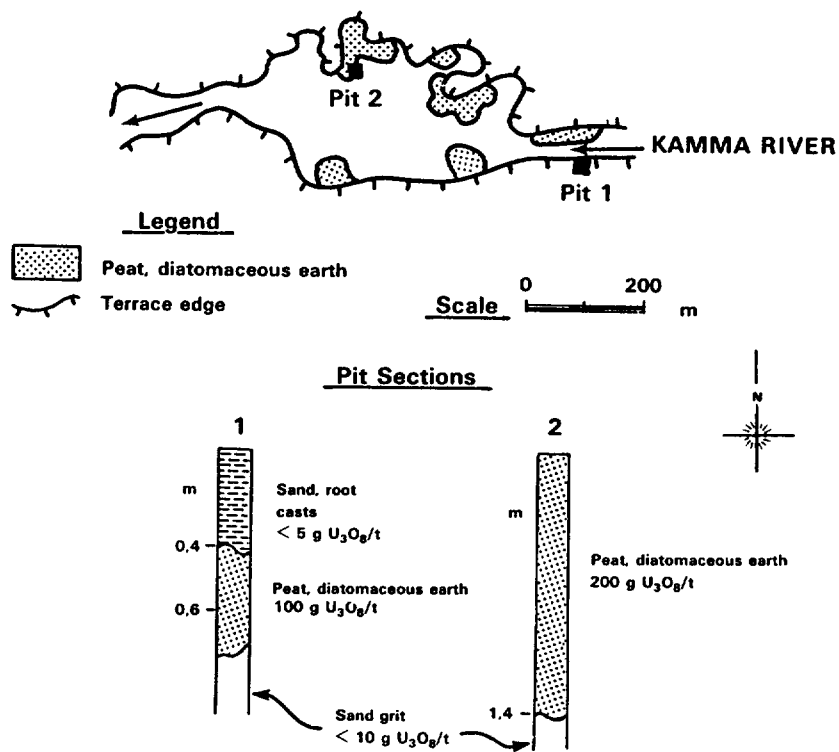


Figure 7
Geology of the Kannikwa uranium occurrence.

organic-rich diatomaceous earth that has been preserved as isolated remnants within enclaves along the banks of the drainage channel (Figure 7). Below this material, gravel, sand and clay lenses constitute the sedimentary fill.

The upper layers are a greenish-brown, calcareous-rich sand, containing iron-rich or lateritised root casts, tubules and the remains of hollow reeds. This band may be referred to as the reed-fringe, which probably surrounded the pond. This is followed by a grey to black zone which is comprised of a series of horizontally laminated beds of diatomaceous earth and organic- or peat-rich material which contains no interstitial calcareous material.

The uranium is almost exclusively located within the organic-rich bands, probably as a urano-organic complex. Generally, the mineralization is patchy and low grade, and has an average thickness of about 0.2 m. It is believed that the Henkries occurrence has higher tonnages and grades.

Disequilibrium is a serious problem in this type of occurrence, as radiometric equivalent uranium values bear little resemblance to the chemical assays; consequently, quantitative radiometric borehole logging at Kannikwa proved to be of little value. Mineralization must be therefore considered to be of Recent age.

4. CONCLUSION

In the Republic of South Africa, the lacustrine occurrences contain the major portion of the surficial uranium resource potential, whereas the fluvial occurrences have a very much smaller potential. Collectively, the total resources of the surficial deposits make only a minor contribution to the total South African resource inventory.

The surficial deposits on the Bushmanland Plateau are not as well documented as those in South West Africa/Namibia. Generally, the sediments are of fluvial, lacustrine and aeolian origin and fill palaeochannels of the main river courses. Gypsum, calcite and carnotite have precipitated in the oxidized sediments, whereas urano-organic complexes occur in the reduced diatomaceous earth/peat occurrences.

The age of the mineralization is between Upper Tertiary and Recent.

REFERENCES

- [1] OECD, Uranium: Resources, production and demand, Report OECD/NEA/IAEA (1983).
- [2] CARLISLE, D., Possible variations on the calcrete-gypcrete uranium model, US Dept. of Energy Report GJBX-53(80) (1980) 38.
- [3] RICHARDS, D.J., Preliminary report on pan mineralization from airborne radiometric surveys, NW Cape Province, S. Afr. Geol. Surv. Open-File Report 6 (1975) 8.
- [4] SCHUTTE, F.J.P., Ground follow-up of airborne radiometric anomalies in the North West Cape Province, S. Afr. Geol. Surv., Open-File Report 8 (1976) 6.
- [5] LEVIN, M., Uranium occurrences in the Gordonia and Kuruman Districts, S. Afr. Atomic Energy Board, Pelindaba, South Africa, PER-37 (1978) 24.

SURFICIAL URANIUM OCCURRENCES IN THE UNITED REPUBLIC OF TANZANIA

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ABSTRACT

SURFICIAL URANIUM OCCURRENCES IN THE UNITED REPUBLIC OF TANZANIA

Surficial uranium occurrences of undetermined economic potential occur in Central Tanzania, mostly within the Bahi interior drainage system. Low-grade, spotty uranium, occurring partly as discrete minerals (uranyl vanadates and silicates), is found in three types of deposit. The most common type consists of mineralized, near-surface, poorly developed pedogenic calcretes in Upper Tertiary to Recent sandy clays formed in the depressions (mbugas) of the present drainage systems. A second type occurs at the surface and consists of thin, mineralized, strongly silicified sheet calcretes developed directly over weathered granitic basement rocks. The third type is mineralized and silicified calcareous Upper Tertiary valley-fill sediments, locally called Kilimatunde Cement, lying either at depth in the mbugas or uplifted by rift faulting and exposed by present-day drainage that does not coincide with the palaeodrainage system.

1. INTRODUCTION

In 1977-78, a systematic airborne survey of Tanzania, comprising spectrometry and magnetics, was carried out by Geosurvey International Ltd of Nairobi, Kenya, on behalf of the Tanzanian Government. Since 1978, ground follow-up work was carried out by Uranerzbergbau-GmbH of Bonn, Germany, as part of a joint venture agreement with the Tanzanian Ministry for Minerals. One of seven areas of interest lies in Central Tanzania, west of Dodoma, the future capital. Approximately 70 airborne radiometric anomalies occur in this area (Figure 1), the majority being in the southern part of the Bahi and Lake Eyasi interior drainage systems, clustered close to the headwaters in the vicinity of north-south-trending basic dykes.

In 1978-79, 40 airborne radiometric anomalies were investigated on the ground with the aim of assessing the potential for surficial uranium deposits (the terminology proposed by Toens and Hambleton-Jones [1] is followed here). Investigations did not go beyond the stage of regional prospecting and, therefore, the conclusions given in this paper are somewhat speculative.

2. SETTING AND CLIMATE

The area of interest covers the southern part of a system of interior drainage basins forming an important continental divide between the systems that drain to the Indian Ocean to the east and south, the Mediterranean to the north, and the Atlantic to the west (Figure 1). Elevations range from 820 m (Bahi Swamp) to 1 550 m; the fairly high relief results in present-day active stream erosion.

The climate is semi-arid, with a short rainy season. The annual rainfall is 400 to 600 mm, except in the depressions, where it amounts to only about 100 mm. The potential evaporation is higher than the rainfall throughout the year; the mean annual temperature is around 22 °C [2]. Therefore, some of the climatic conditions necessary for the formation of surficial uranium deposits [3] are present.

3. GEOLOGY

The area is underlain by Late Archean rocks of the Tanzanian shield, 2 550 Ma [4,5], consisting predominantly of biotite granites, accompanied by metasediments (migmatites, gneisses, quartzites, amphibolites) and "greenstones" (metavolcanics of the Nyanzian System). The unaltered granites usually contain less than 6 ppm U_3O_8 , which occur in allanite, sphene, zircon and apatite and are, therefore, *a priori* not fertile. However, in numerous locations, concentrations are higher (up to 28 ppm U_3O_8). In addition, some airborne radiometric anomalies (Figures 1 and 2) were found to be caused by weakly mineralized shear zones in granite, with quartz veins that contain between 60 and 390 ppm U_3O_8 . Lateritic material derived from the weathering of biotite granite locally also has elevated U_3O_8 contents, e.g. around 40 ppm at Issuna (Figure 2). Part of the granites and their weathering products are, therefore, the main source rocks for uranium in the area.

The Tertiary/Quaternary geologic evolution of the area may have begun in Early Tertiary with lateritic weathering and peneplanation; laterites are now preserved only on hillslopes.

Faulting related to the eastern Rift System took place in the Miocene-Pliocene and resulted in the formation of interior sedimentary basins: these depressions were filled with lacustrine and valley-fill sediments, locally called

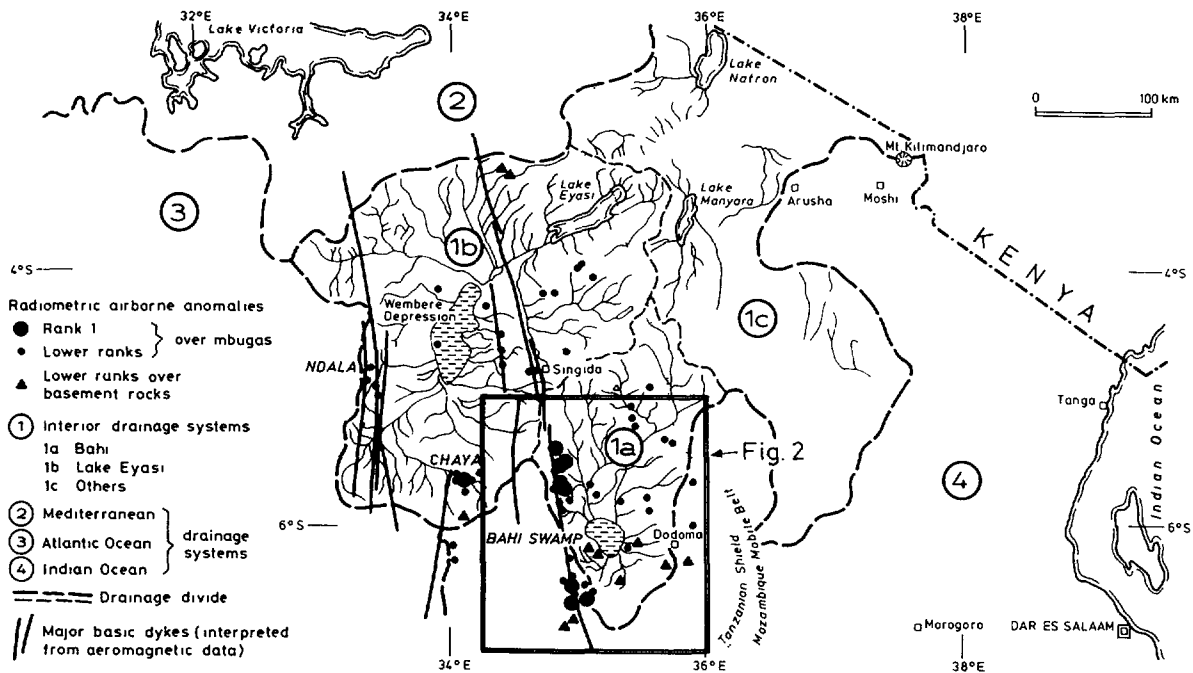


Figure 1
Airborne radiometric anomalies over the interior drainage systems of central Tanzania.

Kilimatinde Cement [6]. The rift faulting reached its peak in the Pliocene-Pleistocene and dissected the area into tilted blocks, whereby the original drainage system was disrupted and drastically modified. Parts of it were uplifted and are being eroded by the present drainage; other parts were down-faulted and covered by younger (Pleistocene to Recent) sediments (e.g. the Bahi Swamp). These consist of black, partly calcareous and gypsiferous sandy clays that are found in depressions of the area and are locally called mbugas. They are generally closed drainage basins which are flooded during the rainy season. Salt crusts, consisting of carbonates, sulphates, and chlorides [7], precipitate as a result of high evaporation rates during the dry season. The mbugas can therefore be classified as salt lakes. Their dimensions vary from a few km² to the 1 100 km² of the Bahi Swamp (Figure 2). Several of them have been investigated by the Geological Survey of Tanzania as potential local water supplies [8, 9] and also for their gypsum and limestone resources [7, 10, 11, 12]. Because of their tectonic control, the mbugas attain considerable depths, e.g. 90 m in the Makutapora mbuga [5] and 102 m in the Bahi Swamp [9].

4. SURFICIAL URANIUM OCCURRENCES

Three types of surficial uranium occurrences have been recognized (Figure 3).

4.1 Mineralized Mbuga Sediments

Most uranium anomalies and occurrences belong to this type, e.g. those in the Bahi North, Kianju, Iseke, Makutapora, and Lake Hombolo mbugas within or adjacent to the Bahi interior drainage system (Figure 2) and in the Ndala mbuga in the Lake Eyasi interior drainage system (Figure 1). The weak radiometric anomalies at surface reach maximum dimensions of 1 000 by 200 m (Kianju mbuga). Pits excavated over radiometric maxima show the following idealized stratigraphic profile of the mbugas (from top to bottom):

1. **Mbuga clay** (1.2 to 1.5 m thick): black sandy clay, with 2 to 10 % sand grains, local quartz pebbles, and varying amounts of gypsum crystals; non- to weakly mineralized with uranium;
2. **Transition zone** (0.3 to 0.5 m, locally up to 1 m thick): grey calcareous clay, locally gypsiferous, with up to 50 % calcrete nodules (to 0.25 m diameter); contains most of the uranium;
3. **Calcareous zone** (thickness > 0.5 m): grey calcareous clay to white calcrete, locally with silicified nodules; only the top section is slightly mineralized;
4. **Regolith** or weathered basement rocks;
5. Fresh basement rocks.

A similar profile, containing the uranyl silicates, weeksite and haiweeite, is described from Quaternary sediments in an unspecified locality in the USSR by Chernikov et al. [13].

The calcareous replacement occurs well above the water table — which is usually below 20 m — and is, therefore, of pedogenic origin. The CaO content of the impure calcretes reaches 41.7 %, whereas the MgO

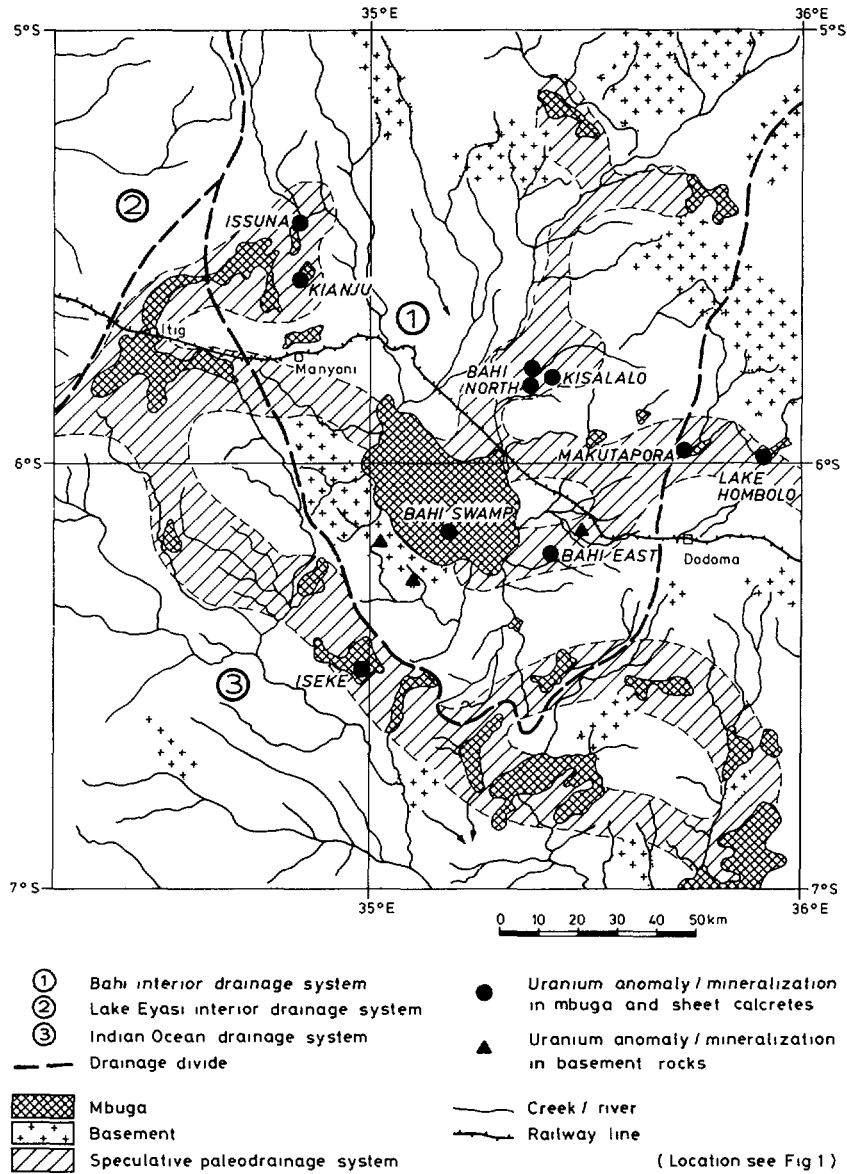


Figure 2
Uranium anomalies related to the Bahi interior drainage system

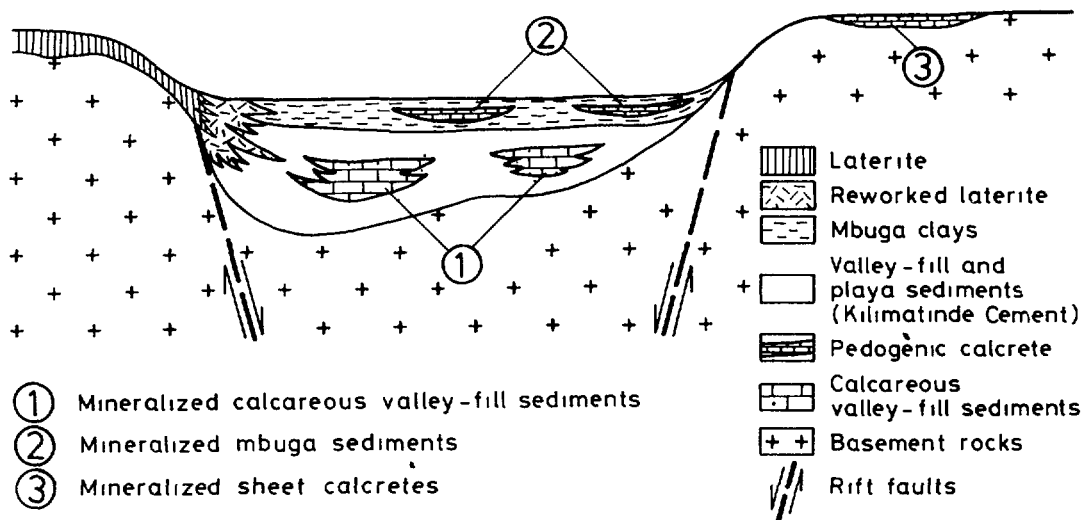


Figure 3
Diagrammatic section showing three types of surficial uranium deposits and their geologic settings

content is always low, between 0.53 and 2.34 % (15 analyses). This composition indicates a predominance of calcite, which is in general agreement with the worldwide distribution [14]

Yellow secondary uranium minerals coat cracks in the clays or are disseminated in the calcrete nodules, they are particularly concentrated within the "transition zone", at depths of about 1.5 m. Part of the mineralization is likely to consist of uranium adsorbed on clay and matrix minerals. Three uranium minerals have been determined by X-ray diffractometry, namely carnotite (Bahı North, Lake Hombolo), metatyuyamunite (Bahı North) and betauranophane (Lake Hombolo). Grades vary between a few tens and 350 ppm U_3O_8 over 0.5 m, the V_2O_5 contents vary between a few and 200 ppm and show no apparent correlation with U_3O_8 . The ThO_2 contents have been investigated only in the Ndala mbuga where they are rather high, (12 to 75 ppm), and reflect the nearby granitic source rocks of the clayey sediments. The U_3O_8 : ThO_2 ratio is approximately 1 in the mbuga clays and increases to approximately 8 in the underlying "transition zone"

4.2 Mineralized Sheet Calcretes

Spotty uranium mineralization has been found in strongly silicified pedogenic sheet calcretes (0.1 to 0.5 m thick) overlying weathered granitic rocks and exposed in creek beds at Kisalalo (Bahı North area) and at Bahı East (Figure 2). Grab samples contain 75 to 470 ppm U_3O_8 but less than 100 ppm V_2O_5 . At Kisalalo, the white, porous, silicified calcrete (46.9 % SiO_2 , 30.9 % CaO) contains spotty visible secondary uranium mineralization in the form of weeksite [15]. It occurs in 0.1 mm long flakes coating opal-like silica that forms concretionary textures and irregular bands replacing the extremely fine-grained calcitic ground mass.

4.3 Mineralized Calcareous Valley-Fill Sediments

The valley-fill sediment, consisting of Kilimatinde Cement, was deposited in fluvial palaeochannels of Upper Tertiary age. It is of a grey-white, fine- to coarse-grained, poorly sorted sandstone, with varying amounts of feldspars and a kaolinitic, clayey matrix, and contains interbedded layers of reworked laterite, conglomerates, grits, and clays. It was originally porous and a good aquifer but it has subsequently been partially replaced by calcite and later strongly silicified. The Kilimatinde Cement is now a silicified calcareous sediment.

In the Bahı Swamp (Figure 2), a 150 mm core intersection with 0.24 % eU_3O_8 was found at depth 68.3 m in waterbore G S 19/53, drilled in 1953 [9]. The intersection is in the upper portion of strongly silicified Kilimatinde Cement, overlain by a thick sequence of calcareous clays and mbuga clays. The mineralization is described as "uranium absorbed in strontianite ($SrCO_3$)" [9]. This interpretation is doubted, however, because at this concentration, discrete uranium minerals should be present.

The groundwater reservoir of the Makutapora mbuga has surface dimensions of approximately 2 by 12 km and a depth of 90 m and is used for the water supply to the town of Dodoma, about 25 km to the south (Figure 2). A radiometric scan of the drill chips from borehole 97-70, filed with the Geological Survey of Tanzania, detected an anomaly at a depth of 72-73 m. The anomalous sample consists of white, silicified calcareous sandstone and contains 500 ppm U_3O_8 . Four water samples taken from wells adjacent to the mineralized hole contain between 4 and 27 ppb U_3O_8 .

At Issuna (Figure 2), late Tertiary rifting has tilted the palaeochannel and a 6 m thick section of the Kilimatinde Cement has been exposed by erosion within the present drainage. It is believed that the cement extends along a 11 km long palaeochannel to the south under the cover of the Issuna mbuga. At Bahı North (Figure 2), the Kilimatinde Cement is partly preserved under about 2 m of black, calcareous mbuga clays. At these two localities, uranium mineralization is spotty and consists of unidentified secondary yellow uranium minerals coating pores and minute cavities of the silicified calcareous sandstone. The U_3O_8 content varies from 100 to 500 ppm in grab samples but is only 100 ppm over 0.3 m in channel samples.

4.4 Mineralogy

Uranium minerals could be determined only in the highly mineralized samples of the pedogenic mbuga calcretes and silicified sheet calcretes. The following four species could be identified by X-ray diffractometry: the two uranyl vanadates, carnotite (K) and metatyuyamunite (Ca), and the two corresponding uranyl silicates, weeksite (K) and betauranophane (Ca). The two vanadates are found in calcretes, whereas the two silicates occur in strongly silicified calcretes, and are, therefore, possibly later phases associated with the silicification process.

4.5 Hydrogeochemistry

The present hydrogeochemistry of the drainages has not been investigated in detail. The few water samples taken indicate that the pH of the waters is generally 5.5 to 6.5, i.e. too acid for strong carbonate replacement. In contrast, the uranium content is commonly anomalous (over 4 ppb U_3O_8) with some exceptionally high values, such as at Bahı North (275 ppb U_3O_8), at Bahı East (100 ppb U_3O_8), in the southern delta of the Bahı Swamp (4.900 ppb U_3O_8), and in the exit of the Ndala mbuga (300 ppb U_3O_8).

5. CONCLUSIONS

Two episodes of carbonatization and uranium mineralization have been recognized, as schematically illustrated in Figure 3.

The first affected the Upper Tertiary valley-fill sediments (Kilimatinde Cement) of palaeodrainages principally controlled by the rift tectonics. The minor mineralization found associated with this carbonated and silicified sandstone unit could indicate potential for as yet undiscovered, economic, calcrete-related deposits. This potential, however, is limited by both the nature of the evolution of these drainages and the depth at which the target unit can occur beneath the mbugas. The continuous rift movements which disrupted and modified the palaeodrainage system could have imposed a negative factor in the ability of any related groundwater system to develop sufficiently to precipitate uranium within a favourable host environment. Further, even if considerable mineralization did develop, the modification of the palaeodrainage system and of the related groundwater regime might have resulted in the remobilization and destruction of older uranium concentrations. The distribution of the larger mbugas seems to form a regular pattern, which might reflect the original drainage system as speculatively indicated on Figure 2. Any possible larger and continuous mineral deposits that could be associated with these would be completely "blind", occurring under a thick cover of mbuga clays; the two known intersections have been found by chance in waterbores.

The second episode is recent and probably still active. It consists of the development of discontinuous pedogenic calcretes in the mbuga clays and of thin, strongly silicified sheet calcretes over granitic rocks. Uranium occurs either as spotty discrete uranium minerals (uranyl vanadates and silicates) or as uranium adsorbed on clays. Uranium occurs at, or near, the surface and causes most of the airborne anomalies. Low grades and lack of continuity are the general rule, and pedogenic calcretes have no economic potential.

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REFERENCES

- [1] TOENS, P.D., HAMBLETON-JONES, B.B., Definition and classification of surficial uranium deposits, this Volume.
- [2] Atlas of Tanzania, Ministry of Lands Housing and Urban Development, 2nd ed. (1976).
- [3] CARLISLE, D., MERIFIELD, P.M., ORME, A.R., KOHL, M.S., KOLKER, O., The distribution of calcretes and gypcretes in southwestern United States and their uranium favourability based on a study of deposits in Western Australia and South West Africa (Namibia), US Dept. of Energy, Open File Report GJBX-29(78) (1978).
- [4] GABERT, G., WENDT, I., Datierung von granitischen Gesteinen im Dodoma- und Usagaran-System und in der Ndembera Serie (Tanzania), Geol. Jb. **11** (1974).
- [5] BELL, K., DODSON, M.H., The geochronology of the Tanzanian shield, J. Geol. **89** (1981), 109–128.
- [6] PICKERING, R., A preliminary note on the Quaternary geology of Tanganyika, Joint Meeting, East-Central, West-Central and Southern Regional Committees for Geology, Leopoldville (1958) 77–89.
- [7] HARRIS, J.F., Summary of the geology of Tanganyika. Part IV: Economic Geology, Geological Survey of Tanganyika, Mem. 1 (1961).
- [8] FAWLEY, A.P., Geology and underground water resources of the Makutapora depression (Dodoma water supply investigation), Geological Survey of Tanganyika, Records V (1955) 41–52.
- [9] FAWLEY, A.P., Diamond drilling in the Bahi Swamp, Geological Survey of Tanganyika, Records VI (1956) 47–51.
- [10] BASSETT, H., Notes on mbuga and surface limestones, Geological Survey of Tanganyika, Records III (1953) 83–85.
- [11] FAWLEY, A.P., An impure gypsum and dolomitic limestone deposit at Msagali, Mpwapwa District, Geological Survey of Tanganyika, Records V (1955) 36–40.
- [12] CARTER, G.S., The Itigi gypsum occurrence, Geological Survey of Tanganyika, Report GSC/17 (1961) unpublished.
- [13] CHERNIKOV, A.A., SIDORENKO, G.A., VALUYEVA, A.A., New data on uranyl minerals in the ursilite-weeksite group, Int. Geol. Rev. **20** 11 (1978) 1347–1356.
- [14] GOUDIE, A., The chemistry of world calcrete deposits, J. Geol. **80** (1972) 449–463.
- [15] GAUTIER, A.M., BIANCONI, F., A weeksite occurrence from Tanzania, in press.

SURFICIAL URANIUM DEPOSITS IN THE UNITED STATES OF AMERICA

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ABSTRACT

SURFICIAL URANIUM DEPOSITS IN THE UNITED STATES OF AMERICA

Two important surficial uranium deposit types occur in the United States: 1) young uranium deposits associated with organic-rich, poorly drained, fluvial-lacustrine systems; and 2) carnotite deposits in calcrete horizons in the upper part of the Miocene and Pliocene Ogallala Formation in the southern High Plains of Texas. These two deposit types constitute a potentially large, but at present poorly understood uranium resource in the United States. The "young" uranium deposits are best known in northeastern Washington and northern Idaho, where they have formed in bogs, meadows, swamps, and lake bottoms along valleys in glaciated highland areas underlain by granitic massifs. The deposits are only slightly radioactive, as they generally have reached only 5 to 10 % of radioactive equilibrium. Grades in this area reach 1 % uranium and some deposits are as large as 500 metric tons. These deposits are amenable to small-scale mining methods.

The carnotite deposits in calcrete in Texas resemble the deposits at Yeelirrie in Western Australia in that, 1) the deposits formed in calcrete that probably developed along a Pleistocene palaeodrainage; 2) carnotite occurs in vugs and fractures; 3) dolomitization and silification also occurred; and, 4) strontium is an important constituent of the deposits.

Other types of surficial uranium deposits occurring in the United States and described here include the Lost Creek schroëckingerite deposits in Wyoming and karst cave tyuyamunite deposits in Wyoming and Montana.

1. INTRODUCTION

Two important varieties of surficial uranium deposits occur in the United States: 1) Holocene uranium deposits associated with modern, organic-rich, poorly drained, fluvial-lacustrine environments in northeastern Washington, northern Idaho, the Sierra Nevada, the Colorado Front Range, and possibly New Hampshire and Maine; and 2) latest Pliocene to Holocene (?) carnotite deposits in calcrete horizons at the top of the Miocene and Pliocene Ogallala Formation in the southern High Plains of Texas (Figure 1). These deposits have considerable potential for contributing to the uranium resources of the United States. Other lesser occurrences of surficial uranium deposits are abundant in the United States; two prominent ones are briefly described below because they resemble significant deposits found elsewhere in the world.

Uranium in the first deposit type has generally been so recently emplaced that much of it is grossly out of radioactive equilibrium. These deposits, termed "young" uranium deposits [1], show equivalent uranium values to be only 5 to 10 % of chemical uranium (R.R. Culbert, written communication, 1982). Gamma decay from these deposits is not readily detected by most scintillometers and spectrometers, that normally detect the higher gamma energies associated with late daughters in the uranium-decay series. These deposits, however, contain uranium and its younger daughter products that emit low-energy gamma rays which are amenable to low-energy gamma-spectrometry techniques [2].

The carnotite deposits in Texas, because of their greater age, show a greater range in radioactive equilibrium than the Holocene deposits in northeastern Washington and northern Idaho. They most closely resemble uranium deposits in calcreted valley drainages at Yeelirrie in Western Australia. Little published information is yet available on the distribution, detailed stratigraphy, geochemistry, grade, and tonnage of either type of deposit in the United States, but the geologic and climatic setting of both deposit types is reasonably well known in two areas described below.

2. YOUNG SURFICIAL URANIUM DEPOSITS

In several areas in Canada and the United States, significant deposits of uranium have formed and are forming in several types of organic-rich surficial geological environments. A preliminary classification of these environments based on studies in British Columbia and other areas in Canada [1,3] indicate two groups: 1) lacustrine or playa oxidizing to reducing environments dominated by alkaline, uraniferous waters; and 2) fluvial environments rich in organic matter dominated by fresh, uraniferous waters. These studies suggest that where the uraniferous waters are alkaline, a closed or partly closed basin environment is required before uranium can be trapped in organic-rich sediments, whereas if waters are fresh, uranium may be trapped wherever organic-rich sediments are encountered. The environments trapping uranium often trap other metals, such as molybdenum; however, little work has been done on molybdenum or any other associated metals in these deposits.

Specific types of geologic terranes appear favourable as hosts for these uranium deposits. The majority of the known deposits occur in granitic terranes. Uraniferous granitic terranes, such as those in northeastern Washington and northern Idaho, are exceptionally favourable; however, granitic to granodioritic terranes with a uranium content generally less than 5 ppm, such as the Sierra Nevada in California and Nevada, also host these

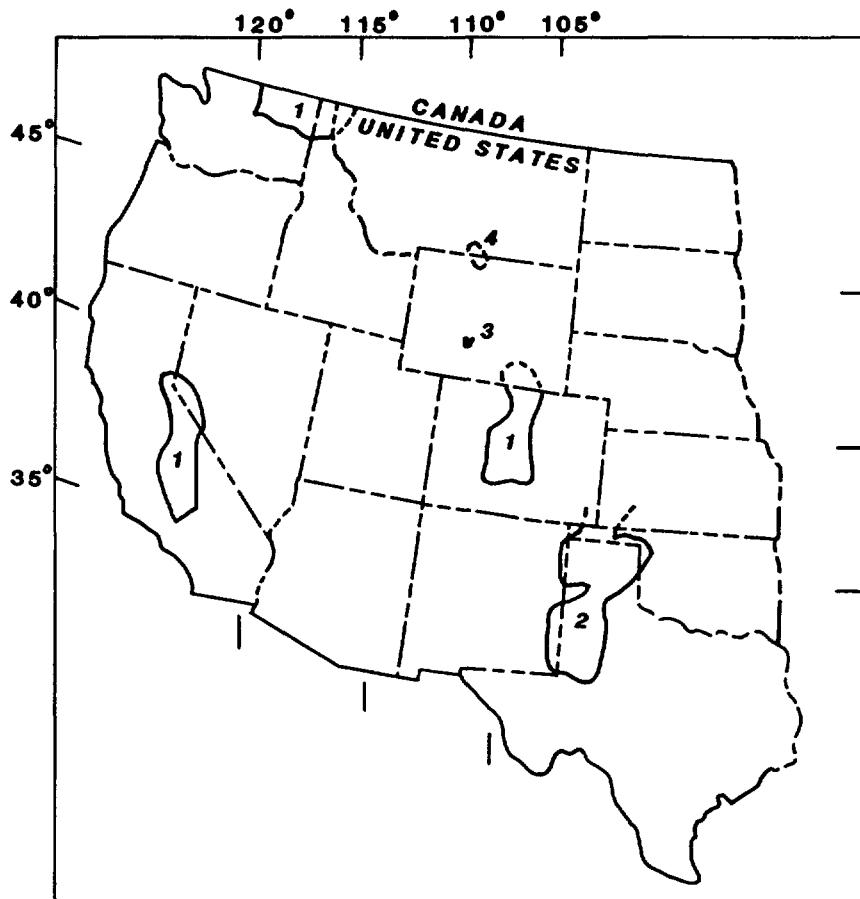


Figure 1

Location of surficial uranium deposits in the western United States

1. Areas of known or probable young surficial uranium deposits
2. Areas of known or probable carnotite-bearing calcrete deposits
3. Lost Creek schroeckingerite deposits
4. Karst cave tyuyamunite deposits.

Dashed lines indicate uncertain boundaries. Queried where limits to area are unknown.

deposits. Fracturing and shearing of potential source rocks in structurally disturbed areas may enhance the availability of uranium. Additionally, recent glaciation may also make more uranium available by exposing fresh, little-weathered rock to the surface environment.

In the late 1950's, uranium deposits were discovered in alpine meadow sediments in Kern, Madera, and Fresno Counties on the west side of the Sierra Nevada, California [4,5]. Although of high grade, these deposits were small and attracted little attention after US Atomic Energy Commission exploration and mining incentives were terminated in late 1957. In the mid- to late 1970's, exploration activity in uraniferous granitic terranes in British Columbia and in northeastern Washington and northern Idaho demonstrated that a large number of young surficial uranium deposits occur in meadow, bog, swamp, marsh, and lake-bottom sediments. The maximum known deposit size in this area is about 500 metric tons uranium and the maximum grade about 1.0 % uranium.

More recently however, regional reconnaissance by R.R. Culbert (written communication, 1982) has shown that young surficial uranium deposits are widespread in several areas in the western United States (Figure 1). Young deposits have been found along the east edge of the Sierra Nevada in California and in adjacent parts of the Nevada Basin and Range. Stream sediment geochemical data from Precambrian granitic terranes in the Colorado Rocky Mountains (R.S. Zech, written communication, 1982, and [6]) suggest that such deposits occur there. In addition, this deposit type may also be present in granitic terranes in Maine and New Hampshire (E.G. Boudette, oral communication, 1982). Several deposits have been recognized in New Brunswick and Nova Scotia in areas with similar geologic settings [1,3]. One young uranium deposit has been identified over the granite at Sunapee (E.G. Boudette, oral communication, 1982) in New Hampshire.

The best known of the young surficial uranium deposits are those in northeastern Washington and northern Idaho. This area experiences a cold temperate climate with long, cold, snowy winters and moderate summers. The area is heavily forested and is drained by major tributaries of the Columbia River. Relief in the area ranges from 1 200 to 1 500 m. Many of the low-lying areas are covered by glacial, glacio-fluvial, and glacio-lacustrine deposits, and are poorly drained.

The area is underlain principally by upper Precambrian to Mesozoic sedimentary and metasedimentary rocks, Jurassic to Eocene plutonic rocks, and Eocene and Miocene sedimentary and volcanic rocks. Thin, surficial Quaternary sediments cover bedrock in many areas. The known surficial uranium occurrences and deposits are associated with the plutons of granitic composition; however, the surficial environment in areas underlain by other major rock types has not been adequately examined. The uranium donor plutons are batholithic in size, are elongated in a north-south direction, and generally underlie highland areas drained by narrow, flat-bottomed valleys. Many of the plutons in the area were shown by Nash [7] and Castor et al [8] to contain anomalous uranium.

Within this terrane, organic-rich sedimentary deposits have formed in several geomorphic environments: 1) boggy meadows along valleys at the drainage divides between two streams; 2) swamps upstream from beaver ponds or other drainage impediments along stream valleys or on the stream deltas at lake inlets; 3) bogs forming at the edge of closed lakes during infilling of the lake; and 4) swamps and meadows in floodplains or cutoff meanders along river valleys. Each of these environments is capable of trapping uranium; however, the distribution of the known uranium deposits in northeastern Washington and northern Idaho suggests that environments along low-order streams (+ 1 to 3) contain the majority of the deposits. Deposits also occur where shallow groundwaters following low-order stream drainages move into river valleys and encounter organic-rich environments. This suggests that uranium is generally effectively removed from shallow groundwater at the first encounter with organic sediments. Studies of uraniumiferous spring waters in a boggy meadow environment on the west side of the Sierra Nevada [5] show that the uranium content of spring waters was reduced by a factor of ten after flow through a boggy meadow.

The deposits in northeastern Washington and northern Idaho (and possibly in the other areas described here) range in size and grade depending on: 1) the cross-sectional area and volume of the organic-rich environment; 2) the efficiency of the environment in trapping uranium; and, 3) the volume and uranium content of the waters flushing through the host.

In northeastern Washington and northern Idaho, the host and associated sediments for these deposits typically consist of one or more of the following lithologies: 1) live and decaying plant material at the surface; 2) light brown to dark-brown peat with varying clay and sand content; 3) light-grey to black clayey sand; 4) lacustrine shelly marl; 5) air-fall or reworked air-fall ash; 6) blue glacial (?) clay; and 7) coarse sand and gravel. Glacio-fluvial or glacio-lacustrine sediments or weathered bedrock almost invariably underlie the organic-rich uranium host sediments in this area.

The character of the peat varies greatly, depending on the vegetation contributing the organic matter and the thickness and maturation of the peat. Most of the sediments in this area contain at least one ash bed with a thickness of up to 1.5 m. The marl occurs principally where lakes have been infilled. The grey to black colour of the finer sand may be due to sulfides or humates, or both. The total thickness of these sediments ranges from 0 to 10 m.

Organic-rich sediments associated with valley alluvial systems are usually thin, with perhaps a maximum of 3 to 4 m, and have a greater percentage of clastic material than those associated with lakes. Peaty material forms blanket-like units elongated along the axis of the valley drainage. Upstream and downstream, the peaty material intertongues with clastic sediments and grades laterally into soils. Ash beds form discontinuous sheets intercalated with the organic-rich sediment.

In contrast, lake-edge bogs and lake-delta and lake-bottom sediments are generally fairly thick and low in clastic sediment. One bog deposit near Colville, Washington, which lies adjacent to a small kettle lake, is about 7 to 8 m thick. Others in British Columbia are known to be as much as 12 m thick. At its centre, the lake bog near Colville consists of an upward succession of sand and gravel, blue clay, lacustrine marl, ash, peat, and surface organic matter. These sediments pinch out laterally as the edge of the depression that defines the lake basin is reached.

The distribution of uranium in all these environments depends on the direction of water flow and the permeability of the peat and the intercalated sediments. Where the principal flow of surface and shallow groundwater is down the axis of the valley, uranium is concentrated at the upstream edges of the valley bogs and swamps. In one valley west of Blueside, Washington, for example, two swampy areas occur along a 2 km length of the drainage. The highest concentrations of uranium (0.1 to 0.2 %, 1 to 2 m thick) occur in forest litter and underlying peat at the upper end of the upper swamp. Uranium concentrations are lower throughout the lower end of the upper swamp and in all of the lower swamp.

In some valley settings, groundwater appears to be upwelling beneath the organic-rich environment, and in these uranium is concentrated at the bottom of the sediments. In other settings – for example, spring-fed meadows along a valley slope – the highest concentrations occur at the surface and the uranium content decreases downward. Uraniferous waters, in this case, emerge from the spring, move downslope, and then filter down through the meadow sediment.

In northeastern Washington and northern Idaho, uranium occurs principally in the peat, lacustrine marl, and grey to black silty sand. Other lithologies generally contain less than 100 ppm uranium. The maximum concentration

of uranium in this area is about 1 % (dry weight) but average grades are in the range of 100 to 1 500 ppm uranium. In northeastern Washington and northern Idaho (Figure 1), hundreds of small uranium deposits (2 to 50 metric tons of contained uranium), and also an unknown but probably large number of larger deposits (50 to 500 metric tons of contained uranium) are likely to occur.

The initial phase in the search for these deposits should concentrate on identifying potential uranium-donor terranes, especially granites, in areas climatically favourable for organic-rich environments. The next phase should consist of reconnaissance sampling of favourable surficial environments within the potential donor terranes. Follow-up and detailed studies are conducted after mineralized organic-rich environments (greater than 100 ppm uranium) are encountered. All stages of the exploration may be assisted by radiometric surveys; however, radiometric surveys should be interpreted with caution. They may be effective in identifying potential donor terranes, but the low gamma radioactivity of the deposits themselves reduces the ability of the radiometric survey to identify the deposits. The deposits are usually water-saturated and low in density, which tends to further lower their radioactivity. Portable, low-energy gamma scintillometers are not yet available. Use of Geiger counters (which can measure beta activity) or sampling waters for alpha activity may be useful techniques.

To date, the young deposit type has been identified principally in areas with cool, temperate climates in the northern hemisphere. Much geochemical sampling for uranium in the surficial environment in the United States and Canada has deliberately avoided organic matter in order to avoid biasing sample data sets. This practice may have prevented recognition of surficial uranium deposits in otherwise favourable areas, such as the granitic terranes in the mountainous areas of Colorado. Existing regional data bases should be searched for reports of ground, spring, and surface waters high in uranium (perhaps greater than 5 ppb) and for organic-rich sediment samples high in uranium (greater than 100 ppm).

Young deposits offer many mining advantages. The uranium is much less radioactive than in conventional mines, thus radiological health hazards are considerably reduced. The deposits are at or near the surface and can be readily stripped by light equipment. The ore is generally highly porous and permeable and requires little pretreatment prior to chemical extraction techniques (in heap or tank leaching). The deposits may also be amenable to *in situ* leach techniques. These deposits are thus amenable to small-scale mining and milling operations, especially if deposits are clustered geographically, so that several deposits could feed ore to one large mill. One deposit on the northern fork of Flodelle Creek in Stevens County Washington went into production in mid 1983, the only uranium mine started up in the US in 1983.

3. SURFICIAL CARNOTITE DEPOSITS IN CALCRETE HORIZONS IN TEXAS

Most of the southern High Plains in the Panhandle region of Texas and adjacent parts of New Mexico is underlain by the Miocene and Pliocene Ogallala Formation and Pleistocene to Holocene fluvial, aeolian, and lacustrine deposits. During the latest Pliocene and throughout the Pleistocene, alternating periods of wet and dry climatic conditions produced successive layers of calcrete at the top of the Ogallala and within the overlying Pleistocene sediments. The calcrete has been interpreted by Reeves [10] to be largely pedogenic in origin (i.e. caliche) however the geochemistry of some of the calcrete suggests that it is, in part, non-pedogenic. Since the Late Pleistocene, this part of Texas and adjacent New Mexico has undergone significant uplift, and these Miocene to Pleistocene deposits and the underlying rocks are being slowly eroded. In most of the area, however, thick calcrete at the top of the Ogallala forms a resistant caprock that appears to have protected the terrane from rapid dissection. Thus the boundary of the southern High Plains in Texas and eastern New Mexico is marked by east- and west-facing caprock scarps. Within this terrane, the surface generally lacks integrated drainage and numerous small internal basins containing playa lakes occupy most of the area.

The Ogallala and the Pleistocene sediments (largely derived by reworking of the Ogallala) are arkosic and (or) tuffaceous. Several Pleistocene ash falls periodically inundated the High Plains of Texas and were incorporated into the section. Uranium contents of surface samples of the Ogallala Formation average about 2 ppm but are as much as 40 ppm [12, 13]. In the Plainview, Lubbock, and Big Spring areas, the groundwaters in the Ogallala Formation and the overlying Pleistocene units contain uranium ranging from 2 to 10 ppb with values as high as 220 ppb [11, 12, 13]. The area south of Lubbock contains uniformly anomalous groundwaters (50 ppb uranium or greater) over a large area [13]. These groundwaters are inferred to have derived their uranium from the Ogallala and possibly the ashes in the Pleistocene sedimentary units [13, p. 17]; however, much of the uranium may have been derived from more distant sources to the west during the latest Pliocene and Pleistocene, when the southern High Plains were hydrologically connected to the southern Rocky Mountains by major fluvial systems. Evaporative concentration of these waters is inferred to have taken place episodically since the Late Pliocene.

Uraniferous calcrete has formed in several localities, principally in horizons at the top of the Ogallala. Such deposits are known in the Lubbock area and also in areas south and southwest of Lubbock [14]; however, much of the area underlain by the Ogallala in Texas and adjacent states (Figure 1) may contain similar deposits. In this area, the Ogallala and overlying Pleistocene deposits are being dissected locally by stream drainages, and

uranium concentrations in calcrete are exposed in the modern stream-valley walls. Subsurface extensions of the uraniferous calcrete are hidden by younger deposits covering the interfluvial areas of the modern stream drainages.

At one occurrence, the uraniferous calcrete is lens-like in form, attaining a thickness of 1.5 to 2.5 m in the middle. In the thick, middle part of the horizon, carnotite occurs in small vugs and along fractures in dense calcrete. The calcrete consists principally of dolomite, calcite, and alpha-quartz, with lesser amounts of alpha-cristobalite and celestite. Surface samples of the calcrete contain about 0.5 to 5.0 % strontium, 27 to 425 ppm uranium, and 44 to 120 ppm vanadium. At another occurrence, carnotite is absent, but samples of the silicified and dolomitized calcrete contain 100 to 300 ppm uranium and 0.3 % strontium.

Dolomitization and the introduction of significant amounts of strontium in these occurrences imply that the calcrete formed, at least in part, by interaction with weakly to possibly moderately saline groundwaters rather than by pedogenic processes alone. Although the palaeogeomorphic setting of these occurrences cannot be reconstructed with present information, the preliminary mineralogic and geochemical data suggest that the deposits in the Lubbock area resemble the calcrete uranium deposits at Yeelirrie in Western Australia [15, 16]. The conditions that produced these uraniferous calcrete deposits in the Lubbock area do not exist today and the deposits are at present being destroyed by erosion.

4. OTHER SURFICIAL URANIUM DEPOSITS

Numerous other surficial uranium deposits of various types occur in the United States. Among the most important of these are the Lost Creek schroekingerite deposits in Wyoming [17] and the karst cave tyuyamunite deposits in the Bighorn and Pryor Mountains of Montana and Wyoming [18], (Figure 1). The following discussion of these two areas is summarized from the reports referred to above.

The Lost Creek schroekingerite deposits occur in the north-central part of the Great Divide Basin, a semi-arid topographic basin of interior drainage in central Wyoming. The deposits occur above the present-day water table, 0.7 to 2.6 m below ground level, in gently north-dipping sandstone and siltstone beds of Eocene age and in Quaternary sand and gravel that locally overlies the Tertiary sedimentary rocks. No deposits are known below the water table. Schroekingerite, the only uranium mineral present, occurs in subhorizontal tabular bodies as concretions or pellets 0.5 to 3 cm in diameter, as small crystals coating sand grains, as tabular masses along partings in shale, and as veinlets and encrustations. Gypsum, opal, and carbonate minerals are intimately associated with the uranium mineral. The schroekingerite is soluble, and thus the deposits are ephemeral and tend to be redistributed after periods of rain. The schroekingerite and other minerals were deposited from uraniferous groundwaters (as much as 46 ppm uranium) in a manner similar to the formation of non-pedogenic calcrete in many semi-arid and arid areas in the western United States.

During Late Mississippian or Early Pennsylvanian time, a karst terrane formed in the upper part of the Mississippian Madison Limestone in the Montana and Wyoming areas of the western United States. This karst terrane is now exposed in the Pryor Mountains of south-central Montana and the Bighorn Range of north-central Wyoming (Figure 1). Some of the caves and solution channels are filled with limestone rubble, siliceous sinter, and fine-grained sediment. Tyuyamunite occurs as fine crystals disseminated in silt and sinter, as films on secondary calcite, and as crusts and films on walls and blocks. Not all caves are mineralized and uranium deposits vary from minor accumulations in small solution openings to substantial accumulations in a series of interconnected openings covering tens of metres laterally and a known depth of 53 m. The favoured hypothesis for the origin of these deposits is that during the present erosion cycle, downward-moving groundwaters leached uranium from surrounding terranes and deposited it in openings in the karst.

These surficial schroekingerite and tyuyamunite deposits appear to be relatively limited in geographic distribution and resource potential compared to the potential of the deposits described in the previous sections.

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REFERENCES

- [1] CULBERT, R.R., LEIGHTON, D.G., Young uranium deposits, In: Unusual Uranium Deposits, (Ed.) Gabelman, J., American Association of Petroleum Geologists Special Paper, in press.
- [2] CULBERT, R.R., LEIGHTON, D.G., Low-energy gamma spectrometry in the geochemical exploration for uranium, J. Geochem. Explor. **14** (1981) 49–68.
- [3] CULBERT, R.R., BOYLE, D.R., LEVINSON, A.A., Surficial uranium deposits in Canada, this Volume.

- [4] SWANSON, V.E., VINE, J.D., Uranium in organic substances from two alpine meadows, Sierra Nevada, California, US AEC TEIR740 (1958) 209–214.
- [5] BOWES, W.A., BALES, W.A., HASELTON, G.M., Geology of the uraniferous bog deposit at Pettit Ranch, Kern County, California, US AEC Report RME-2063 (1957) 27.
- [6] COLLINS, D.B., GRAHAM, D.C., HORNBAKER, A.L., National uranium resource evaluation, Leadville Quadrangle, Colorado, US DOE Report PGJ/F-027(82) (1982) 81.
- [7] NASH, J.T., Uranium and thorium in granitic rocks of northeastern Washington and northern Idaho, with comments on uranium resource potential, US Geol. Surv. Open-File Report No. 79-233 (1979) 39.
- [8] CASTOR, S.B., BERRY, M.R., ROBINS, J.W., Preliminary report on uranium and thorium content of intrusive rocks in northeastern Washington and northern Idaho, US DOE Report GJBX-89(77) (1977) 40.
- [9] ARMANDS, G., Geochemical prospecting of a uraniferous bog deposit at Masugnsbyn, northern Sweden, In: Geochemical Prospecting in Fennoscandia, (Ed.) Kvalheim, A., Interscience, New York (1967).
- [10] REEVES, C.C., Jr., Origin, classification, and geologic history of caliche on the southern High Plains, Texas and eastern New Mexico, J. Geology, **78** 3 (1970) 352-362.
- [11] NICHOLS, C.E., BUTZ, T.R., CAGLE, G.W., KANE, V.E., Wide-spaced uranium geochemical survey in the Plainview, Lubbock, and Big Spring quadrangles, Texas, US DOE Report K/UR-10, Union Carbide Oak Ridge Gaseous Diffusion Plant (1977) 71.
- [12] SENI, S.J., MCGOWEN, J.H., RISNER, R.S., National Uranium Resource Evaluation, Amarillo Quadrangle, Texas, US DOE Report GJQ-013(81) (1981) 24.
- [13] MCGOWEN, J.H., SENI, S.J., ANDERSEN, R.L., THURWACHTER, J.E., National uranium resource evaluation, Lubbock Quadrangle, Texas, US DOE Report GJQ-012(81) (1981) 48.
- [14] FINCH, W.I., Uranium in west Texas, US Geol. Surv. Open-File Report 75-356 (1975) 20.
- [15] MANN, A.W., DEUTSCHER, R.L., Genesis principles for the precipitation of carnotite in calcrete drainages in Western Australia, Econ. Geol. **73** 8 (1978) 1724–1737.
- [16] BRIOT, Ph., Sur la genese de certains gites uraniferes, Min. Dep. 17 (1982) 151–157.
- [17] SHERIDAN, D.M., MAXWELL, C.H., COLLIER, J.T., Geology of the Lost Creek schroeckingerite deposits, Sweetwater County, Wyoming, US Geol. Surv. Bull. 1087-J (1961) 391–478.
- [18] BELL, K.G., Uranium in carbonate rocks, US Geol. Surv. Prof. Paper 474-A (1963) 29.

SURFICIAL URANIUM DEPOSITS: SUMMARY AND CONCLUSIONS

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ABSTRACT

SURFICIAL URANIUM DEPOSITS: SUMMARY AND CONCLUSIONS

Uranium occurs in a variety of surficial environments in calcretes, gypcretes, silcretes, dolocrete and in organic sediments. Groundwater moving on low gradients generates these formations and, under favourable circumstances, uranium deposits. A variety of geomorphic settings can be involved. Most surficial deposits are formed in desert, temperate wetland, tropical, or transitional environments. The largest deposits known are in sedimentary environments in arid lands. The deposits form largely by the interaction of ground or surface waters on the geomorphic surface in favourable geologic terrains and climates. The deposits are commonly in the condition of being formed or reconstituted, or being destroyed. Carnotite is common in desert deposits while in wetland deposits no uranium minerals may be seen. Radioactive disequilibrium is common, particularly in wetland deposits. Granites and related rocks are major source rocks and most large deposits are in regions with enriched uranium contents, i.e. significantly greater than 5 ppm uranium. Uranium dissolution and transport is usually under oxidizing conditions. Transport in desert conditions is usually as a bicarbonate. A variety of fixation mechanisms operate to extract the uranium and form the deposits. Physical barriers to groundwater flow may initiate ore deposition. Mining costs are likely to be low because of the near surface occurrence, but there may be processing difficulties as clay may be present and the saline or carbonate content may be high.

1. INTRODUCTION

During the last 30 years, many deposits and occurrences of uranium have been found in highly diverse surficial environments. These include lateritic terranes in tropical areas, valleys and playas in desert regions, alkaline lakes in semi-arid basins and high plains, and organic-rich valleys and lake bottoms in more temperate areas. These deposits occur on virtually all the continents and constitute significant uranium resources world-wide. Exploration in equatorial regions has concentrated on aeroradiometric anomalies that occur over lateritic landscapes that developed under Holocene, Pleistocene, or latest Tertiary tropical conditions. Occurrences of surficial uranium have been discovered in central Africa, Brazil, India [1] and China, but little information is at present available about them.

In 1972, after several years of exploration in arid areas of Australia and Africa, geologists discovered carnotite-bearing, highly cemented sediments in drainages at Yeelirrie in the desert of Western Australia. Discoveries soon followed in Namibia and South Africa, and, later, in Mauritania, Somalia, Algeria, and elsewhere. The Yeelirrie deposit, the Langer Heinrich deposit in Namibia, other similar deposits in these two areas and elsewhere, and a variety of occurrences in cemented surficial sediments, became widely labeled as calcrete uranium deposits by many geologists. Prior to its use with surficial uranium deposits, the term calcrete had been used mainly as a synonym of the terms caliche, kunkur, or others [2] to describe calcite-cemented pedogenic sediments in semi-arid to arid terranes. Use of the term created some confusion, because early studies of the Australian deposits showed that, although some host rocks are pedogenic, the extensive mineralized calcretes along valley drainages formed mainly by the diagenetic cementation of sediments in the vadose zone. The terms groundwater calcrete and valley calcrete were used by many writers to distinguish this type of cemented sediment from strictly pedogenic types [3, 4]. As these sediments and the uranium deposits associated with them were explored and studied in detail in Australia, Africa, and elsewhere, cements such as gypsum, silica, dolomite, and clay were found in greater amounts than was calcite. The terms gypcrete, silcrete, and dolocrete were used where appropriate. Carlisle [5, 6] summarized previous work on "calcrete" uranium deposits in Australia and Africa. He stressed the distinction between pedogenic, non-pedogenic, and hybrid mechanisms for the formation of the cemented surficial sediments and the emplacement of their associated uranium.

Geologists recognized varied geomorphic settings of the deposits, and discovered, for example, that some deposits occurred at the edges of and within playa lakes downstream from uranium deposits in valley settings. Noting the variation in geomorphic settings, the confusion in the use of the terms calcrete, gypcrete and silcrete, and considerable variation in the degree of cementation in these uranium host rocks, Toens and Hambleton-Jones [7] proposed a classification that emphasized the geomorphic setting.

Uranium has long been known to accumulate in organic-rich sediments such as peat [8]. Little exploration activity has been focussed on these occurrences because they were generally thought to be local phenomena of limited extent. Recently, however, economically significant deposits of uranium have been found in surficial, organic-rich, valley-fill and lacustrine sediments on granitic terranes in moderately wet, temperate climates [9, 10]. Production from one deposit in northeastern Washington in the United States began in the fall of 1983.

2. TYPES OF SURFICIAL URANIUM DEPOSITS

Although surficial uranium deposits seem likely to form under almost a continuum of climatic conditions [11], most of the surficial uranium deposits are formed in four climatic types: 1) hot and dry (desert), 2) hot and wet (tropical), 3) temperate and cool (wetlands), and 4) climates transitional between the first and the third. This classification is not intended to be exhaustive, but includes the major types of surficial uranium deposits described in this volume.

- I Desert
 - A Non-pedogenic*
 - 1 Valley-fill
 - 2 Playa
 - B Pedogenic*
 - C Hybrid*
 - 1 Non-pedogenic deposits with a pedogenic precursor
 - D Ephemeral evaporative
 - 1 Karst cave tyuyamunite
 - 2 Schroeckingerite
- II Wetland
 - A Valley-fill
 - B Lacustrine
- III Tropical
 - A Deposits developed in lateritic weathering profiles over uranium-rich source rocks
 - B Gossans
 - 1 Supergene enrichment of primary uranium orebodies
 - 2 Epigenetic uranium entrapped in redox fronts above sulphide orebodies
- IV Transitional
 - A Alkaline lake limestone, dolomite, chert, organic-rich siltstone and mudstone, diatomaceous earth

3. SIZE, GRADE, AND MORPHOLOGY

Sedimentary rocks in arid lands contain the largest known surficial uranium deposits. The deposit at Yeelirrie contains about 45 000 t (metric tons) of U_3O_8 at an average grade of 0.15% [12]. Innumerable smaller deposits and occurrences of non-pedogenic and pedogenic uranium dot the landscape in favourable areas in Western Australia, Namibia, Somalia, and Mauritania. Because of the tendency for uranium in valley sediments like those at Yeelirrie to occur in irregularly distributed fractures and cavities, sharp lateral variations in ore grade are common.

Wetland surficial uranium deposits range in size from less than a hundred kilograms of contained uranium in thin, organic-rich soil near a uraniferous spring to about 500 t along extensively mineralized valley-fill sediments. The grade in these deposits ranges from slight enrichments (a few tens of parts per million) to about 3.0% (dry basis) in uraniferous peat in Sweden [13]. The grade is limited by the uranium content in local groundwater and surface water, the percentage of organic matter in the sediment, and the geochemical enrichment factor for organic matter of about 10 000 suggested by Szalay [8].

Experimental studies by Gruner and Rogers [14] suggest an upper limit to the uranium content of peat of about 13 to 15 weight percent (dry basis). Thus, wetland uranium deposits, although not large, may attain grades that compare favourably with other types of mined uranium deposits. In favourable terranes, the deposits occur in clusters along a single drainage and its tributaries or in adjacent drainages.

The geometry of surficial uranium deposits is strongly controlled by the shape of the host sedimentary bodies, and because the deposits most often form in near-surface sedimentary units of low gradient, they are generally subhorizontal and tabular. In plan view, two geometries dominate: the elongate, sometimes sinuous shapes associated with channel or valley-fill sediments, and the irregular, ovoid shapes associated with lacustrine and playa sediments.

These overall geometries are further modified by a 'nugget' or 'beads on a string' effect. That is, within a mineralized horizon, concentrations of higher-grade uranium almost always exist. This effect seems to be more pronounced in these deposits than in many other types. In valley calcretes of Western Australia, a low-grade blanket of uraniferous alluvium (less than 100 ppm) commonly extends for several tens of kilometres along the valley. Within the low-grade zone are isolated patches of higher grade material. Locally, clusters of ore grade material constitute significant deposits.

* The terms calcrete, gypcrete, and silcrete ought to be used here where the major cementing agent has been identified.

4. PRESERVATION IN THE ROCK RECORD

Surficial uranium deposits form largely by the interaction of groundwater or surface water on the geomorphic surfaces in favourable geologic terranes and climatic zones. Groundwaters, surface waters, and geomorphic surfaces are all dynamic phenomena. The formation of these uranium deposits is a continuous process for they are either being reconstituted, or being destroyed by chemical or physical processes. Because the specific sedimentary hosts in which uranium is deposited tend to form in regions that are being denuded, such rocks are not commonly preserved in the geologic record. Deposits in Namibia, for example, are at present being destroyed by erosion related to late Pleistocene uplift [15]. Uranium in sediments along valleys in Western Australia is at present being dissolved, moved, and redeposited in playas downstream [16]. If the sedimentary hosts are preserved, they are considerably altered diagenetically once removed from the surface environment, and uranium may be lost. There are some exceptions; for example, in France, uranium deposits occur in lateritic weathering profiles of Cretaceous and Tertiary age [1] where uranium occurs with ferric oxyhydroxides that precipitated beneath palaeosurfaces.

5. MINERALOGY AND GEOCHEMISTRY

Uranium deposits in deserts are generally characterized by carnotite as fracture coatings, void fillings, and, less commonly, disseminated in the cement. These deposits also contain various amounts of associated authigenic minerals, principally calcite, dolomite, gypsum, silica, halite, and clay. The degree of cementation ranges from as little as 5% to almost complete replacement of the sediment by authigenic material. The host rock is usually zoned mineralogically with respect to the water table or to the surface. A typical vertical profile at the Yeelirrie deposit consists, from top to bottom, of calcite-cemented sediment (calcrete) above the water table. Dolomite content typically increases downward in the calcrete, then tapers off as the base of the calcrete is approached. Waters associated with the Yeelirrie deposit contain significant quantities of zinc, strontium, and fluorine; the host rock there and at other deposits contains minor amounts of celestite, fluorite, and barite [10, 17].

In wetland deposits, uranium is the only metal present in significant quantities, although molybdenum has been detected in some deposits [9, 10]. The deposits usually are in reducing environments that may range in organic-matter content from a few percent to almost 100%. No uranium minerals have yet been recognized in these deposits. Hydrogen sulphide and sulphur-bearing minerals may be present. Little diagenetic change has occurred in the sedimentary hosts except that some organic matter has matured. The importance of the degree of maturation of organic matter in the entrapment of the uranium is uncertain.

Uranium deposits in lateritic profiles are geochemically and mineralogically variable and complex [1]. In addition to abundant iron and manganese hydroxides and oxyhydroxides, the deposits generally contain titanium hydroxides, kaolinite and gibbsite. Nickel, vanadium, copper, molybdenum, zinc, cobalt, arsenic, selenium, and sulphur can be present in significant amounts, depending on the substrate.

6. ISOTOPIC DISEQUILIBRIUM AND AGE

Isotopic disequilibrium is the expected condition for most surficial uranium deposits. The Western Australian deposits show significant variations from equilibrium. Dickson [16] reports a range of the ratio of chemical uranium to radiometric equivalent uranium from about 0.75 to 1.15 for the high-grade zones in a series of deposits; average values are close to 1.00. Low-grade zones (less than 200 ppm) usually have a wider range of disequilibrium values but also tend to have excess ^{226}Ra . Deposits in playa delta and playa bottoms tend to show excess uranium. Namibian deposits show a range of disequilibrium values from 0.5 to 2.0 [15].

Wetland uranium deposits show varying degrees of isotopic disequilibrium. Uranium by chemical analysis almost always exceeds radiometric equivalent uranium. The disequilibrium ratio for a series of deposits studied by Culbert in Canada and in the western United States is in the range of 0.05 to 0.10 [18], which reflects the generally youthful character of the deposits. The low radiometric signature makes exploration for this deposit type more difficult.

Isotopic disequilibrium and ore textures in the deposit at Yeelirrie suggest that uranium continually dissolved and reprecipitated during an extended period in the late Pleistocene and Holocene [16]. The age is not known for the Yeelirrie deposit or for any other nearby deposits. Isotopic disequilibrium can be explained by several different models for uranium emplacement and movement. The most geologically reasonable models suggest that the uranium was deposited from 0.1 to 0.75 Ma ago. The age of Namibian deposits has been estimated from the regional geologic setting to be at least 0.5 Ma [15], but the deposits probably formed during a period of several tens to several hundreds of thousands of years. Most wetland uranium deposits are younger than 12 000 years [9, 10], the maximum age for the host sediment, and probably continue to form today.

7. SOURCE AND TRANSPORT

Granites and related igneous rocks and, to a lesser extent, high-grade metamorphic rocks that were partially melted are the major source terranes for uranium in arid land and wetland surficial uranium deposits [5, 9, 10]. The source for vanadium, an important constituent of most arid land surficial uranium deposits, is a point of controversy. Workers in Australia have proposed two sources: the mafic minerals associated with granites

(specifically hornblende, biotite, and the iron- and titanium-oxide minerals), or the metavolcanics of the greenstone belts. Further work seems essential, and some of that work ought to focus on the provenance of the fluorine, zinc and strontium in groundwaters at the Yeelirrie deposit [17].

Although most large surficial uranium deposits are near source rocks that are enriched in uranium (significantly greater than 5 ppm), many deposits have formed in terranes where granites and other rocks appear to have average (1 to 5 ppm) uranium contents. Additional favourable circumstances, such as extensive fracturing or an unusually labile mineralogic residence for the uranium, may allow sufficient uranium in solution to enter the surficial environment and to be deposited [9, 10].

The transport of uranium required oxidizing conditions in the source and in the environments between the source and the host. Transport is less sensitive to the presence of complexes because, although complexes increase the solubility of uranium, a wide variety of complexes occur in almost all natural waters. For virtually all surficial uranium deposits, uranium is liberated from source rocks by leaching and is transported by oxidizing surface waters or shallow groundwaters. In arid lands, uranium is generally leached from source rocks by slightly alkaline, oxidizing waters and carried as uranyl carbonate or bicarbonate complexes. Oxidizing conditions persist and the alkalinity and salinity of the waters tend to increase downflow, keeping the uranyl ions in solution until fixation mechanisms intervene. In tropical environments, the near-surface soil horizons are typically acid and uranium is probably complexed by sulphate or phosphate ions. In wetlands, the waters are usually acid or close to neutral and are relatively fresh but still carry inorganic or organic complexing agents well in excess of any contained uranium. In tropical and wetland environments, transport distances are generally short (a metre to a few kilometres), whereas in arid lands, transport distances may be long (several tens of kilometres).

During transport from source to eventual host, uranium may be concentrated first in a protore, such as an older weathering horizon which is later dissected, and then remobilized. In Western Australia, pre-existing lateritic soil profiles may have served a sink for uranium [17].

8. FIXATION MECHANISMS

The processes involved in the fixation of uranium in surficial environments include one or more of the following (modified from Boyle [11]):

1. Dissociation of soluble complexes; for example, uranyl carbonate species through loss of CO_2 to the atmosphere or precipitation of a carbonate mineral.
2. Evaporative concentration of solute species in near-surface groundwaters.
3. Change in valence state of vanadium or uranium which decreases the solubility of the ore mineral. For example, carnotite may form, in part, by the oxidation of V(IV) to V(V) where sufficient uranium (VI) is available.
4. Mixing of waters creating local supersaturation with respect to uranium minerals.
5. Sorption by organic matter followed by reduction of the uranium by reduced sulphur species or organic matter.
6. Sorption by silica, iron hydroxides or oxyhydroxides, and clay.

For many arid land and wetland deposits, physical barriers to groundwater flow or changes in slope may initiate ore deposition. In non-pedogenic calcrete-hosted uranium deposits along valleys, basement highs in the alluvium near the deposit may have been barriers to flow. These barriers direct groundwater toward the surface, where evaporation increases, CO_2 exsolved, and the groundwater can mix with more oxygenated waters or with waters containing different solutes. In cool, wet climates, organic matter can accumulate where drainage impediments or changes in slope along valleys cause the water table to be high, promoting plant growth and inhibiting decay. Flow velocities are reduced, increasing the time of interaction between organic-rich sediments and passing uraniferous solutions.

9. ECONOMICS

The economics of surficial uranium deposits is uncertain because there is little mining history. Uranium in arid lands forms individual deposits large enough to support substantial mining and milling operations. The deposits tend to be in remote areas whose industrial infrastructure is small and where startup costs are high. These deposits have relatively low mining costs because they are generally near-surface (2 to 11 m) and can be mined by shallow open-pit techniques. Extraction costs may be high, however, because of the complex mineralogy of the deposits [19]. The abundant carbonates and the high calcium-magnesium ratio of the carbonates in the ore require alkaline leach techniques rather than acid-based techniques. Abundant clay and fine quartz in the ores tend to form suspensions in the pulp, from which the leachate is difficult to separate. The high salt content of the ore and the salinity of available water in many of the areas tend to make the leachates saline and this salinity has a tendency to foul resins. However, high salinities tend to flocculate clays, and thus assist in part of the milling process.

The problems of mining and milling surficial uranium deposits in tropical areas are similar to those in desert areas. Clearly, some deposits are large enough to sustain mining and milling operations; however, these deposits tend to be in remote areas and startup costs will be high. As with most surficial deposits, mining costs are likely to be relatively low. The generally complex mineralogy may require nonstandard extraction techniques and the presence of clays may present some unusual problems.

The wetland uranium deposits are relatively small and clusters of deposits may be necessary to support a small milling operation. Isolated deposits will probably not be economic in the near future. The mining costs are low as the host is at or near the surface (0 to 6 m) and is poorly consolidated. Extraction costs are also likely to be low. Mildly acid-oxidizing leach solutions appear to work well. The low radioactivity of the deposits may allow return of the spent ore to the mining site without special treatment of the material or perpetual care, especially if the extraction techniques do not alter the physical or chemical character of the original material significantly. Grade control of the mill feed may be a problem as standard measuring techniques based on gamma-ray devices cannot be used. Some development work on low-energy gamma or alpha counting devices may be needed for grade control.

REFERENCES

- [1] SAMAMA, J.C., Uranium in lateritic landscapes, this Volume.
- [2] GOUDIE, A., The chemistry of world calcrete deposits, *J. Geol.* 80 (1972) 449–463.
- [3] MANN, A.W., HORWITZ, R.C., Groundwater calcrete deposits in Australia: some observations from Western Australia, *J. Geol. Soc. Aust.* 26 (1979) 293–303.
- [4] BUTT, C.R.M., MANN, A.W., HORWITZ, R.C., Regional setting, distribution and genesis of surficial uranium deposits in calcretes and associated sediments in Australia, this Volume.
- [5] CARLISLE, D., MERIFIELD, P.M., ORME, A.R., KOHL, M.S., KOLKER, O., The distribution of calcretes and gypcretes in the southwestern United States and their uranium favourability. US Dept. of Energy, Open File Report GJBX-29(78) (1978) 174.
- [6] CARLISLE, D., Possible variations on the calcrete-gypcrete uranium model, US Dept. of Energy Report GJBX-53(80) (1980) 38.
- [7] TOENS, P.D., HAMBLETON-JONES, B.B., Definition and classification of surficial uranium deposits, this Volume.
- [8] SZALAY, A., The significance of humus in the geochemical enrichment of uranium, In: *Proc. 2nd Int. UN Conf., Peaceful Uses Atomic Energy, Geneva (1958)* 1731.
- [9] CULBERT, R.R., BOYLE, D.R., LEVINSON, A.A., Surficial uranium deposits in Canada, this Volume.
- [10] OTTON, J.K., Surficial uranium deposits in the United States of America, this Volume.
- [11] BOYLE, D.R., The genesis of surficial uranium deposits, this Volume.
- [12] MANN, A.W., DEUTSCHER, R.L., Genesis principles for the precipitation of carnotite in calcrete drainages in Western Australia, *Econ. Geol.* 73 (1978) 1724–1737.
- [13] ARMANDS, G., Geochemical prospecting of a uraniumiferous bog at Masugnsbyn, northern Sweden, In: *Geochemical Prospecting in Fennoscandia*, (Ed.) Kvalheim, A., Interscience Publishers, New York (1976) 127–154.
- [14] GRUNER, J.W., ROGERS, J.J.W., The absorption of uranium by peat, US Atomic Energy Commission Report RMO-1021 (1952) 33.
- [15] HAMBLETON-JONES, B.B., Surficial uranium deposits in Namibia, this Volume.
- [16] DICKSON, B.L., Uranium series disequilibrium in the carnotite deposits of Western Australia, this Volume.
- [17] BRIOT, P., FUCHS, Y., Processus de minéralisation uranifères des calcretes: Une hypothèse non pédologique, this Volume.
- [18] CULBERT, R.R., written communication, 1982.
- [19] SIMONSEN, H.A., Beneficiation of surficial uranium deposits, this Volume.

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