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**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)**

**BY
DONALD CARLISLE**

With Sections by

**Paul M. Merifield
Antony R. Orme
Martin S. Kohl
Oded Kolker**

**In Consultation With
Owen R. Lunt**

January 6, 1978

MASTER

**Prepared for the United States Department of Energy
Under Subcontract Number 76-022-E Between
Bendix Field Engineering Corporation and
The Regents of the University of California**

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YEELIRRIE

LANGER HEINRICH

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SUMMARY

Calcrete, dolocrete, and gypcrete carnotite deposits in arid Western Australia and the Namib Desert of South West Africa are derived from weathering of granitoid rocks followed by lateral transport in vadose and phreatic waters within the regolith. Occurrences are abundant in both regions, though only a few are of ore grade. The only uranium mineral is carnotite except for the reported occurrence of soddyite in a part of South West Africa. Carnotite is deposited in association with authigenic carbonate (rarely gypcrete) in trunk subsurface drainages and calcrete deltas. Concentrations occur in areas of constricted flow or where waters are forced close to the surface. Transport of uranium in the meteoric waters is apparently as uranyl carbonate complex ions. Precipitation of carnotite occurs in, adjacent to, and commonly just below a calcrete mass, apparently close to the existing water table and entirely in an oxidizing environment. The uranium is continuously hexavalent. The calcrete hosts are not sheetlike pedogenic or soil calcretes of the sort known as caliche in United States, but they are crudely lenticular masses of alluvium and soil cemented by calcium or calcium-magnesium carbonate which are up to tens of meters thick, several hundred meters to a few kilometers wide, and tens of kilometers in length in the axial portions of paleostreams or existing drainage systems. They are products of lateral groundwater flow and are therefore nonpedogenic. In Australia these "valley calcretes" cement and replace detritus largely derived from the kaolinitic portions of laterized granitic rocks, and they are earthy to aphanitic in texture but highly permeable as a result of shrinkage cracks and karstic features, especially within peculiar but abundant "mound" structures. In South West Africa the uraniferous valley calcretes cement coarse to fine alluvium, resembling concrete in texture, and they are overlain in occurrences close to the ocean by gypcrete which can itself contain ore-grade mineralization. Pedogenic modifications can occur at the surface in both regions.

The study has led to a genetic classification of calcretes (Table 3.3) emphasizing uranium favorability and based upon the essential distinction between pedogenic and nonpedogenic processes. The terminology developed

in Section 3.0 and the relationships of calcrete genesis to zones of authigenic carbonate deposition (the soil moisture zone, the gravitational water zone, and the capillary fringe, Figure 3.3) are used throughout the report.

In Western Australia the region of uraniferous nonpedogenic (valley, deltaic, and lacustrine) calcretes coincides with a particular extremely arid climate and with the occurrence of acidic soils and extensive authigenic silica (Wiluna Hardpan) in the catchment areas. The great majority of carnotite prospects, with Yeelirrie orebody at their center, overlie Archean Yilgarn granites and greenstones in the southerly part of the valley calcrete region, but valley calcretes are not restricted to the Yilgarn Block. South of the valley calcrete region siliceous hardpans are absent, pedogenic calcrete (caliche) is widespread, and uranium concentrations have not developed. Recognition and explanation of this boundary, the "Menzies Line," (Table 4.3, Section 4.3) are central to the genetic models for Western Australia (Figures 4.20, 4.21) and for the development of one of the most important of the favorability criteria (Section 7.1), namely that uranium must remain in solution throughout most of the catchment area if economic concentration is to take place and that this is unlikely if pedogenic calcrete deposition is occurring extensively throughout that area. On geological evidence valley calcretes and uranium mineralization in Western Australia are latest Pleistocene to Holocene: therefore, the pattern of present climate is relevant to their origin. Valley calcretes are not coincident with the distribution of salt lakes. Deep laterization and the formation of silcretes on the Old Plateau long predate the calcretes. They represent an entirely different process and climate. Topographic gradients are extremely low both north and south of the Menzies Line.

Carnotite precipitation results mainly from evaporative concentration, destabilization of uranyl carbonate complexes, and oxidation of V(IV) to V(V). Common-ion precipitation of calcium or magnesium carbonate and loss of CO₂ when followed by desiccation are important. Carnotite and carbonate are initially contemporaneous, but reworking has enriched uranium concentration prior to stabilization of carnotite. Films of

microcrystalline quartz, "opal," protect epigenetic carnotite from dissolution at Yeelirrie. Nevertheless, carnotite is undergoing dissolution from calcretes today, and, in several elevated and dissected calcretes, has been largely removed.

The Yeelirrie orebody and its environs are described in considerable detail (Section 4.2.1), including essentially all of the data provided by Western Mining Corporation. This provides a basis for comparative discussions of three other prospect areas, the Hinkler Well Drainage, north Lake Way, and Lake Maitland. Although all of the visible mineralization at Yeelirrie is texturally epigenetic, evidence is presented for contemporaneous carnotite and carbonate, mainly dolomite, in the "young" mounds of Holocene calcrete deltas on the Hinkler Well drainage and north Lake Way. Important hydrogeochemical data have been provided for both of these drainages by Mann and Deutscher of the CSIRO in Perth.

The calcrete and gypcrete host rocks in South West Africa differ from the Australian calcretes, notably in their Late Tertiary age, the abundance of coarse detrital fragments which constitute the skeletal framework of the calcrete, the fact that carbonate is predominantly sparry calcite with neither dolomite nor opal, the presence of abundant gypsum in the upper parts of occurrences within 60 km of the Atlantic, and in the vertical gradation into pedogenic sheet calcrete and gypcrete. Reasons for the coarse detritus are: 1) the very appreciable relief between the Great Western Escarpment, with elevations in excess of 2,000 m in the Khomas Hochland, and the broad coastal platform of the central Namib Desert in which the principal known uraniferous calcretes and gypcretes are found and 2) the relatively modest degree of chemical weathering--about as intense as much of the Mojave Desert in the United States. The calcrete does not develop abundant dehydration or shrinkage cracks as does the Australian calcrete, and it is not a good aquifer, though it is appreciably permeable. At several places irregular solution tubules and replacement bodies about the size of a finger but sometimes much larger have developed. Commonly these have a shell of impure calcite and a sandy filling, and, under some conditions, the sandy fillings of these tubules are richly mineralized with carnotite.

Gypcrete with the same kind of aggregate as the calcrete occurs directly above calcrete within the belt of almost ever-present fogs from the Atlantic Ocean. Thicknesses up to 25 meters, but more commonly 7 to 10 meters, were observed in paleochannels on the Tumas River property of Anglo-American Corporation which is some 40 km inland from the ocean. Gypcrete thins to a few centimeters or less on the Langer Heinrich calcrete-uranium property some 80 km from the ocean. An ubiquitous overlying layer of surficial gypcrete or, inland from the fog limit, surficial calcrete, covers the entire Namib Desert except only where masked by recent wind-blown sand or alluvium or where bedrock is exposed in sparse inselbergs or ridges or in recent drainage incisions along the main rivers and their tributaries. Carnotite is found only very rarely in this superficial gypcrete or calcrete, and in those places it is thought to have been recently reworked.

No clear-cut regional separation of valley calcretes from pedogenic calcretes such as that manifest by the Menzies Line of Western Australia is known in southern Africa, but this could be because the valley calcretes are Late Tertiary, whereas the pedogenic calcretes are Pleistocene to Holocene. Since the Namib Desert is not a region of interior drainage, salt lakes are not found and no deltalike masses of calcrete have formed. Some of the sheetlike calcretes around Etosha Pan in the north could conceivably be deltaic, and there are many playa lakes in eastern South West Africa.

Carnotite associated with calcrete or gypcrete is reported to occur over the entire width of the Namib Desert and from the Kuiseb River in the south to points near the coast only a few tens of kilometers south of the Angolan border. As in Australia, carnotite also occurs in associated sediments in very significant amounts and is more widespread in weathered bedrock than it is as yet reported to be in Australia. At Langer Heinrich some ore-grade mineralization occurs in a "clayey" calcrete only slightly indurated. On the Tumas River, ore-grade material occurs primarily within gypcrete above apparently barren to subeconomic calcrete but particularly in uncemented or poorly cemented alluviated aeolian sand within the gypcrete. In the south central Namib near the Kuiseb River, carnotite occurs in presently noneconomic amounts in

weathered schist, particularly near residual patches of overlying calcrete. At Langer Heinrich, carnotite extends downward into schist bedrock beneath the calcrete orebody for as much as 4 meters with no sign of CaCO_3 cementation.

In spite of the differences and the much greater difficulty in recognizing and delineating valley calcretes in South West Africa than in Western Australia, marked similarities between the two regions provide support for the main generalizations from the Australian study. Principal among these are 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, or which act as sills and thus force the water close to the land surface where it is subject to loss of dissolved CO_2 , to evaporation, and to oxidation greatly favor the formation of uraniferous calcretes. As in Australia the larger part of all valley calcretes and gypcretes is unmineralized. Ore-grade mineralization is roughly horizontal in attitude and probably related to past or present groundwater tables. Source rocks are important and not hard to find; Proterozoic migmatites, pegmatites, alaskites, and granites abound, many appreciably anomalous in uranium. The unusually uraniferous alaskitic pegmatites and migmatitic granites of the central high-grade metamorphic zone of the Damara Belt (e.g., Rössing, 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 said to be abnormally rich in vanadium.

Carnotite precipitation mechanisms are thought to be essentially similar to those postulated for Western Australia. One difference is the presence of abundant gypcrete on the Namib Platform and the probability of common-ion precipitation of calcite at the contact of carbonate- and sulfate-saturated waters there rather than on the margins of salt lakes. Although all of the megascopic carnotite appears to be epigenetic to its host, filling pore spaces and solution tubules or replacement bodies, though not noticeably in fractures as at Yeelirrie, one cannot say that

some carnotite and some calcrete may not be contemporaneous.

Criteria for uranium favorability deduced from the Australian and South West African studies have been applied in a preliminary way to the southern Basin and Range Province of the United States. The criteria include:

1. Adequate source terrain, deeply weathered;
2. Anomalous groundwater uranium and vanadium contents;
3. Large catchment area;
4. Low drainage gradients;
5. Very limited runoff;
6. Nonpedogenic calcrete;
7. Absence of soil carbonate deposition or other uranium fixing processes in the catchment area;
8. Evaporative concentration of uranium, vanadium, and potassium downdrainage;
9. Constricted, shallowing, or upwelling groundwater flow within the valley calcrete area due to bedrock or impermeable sediment barriers;
10. Reconcentration of carnotite;
11. Stabilization of carnotite; and
12. Moderate to low relief and tectonic stability.

Several of these are reviewed in relationship to southwestern United States, and preliminary maps are presented in the final section of the report. Climate enters into at least seven of the criteria listed. Lack of tectonic stability and its influence on topography, subsurface morphology, and possible burial or destruction of carnotite occurrences are obviously major factors in the study area. It may be interesting to observe, however, that although ancient stable surfaces of low relief are most favorable, the duration of mineralization may not need to be excessive, judging from the apparent age of Western Australian occurrences.

The procedure has been to search for areas in which nonpedogenic calcrete or gypcrete may have developed and where additional study or exploration might be justified. LANDSAT and selected U-2 and low level air photographs, a variety of published geological maps and reports, soils maps, and private communications provided initial guidance. A caliche

distribution map (Plate VII-1) of the study area has been compiled from soil survey and field data. Many areas were visited and some of the more interesting are described briefly, including parts of Clark County, Nevada, where occurrences of carnotite in calcrete previously known and one occurrence newly discovered during the study are reported.

2.0

INTRODUCTION

2.1

OBJECTIVES AND METHODS OF THE RESEARCH

The study upon which this report is based is part of the National Uranium Resource Evaluation (NURE) program of the United States Energy Research and Development Administration. Its purpose is to evaluate the possible favorability of calcrete, caliche, and gypcrete in the southern Basin and Range Province of the United States as host rocks for uranium mineralization.

Recent interest in calcretes and gypcretes as uranium hosts is a consequence of the discovery in 1972 of a carnotite calcrete orebody at Yeelirrie in Western Australia and of another similar deposit in 1974 at Langer Heinrich in the Namib Desert of South West Africa (Namibia), as well as nearby occurrences of carnotite-rich gypcrete. The Australian deposit contains 46,000 tonnes of U_3O_8 at an average grade of 0.15%, of which 24,000 tonnes are above 0.36%. Its average depth is 8 m. Ore reserves have not been announced for the South West African deposit, but they are considered to be substantial, and they, too, are at a shallow depth, as are the gypcrete occurrences. Numerous additional occurrences have been found in both areas. Uraniferous calcrete of potential ore grade has been found also in Somalia and is reported from Mauritania and Angola.

The deposits are only distantly related to evaporite uranium occurrences, on the one hand, and sandstone deposits, on the other. They are essentially a new type.

The plan of research has been to make an evaluation and comparison of the known uraniferous calcretes and gypcretes of Western Australia and South West Africa, to place these in a practical classification scheme which relates the mineralization to significant observable geological parameters, and, at the same time, to develop criteria for the likelihood of uranium mineralization. The classification and the criteria have then been applied to a study area of some 135,000 square miles in the southwestern United States with the aim of estimating uranium potential in calcretes or gypcretes and of assisting in the identification of target areas for exploration or detailed study. Specific areas in the southwestern United States have been examined in detail to test the criteria

developed.

The methods have been observational and the report is primarily descriptive. The mechanisms through which uranium has been derived, transported, and precipitated as carnotite in calcrete or gypcrete are inferred from field and, to some degree, textural relations but have not been investigated experimentally in this study. Field hydrogeochemical data are very limited. Some such data have been made available and models of ore genesis have been published by the Division of Mineralogy of the Commonwealth Scientific and Industrial Research Organization at Perth. Geologists and geochemists with the Atomic Energy Board of the Republic of South Africa and with private industry in both countries have contributed data and ideas verbally. All of these have been extremely useful. A great many questions are unanswered and large areas remain for future investigation.

2.2 TIMING, AREAL BOUNDARIES, AND RESPONSIBILITIES

Confirmation of the contract was received on July 13, 1976. The foreign examination was completed between August 18 and October 13, 1976, and field work in the southwestern United States and office and laboratory studies continued through June 1977.

The boundaries for the study of calcrete and gypcrete uranium favorability in the United States (Figure 7.11), specified in the contract for research, include far eastern and southern California, southernmost Nevada, and the Basin and Range portions of Arizona and New Mexico. The extensive calcrete occurrences of the Llano Estacado and the southern High Plains of Texas and New Mexico are not included in the project.

Carlisle is responsible for overall organization and for the mineral deposit geology of the occurrences; Merifield is responsible for the application of remote sensing techniques and for geology; Orme is responsible for geomorphology in South West Africa and the United States; Lunt is primarily responsible for the evaluation of soil studies.

Carlisle is sole author for Sections 3.0, 4.0, 5.0 (except 5.1, coauthored with Orme), and 6.0 and principle coauthor with Merifield for Section 7.0. Graduate student Martin Kohl has contributed his data from ongoing research on the Jean-Sloan, Nevada area, and Oded Kolker has developed the caliche map of the study area in the southwestern United

States and summarized his analysis for the report. John Cottrell assembled the data and figures on climate and made numerous other contributions.

2.3

PROCEDURE AND SOURCES OF INFORMATION

2.3.1

Preparation

Upon receiving notification of project funding, arrangements were made for employment of from two to four graduate students and one post-doctoral geochemist (Dr. Patrick Payton) at UCLA. During the first month, principal and co-principal investigators of the research team visited with members of the U.S.D.A. Soil Conservation Service and with soil scientists and geologists, both at universities and in industry in California and Nevada, concerned with surficial deposits, remote sensing, and uranium exploration. Published and unpublished data, photographs and written replies were obtained from numerous individuals and organizations in the United States, Australia, and southern Africa.

Following this, a brief field examination was made of the several varieties of caliche and of carnotite-bearing caliche localities in Clark County, Nevada.

A card catalog of more than 800 references related to the research was assembled.

2.3.2

Australian Study

Upon arrival in Australia on August 18, 1976, Carlisle met with several industry representatives and exploration geologists in Sydney and Melbourne, who are currently or were previously interested in calcrete uranium occurrences, and also with several members of The Uranium Working Group at the International Geological Congress, then in session, who had knowledge of calcrete uranium occurrences in Australia or Africa. Among the latter were James Cameron, International Atomic Energy Agency, Vienna, who very briefly described some little known calcrete-type occurrences in Somalia, and also J. W. von Backström, Director of Geology, Atomic Energy Board, South Africa, who described some aspects of the calcrete uranium deposits in South West Africa.

In an attempt to understand more thoroughly the work of Australian soil scientists bearing on the definition, genesis, and distribution of calcrete, as well as its relationship to other duricrusts and soil types,

Carlisle went to Adelaide to meet with Dr. C. G. Stephens (CSIRO Division of Soils, retired) and with Keith H. Northcote, Head, Pedology Section, CSIRO Division of Soils, Adelaide, and chief author of the current soils map of Australia. Dr. Stephens has emphasized the distinction between "relative" and "absolute" accumulation in the formation of duricrusts and has appealed to the concept of very far-traveled silica in the formation of silcretes during the laterization period. One of the major concepts of these discussions which was not fully appreciated until the visit to the uranium deposits of Yeelirrie and vicinity was the recognition by Stephens and Northcote of the contrast between calcareous brown soils, which occur in southern Western Australia and in southern South Australia and Victoria, and earthy loams with a red-brown siliceous hardpan without caliche or kunkar, which are characteristic of the valley calcrete region containing Yeelirrie. The former are characterized by the growth of Mallee, a Eucalyptus variety, and the latter by Mulga, an acacia tree.

At the South Australian Department of Mines and Geological Survey, Brendon Thomson, Jon Firman, and Roger Major discussed the recognition and approximate dating of several ages of silcrete and a somewhat confusing usage of "calcrete" to include lacustrine fossiliferous limestones. Calcretes have been drilled in South Australia and some carnotite found, but no uranium ore-bodies to date. A variety of calcretes, silcretes, and laterites were examined in the Alice Springs area, and discussions were held with David Clarke of the Geological Survey of the Mines Department regarding previous exploration and drilling for calcrete uranium in the Burt Plain and Woola Downs areas north of Alice Springs.

At Perth Carlisle was met by Dr. Allan Mann, geochemist and foremost authority on calcrete uranium with the Division of Mineralogy, CSIRO. He was introduced to Mr. Arthur Gaskin, Chief, and the following staff concerned with calcrete: Charles R. M. Butt, Rudy C. Horowitz, Rex Deutscher, H. Max Churchward, Robbin Hill, and Eric Bettenay. After orientation discussions, Carlisle and Mann continued to the Yeelirrie area. Dr. Eric Cameron, Senior Geologist, Western Mining Corporation, Ltd., and discoverer of Yeelirrie, led a visit through that deposit and invited Carlisle to return there for further studies. Several days were spent on the Hinkler Well Basin uraniferous calcrete drainage northeast of Yeelirrie and on the calcrete deltas on east and north Lake Way in company

with Mr. David Crabb of Carpentaria Exploration and Mr. John Allen of Delhi Exploration, respectively. It was not possible to visit Lake Maitland, where the mineralization is entirely beneath the playa, nor many other lesser occurrences, including Nowthanna, with carnotite in calcrete. Soil kunkars near Menzies and as far south of Kalgoorlie as Norseman were examined.

Upon return to Perth on September 14, discussions were held with CSIRO personnel and with Colin C. Sanders (formerly of Geological Survey of Western Australia, now of Department of Conservation and Environment, and leading authority on hydrology of calcrete), J. H. Lord (Director, Geological Survey, Western Australia) and staff, and, once again, with Dr. Eric Cameron (Western Mining Corporation, Ltd.).

2.3.3 Southern African Study

After arrival in Johannesburg on September 17, Carlisle visited Dr. Frank Netterberg, of the CSIR National Institute for Road Research, in Pretoria. Dr. Netterberg is an authority on calcretes, particularly with reference to their use as road metal in southern Africa, but also for his classification of calcretes and concepts of genesis. During the following two days, consultations were held with Dr. Jacob W. von Backström, Director, Geology Division, Atomic Energy Board, Republic of South Africa, and Dr. Brian B. Hambleton-Jones, geochemist with the Atomic Energy Board, both at Pelindaba, the AEB facility near Pretoria. Drs. von Backström and Hambleton-Jones provided several technical notes and reports, some of which were accepted on a restricted basis for confidential use in connection with this project.

Following conversations with Mr. J. Fouché, of General Mining & Finance Corporation, Ltd., and Dr. D. A. M. Smith, of Anglo-American Corporation, South Africa, Ltd., in Johannesburg, Carlisle flew to Windhoek, South West Africa, and then flew by small plane over the Khomas Hochland, Namib Desert, and the northerly part of Spergebiet No. 2, meeting briefly with Dr. Henry Gewald and Dr. Franz Wagner, Anglo-American geologists. Four days were spent examining the Anglo-American gypcrete, calcrete, and bedrock deposits near the Tumas River in company with Mr. Clive Kirk, resident geologist, and associates and also collecting samples from the region for sulfur isotope analysis in relation to origin of the gypcrete.

The Langer Heinrich calcrete uranium deposit was visited next with Mr. Joe Hartleb, resident geologist, and further discussions on this deposit were held with Mr. Klaus Linning, Divisional Geologist for General Mining & Finance Corporation. Both of the above deposits are within the Namib Desert Park.

A one-day visit was made to the calcrete uranium deposit of Bantu Mining Corporation in the Damara Homeland north of Namib Desert Park and to a most interesting prospect of Goldfield Consolidated west of the Bantu property. At the former, Carlisle was guided by Mr. Jan van der Merwe, geologist, and Mr. S. Z. E. Dippenaar, chief technician; at the latter by Mr. J. A. Pinna, geologist, and Mr. van Devender, technician. Following this, Carlisle made a very instructive visit under the guidance of Mr. Tom Richards, mine geologist, to noncommercial carnotite occurrences in weathered bedrock at the Uis pegmatite tin mine operated by ISCOR. Two days were spent looking at the very extensive calcretes in the vicinity of Etosha Pan, returning to Windhoek and Johannesburg on October 4. Finally, at the invitation of Dr. Rodney W. Walshaw, Deputy Director of the Geological Survey of Botswana at Lobatse, Carlisle spent three days in the field in southeastern Botswana examining calcretes with Mr. Roger Keys, survey geologist.

Concluding discussions with Dr. von Backström of the AEB and Dr. D. A. M. Smith and Dr. Franz Wegner of Anglo-American Corporation completed the 27-day visit.

2.4

ACKNOWLEDGEMENTS

We are greatly indebted to all of the persons mentioned above for their generous assistance, for the data that they have supplied, and for the many very helpful discussions. Several of the industry representatives have reviewed portions of the manuscript relevant to their own deposits. In addition, many industry personnel have contributed information with the request that they remain anonymous, and we are indeed grateful to them. In Australia, vehicles and gear were made available on two occasions by the Commonwealth Scientific and Industrial Research Organization, and, in South West Africa, a vehicle, air transportation, and gear were made available by the Anglo-American Corporation and General Mining and Finance Corporation.

Quantitative meteorological data and related information have been kindly supplied in considerable detail by the Bureau of Meteorology, Perth Australia; by Mary K. Seely, Director of the Desert Ecological Research Station, Gobabeb; and by the Weather Bureau at Windhoek, South West Africa. Publications, maps, and air photographs have been donated or obtained for us in Australia by the CSIRO Division of Soils and Division of Mineralogy, by the Geological Survey of Western Australia, and by Western Mining Corporation. In South Africa, Frank Netterberg of the CSIR provided his own published and unpublished maps and reports. A report on Somalia has been contributed by James Cameron of the I.A.E.A.

The writer has also profited greatly from discussions with a great many people in or visiting the United States, including Leland H. Gile, Richard F. Logan, Donald Langmuir, Andrew Goudie, Frank Netterberg, Allan W. Mann, and James B. Cowart.

We would especially like to thank Mary McNeil, Senior Staff Geoscientist with Bendix Field Engineering Corporation for conceiving what has become a very provocative and worthwhile study. She has supplied continuing information and assistance from the earliest stages to editing of the manuscript.

John Cottrell, Karen R. Hochstrasser, Martin S. Kohl, and Oded Kolker, graduate students at UCLA, have been principal assistants in the office and in the field. Students Sharron Larson, Bruce Bilodeau, and Marvin Katz

assisted for shorter periods. Drs. Patrick Payton and Emil Kalil performed delayed neutron analyses for uranium at UCLA. Sulfur isotope analyses on marine muds and gypcretes from South West Africa were made by Ms. Barry Wall. Juliana Guenther and Victoria Doyle have done the drafting; Ram Alkaly, thin sections; Lowell Weymouth, the photography; and Rosemarie Jergovic, both the several drafts and the final typing.

3.0

DEFINITIONS, GENESIS, AND CLASSIFICATION OF
CALCRETE, CALICHE, AND GYPCRETE

3.1

URANIFEROUS AND NONURANIFEROUS CALCRETES AND GYPCRETES

The calcrete, dolocrete, and gypcrete host rocks for recently discovered carnotite orebodies and prospects in Western Australia, South West Africa, and reportedly in Somalia, Mauritania, and Angola consist of authigenic carbonate or gypsum added to alluvium, soil, or other regolith. But they are nonpedogenic. The carbonate, gypsum, and uranium has been added by lateral transport rather than by vertical redistribution. Nor are they marine or lacustrine sediments nor evaporites in the usual sense. Uranium mineralization occurs in contiguous clay, sand, and weathered bedrock as well as calcrete or gypcrete. Uranium has been transported and the carnotite deposited in an entirely oxidizing environment with uranium continuously in the six-valent state.

These host rocks are nevertheless closely related to caliche (kunkar, kankar, crôte calcaire, surficial calcrete, caprock, etc.) and to other duricrusts (ferricrete, silcrete). Their compositions and textures cover much the same range, or in some cases are indistinguishable, and their genesis, like that of all duricrusts, takes place within the zone of weathering. Their deposition is facilitated by loss of H_2O and, for the carbonate, loss of CO_2 . The fundamental genetic difference is that surficial (pedogenic) caliches derive their authigenic cement only from soil, dust, loess, ash, organic debris, or the air, whereas the uranium host rocks draw upon a very large terrane of weathering rock or regolith, as well as adjacent sources. Therefore, they occur along the axes and gathering points of groundwater drainages. To become orebodies they also must have a source terrane which is large in comparison with their own size or anomalously rich. The elements must be maintained in solution until they reach areas of groundwater convergence where carnotite will, in fact, precipitate. As a consequence, they develop a predictable morphology and a distribution related to source terrane,

near-surface groundwater flow, and the configuration of bedrock or other relatively impermeable materials. With the exception of reported soddyite $[(\text{UO}_2)_5(\text{SiO}_4)_2(\text{OH})_2 \cdot 5\text{H}_2\text{O}]$ in some of the occurrences in South West Africa, carnotite $[\text{K}_2(\text{UO}_2)_2(\text{VO}_4)_2 \cdot 3\text{H}_2\text{O}]$ is the sole uranium mineral found in the deposits.

A clarification of terms is needed. Throughout this report the writer will use the term pedogenic calcrete or descriptive names such as superficial-sheet calcrete, soil-horizon caliche, kunkar, or superficial gypcrete for calcareous or gypsiferous duricrusts generated by purely soil-forming, i.e., pedogenic, processes entirely within a soil profile and of wide lateral extent (Figure 3.1b, Plate III-1). Nonpedogenic calcrete or such descriptive names as deltaic calcrete or valley gypcrete will be used for bodies formed in alluvium or soil along the axes of drainage systems through introduction of cementing materials by laterally moving subsurface water (Figure 3.1a, b; Plate III-1). It is the latter which have on occasion become the hosts for significant uranium mineralization.

3.2 CONFLICTING USAGE OF CALICHE AND CALCRETE IN AMERICAN, SOUTHERN AFRICAN, AND AUSTRALIAN LITERATURE

3.2.1 Overview

The genetic distinction between superficial sheet duricrusts and valley duricrusts was recognized long ago by Lake (1891) who described "valley laterite" in India and by D'Hoore (1954) in reference to the development of laterites in the Belgian Congo. Those laterites, according to D'Hoore, which have derived their iron from superjacent or subjacent regolith may be said to be products of "relative accumulation" whereas those which derive their iron by lateral movement of groundwaters from hill slopes into the zone of oxidation may be said to have been formed by "absolute accumulation." Recognition of D'Hoore's principle, though not necessarily his terminology, is critical for the understanding of the genesis and distribution of uranium deposits in calcrete or gypcrete.

Figure 3.1
Valley Calcrete
Western Australia

Valley Calcrete
and
Surficial Calcrete
or Gypcrete
Namib Desert
South West Africa

Superficial-sheet calcretes (gypcretes) are the products of vertical redistribution within the soil, i.e., "relative accumulation." Valley and deltaic calcretes (gypcretes) and their carnotite mineralization are the products of lateral transport and, therefore, "absolute accumulation." The distinction has seldom been made adequately clear in discussions of caliche or calcrete (gypcrete), nor has it been used as a basis for classification. A multiplicity of terms and differing usages of the same terms have developed over three-quarters of a century (see reviews of terminology in Goudie, 1973; Reeves, 1976).

3.2.2 "Caliche" in the United States and Concepts of Genesis

In the United States, the word calcrete has been used frequently only since the announcement of the Yeelirrie and Langer Heinrich uranium deposits. Caliche, the term most commonly employed here, was introduced into the literature by Blake (1902) and refers, overwhelmingly, to a pedogenic horizon or horizons (Bretz and Horberg, 1949; Brown, 1956; Aristarain, 1970; and Reeves, 1976, p. 85). It is essentially synonymous with a well developed calcic horizon or ca horizon in U.S. soils terminology or, if indurated, with "petrocalcic horizon" (Soils Survey Staff, 1975, p. 45-47; Flach et al., 1969). A calcic or petrocalcic horizon can develop at almost any level within the soil. It may contain calcium or calcium and magnesium carbonate. A petrocalcic horizon is a continuous, cemented or indurated calcic horizon which tends to plug the soil causing a perched water table and, commonly, the development of laminar caliche above the plugged horizon (Figure 3.2). This kind of carbonate-rich soil horizon is most commonly thought to develop in an arid or semi-arid climate where substantial quantities of calcium or calcium and magnesium from the soil itself, from organic litter, from rain, or from airborne materials are transported downward by water which becomes richly carbonated as it infiltrates the biotic layers of the soil during rainy periods followed by long durations of desiccation and loss of CO₂. Playa lake dust, particularly if gypsiferous, is recognized as a major source of calcium. The CO₂ is predominantly of organic or inorganic origin within the soil but may

Figure 3.2
Stages of Morphogenic Sequences of Carbonated Soil Horizons
(After Gile, et al., 1966)

Gravelly Soils

Thin, discontinuous pebble coatings

Continuous pebble coatings
some interpebble fillings

Many interpebble fillings

Laminar horizon overlying
plugged horizon

(Thickened laminar and
plugged horizons)

Nongravelly Soils

Few filaments or
faint coatings

Few to common nodules

Many nodules and
internodular fillings

Laminar horizon overlying
plugged horizon

(Increasing carbonate
impregnation)

Youngest Geomorphic Surface on which Stage of Horizon Occurs

Fillmore, <2600 to 5000
years

Leasburg, >5000 years
latest Pleistocene

Picacho, Late Pleistocene

Jornada, Mid-to
Late Pleistocene

La Mesa, Mid-Pleistocene

also be derived from the air via rain or airborne materials. It is not necessary that there be a perennial deficiency of soil moisture, but there must be long periods of soil moisture deficiency. The ultimate development of a "plugged horizon" or hardpan which causes a perched water table, and possibly deposition of laminar caliche above it, takes place only if the ground surface is neither rapidly eroded nor alluviated for a substantial period of time. Petrocalcic horizons extending to 1.5 m below the surface are not uncommon.

Concurrent or alternating periods of carbonatization and aggradation result, in some places, in a single thick horizon or a sequence of multiple caliche horizons totaling up to several meters or tens of meters thick. Brown (1956) has suggested this for thicker sections on the northeastern Llano Estacado of Texas. Gardner (1972) ascribes a caliche 2.6 m (8.5 ft) thick, the petrocalcic portion of which he calls calcrete, northeast of Las Vegas, Nevada to aeolian aggradation. He suggests that perhaps 25% of the Ca^{2+} and HCO_3^- has been derived from rainwater and the remainder from dust.

Under certain uncommon circumstances on a very flat terrane, derivation of CaCO_3 from below is thought to occur and is included in the pedogenic process. According to the Soil Survey Staff (1975, p. 45-46),

" In soils that have, near the surface, ground water that contains an appreciable amount of calcium bicarbonate, the capillary rise and the evaporation plus transpiration cause precipitation of a large amount of lime. Depending on the depth from the surface to the capillary fringe, lime may be deposited at the surface or in the soil at a depth of about 30 to 60 cm. . . . [However] deposition from ground water at a depth of 3 m or more is more nearly a geologic than a pedologic process."

Shallow pedogenic caliche of this origin was described by Breazeale and Smith (1930). Pedogenic caliche may also form by in situ dissolution and reprecipitation of CaCO_3 on an outcropping limestone (Soil Survey Staff, 1975, p. 45; Goudie, 1973, p. 128). It is rather common, in fact, for a thin caliche or calcrete to develop on the surface of a valley or other nonpedogenic calcrete. We will refer to this particular variety as reconstituted calcrete. Soils maps do not invariably distinguish between these and a ca horizon derived from limestone in situ. Caliches of this origin on the lacustrine limestones of San Simon Valley and the

Verde formation of Arizona, among others, are examples which on the basis of soils maps and also from aerial reconnaissance may appear at first to be examples of valley calcrete.[†] Lateral transport is not excluded in the formation of caliches but is given little attention by pedologists except for the possibility of sheet-flood as a source of calcium (cf. Goudie, 1973, p. 122-124, fluvial models).

The possibility of non-illuvial, i.e., nonpedogenic caliches, was early recognized by some hydrologists and geologists in southwestern United States, e.g., Lee (1905). One of the best descriptions of nonpedogenic carbonate is by Ruhe (1967). Pedologists sometimes refer to these as groundwater caliche or "geological carbonate." Lattman (1973) discusses nonpedogenic caliches, introducing sheet-flood as a mechanism to explain 1) some surficial laminar caliches, 2) case hardening, a carbonate-cemented skin on vertical faces (Lattman and Simonberg, 1971), and 3) gully-bed cementation which results from carbonate transport in ephemeral stream courses, permeation of the stream bed and walls, and precipitation of CaCO_3 as the stream dries. None of these processes, however, gives rise to caliches or calcretes of the size, shape, or distribution of the valley calcretes of Western Australia or South West Africa.

3.2.3 "Calcrete" in Southern Africa

Lamplugh (1902, 1907) introduced his new term "calcrete" to southern Africa in a paper on the Zambezi Basin, Rhodesia. He ascribes "valley-calcretes [his term]" to the "slow oozing of water from loamy flats." "Calcrete" has been used repeatedly in southern Africa since that time for both thin sheets and thick carbonated gravels. Netterberg (1966, 1967, 1969a, 1969b, 1969c, 1970, 1971, 1974a, 1974b, 1976) is explicit in his distinction between pedogenic and nonpedogenic calcretes in southern Africa. He states (1969c, p. 88),

"A calcrete may be defined as almost any terrestrial unconsolidated material which has been cemented and/or replaced by dominantly calcium carbonate. The unconsolidated material could be residual soil, alluvium, weathered rock, colluvium, or a soil in the

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[†] The presence of a calcic horizon is not necessarily indicated by the taxonomy of a soil. In the U. S. system of classification (Soil Survey Staff, 1975) it enters into the great group name only in the Aridisol and Mollisol orders which lack an argillic horizon.

pedological sense, but for the sake of convention, cave deposits are excluded. The term 'dolocrete' is suggested for application to a 'calcrete' in which the cement is dominantly dolomite. The mechanism of calcification is not restricted and calcretes may be of pedogenic or non-pedogenic origin, or both."

Netterberg uses "groundwater calcrete" to describe nonpedogenic varieties and gives as examples the thick (10 m or more) calcreted Tertiary sands and gravels on the Vaal and other rivers of central South Africa. These are calcified throughout and lack any pedogenic profile or specific hardpan, nodular, laminated or plugged horizons such as may be found in surficial-sheet calcretes. He believes that the gravels were largely calcified after deposition was complete as a falling water table descended slowly through the alluvium. Netterberg (1971) also reproduces an air photograph interpretation showing calcrete in a fossil drainage line northwest of Tsumeb, South West Africa and presents an idealized section across a "typical riverside or pan calcrete deposit" which suggests elongation of valley calcretes along paleodrainage courses not unlike those of Western Australia described below. Valley calcretes of the Namib Desert are illustrated in Figure 3.1b.

3.2.4 "Calcrete" in Western Australia

In Western Australia today, calcrete means valley calcrete (Plates IV-1, IV-2, and Figure 3.1a), and the differences between this and kunkar (= soil horizon calcrete = caliche) are explicitly recognized by the Geological Survey and Department of Mines, the CSIRO, and nearly all geologists working in that state. Beginning with the frequently quoted definition of Sofoulis (1963),

"The calcrete deposits are here referred to as an assemblage of subsurface limestone and opaline silica deposits that are generally associated with fine gravel beds of riverine origin. These formations occur in broad fossil valleys that still serve as trunk valleys for the present drainage systems. . . . Many of the deposits locally recorded in other parts of the State as kunkar, travertine, tufa, creek limestone, caliche, etc., are believed to be calcrete deposits."

According to Sanders (1973),

"The Geological Survey of W. A. uses calcrete to define those 'limestone deposits associated with fluvial valley-fill sediments that occur in both broad fossil valleys and in existing

trunk drainage systems of the arid interior of the state' (Sofoulis, 1963; Sanders, 1969). The limestones occur mainly at valley floor level characterized by an indurated nodular surface, that may show karstic features such as sink holes, solution pipes, mounds and cavities. Below ground level the deposit may be powdery, granular or massive, and contain unconsolidated detrital bands and cellular opaline silica layers. The sequences in places attain thicknesses up to 30 m but are usually of the order of 5 to 10 m thick. They are partly saturated with groundwater, the water table usually lying at a shallow depth. . . .

"Most valley calcretes above the water table have a kankar-like surface, but their thickness and confinement to drainage lines indicate a genetic and depositional control, at least below the water table, different from that of kankar.

". . . slow replacement of fluviatile silt, sand and gravel by calcium carbonate precipitated from percolating carbonate-saturated ground and soil water is the main mechanism in calcrete formation. Silica taken into solution is often reconstituted into chert (opaline silica) at about the water table. Evidence for the replacement origin is provided by the common occurrence of localized patchy calcrete within extensive fluviatile sediments; also, in laboratory examination of bore cuttings, calcite is seen to interfinger and penetrate relict alluvial grains including quartz. Moreover the groundwater in situ pH is high, commonly between 8.0 and 9.5, a condition reported by a number of authors as being favourable for silica-carbonate inter-reaction.

"Calcrete most commonly occurs along flat reaches of the drainage and around salt lakes. . . . Often the opaline rock is fractured and fissured, the joints being encrusted with concretionary secondary carbonate. Some of the larger fissures have become avenues for groundwater movement and have been enlarged by water action to 0.3 m or more in width. Occasionally large caverns have formed, and these may connect with the surface. Calcrete has a high secondary porosity, and in zones of uranium mineralization, carnotite and some other exotic radioactive minerals may occupy pores and fractures mainly at the water table."

Mabbutt, who has made major studies both on the Namib Desert, South West Africa where he reported on calcreted valley gravels slightly north of the main calcrete and gypcrete uranium deposits (Mabbutt, 1952; see also Section 5.1) and also in Australia (e.g., Mabbutt, 1961, 1965), takes essentially the same position as Sofoulis and Sanders with respect to calcretes in Western Australia (in Mabbutt et al., 1963).

3.3

NONPEDOGENIC CALCRETE DEPOSITION

3.3.1

Zones of Subsurface Water

Figure 3.3 illustrates the zones of subsurface water where a groundwater table is present at moderate depth. The "soil moisture zone" is defined as that part of a soil or other regolith which is subject to large fluctuations in the quantity and the composition of water in response to evapotranspiration. Because of the limited depth through which water can be evaporated rapidly by a combination of capillary forces and vapor transport or to which a large number of plant roots penetrate, the effective thickness of the soil moisture zone is typically not more than 1 - 2 m. The next lowest "intermediate-vadose" or "gravitational-water" zone contains liquid water only during recharge and even then its distribution may be quite uneven. This zone may be absent where the water table approaches the surface or it may be tens to hundreds of meters thick in very arid regions. The capillary fringe is the zone through which groundwater can rise in the liquid state above the water table under the influence of surface tension or cohesive forces between water and soil particles. In fine-grained unconsolidated sediments the maximum capillary rise is perhaps 1 - 2 m, in sands 0.1 - 1.0 m, and in gravels less than 0.1 m (Davis and De Wiest, 1966, p. 188). The transition between the capillary fringe and the gravitational water zone, if present, is abrupt in coarse-grained sediments, but very gradual and irregular in clays or silts or during periods of recharge through the vadose zone. At the water table the capillary fringe becomes fully saturated and $P_{H_2O} = 1$ atmosphere. During dry periods when evaporation is taking place at the ground surface, P_{H_2O} decreases irregularly upward from the water table to the partial pressure of water in the atmosphere.

3.3.2

Moisture Tension and CO_2 Pressures

The position of the upper surface of the capillary fringe and the availability of water to move in the liquid or in the vapor state can be related to the energy of attraction between water and soil or sediment. This tendency of materials to retain water is known as the "water potential," "moisture tension" (Soil Survey Staff, 1975), or sometimes "soil suction." The lower the moisture content, other things

Figure 3.3

Zones of Pedogenic Caliche and Groundwater Carbonate Deposition in Relation to Subsurface Water

being equal, the greater is the moisture tension. In wet soils or sediments, moisture tension is primarily a function of capillarity and is low. In dry to extremely dry materials it is a function of adsorption or adhesion and is high. In Figure 3.3, therefore, moisture tension increases in an irregular way from the water table up to the ground surface precisely as P_{H_2O} decreases. Above the capillary fringe during dry periods, water is able to move only by evaporation into the soil pore air whence the vapor will migrate in the direction of decreasing P_{H_2O} . The shape of the moisture tension curve between the groundwater table and the surface ranges widely from place to place and from time to time owing to irregularities in wetness, solute content (which increases moisture tension), temperature (inversely related to moisture tension), and, most importantly, a wide range of physical properties, including grain size and specific surface, which affect capillarity and adhesion (Kohnke, 1968; Baver *et al.*, 1972). Moisture tension exerts a controlling influence on carbonate deposition because it determines the position at which open pore spaces will appear within the soil and the propensity with which water vapor will escape into them.

The importance of P_{CO_2} for carbonate deposition arises from the following:

or in summary:

Exsolution of CO_2 from a groundwater approaching saturation with calcium and carbonate will drive equations (1) and (2) to the left, increasing pH and CO_3^{2-} ion activity which in turn will cause the precipitation of $CaCO_3$. At constant P_{CO_2} calcite becomes less soluble with increasing temperature.

P_{CO_2} and the activities of CO_3^{2-} and HCO_3^- ions and H_2CO_3 in subsurface water are not likely to follow the moisture tension curve except in a very general way. This is mainly because the great bulk of CO_2 in soil is

produced in the richly organic soil moisture zone. Whereas atmospheric air contains 0.03% CO_2 (and $P_{\text{CO}_2} = 10^{-3.5}$), agricultural soils typically contain 6 - 10 times that amount at 15 cm (6 in) depth and up to 300 - 500 times that amount at 1.8 m (6 ft) depth, depending on the season, soil, crop, tillage, and biological activity. (Water in equilibrium with the higher values of P_{CO_2} could dissolve 10 times as much CaCO_3 as normal rainwater, i.e., 400 - 750 ppm versus 40 - 50 ppm at 25°C.) In temperate regions, CO_2 production reaches high levels in the late spring and early fall and minima in summer and winter. Soaking of the surface layers with water and poor ventilation inhibit CO_2 escape; soil gases in India have been reported to contain 16 - 20% CO_2 during monsoon periods (Adams and Swinnerton, 1937). Data for greater depths have not been collected by agriculturalists, but it is very likely that during rainy periods and while vadose water continues to descend through the intermediate zone the CO_2 content of subsurface water remains high and O_2 contents low, at least to depths where it might mix with less carbonated groundwater. During such recharge periods carbonate may be dissolved throughout the vadose and perhaps the phreatic water zones.

P_{CO_2} decreases with prolonged desiccation and consequent diminution in biologically produced CO_2 . At these times values of P_{CO_2} probably diminish upward from the water table to the surface. Highly saline soils and fluvial sediments such as those in extremely arid parts of Western Australia and South West Africa may show upward diminishing $P_{\text{H}_2\text{O}}$ and P_{CO_2} throughout the larger part of the year, although, to the writer's knowledge, this has not been investigated.

3.3.3 Zones of Nonpedogenic Carbonate Deposition

Authigenic carbonate can be precipitated in all of the groundwater zones shown on Figure 3.3. Illuvial carbonate deposition in the soil moisture zone, the process emphasized by soil scientists (3.2.2 above), produces pedogenic calcrete, i.e., ordinary soil-horizon caliche. Because there is no lateral concentration, the likelihood of developing a significant uranium concentration in this environment, except from a contiguous deposit, are negligible in the writer's view. Trace amounts

of uranium can be found around carbonate nodules or near the base of some illuvial calcretes or caliches, apparently in response to leaching of overlying soil layers. The possibility is intriguing that windblown dust from the surface of a playa draining a uraniferous terrane, for example, might contribute detectible uranium to this environment. In Western Australia, however, the presence of soil-horizon caliche (kunkar) is a negative criterion for economic calcrete uranium occurrence.

Turning to nonpedogenic calcretes, these are thought by the writer to have formed in three particular environments considered next.

3.3.3.1 Carbonate Deposition in the Soil Moisture Zone by
Capillary Rise from a Shallow Water Table: A
Mechanism for Valley Calcrete

In alluviated valleys of low relief, groundwater flowing toward the valley axis commonly approaches the surface without actually emerging in a flowing stream. In some situations the water table is shallow enough for the capillary fringe to intersect the soil moisture zone, in which case carbonate-charged water is able to move upward during periods of strong evapotranspiration to a level within the soil moisture zone where loss of CO_2 causes carbonate precipitation. Because the groundwater table and the thickness of the capillary fringe fluctuate with climate and with precipitation and evapotranspiration, authigenic carbonate deposited by this mechanism is likely to be thicker and more poorly stratified than illuvial calcrete or caliche. Deposition will occur mainly in areas where topography, bedrock morphology, permeability barriers, or salinity-density differences cause a gradual shallowing or actual upwelling and slowing of laterally moving groundwater. As will be shown in Section 4.1.4 below, the uraniferous valley calcretes and deltaic calcretes of Western Australia (Figure 3.1a) fit this model rather well.

3.3.3.2 Deposition of Carbonate from the Capillary Fringe, with a
Moderately Deep Water Table

During periods of strong evapotranspiration over a moderately deep water table (Figure 3.3) pore spaces above the capillary fringe become

filled with soil air, in which case P_{H_2O} decreases irregularly upward and P_{CO_2} will follow a path determined largely by the rate at which CO_2 is produced in the organic-rich soil layers and the rate of soil aeration. In highly saline soils, or during periods of intense desiccation such as occur in the valley calcrete regions of Western Australia and South West Africa, the production of CO_2 in the soil may be minimal, and P_{CO_2} may, in fact, decrease more or less continuously upward. In either case, with Ca^{2+} and carbonate in the groundwater, loss of CO_2 into the soil air in the upper parts of the capillary fringe and consequent precipitation of $CaCO_3$ may occur down to very appreciable depths (Schoeller, 1959, p. 16), though the rate may be slow.

Netterberg (1969a, 1969b, 1971, and Section 3.2.3 above) invokes this mechanism to explain the calcification of thick alluvial sands and gravels in Southern Africa. By postulating a fluctuating water table which progressively declines through the entire section and showing that carbonate will be dissolved and reprecipitated in groundwaters of varying P_{CO_2} , he explains the development of a massive calcrete without layering or lamination other than the inherited bedding of the host sediments. He refers to these as nonpedogenic or "groundwater calcretes." It seems equally likely, if not more so, that thick calcreted gravels of this sort could develop with a slowly rising groundwater table. The model in conjunction with the one considered next would then be particularly applicable to the uraniferous Namib Desert valley calcretes of South West Africa. As described in Section 5.1.3 below, these occur in sands and gravels up to 100 m or more thick that have filled broad valleys on the old Tertiary and pre-Tertiary "African" surface after the climate had become increasingly arid during the Pliocene.

The writer has included these deep calcretes of the Namib Desert in the category of valley calcrete even though the gravels have been cemented through their entire width and depth and not simply along the axial portions and upper layers of the valley fills as have those of Western Australia. Reasons for the difference are discussed in Section 5.1.5 below, after more complete descriptions of the two regions.

A noteworthy feature of calcrete that develops from groundwater

Plate III-1. PEDOGENIC, GRAVITATIONAL WATER, AND RECONSTITUTED CALCRETE.

- a) Pedogenic calcrete beneath mature surface undergoing dissection. Mormon Mesa, Nevada
- b) Closeup of pedogenic calcrete showing stage 4 plugged horizon and laminar horizon largely reworked.
- c) Gravitational water calcrete; carbonate deposition controlled by fractures and permeability differences. Mojave Desert, California.
- d) Rockhouse structure in reconstituted calcrete. Botswana.

unrelated to a soil profile was pointed out to the writer in the Las Cruces area by Leland H. Gile. The carbonate is often coarsely crystalline and quite clean and clear, lacking the illuvial clay impurities which characterize soil B horizons. This, too, is characteristic of the Namib Desert deep calcretes in contrast with those of Western Australia.

3.3.3.3 Deposition of Carbonate in the Intermediate Vadose Zone from Gravitational Water

Coarse alluvial sands and gravels, fanglomerates, and soils in the western United States commonly show irregular patches, layers, stringers, and veins of carbonate cement from one to several meters below the surface (Plate III-1). They occur mainly along pronounced textural-permeability changes. Stuart and Dixon (1973) have drawn attention to this kind of occurrence, especially in arid regions where, owing to surface tension effects, coarse sand or gravel underlying fine-grained sediments impedes the downward migration of water or causes it to descend along narrow paths, permitting evaporation into soil air and a patchy distribution of carbonate. In other places fine-grained layers may detain gravitational water. Many other features, including decaying plant roots, can cause P_{H_2O} and P_{CO_2} gradients and localized deposition of authigenic carbonate.

Again, calcite precipitated from deeper vadose water is likely to be somewhat coarser and cleaner than calcite precipitated in a clay-rich soil horizon. If the movement of water is mainly vertical, the likelihood of significant uranium mineralization without a rich overlying or underlying source is extremely low. However, lateral flow may be appreciable through coarse-grained fanglomerates, for example, in which case uranium may be leached from a large area. The process may have contributed both to initial mineralization of the Namib Desert valley calcretes and to the reworking and reconcentration of carnotite. Shows of carnotite in calcreted fanglomerate near Jean-Sloan, Nevada may also have originated in this way (see Section 7.3.2). Carnotite associated with calcite in fractures in weathered bedrock on the Namib Desert (Sections 5.2.3.4 and 5.2.4.2) may be another example.

3.4

CLASSIFICATION OF CALCRETES AND GYPCRETES

3.4.1

Stages of Maturity

Nearly all of the comprehensive classifications of calcretes are based in some way on the maturity or degree of induration of calcrete and none makes use of genetic or morphological distinctions between pedogenic and nonpedogenic calcretes. The terminology is useful in the description of both, however, and since the maturity and the age of a calcrete may relate in some way to uranium mineralization, an understanding of the classifications is important. We begin with the widely applicable system developed at Las Cruces, New Mexico.

3.4.1.1 Stages or Morphogenetic Sequences in Carbonate Accumulation

(Gile, Peterson, and Grossman, 1966)

Between 1957 and 1970 the Desert Soil-Geomorphology Project involved a team of soil scientists and geologists in an intensive study of a 400-square mile area centered on Las Cruces, New Mexico (Ruhe, 1967; Hawley and Gile, 1966; Gile et al., 1970). The climate is arid (Figure 7.8 herein), the soils, both gravelly and nongravelly, calcareous and noncalcareous, are on a series of terraces of successively younger age down to the present river flat. The terraces are well drained so carbonate accumulation by capillary rise from a shallow groundwater table is extremely unlikely. The sequential model of carbonate accumulation which has grown out of this project is outlined in Figure 3.2 and summarized by Gile et al. (1966, p. 359) as follows:

"In gravelly sediments the morphogenetic sequence is:

- (I) carbonate forms thin discontinuous pebble coatings,
- (II) carbonate continuously coats pebbles and fills some interstices between pebbles, (III) carbonate continuously coats skeletal grains and plugs interstices to cement the soil and form a K horizon,[†] and (IV) carbonate forms a laminar horizon on top of an indurated, plugged horizon (a petrocalcic horizon). The sequence in nongravelly sediments differs in that stage I consists of carbonate filaments or faint coatings, stage II consists of few to common carbonate nodules, and stage III

[†]The term K horizon in this quotation and in Figure 3.2 refers to the terminology of Gile et al. (1965) for authigenic carbonate-rich horizons [in which K2 is the most prominent and K3 is transitional to underlying horizons, m horizons are indurated, K2lm is laminated, and K22m is massive, blocky, and plugged]. Thicknesses are typically 1 - 2 m.

consists of many nodules and internodular fillings.

"The sequence in gravelly sediments can be completed on late-Pleistocene surfaces, whereas stage IV morphology is found in soils of nongravelly sediments only on mid-Pleistocene surfaces. In many soils on older surfaces, the carbonate horizon morphology suggests more than one major cycle of carbonate accumulation."

The contrast between gravelly soils and nongravelly soils for Stages I, II, and III is quite comparable with the contrast between South West African (Sections 5.1.5, 5.2.1) and Western Australian (Section 4.2.1.9) valley calcretes. Two major conclusions of the Desert Soil-Geomorphology Project are 1) the maturity (stage) of caliche is correlative with the age of the geomorphic surface below which it forms and 2) gravelly soils are more quickly calcified than nongravelly soils, other things being equal.

This latter conclusion, especially, helps in understanding the valley calcretes of coastal South West Africa.

3.4.1.2 Netterberg's Stages in the Development of Calcrete

Netterberg's (1967, 1971) classification (Table 3.1) is also evolutionary and quite self-explanatory. He applies the scheme to both pedogenic or surficial sheet calcrete (caliche) and also to nonpedogenic groundwater calcrete, or valley calcrete. He believes, however, that groundwater types do not often develop beyond Stage 2. This seems to be generally true for the relatively coarse valley calcretes of South West Africa, which always retain some permeability and thus permit the continued escape of H_2O vapor and CO_2 . It is not true for the Western Australian valley calcretes which do reach Stage IV, becoming dense and rocklike in the porcellaneous varieties (see Yeelirrie, 4.2.1).

3.4.1.3 Goudie's Classification

The classification of Goudie (1973), reproduced as Table 3.2, is a synthesis of other schemes and follows Netterberg's in part. A wide range of parent materials is assumed, and attention is drawn to recycling. An interesting point is the reference to solution brecciation and recementation which is a prominent feature of many mature surficial sheet calcretes. The resulting natural terrazzo has been called

Table 3.1
Stages in the development of calcretes

Any of the developmental stages in Table 1 may be pedogenic in origin, but it is thought that ground water types do not often develop beyond stage 2. The mature calcrete profile is regarded as one which contains a capping of reasonably unbroken hardpan (stage 4). Hardpan thus represents the final stage of development of all calcretes. Boulder calcrete represents the weathered stage. (Netterberg, 1971. Reproduced by courtesy of the author and the National Institute for Road

Table 3.2

A descriptive-evolutionary classification of calcrete

"rockhouse structure" (Plate III-1). Since it is indicative of intensive leaching of the calcrete, rockhouse calcrete will not itself contain uranium, though it may overlies mineralized nonpedogenic calcrete.

3.4.2   A Genetic and Morphological Classification
of Calcretes, Dolocretes, and Gypcretes with
Emphasis on the Sources of Authigenic Cement
and Their Uranium Favorability

A classification and a terminology for calcretes and gypcretes has been developed by the writer (Table 3.3) with the distinction between pedogenic and nonpedogenic processes as the prime criterion. It is recognized that many calcretes and gypcretes, especially those in the nonpedogenic category, may have a multiple genesis. Genesis, moreover, is an inference. The location, shape, and internal structure of calcretes are commonly quite sufficient to make that inference and to fit the deposit into the classification.

Contrary to the usage of Hunt (1972), lakeshore tufa, "beachrock" and spring tufa, travertine, or sinter are specifically excluded from calcretes or caliches, as are lacustrine limestones, since they manifest environments quite different from those of pedogenic or nonpedogenic calcretes. In practice, the differentiation of these from true calcretes may be very difficult, especially in ancient buried occurrences. True valley calcretes do, in fact, grade into marls in areas where the groundwater has been so impeded that it forms a marsh. The writer has collected fresh water molluscs from such valley calcretes in Botswana, and many similar occurrences are reported in the literature (Goudie, 1973, p. 126).

"Soil" and "soil profile" in Table 3.3 are not restricted to earthy materials containing living matter in the strict pedological sense, but include other regolith and sediments. "Authigenic" means deposition from solution in place after the host sediment has been deposited. The new material may be derived internally or externally to the host which, in the case of a soil, is taken to be the entire

TABLE 3.3

A GENETIC AND MORPHOLOGICAL CLASSIFICATION OF CALCRETES
(DOLOCRETES AND GYPCRETES) WITH EMPHASIS ON THE SOURCES OF
AUTHIGENIC CEMENT AND THEIR URANIUM FAVORABILITY

CATEGORY	PROCESS	URANIUM FAVORABILITY ASSUMING A SOURCE TERRANE
I. PEDOGENIC CALCRETES, CALICHES, AND CARBONATE HORIZONS Caliches, Surficial-sheet Calcrettes, Kunkars (Dolocretes, Gypcretes)	The authigenic cement has been concentrated vertically within a soil profile (i.e., by "relative" accumulation).	
A. Illuvial Calcrete, Caliche, or Kunkar	Precipitation of cement within the soil moisture zone after downward transport and evapotranspiration. Equivalent to a well developed calcic horizon or petrocalcic horizon in U S soils terminology.	Very low to negligible. Trace amounts of uranium may occur in lower parts of carbonate horizons in contact with clay or other materials.
B. <u>In Situ</u> Calcrete	A less common variety of pedogenic calcrete. The cement is derived from subjacent rock or sediment by weathering in place.	Low unless developed on a rich substrate.
C. Capillary Rise Pedogenic Calcrete	A probably rare variety of pedogenic calcrete (cf. II.A.1). The cement is derived by capillary rise from stagnant groundwater sufficiently shallow over a wide area that the capillary fringe intersects the soil moisture zone, but without significant lateral transport.	Same
II. NONPEDOGENIC CALCRETES	The authigenic cement has been introduced into the host soil or sediment by non-soil-forming processes (i.e., by "absolute" accumulation).	
A. Groundwater Calcrettes	Concentration of authigenic cement externally derived from laterally moving groundwater fluvial contributions may be appreciable.	
1. VALLEY CALCRETE	Precipitation of cement within the soil moisture zone and/or capillary fringe by capillary rise from a shallow groundwater table influenced by bedrock morphology.	High in areas of constriction and upwelling of groundwater. Destroyed by dissection and leaching.
a. Western Australian Variety		
b. Namib Desert Variety	Precipitation of cement within the capillary fringe or gravitational-water zone from a changing water table.	Same
2. DELTAIC CALCRETE	Precipitation as in Valley Calcrete, 1.a. above, but with lacustrine clays and hypersaline pore water causing groundwater to slow and approach the surface. The downdrainage equivalent of Valley Calcrete.	Low in mature, elevated calcrete deltas. High in recent calcrete deltas with zones of upwelling.
3. GROUNDWATER LACUSTRINE CALCRETE	Precipitation by a variety of processes. May be related to deltaic calcrettes. Not to be confused with normal lacustrine limestones, nor with lake shore tufa or "beachrock" formed by surf action in hypersaline lakes.	Same
4. OTHER GROUNDWATER CALCRETE	e.g., "Cienega" calcrete from groundwater seeps.	Unknown
B. Gravitational Water Calcrete	Deposition of authigenic cement from waters descending through the intermediate (gravitational water) vadose zone with varying amounts of lateral transport.	Low in patchy carbonate derived from descending waters. Moderate in carbonate conglomeration depending upon amount of lateral concentration. May facilitate reconcentration of carnotite. Moderate in weathered bedrock.
C. Fluvial Calcrettes	Concentration of authigenic cement from sheet-flood or streams. (See text; Lattman, 1975; Goudie, 1973.)	Very low to negligible
1. Gully Bed Cementation		
2. Case Hardening		
3. Fluvial Laminar Crusts		
III. RECONSTITUTED AND DETRITAL CALCRETES		
A. Brecciated and Recemented Calcrete	Mainly a surficial process associated with weathering, erosion, or solution and collapse of pre-existing calcrete and commonly producing "rockhouse structure."	Negligible in itself but may occur above mineralized nonpedogenic calcrete.
B. Loose Detrital Calcrete	Boulder calcrete, gibbers (Australia), calcrete debris.	Negligible

profile. Deposition of cement source material from the air and its incorporation downward into the soil profile of a calcrete or gypcrete is considered to be "illuvial" and not an example of "absolute" accumulation. Admittedly, this is commonly the major source for authigenic cement, as in the case of calcretes downwind from a playa or the Namib Desert gypcretes with SO_4 from marine fogs. It could be a significant source for uranium downwind from shroekingerite-bearing playas, for example. Reprecipitation of the uranium in a surficial-sheet calcrete or gypcrete without lateral groundwater transport and concentration in some small body, however, would leave it still widely dispersed.

The genesis of gypcrete is not uniformly analogous to the genesis of calcrete, and there is no reason that the classification should be equally applicable to both. Nevertheless, the gypcrete of the uraniferous areas of the Namib Desert in South West Africa and some other areas can be subdivided into categories roughly analogous morphologically and in part genetically to the calcretes:

Valley Gypcrete in the Namib Desert consists of gypsum-cemented alluvium in bodies which are elongate along paleodrainages. They rest upon underlying calcrete or bedrock and are overlain by surficial sheet gypcrete. The genesis is not completely clear, most investigators favoring replacement of carbonate in pre-existing calcrete by sulfate and water derived from marine fogs. Lateral groundwater transport of gypsum and direct interaction of airborne marine sulfate with carbonated groundwater is not unlikely in the writer's view.

Some gypsite occurrences in the McKittrick area of the southwestern San Joaquin Valley of California may be true valley gypcretes. These are long narrow bodies along the beds of dry washes covered by thin unconsolidated sand and gravel. If the gypsum were merely washed in mechanically from surrounding hills or simply a lacustrine evaporite, it would not fit this category. However, according to van Planck (1952, p. 49), "The channel gypsite may also have originated from gypsiferous ground water that accumulated in the channels." Similarly, some of the gypsite in the deeper sediments of the Tularosa Basin near White Sands,

New Mexico may have been deposited beneath the surface from shallow groundwater flowing from the valley flanks (Weber and Kottowski, 1959), as may some of the gypsite in Gypsum Wash east of Las Vegas, Nevada.

Deltaic Gypcrete is not known to the writer.

Surficial-sheet Gypcrete is the sulfate analogue, morphologically, of surficial-sheet calcrete. On the Namib Desert, where gypcrete crusts continue to form, the sulfate ion is from oceanic fog. Sheet gypsite also forms in situ on underlying rock-gypsum, as efflorescences and crusts and on sabkhas by capillary rise from groundwater. In U.S. soils terminology (Soils Survey Staff, 1975, p. 46-47), "gypsic horizon" and "petrogypsic horizon" are analogous to "calic" and "petrocalic horizon." The gypsum content of a petrogypsic horizon usually exceeds 60%.

As with calcretes, lacustrine evaporites and bedded gypsum deposits are not included under gypcrete.

3.4.3 Buried Paleocalcretes

Calcretes exposed at or near the surface today are thought to be Tertiary to Recent in age.

Buried fossil calcretes (cornstone, pedocal, paleosol, caliche) of much greater age have attracted increasing attention since their recognition in the Old Red Sandstone of South Ayrshire, Scotland (Burgess, 1961). The same deposits had been called cornstones, a name defined by Buckland (1821) for concretionary marlstones of uncertain origin in which the concretions formed contemporaneously with the marlstone. Burgess (1961) suggested the name pedocal be used, however, because of the ambiguous usage of the term cornstone, specifically discussed by Allen (1960). Subsequently, Allen (1965) described "caliches or pedocals" in the Old Red Sandstone of Anglesey, North Wales, and Steel (1974) recognized the extensive development of "cornstone (fossil caliche)" in the New Red Sandstone of Western Scotland. Burgess, Allen, and Steel clearly relate these carbonate deposits to the calcareous soil horizons described by Gile and Hawley (1966), Reeves (1970), and Goudie (1973, 1975).

Recently, Hubert (1977) discovered "paleosol caliche" in the New Haven

Arkose, Connecticut, and Robert Lupe (personal communication, 1977) has found calcareous and siliceous paleosols in the Chinle Formation in Utah. The latter are not known to be uraniferous.

The uranium favorability of ancient buried calcretes is entirely unknown. Its investigation has been beyond the scope of research for this report. An obvious uncertainty is the question of whether carnotite could remain stable at moderate depths over a long period. Conceivably, coatings of chalcedony could provide some protection, as seems to be the case with some carnotite at Yeelirrie. More hopefully, one might look for remobilized concentrations at higher levels or reduced, U(IV), uranium minerals at depth.

4.0 URANIFEROUS CALCRETE OCCURRENCES IN AUSTRALIA

4.1 DISTRIBUTION AND GEOGRAPHIC, GEOMORPHIC, AND GEOLOGICAL SETTING

4.1.1 Location and Geographic Setting

With only a handful of exceptions, none of which are known by the writer to be economic, the reported uraniferous calcrete occurrences of Australia are in nonpedogenic valley calcretes and dolocretes in the most arid parts of central Western Australia (Figures 4.1 - 4.4, Plate IV-1). They are inland from the active coastal streams on the Indian Ocean, west of the great sandy deserts, i.e., of longitude 124°E, south of the Tropic of Capricorn, and entirely north of the "Menzies Line," a curving boundary passing through the town of Menzies, latitude 29°41'S.

Valley, deltaic, and lacustrine calcretes with at least traces of carnotite or anomalous radioactivity are extremely common in arid Western Australia, not just in the Yeelirrie drainage, but in all of the Yilgarn Block north of the Menzies Line (Plate IV-1) and as far north as the Gascoyne Block and the Bangemall Basin. Fifty-two significant prospect areas are shown on Plate IV-1. About a dozen additional areas are shown by Butt et al. (1977), received during final preparation of this report.

The region of greatest economic interest to date is an area of about one-quarter million square kilometers within the northern part of the Archean Yilgarn Block (Figure 4.1). In physiographic terms it is almost entirely within the Salt Lake Division (Figure 4.2), or Salinaland of Jutson (1950), which in turn is part of the Great Plateau of Western Australia (Suess, 1906). It is a region of extremely low relief, most of the terrain lying between 400 and 600 m, rarely reaching 650 m. Drainages are internal in all but the wettest of years. The average annual rainfall is 170 - 250 mm, concentrated in erratic late summer storms during the time that temperatures and evaporation rates remain high, and in the autumn (Figures 4.16, 4.17). Annual potential evaporation, 3300 - 4200 mm, exceeds precipitation by 12- to 20-fold. The consequent soil moisture regime is an important factor in calcrete genesis enlarged upon below.

FIGURE 4.1
DISTRIBUTION OF VALLEY CALCRETES IN RELATION TO THE
GEOLOGY OF WESTERN AUSTRALIA

--- Approximate boundary of valley calcretes (After Sanders, 1973, Mann, 1976, and personal comm.)

Geology after Geological Map of Australia

- T Tertiary (limestone, sandstone, siltstone)
- J-K Jurassic and Cretaceous (sandstone, siltstone, shale, limestone)
- P Paleozoic, Permian (sandstone, siltstone, shale, tillite, limestone)
- P Proterozoic
  - Pm Quartzite, shale, chert, dolomite — BANGEMALL BASIN
  - Shale, quartzite, dolomite, conglomerate,
  - Pl limestone, basalt, I F, metamorphic and granitic rocks
- A Archean
  - Ag Granitic rocks and gneiss
  - Avs Greenschist belts (basic volcanics and metasediments)

Yeelirrie, the first deposit with announced reserves, is almost exactly at the center of the main body of prospects and only slightly south of the center of valley calcrete distribution (Figure 4.1). It is also near the center of the region of most persistent and extreme soil moisture deficiency (A_w on Figure 4.4). This location is thought to be significant by the writer in the light of changing Quaternary climates and the resultant expansions and contractions of the most arid central region.

Prior to the discovery of carnotite mineralization, this part of Western Australia was known mainly for several famous gold mines around such towns as Wiluna, Meekatharra, Sandstone, Agnew, Cue, and Mt. Magnet. The names of the mining districts in the calcrete region, Murchison, East Murchison, Mt. Margaret, and North Coolgardie Goldfields, reflect that period. Today most of the towns are agricultural settlements of a few hundred inhabitants or fewer. The last operating gold mine at Kalgoorlie, Mount Charlotte, closed in September 1976. In the mid-1960s a new period of mineral exploration began with the discovery of massive and disseminated nickel sulfide ore deposits in Archean ultramafics and basalts at Kambalda 55 km south of Kalgoorlie. Intensive exploration through all of the Archean greenstone belts of the Yilgarn Block has led to the discovery of several more nickel sulfide deposits, including Mt. Keith and Perseverance near Agnew, both within 100 km of Yeelirrie. Airborne exploration for nickel, in fact, is credited for leading to the discovery of uraniferous calcrete at north Lake Way. As in Precambrian greenstone belts elsewhere, massive copper-zinc sulfide deposits are also an exploration target.

Calcretes play a role in the economics of many of the mining properties in this arid area because they are a prime source of water. One of the calcretes used by gold mines near Wiluna is estimated to have a potential safe yield of 10 million litres (2.4 million U.S. gallons) per day (Cameron, 1976).

Sheep ranching is the dominant agricultural activity and source of income for the sparse population. Yeelirrie Homestead is itself a sheep station, and, like many other similar stations, it is partly dependent upon water derived from or close to valley calcrete.

Good roads connect all of the main towns and scheduled air services connect Wiluna, Meekatharra, and Kalgoorlie with Perth.

FIGURE 4.3
DISTRIBUTION OF THE WILUNA HARDPAN "DURIPAN" IN U.S.
SOILS TERMINOLOGY

Explanation for Figure 4.4

Soil Moisture Regimes of Western Australia

Inferred from Climadiagrams

Ustic Regimes: Monsoonal climate mainly. Summer or late summer rain. Evaporation decreases during rain period.

U Ustic proper.

$$E < P \text{ in wet months}$$

U_s Subustic.

$$E^{0.75} < P \text{ in wet months}$$

Aridic Regimes: Hot, dry climate. Soil never moist for long periods. Mean monthly precipitation never exceeds evaporation (E) or $E^{0.75}$. Summer evaporation peak.

A_N Aridic Nullagine type. Episodic storms in late summer to autumn.

$$E_a/P_a = 9-10$$

$$E_w/P_w = 3.5 \text{ (10)}$$

$$E_a - P_a < 3250 \text{ mm}$$

A_W Aridic Wiluna type. Episodic storm rains in late summer to autumn with continued high evaporation.

$$E_a/P_a = 12-20$$

$$E_w/P_w = 10-12$$

$$E_a - P_a > 3000 \text{ mm}$$

A_K Aridic Kalgoorlie type. Indefinite rain season.

$$E_a/P_a = 6-16$$

$$E_w/P_w = 10 \text{ or less}$$

$$E_a - P_a < 3000 \text{ mm}$$

Xeric Regimes: "Mediterranean" climate. Winter rain. Summer evaporation peak.

X Xeric proper.

$$P > E \text{ in all three winter months}$$

X_s Subxeric.

$$P > E^{0.75} \text{ in all three winter months}$$

(a = annual; w = wet month)

FIGURE 4.4

SOIL MOISTURE REGIMES OF WESTERN AUSTRALIA INFERRED FROM CLIMADIAGRAMS

Carlisle *et al.*, 1977 (Derived from data supplied by Aust. Bur. Meteorology, 1977; Gaffney, 1975; Gentili, Walter and Lieth, 1967)

4.1.2 Bedrock Geology in the Valley Calcrete Region

Yeelirrie and the calcrete uranium prospects presently of greatest economic interest occur exclusively above Archean rocks of the Yilgarn Block (Figure 4.1). The main region of valley calcretes, however, extends over an area at least as large again to the north. There the calcretes have been developed above Lower Proterozoic granitic and high-grade metamorphic rocks of the Gascoyne Block, Lower and Middle Proterozoic volcanic and sedimentary rocks of the Nabberu and Bangemall Basins, and even above Paleozoic and Cretaceous sedimentary rocks of the Officer Basin. Carnotite prospects in calcrete have been explored in this more northerly area, and in fact one of the earlier observations of anomalous radioactivity in association with calcrete was in an area northwest of Wiluna underlain by Lower Proterozoic sedimentary rocks (Sanders, 1973). To date, however, the Yilgarn Block appears to provide much the more favorable setting. Archean granites are the most probable uranium source rocks. The infolded north-northwesterly trending belts of greenstone, metasediments, amphibolites, gabbros, and felsic volcanic complexes may contribute calcium, magnesium, and vanadium to groundwaters. In addition, because of their greater resistance, they have interfered with southeasterly trending paleodrainages and thus contributed to the development of a predominantly internal drainage system and also to the deposition of valley calcrete by constraining groundwater flow.

In the calcrete uranium region roughly 50 percent of the Yilgarn block is composed of granitic rocks. The remainder consists of the north-northwesterly trending, generally synclinal complexes of greenstone, felsic volcanics, and metasedimentary rocks, including banded iron formation and quartzite. These complexes are metamorphosed only to greenschist or low-pressure amphibolite facies in the area of interest, though the grade and depth of metamorphism increases appreciably toward the southwestern corner of the block. The granitic rocks are complex, including "(a) composite or noncomposite, generally synkinematic plutons of tonalite, granodiorite, adamellite, and less commonly syenite; (b) large areas of banded and nebulitic migmatite; (c) large areas of relatively homogeneous coarse porphyritic, generally post-kinematic adamellite; and (d) elongate belts of orthogneiss and paragneiss" (Gee, 1976). They

yield whole rock Rb/Sr ages of 2.6 to 2.7 b.y.

Uranium contents of from less than 2 to 25 ppm are reported by Mann and Deutscher (1978) from granites in the northerly part of the Yilgarn Block. Vanadium contents are only slightly less, but larger amounts are present in some clays, laterites, and mafic rocks of the greenstone belts (Jones, 1965).

Near Wiluna, beneath the mid-sector of the valley calcrete region, a profound unconformity separates the Archean Yilgarn portion of the shield from the more northerly, very gently dipping Proterozoic mafic lavas, shale, quartzite, sandstone, conglomerate, limestone, and some iron formation of the Nabberu Basin. These rocks have been referred to as the "Nullaginan" (Mabbutt et al., 1963) and are shown as Lower Proterozoic, 2.2 - 1.64 b.y., on the Geological Map of Australia (Bureau of Mineral Resources, 1976) but have also been lumped with Middle Proterozoic, Adelaidean quartzite, shale, chert, and dolomite of the Bangemall Basin (Geological Society of Australia, 1971, Tectonic Map). The unconformity follows an irregular line almost through Wiluna.

It may be of interest, in view of the frequently observed physical and temporal association of Athabasca-Jabiluka type pitchblende deposits with Proterozoic unconformities, that prior to erosion this Archean-Proterozoic unconformity in Western Australia almost certainly extended for at least 180 km south of Wiluna (Sanders, 1973, p. 19), covering the greater part of the region of significant carnotite mineralization in valley calcrete.

The Yilgarn Block is overlapped by Permian glacial sediments and Cretaceous sedimentary rocks of the Officer Basin on the east and is bordered by Proterozoic metamorphic and plutonic rocks of the Albany-Fraser Province on the south and southeast. The western margin of the block is defined by the Darling Fault, trending north-south for 1000 km and having up to 15,000 m of vertical movement since the Permian alone (Johnstone et al., 1973). Scattered small outliers of Permian sedimentary rocks, apparently continental, rest on the Archean in the valley calcrete region (Bunting and Williams, 1975).

4.1.3 Surficial Geology of the Calcrete Environment

4.1.3.1 Ancestral Rivers on the "Old Plateau"

The genesis of valley calcretes and, prior to them the laterites and silcretes of Western Australia, is related to the persistent stability of the emergent Precambrian shield throughout the Phanerozoic and to a geological setting that began to take shape at least as early as the middle Mesozoic. The topics reviewed next are essential to an understanding of calcrete uranium genesis.

Beginning in the Late Permian and continuing through the Early Cretaceous, rifting between the protocontinents of Australia, India, and Antarctica resulted in the creation of graben in the regions of the Perth and Eucla Basins. Coarse fluvial sandstones and other continental sediments were transported into these graben by a network of rivers flowing southwesterly and southeasterly from the northerly portion of the Precambrian Shield (Johnstone et al., 1973). That ancient drainage system appears to have become increasingly less effective as a source of sediments after the Early Cretaceous, but the pattern of stream courses was maintained even to the present. The subdued subaerial surface of which it was a part has been the subject of long debate and a multiplicity of names (Finkl and Churchward, 1973; Hills, 1961; Woolnough, 1927; Jutson, 1950; King, 1950). The ancient surface is preserved today only as remnants on broad divides, fragments of a rolling upland to which Jutson (1950) has given the name Old Plateau.

4.1.3.2 The Lateritic Profile

During the later stages of its evolution, a prolonged period or periods of deep weathering under a humid climate and, very likely, a fluctuating water table produced a lateritic weathering profile over most of the Old Plateau which is without counterpart in South West Africa or North America. As much as 40 m or more thick, the full profile on granitic rocks consists of an uppermost iron- and aluminum-rich resistant duricrust (ferricrete), 1 - 3 m thick, a transitional mottled zone as much as 10 m thick, and a pervasively kaolinized pallid zone grading into weathered bedrock (Walther, 1915; Woolnough, 1918, 1927; Prescott and

Plate IV-4 BREAKAWAYS

- a) Typical breakaway on Barr Smith Range. Resistant mottled zone over pallid zone on skyline.
 b) Breakaway beneath Old Plateau. Pediment of New Plateau on pallid zone, foreground.
 c) View southerly into Yeelirrie basin from Barr Smith Range. Upper pallid zone foreground, pediment middle.
 d) Mottled zone on upper breakaway.

Pendleton, 1952; Mabbutt, 1961; Mulcahy, 1960, 1967, 1973; Mulcahy and Churchward, 1973). Good exposures are commonly seen in escarpments or "breakaways" (Plates IV-2, IV-4) which mark the boundary between the relict Old Plateau and alluviated valleys of the New Plateau. The uppermost duricrust varies considerably in its degree of iron enrichment and thickness, depending in part upon bedrock lithology but also apparently upon the amount of chemical and physical transport of components during and since its formation. On the partly eroded crest of granitic breakaways and along the edges of high level sand plains (Plate IV-2, Profile B-B') the amount of iron is not overly impressive and is commonly equaled or exceeded by the abundance of resistant nodular silcrete. Textures are pisolitic to gravelly and in places poorly cemented. The iron-stained mottled zone (Plate IV-4) is gritty and moderately to strongly kaolinitic with relict quartz grains but little else on granitic profiles. Silicification may be appreciable, and hardening of exposed faces is common. Porosity and permeability are high, permitting rainwater to seep through the rock and resulting in an eluviated and pitted surface on cliff faces and overhangs. The pallid zone is even more strongly kaolinized and less resistant to erosion. Relict granitic texture is visible and permeability is large. Cavernous weathering on breakaway faces commonly undermines the mottled zone and duricrust. Less weathered and even fairly fresh granite appears on many lower breakaway faces or upper pediment slopes. On ultramafic rocks, green to brown montmorillonitic and saponitic clays with abundant chalcedonic silica and cristobalite occur in place of kaolinite in the pallid zone (Nickel et al., 1977).

In view of the intense leaching of alkalies and alkaline earths from the lateritic profile, the occurrence of soluble salts, especially NaCl, in breakaway profiles is surprising. The salt is thought by many to be of recent marine origin transported inland on rain clouds (Teakle, 1937; Mulcahy, 1960; Morgan, 1972; Mulcahy and Churchward, 1973) but is equally if not more likely to be derived from dry salt lake dust (Hutton and Leslie, 1958). It has apparently concentrated on exposed evaporitic faces after being transported through the upper lateritic profile in rain water.

4.1.3.3 Silcrete

In many places a resistant silcrete covers the surface of the Old Plateau. Where indurated and up to a few meters thick it is known as grey billy or simply billy and is routinely mapped as a Tertiary rock unit. Silcretes and laterites are closely associated in some places and widely separated in others (Stephens, 1971). Silcrete commonly occurs within the lateritic profile. Some workers have argued that the formation of laterites, ferricretes, bauxites, and silcretes are all part of a single process (e.g., Grant, 1975) or of an essentially synchronous cogenetic process (Stephens, 1971). Most believe, however, on the basis of geological evidence (e.g., Smale, 1973; Alley, 1976; Firman, 1976) or of chemistry (Hutton, 1976) that laterites and silcretes have formed under different conditions. The prevailing view appears to recognize considerable lithological and geomorphic control, silcretes being favored by flat areas and sluggish drainage, but emphasizes the need for a much more arid climate to generate silcrete (Smale, 1973). Stratigraphic data and the inference of increasing aridity through the Tertiary lead to the conclusion that the major period or periods of silcrete formation are slightly younger than the major period of laterization on the Old Plateau. Silcretes are not known to contain uranium mineralization.

Silcrete is not to be confused with "hardpan," which consists of soil or alluvium cemented by silica of recent origin in the valley calcrete region (Section 4.3.2). "Opaline," actually microcrystalline, silica is also very frequently encountered as a replacement of valley calcrete, often in association with carnotite.

4.1.3.4 The Ages of Laterite and Silcrete

The pre-Tertiary age of the Old Plateau and an Oligocene to Miocene age for the major period of laterization on the southeasterly part of the Yilgarn Block has been deduced from strata in the south. Marine transgression began in the Eucla Basin in the Early Cretaceous, and by the middle of that epoch much of Australia east and west of the shield was submerged. During the Middle and Late Eocene, marine sediments again were deposited in the Eucla Basin and along the south coast, spreading north

finally almost to Kalgoorlie where thin limestone and spongolite of the Late Eocene Plantagenet Group rests on portions of the ancient drainage system. Marine sedimentation in the Eucla Basin was completed in the Middle Miocene with deposition of Colville sandstone in the northerly part and coeval very extensive Nullarbor Limestone over the entire south and central portion. The Late Eocene Plantagenet Group and other Cretaceous rocks are all laterized, whereas the Middle Miocene Colville sandstone is not (Johnstone et al., 1973). A similar age is suggested for northern South Australia where significant laterization is thought to have begun in pre-Tertiary times and silcrete formation in the Eocene, both continuing through much of the Tertiary, though not quite in the same areas at the same time (Alley, 1976; Hutton, 1976). Laterite continues to form today on the humid coastal plain south of Perth and has formed throughout the Quaternary in more interior southwestern parts of the state not only on peneplain remnants but on a variety of surfaces (Mulcahy, 1960). On the other hand, little, if any, laterite appears to have formed in the very arid region of valley calcretes since the Miocene or perhaps the Eocene (van de Graaf et al., 1976).

4.1.3.5 The "New Plateau," Arid Alluviation, and the Salt Lake System

The entire Precambrian shield appears to have been raised by approximately 300 m since deposition of Late Eocene shallow marine Plantagenet Group sediments over the ancient weathered surface south of Kalgoorlie (Johnstone et al., 1973). Evidence from the south suggests that uplift occurred during two main phases in the Oligocene and Miocene-Pliocene and may have continued into the Quaternary (Cope, 1975). With rejuvenation, the ancient rivers of the Old Plateau (Figure 4.2) cut through the lateritic duricrust into the soft pallid zone below.

Toward the later part of the Tertiary, the humid climates which had made possible the great rivers of the ancient system and the major period of laterization on the old surface appear to have deteriorated. Aridity may have begun as early as Mio-Pliocene, 7 - 10 m.y. ago, as cooling of the southern ocean is thought to have reduced the incursions of warm, moist air masses into the interior of Australia. This early period of aridity did not persist, and the major trend toward drier

climates of the present appears to have begun at about 2.5 m.y. "During this transition lake basins contracted, the subtropical floral and faunal elements retreated as southern Australia took on its seasonally hot, dry and arid climate that persists today" (Bowler, 1976, p. 283). With the onset of extremely arid conditions, the rejuvenated paleodrainage system began to choke with sediments. As today, the meager runoff was incompetent to carry the debris. At various points along the streams, determined in part by more resistant greenstone belts, drainage was eventually blocked and salt lakes formed. As sediments accumulated in the shallow valleys, the topography began to take on its present gentle form. Alluviation of the valleys, erosion of the pedimented flanks, and retreat of the marginal scarps have continued slowly through the Quaternary, but the rejuvenated drainages have never become more than partly filled, and this, it will be seen, contrasts strikingly with end-Tertiary arid alluviation of calcreted valleys on the Namib Desert of South West Africa. The "New Plateau" is in part a depositional surface--the alluvial plains and sand plains along the central parts of the valleys; and in part erosional--the pedimented Archean basement on the flanks.

4.1.3.6 Breakaways, Some Carnotite

Breakaways are the short, steep escarpments which form the interface between the Old and New Plateaus. They are entirely within the lateritic profile. The combination of a very resistant duricrust cap and a thick underlying kaolinitic pallid zone over less weathered bedrock has resulted in the prominent scarp edge, the undercut cliff, and subjacent pediment. Breakaways are not always present and, in fact, the distinction between the Old and New Plateau is not so straightforward in the field where, on some slopes, one grades imperceptibly into the other. Much of the research and the debate on landforms and soils in Western Australia revolves about the mechanisms responsible for the complex morphology of the New Plateau. (In addition to references already cited see, e.g., Stephens, 1946; Mabbutt, 1961, 1965; Bettenay, 1962; Mulcahy, 1960, 1967, 1973; Mulcahy and Bettenay, 1972; Mulcahy and Churchward, 1973; Bunting et al., 1974; Finkl and Churchward, 1973.)

Traces of carnotite have been found on granitic breakaway faces (Langford, 1974; Mann, personal communication, 1976), which may be somewhat surprising in view of the intense leaching manifest by the pallid zone. Under the arid climate of the region, with rare episodes of deep wetting during periods of high temperature and evaporation, uranium is apparently mobilized from granite and transported toward the evaporative surface. The precipitation of carnotite on that surface suggests that adequate vanadium and potassium must be available under present conditions. A single sample pair of contiguous weathered and unweathered granite collected by the writer from the Yeelirrie basin shows a 30 percent enrichment of uranium in the weathered portion (4.29 ppm vs. 3.26 ppm) and conceivably may be an example of the process. Is it possible that some of the components of the carnotite might be derived from dry salt lake crusts in the same way that the NaCl in breakaways may have been?

4.1.4

Calcrete Varieties and Carnotite

4.1.4.1 Nonpedogenic Calcretes

Nonpedogenic valley, deltaic, and groundwater lacustrine calcretes occur north of the Menzies Line and contain significant carnotite. Pedogenic calcretes, caliches, or kunkars occur south of the line and do not.

Valley calcretes, as shown in Plates IV-1 and IV-2 and Figures 3.1a, b, occupy the axial portions of the broad, flat valleys which make up the New Plateau and which, in this region, trend mainly southeasterly toward the Nullarbor Plain. Under the present climate, surface water flows in these valleys only during late summer storms and even then mainly into the many clay pans (playas) or salt lakes along their courses. Rarely, as after cyclone Trixie in 1975, many of the salt lakes will overflow, and drainage to the Nullarbor Plain will be briefly integrated once again (Mann, 1976; Bettenay, 1962).

Present-day streams (Plate IV-2) are short, ephemeral rivulets on the valley flanks, most of which dissipate on the alluvial plains and sand plains before reaching the valley floor. The infiltrative water flows below the surface into the axes of the valleys and into the calcrete aquifers. Slope gradients along the paleodrainages today are exceedingly low, ranging from roughly 0.5% near the headwaters to as little as 0.02% in the vicinity of the Yeelirrie orebody. The thickest and widest calcrete bodies tend to occur where bedrock morphology or some other feature has caused a decrease in slope gradient and where the groundwater table approaches the surface.

Valley calcrete also occurs but is very poorly known in the extremely difficult-of-access desert in central Australia north of the Eucla Basin, in the eastern part of the Great Sandy Desert, and the southern Northern Territory, and in northern South Australia. It is not known to occur in eastern Australia nor south of the Menzies Line.

Deltaic calcrete has formed in the valley calcrete region where the paleodrainages enter salt lakes and the subsurface water has encountered lacustrine clays and hypersaline pore waters. Mann (1976) has pointed out that the sequence from calcium-magnesium carbonates (and celestite) in the

valleys and deltas to gypsum on the lake shore and halite (and numerous other salts of potassium, sodium, and magnesium) within the salt lakes proper is a lateral manifestation of the classical evaporite suite.

Two ages of deltaic calcrete are recognized. Mature, well-formed deltas, essentially identical to valley calcrete in texture and general appearance, stand 1 - 2 m above the clay pans or the salt lakes on their margin. The relief is usually ascribed to deflation during extremely arid periods of the Quaternary (see below), but conceivably may be due in part to differential compaction of lacustrine sediments. Much less obvious are very young or incipient calcrete deltas which appear to be forming today at lake level. The relationship of these to uranium mineralization is given especial attention in Sections 4.2.2 and 4.2.3 below.

Groundwater lacustrine calcrete has formed around the shores of many salt lakes in the valley calcrete region without obvious relationship to the main paleodrainages. Radiometric anomalies are reported to occur over many of these bodies. At Lake Maitland (Section 4.2.4) calcrete is encountered within the main playa of the lake itself and is mineralized.

Most Western Australian valley, deltaic, and groundwater lacustrine calcretes are weakly to strongly dolomitic. This seems to be especially true of the very young or incipient calcrete deltas forming on the mudflats of salt lakes. Sepiolite $[\text{Mg}_4(\text{OH})_2\text{Si}_6\text{O}_{15} \cdot \text{H}_2\text{O} + 4\text{H}_2\text{O}]$ is a fairly common accessory mineral (Mann, personal communication). Sanders (1973 and Section 3.2.4 above) and others have emphasized the secondary "opaline" silica content of Western Australian calcretes, finding that it commonly occurs in layers apparently related to present and former groundwater tables. This is not surprising in view of the almost ubiquitous presence of siliceous hardpan horizons in soils of the valley calcrete region (Section 4.3.3) and of silcrete in the lateritic profile. The bulk of the opaline silica is microcrystalline quartz. Thin layers of reconstituted calcrete, often nodular, laminated, or with rockhouse structure, commonly develop on the surfaces of valley, deltaic, or lacustrine calcrete.

4.1.4.2 Pedogenic Calcretes

With minor overlap the distributions of pedogenic and nonpedogenic calcretes are mutually exclusive in Western Australia. Soil horizon calcrete, caliche, or kunkar is essentially absent north of the Menzies Line (Plate IV-1), but extremely common south of it. The pattern is clearly shown in the Soil Map of Australia (Northcote et al., 1975). North of the Menzies Line and over an area almost precisely congruent with that of the valley calcretes (Figures 4.1 and 4.3), the dominant soils are noncalcareous earthy loams with a red-brown siliceous hardpan. None of these soils occurs in the arid region south of the Menzies Line. Instead one finds great areas of alkaline and calcareous red earths and gray-brown calcareous earths. Toward the moister southwest, various alkaline, neutral, and leached acid soils appear, and in the humid southwest corner of the state, young lateritic soils become abundant and in some places are forming today.

No uranium deposits of economic interest are associated with pedogenic carbonate horizons, and none is found south of the Menzies Line.

An almost exactly correlative and equally striking difference between the terrains north and south of the Menzies Line is shown by the dominance of the Mulga tree (Acacia aneura) in the plant communities of the north, and of Mallees, eucalyptus trees with a multi-stemmed growth habit, in the south. The Mallees are characteristic of drier areas of the winter rainfall belt. The Mulgas favor the more arid summer storm belt.

The name Menzies Line has been used informally by CSIRO geologists and others for a phenomenon recognized by workers in several fields. Botanists and soils scientists appear to have recognized the existence of such a boundary for some time. Sofoulis (1963) shows it as the southern boundary of the region of calcretes (valley calcretes), and Langford (1974) refers to it as Sofoulis' Line. It is also the boundary between distinctive climate and soil moisture regimes (Figure 4.4). Because it is also the southern boundary of calcrete uranium distribution, one wonders if there is an analogous situation in South West Africa, southwestern United States, or elsewhere. Discussion of the possible reasons for the Menzies Line and for the other boundaries of the calcrete

region take up a considerable part of the following sections on Western Australia.

The two smaller regions of valley calcretes shown on Figure 4.1, after Sanders (1973), along the eastern edge of the state are poorly known and separated from the main region by the Great Sandy, Gibson, and Great Victoria Deserts. Sofoulis (1963) has shown all these regions as one. The recent announcement (Williams, 1977) of ore-grade uranium in calcrete at Thatchers Soak (Plate IV-1), which is on the south-easterly edge of the main valley calcrete region, suggests that the Sofoulis generalization may be correct.

4.1.5 Late Pleistocene Age of Valley Calcrete

The uraniferous valley calcretes are developed entirely within the New Plateau. Since they occupy the uppermost parts of valley fills or the shores of salt lakes, they postdate appreciably the time of onset of arid alluviation. Recent work provides some indication of when this might have been. Bowler (1976) has advanced strong evidence to show that, contrary to the situation in the northern hemisphere, periods of greatest aridity in Australia correspond with glacial maxima. This, he believes, is a consequence of greatly intensified atmospheric circulation and increased continental extent corresponding to lowered sea levels during glacial periods as well as reduced seasonal precipitation. Pre-Pleistocene changes, he suggests, relate to growth of the west Antarctic ice cap which by 2.5 m.y. had resulted in an Australian climate pattern probably resembling that of today. Today's arid features, however, are primarily a consequence of later Quaternary fluctuations.

"Before 25,000 B.P. lake levels were generally high and desert dunes were relatively stable. By 25,000 an important change marked the onset of the last major arid phase over the southern part of the continent. Lake levels fell and increasing salinities assisted in the early construction of clay-rich dunes. The trend reached a peak in the interval 18,000 - 16,000 B.P. when gypsum and clay dunes were constructed on the eastern margins of lakes from Western Australia, N.S.W. and Victoria, simultaneously with expansion of desert linear dunes. By 13,000 B.P. the stresses had relaxed; dunes became stabilized and the landscape had acquired many new features that have remained almost unchanged to the present day. . . . The correlation between glacial maxima and dune building episodes suggests the earliest arid landforms in southeastern Australia date from at least 0.3 m.y. Desert dunes were almost certainly present in Central Australia by that time and perhaps considerably earlier." (Bowler, 1976)

If this chronology is accepted, the valley calcretes seen today in the uppermost parts of valley fills and their contained uranium mineralization can hardly have begun to form before Late Pleistocene. A crude idea of the age of typical valley calcrete bodies might be deduced from the Yeelirrie occurrence where calcrete occupies approximately the upper one-fifth of the alluvial fill. If alluviation started at 2.5 m.y. (about the earliest date implied by Bowler's chronology) and continued uniformly, the calcrete body could not have begun to form prior to 0.5 m.y. But the calcrete body itself is not layered (apart from a surficial layer

of reconstituted calcrete), nor is there anything to show that it developed incrementally with the sedimentation. Rather it is a more recent cementation and replacement related to a water table apparently not different from that of today by more than 2 - 3 m. Elsewhere, valley calcrete occupies even a lesser fraction of the total alluvial fill.

In several places large sand dunes, now stabilized, are disposed marginally to mature calcrete deltas (see, e.g., Hinkler Well Drainage, Section 4.2.2, and North Lake Way, Section 4.2.3), which suggests that those calcretes predate the extremely arid 18000 - 16000 B.P. interval of Bowler. On the other hand, as suggested above and as documented in more detail in Sections 4.2.2 and 4.2.3, younger calcrete appears to be developing today at lower levels along the terminal parts of present-day drainages and on young or incipient deltas whose positions are controlled in part by those large dunes. This is in spite of the fact that stabilization of the dunes suggests a climate somewhat more humid today.

It is not unreasonable in the writer's view, therefore, to think that valley calcrete is predominantly Late Pleistocene to Recent in age and that the beginning of the major period of calcrete deposition may correspond with the initiation of the extremely arid phase at 25,000 B.P.

This conclusion contrasts with opinions sometimes expressed orally that calcretes are much older. It also contrasts with the inferred age of uraniferous South West African calcretes.

YEELIRRIE

Key for Plate IV-5

Symbols as on Plate IV-2. Areas such as R with banded groves of Mulga have vigorous water recharge during storms.

4.2 DESCRIPTIVE GEOLOGY OF SOME SPECIFIC OCCURRENCES IN AUSTRALIA

4.2.1 YEELIRRIE (Lat. 27°11'S., Long. 119°55'E., Elev. 500 m)

4.2.1.1 Location, Discovery, and Present Status

The carnotite orebody 20 km northwest of Yeelirrie Homestead in the East Murchison Goldfield District of Western Australia is the largest and richest calcrete uranium deposit known to this date and the first one with publicly announced ore reserves. Approximately 73 km south-southwest of Wiluna and 645 km northeast of Perth, it is almost exactly at the center of the main region of valley calcrete uranium prospects in Western Australia (Plate IV-1).

Discovery of the orebody by Western Mining Corporation resulted from exploration begun in the late 1960s, prompted in part by the possibility of groundwater uranium deposition within the portions of the salt lake environment where chemically reducing conditions might be expected to occur. Aerial radiometric surveys by the Bureau of Mineral Resources were available for some parts of the Yilgarn Block but not yet for the Yeelirrie region. By making use of these surveys, numerous uranium occurrences were detected not simply in the salt lakes but also within interconnecting drainage systems (Eric Cameron, personal communication, 1977). Independently of this work a strong radiometric anomaly was detected at Nowthanna (Plate IV-1) on one of the company's own aerial surveys, and during the evaluation of this anomaly significant carnotite mineralization was discovered in calcrete. Subsequently, the BMR airborne radiometric survey of the Sandstone Sheet became available (Gerdes et al., 1970). A distinct anomaly was shown at Nowthanna Hill and an especially prominent one along the calcrete paleochannel at Yeelirrie (Plate IV-3). With other exploration groups in the region, Western Mining Corporation pegged ground encompassing the anomalous area and eventually most of the exposed calcrete for some 45 km along the paleochannel. In January 1972 the company announced that it had intersected uranium mineralization by scout drilling over a wide area near Yeelirrie. Ground radiometric survey with integrating spectrometer (Figure 4.5) confirmed the airborne results and the absence of thorium in

Figure 4.5
Reproduced by courtesy of Western Mining Corporation, Ltd.

Ground radiometrics

the deposit. A smaller zone of strongest radiometric response about 10 km long was then tested by auger and rotary drilling on a 200 by 500 m grid and some of the higher grade areas were resampled by core drilling. Roughly 1100 reverse-circulation holes and 400 diamond drill holes were drilled within a four-month period, mostly in the range of 10 to 15 m deep. Subsequently, several meter-diameter holes were drilled, and two open-cut slots were excavated within the calcrete, the first (Plate IV-6) across the trend of the orebody 450 m long by 45 m wide and 10 m deep, the second along the trend of the orebody approximately 200 m long by 40 m wide. These openings and the drill holes provide the only opportunities for observing the detailed geology. Stockpiles of ore-grade calcrete mined from the slots and sampled for metallurgical testing are shown in Plate IV-6b.

In November 1972 and in subsequent reports Western Mining Corporation announced that the main ore zone at Yeelirrie, approximately 6000 m long, 500 m wide, and 8 m thick, was estimated to contain 46,000 (metric) tons of U_3O_8 at an average grade of 0.15%, of which 24,000 tons are above 0.36% grade. Metallurgical testing on both laboratory and pilot plant scales has shown that the ore can be processed successfully by an alkaline leach process. Further exploratory and developmental work on the deposit was suspended in June, 1973, pending announcement of the Australian Federal Government's uranium policy.

As a result of the rush which followed the first announcement of ore-grade carnotite mineralization in calcrete, numerous additional occurrences have been found throughout the region of valley calcretes (Plate IV-1).

The writer is particularly grateful to Dr. Eric Cameron, Senior Geologist, Exploration Division, Western Mining Corporation Limited, for his kind cooperation (including a personal tour of the deposit on September 4, 1976 in company with Alan Mann of CSIRO), for permission to revisit and examine the deposit, for facilitating the acquisition of various air photographs and maps, and for very helpfully providing a copy of a 1/100,000 scale contour map of the Yeelirrie basin prepared by Western Mining Corporation. Except where quotations are indicated or credit is given, the inferences drawn are those of the writer.

4.2.1.2 The Yeelirrie Catchment Basin: Size and Growth

The Yeelirrie orebody is an integral part, physically and genetically, of the drainage basin in which it occurs. The basin is broad, extremely flat, and filled in part with alluvium, soils, calcrete, and evaporites derived entirely from within the basin itself or from the atmosphere. The valley heads at the Major Continental Divide 60 km upstream from the orebody, drains southeastwardly, and terminates under the present hydrologic regime, at Lake Miranda, a salt pan 75 km downstream from the orebody (Plate IV-2). It was formerly part of a much longer river draining into the Eucla Basin and that river in turn was probably superimposed in part on the still larger and broader system integrated with the Old Plateau.

The area of the present catchment basin above the Yeelirrie orebody is 3000 km². It appears unlikely to the writer that the catchment of the present (New Plateau) basin has ever been substantially larger than this, judging from the topography to the northwest (across the major continental divide) and from the relationships of its marginal breakaway escarpments to older and contemporary surfaces around the basin. The breakaway scarps on the northeast and the north sides of the basin are inward facing, fairly continuous, and actively eroding the weathered granitic bedrock (Plate IV-5). Many are more than 10 m high. Their serrate shape in plan view is the result of headward erosion by innumerable small streams during late summer storms. Steep cliff faces, some overhanging, are not uncommon. The breakaways on the south are also active, but they are patchy and isolated, the nearer ones facing inward but the farther ones facing south and retreating northward away from Lake Mason toward Yeelirrie basin (Plate IV-2). The pattern of southerly facing breakaways is dominant in this region east of the continental divide. It appears, then, that the Yeelirrie basin has grown and continues to grow laterally on the north and northeast at the expense of the Hinkler Well drainage, but that it is being diminished on the south by expansion of the Lake Mason catchment basin. Drilling data indicate, however, that the lowest points on the present-day surface coincide more or less with the deepest parts of the paleochannel with only minor displacements in alignment (Eric Cameron, personal communication, 1977).

Explanation to Plate IV-6 Yeelirrie

- a) The Yeelirrie valley calcrete looking downdrainage (southeasterly) from orebody vicinity toward Yeelirrie Homestead (not visible). Slot No. 1 at mid-photo with slot No. 2 beyond clay pan.
- b) Yeelirrie slot No. 1 and ore stockpiles. View southwesterly across calcrete orebody which is between the stockpiles.
- c) Yeelirrie slot No. 2. View northwesterly. Calcrete platform mainly on right of slot.
- d) Yeelirrie slot No. 2 southwesterly wall showing mounds of porcellaneous calcrete (light) transecting earthy calcrete.

Plate IV-6 Yeelirrie

No permanent nor single well-defined intermittent stream flows along the axis of the valley itself. The axis is clearly outlined, nevertheless, by outcropping or near-outcropping calcrete, by scattered small clay pans, and by vegetation, especially phreatophyte trees within or along the margins of the calcrete (Plates IV-5, IV-6, IV-12). It is an excellent example of the Cunyu Land System of Mabbutt et al. (1963). The groundwater table within the calcrete, in the vicinity of the orebody, is at roughly 5 m depth and probably varies by not more than 1/2 m from time to time, if that much.

4.2.1.3 Relief, Gradients, Narrowing, and Flattening Near the Orebody

Total relief from the axis of the drainage where the orebody occurs to the marginal scarps or breakaways in the Barr Smith Range on the northeast or the Montague Range on the southwest is about 80 meters. Upstream and downstream from the orebody that relief is developed over a valley width of up to 45 km, but near the lower end of the orebody itself the valley narrows to approximately 18 km between outcrops or near-outcrops of granitic rock (Plate IV-2). The result is an appreciable steepening of the cross-valley gradient and a larger-than-usual supply of alluvium from marginal scarps and pediments in the granite outcrops to both sides of the channel just below the orebody. The tributary washes are clearly shown on aerial photographs (Plate IV-5).

The longitudinal gradient of the valley (Plate IV-2) changes smoothly from 0.45% near its headwaters to approximately 0.075% near Yeelirrie Homestead except that in the vicinity of the orebody itself it is only 0.02%. This very slight flattening of the gradient corresponds with the narrowing of the valley near the orebody, and with the additional supply of alluvium mentioned above. This flattening, in turn, is thought by the writer to have been influential in slowing the rate of groundwater flow within the channel, in the consequent strong development of calcrete and numerous calcrete platforms and mounds (see below) immediately upstream, and conceivably in localizing the orebody itself. The impediment to flow is slight but sufficient to allow ephemeral films of water to cover small clay pans during rare cloudbursts. The

calcrete does not at all resemble a lacustrine limestone in its texture or structures, being very irregular in thickness and neither laminated nor well bedded. It cements and replaces soil and alluvium.

Neither the long profile nor the cross profiles show any evidence for rejuvenation. The only exception to this would be at the far terminus of the drainage in Lake Miranda, where deflation and perhaps differential compaction of the clay-salt pan may have lowered the base level by as much as 2 m, resulting in local dissection of deltaic calcrete.

4.2.1.4 Bedrock, the "Lateritic Profile"; Breakaways and Subjacent Pediments

Except for a portion of the Montague Range greenstone belt along the westerly margin of the basin, the entire catchment area is underlain by Archean granitic rocks. Granite, adamellite, granodiorite, and tonalite have been mapped by Bunting and Williams (1974) around the lower part of the basin east of longitude 120°E. A narrow finger of Archaean greenstone and metasedimentary rock is exposed almost due north of the Yeelirrie orebody in the headwater divide of the next-north drainage, Hinkler Well (Plate IV-2). The Geological Map of Australia (Bureau of Mineral Resources Australia, 1976) shows a projection of this into the Yeelirrie catchment area at about longitude 119°50'E., but neither the aerial photographs nor the maps of Mabbutt *et al.* (1963) or of Churchward (1976) show this, and no other systematic geological maps are available. Conceivably, the narrowing of the valley and the slight flattening of the gradient near the orebody discussed above may reflect a subsurface occurrence of this greenstone or of granitized mafic rocks along its trend.

Outcrops of granite on the older surface (or surfaces) above the breakaways are generally sparse, in part covered by aeolian sand or residual gravel, deeply weathered, variously ferruginized, and commonly heavily silcreted. On the breakaway faces, outcrops are much more abundant and invariably include the iron-stained "mottled zone" transition between overlying or once-overlying lateritized and silcreted granite and the underlying thick kaolinitic or "pallid" zone, i.e.,

the so-called "lateritic profile" (Section 4.1.4.2). The pediments below the breakaways are developed on the pallid zone or, especially in their lower parts, on less deeply weathered granite. The mottled zone is commonly of the order of 1 to 5 m thick. An extrapolation using the contour map supplied by Western Mining Corporation and the Soils, Landform and Regolith map of Churchward (1976) indicates a thickness of at least 40 m of pallid zone and less weathered granitic rock.

Of the 3000 km² catchment, roughly 25% exposes some outcrop to extensive outcrop. The total length of active breakaway scarp and subjacent pediment in the catchment upstream from the orebody is in the order of 200 km, not counting all the irregularities on the breakaways. Of the actively eroding outcrop surfaces roughly equal parts are on lateritic profile and on less weathered granitic rocks. Greenstone Belt rocks are exclusively on the westerly margin of the catchment and compose about 5% of the exposed bedrock.

4.2.1.5 Clastic Sediments, Derivation from Breakaways, and Pediments

Probably more than half of the sediment in the Yeelirrie basin is derived from the lateritic profile and is, therefore, almost completely depleted of soluble ions at the outset. The remainder is from less weathered granitic rock, a minor amount of greenstone, and from the atmosphere.

Brief heavy rains, falling during some of the hottest and driest times of the year, erode and seep into the breakaways. Clay, silt, and sand are swept across the pediments (along with occasional fragments of ironstone, silcrete, or less weathered bedrock) by sheet flood, by minor rills, and by the many intermittent streamlets which head in or near the breakaways. Stream channels are well defined in the upper pediments, but as gradients decrease and water is lost into the pallid zone and through evaporation, a mantle of pedisegment forms. Downslope the pediments give way to a broad alluvial plain. At Yeelirrie, as with nearly all the other basins at this latitude, the alluvial plain merges basinward with a broad red-brown sand plain developed above fluviatile sediments or other regolith. Here sheet flood and wind are the transporting

agents today, but during the extremely arid periods of the very late Tertiary and especially during periods of greater continentality in the Pleistocene (Bowler, 1976), wind was the major factor.

Data provided by Western Mining Corporation (1975) indicate that the noncarbonated surficial sediments near the orebody, though variable in composition, grain size, and sorting, are composed principally of clays (mainly kaolinite with minor montmorillonite and illite), detrital quartz sand, and minor feldspar. Quartz and feldspar are occasionally concentrated in distinct grit or arkose layers. Gypsum may constitute up to 30% of the surficial sands locally. Apart from the pervasive red color of the sediments not much seems to be known about the amount of laterite (ferricrete) detritus in these sediments. Northcote et al. (1975, p. 36) mention that "various gravels of country rock, ironstone and/or siliceous material are present through the solum . . ." of this region. Brewer et al. (1972) report a "high proportion of ferruginous nodules . . ., moderate proportions of nodules of secondary silica, a moderate to low proportion of rock nodules, and a low proportion of kaolinitic concretions" in a microscopic study of similar hardpan-bearing soils 300 km NNW of Wiluna. The ferruginous nodules are, in part at least, detrital laterite fragments or pisolites. Silica cementation of the alluvium and colluvium within 1 1/2 m of the surface is typical and, in fact, all of the sedimented surfaces from the pediments to the calcreted axis of the basin are underlain by extensive hardpan (= duripan), discussed briefly under "soils" below and in more detail in the sections on Wiluna hardpan (4.3.2, 4.3.3).

The thickness of these alluvial, colluvial, and aeolian sediments varies with bedrock morphology. Drilling by Western Mining Corporation indicates a depth to bedrock "seldom more than 30 m and commonly less" in the general vicinity of the orebody, "but at least 85 m of sediments can be encountered in the salt lakes further downstream" (Western Mining Corporation, 1975, p. 3).

4.2.1.6 Soils: Earthy Loam and Red-brown Hardpan

The nature of the soils and the apparent soil moisture regime within them as deduced from climate are important factors in assessing the

favorability of an area for valley calcrete uranium mineralization (Section 4.3.1 below).

Soils of the Yeelirrie catchment basin are characteristic of most, if not all, of the basins in Western Australia in which uraniferous calcretes are found and also the soils in which mulga (Acacia aneura) dominates the tree community. They are shallow earthy loams underlain by red-brown hardpan (silica-cemented soil = duripan in U. S. soils terminology; see also Wiluna hardpan, Section 4.3.2). Except directly over or adjacent to the calcrete itself they are acidic, and they lack completely a calcic or petrocalcic horizon (caliche or kunkar). They are nonsaline, low in organic matter, massive, porous, and freely permeable above the hardpan. Exchange capacity is low. They contrast markedly with the commonly alkaline, commonly carbonate-rich, sometimes-saturated soils of southern and west central Western Australia outside the valley calcrete region. Apart from small occurrences in southwest Queensland and far west New South Wales, they are unique to this part of Australia.

4.2.1.7 Hydrology and Groundwater Chemistry

Weathered bedrock on breakaways and in the pallid zone provides excellent catchment and intake areas, particularly near the base of the pediment or the top of the alluvial plain. Litchfield and Mabbutt (1962) and Morgan (1966) have pointed out how cusped or bar-shaped patches of mulga-dominated vegetation, clearly visible on air photographs (Plate IV-5), are always associated with groundwater recharge. Good quality well water is often found in this situation or in bedrock at depths of from 5 to 20 m. Surface water rarely reaches the valley axis. Much is lost by direct evaporation. That which seeps into the soil tends to move readily downward without much evaporation and precipitation of soil carbonate. Although groundwater salinity increases markedly through the alluvial fans, sand plains, and the main drainage, good water for stock use and on occasion potable water can be found along the upper parts, at least, of the calcreted drainages.

According to Western Mining Corporation (1975),

". . . both quantity and quality of ground water varies appreciably. Because of its highly permeable nature, the calcrete has a great storage potential; tests in the Yeelirrie channel gave a calculated average transmissivity of 0.82 million litres/day/metre (i.e. 55,000 Imperial gallons/day/foot) and produced a yield of approximately 4.5 million litres/day (1.0 million Imperial gallons/day) from an exploratory excavation measuring 450 x 40 x 9 m.

"As yet, no systematic or complete chemical analyses of water in the Yeelirrie channel are available. Stock bores were sampled for water quality and for U abundance, but these sampling sites are biased towards water of relatively low salinity and do not provide a systematic sample of water throughout the aquifer. The data which are available illustrate the general increase in salinity away from the intake point. For example, bores close to the breakaways contain on average < 750 ppm TDS, whereas further downstream, but on the edge of the calcrete, values of over 5000 ppm TDS and occasionally up to 15,000 ppm TDS were encountered. Within the ore zone, the salinity is above 20,000 ppm TDS.

"Uranium is anomalous in many bores in the catchment area, over half those sampled containing > 50 ppb. However, the available bores do not provide a sufficiently systematic cover to define the distribution of uranium in the water over the whole catchment area, or its relationship to the mineralisation; nor are there any complementary analyses of K and V."

Samples of water collected by the writer from the slots at Yeelirrie contained 200 and 750 ppb of uranium.

4.2.1.8 Calcrete Distribution and External Form

Calcrete begins to appear at the surface along the axis of the Yeelirrie paleochannel 30 km downstream from the headwater divide--midway between the orebody and the divide--and it is in almost continuous outcrop for the full 115 km to salt Lake Miranda (Plate IV-2).

The downstream half of the calcrete from below Yeelirrie Homestead to Lake Miranda is irregular in outline and width and includes two small salt lakes with marginal gypsum and aeolian sands. Calcrete deltas have been built outward into each of the three lakes. The original discovery of carnotite in calcrete is reported to have been made near the upper lake. A large delta visited by the writer on the northwest shore of Lake Miranda stands almost 2 m above the adjacent clay pan as a result of deflation or differential compaction of lake sediments. Its margins are

LITHOLOGICAL CROSS SECTION
Figure 4.6

OBLIQUE LITHOLOGICAL SECTION
Figure 4.7

eroded, and, like similar perched deltas on the north shore of Lake Way, it yields a very low radiometric response (80 cps total count; 1.8 cps Bi^{214} ; Geometrics GR 410 unshielded, which is very comparable with red sand plain or clay, well removed from calcrete mineralization, and about one half the Bi^{214} response on several granitic outcrops).

By comparison the upstream half of the calcreted channel which includes the orebody is straight, relatively narrow, and without salt lakes. The strongest development of the calcrete begins about 15 km above the orebody where two tributary drainages, each with minor calcrete bodies (Plate IV-2), enter the main channel. Calcrete reaches a maximum outcrop width of about 5 km just below that point and continues with abundant calcrete platforms or mounds through the low-gradient part of the channel, mentioned earlier, to the lower end of the orebody. At this point the valley narrows and from here to Yeelirrie Homestead the outcrop width is only about 1 to 2 km.

Figures 4.6 and 4.7 from Western Mining Corporation illustrate the broad form of the calcrete and its relationships to overlying and underlying units. Based upon their drilling, Western Mining Corporation (1975) has indicated that the calcrete is

"... occasionally up to 6.5 km in width and 20 m in thickness. The thicker sections of calcrete tend to be developed over the deeper parts of the channel and conversely, discontinuities in the calcrete along the channel appear for the most part to be due to a shallow basement. The form of the calcrete bodies varies from small, scattered pods, to large irregular sheets of lenticular cross section and elongated along the channel. In the Yeelirrie area, only one calcrete horizon has been found, nor is there any evidence of lateral interfingering with the channel sediments."

Cameron (1976) states that

"on a hole to hole basis the profile is quite variable within the general pattern; in the carbonate-rich part of the section, individual units may vary appreciably in thickness or may be absent, but nevertheless the whole carbonate zone appears to maintain a general thickness of approximately 6-8 m, and the calcrete about 4 m, though occasionally up to 7 m."

Exposed well-developed calcrete occupies roughly 1-1/2% of the catchment area above the orebody and constitutes perhaps 1/2 to 1% of the volume of sedimentary fill.

In the following six pages, major portions of the text, Tables 4.1 and 4.2, and Figures 4.6, 4.7, 4.8, and 4.9 describing the lithology, the internal structure, and the mineralogy of the calcrete are taken directly from reports prepared by the staff of the Exploration Division of Western Mining Corporation (Cameron, 1976; Western Mining Corporation, 1975).

4.2.1.9 Lithological Section

"On the basis of diamond drill core and limited excavation, three main horizons can be recognised--the Overburden, the Calcrete and the Clay-Quartz. The significant features of these horizons are summarised in Table [4.1]; a somewhat idealised drill hole profile is shown in Fig. [4.8], and the typical distribution of the various units, both across and along the channel, in Figs. [4.6] and [4.7]." (Western Mining Corporation, 1975)

According to Cameron (1976):

"The various 'horizons' and 'units' [in Fig. 4.8] were established on the basis of the physical characteristics which could be seen in drill core and not as the result of detailed petrographic studies. Nevertheless, it was found that XRD analysis generally supported the logging. . . .

". . . Commonly, but not always, the contacts between them [the units] are gradational. . . . The Overburden is divided into Loam (or Hardpan) and Carbonated Loam units; the Calcrete into Calcrete and Transition Calcrete units; the Clay-Quartz into Carbonated Clay-Quartz and Clay-Quartz units. (The grit and arkose bands are included for the sake of illustration and are not identifiable units.)

"The top of the Overburden is frequently a thin, brown loam, sand or clay. Locally, it may be impregnated with silica at a depth of 15 cm or so, forming a tough 'hardpan' layer.

"In places, the loam may be absent, in which case, the surface material is a buff, carbonated loam which is responsible for the treacherous, fine, powdery soil so characteristic of these calcrete areas. The Carbonated Loam is a transition zone between the Overburden and Calcrete horizons, more in terms of carbonate content than physical appearance. In the upper part of the unit, a gravel or rubble horizon is often present; the gravel consists of spherical concretions of buff carbonate, and the rubble of loam or hardpan peds with a skin of carbonate, both dispersed in a carbonate-rich loam matrix. With depth, a planar structure is developed due to rafts of loam, or hardpan, separated by seams, or cut by veinlets, of carbonate.

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IDEALISED LITHOLOGICAL COLUMN
Figure 4.8

Table 4.1

Summary of the Lithological Characteristics

<u>HORIZON</u>	<u>UNIT</u>	<u>COMMON THICKNESS</u>	<u>CHARACTERISTICS</u>
1. OVERBURDEN	a) Soil/hardpan	<1 mm	Sandy soils; loose, friable; grey or brown; commonly calcareous. Hardpan is an indurated layer, cemented by silica. Red or brown gypseous and saline soils in clay pans.
	b) Carbonated loam	1-2m	Gradational with calcrete and soil--arbitrary limits. Normal and planar structures common. Nodular structures giving rise to a rubbly or gravelly calcareous horizon. Planar structures are calcareous zones or rafts of soil (or hardpan) in carbonate matrix.
2. CALCRETE	a) Calcrete	2-4m	Arbitrarily defined; authigenic carbonate with $\geq 10\%$ clay-quartz relicts. Relicts show every stage of replacement. Variable in character; friable to hard (i.e., earthy to porcellaneous); cellular to massive. Variable colour due to staining. Caverns sometimes several metres in length; swell structures; occasional faults. Small cavities generally with amorphous clay or silica.
	b) Transition calcrete	1-2m	Clay-quartz relicts $> 10\%$. High carbonate content, still in matrix. Considerable variation in composition.
3. CLAY-QUARTZ	a) Carbonated clay-quartz	1-2m	Decreasing carbonate content; as veinlets rather than matrix impregnation. Planar structures common. Sometimes cavernous and may be highly silicified. Celestite locally abundant.
	b) Clay-quartz	20-25m	Carbonate absent. Red or brown clay with quartz (and feldspar) disseminated or concentrated in grit or arkose bands. Celestite not uncommon.

"As the carbonate content increases, the Overburden gives way to the Calcrete Horizon. In the literature it seems that the term 'calcrete' (or its equivalent) is applied to a wide variety of these surface carbonate-rich rocks; likewise at Yeelirrie, they show a great variation in physical characteristics. It is not uncommon to find inclusions of loam or clay-quartz in the calcrete, which vary in size and number, causing some of the variation in appearance, but more importantly, gradational contacts between the units. For the purposes of logging, we have adopted the convention of restricting the term 'calcrete' to those carbonate-rich rocks with less than an estimated 10% of inclusions, and using 'transition calcrete' where the inclusions exceed 10%."

In the following, Cameron emphasizes the apparent metasomatic (?) replacement of soil peds included in the calcrete in addition to simple carbonate cementation. He also brings out an important distinction between "porcellaneous" (i.e., largely aphanitic) and "earthy" calcrete.

"As the carbonate content increases, the rafts of loam in the Carbonated Loam Unit are progressively reduced in size and number; the emphasis changes from loam with subordinate carbonate in seams and veinlets to loam inclusions set in a carbonate matrix in the Transition Calcrete Unit. Every stage in the elimination of these inclusions can be seen from bleaching, incipient carbonation round the edges and transgressive carbonate veinlets, to a stage where their former presence is indicated merely by slightly darker ghosts, giving the calcrete a mottled appearance.

"Calcrete is highly variable in character. One of the more common varieties is white, hard, porcellaneous, nodular and cavernous, forming pronounced mounds when outcropping. On the other hand, some calcretes are soft and friable, in the extreme case so friable that they are powdery. Between these--the 'porcellaneous' and the 'earthy'--there is a complete range of intermediate types." (Cameron, 1976)

The textures of porcellaneous calcrete and earthy calcrete are shown in Plate IV-7. The more nodular, popcorn-like appearance of the porcellaneous variety seems to have resulted from a combination of concretionary and nonconcretionary authigenic growth of carbonate carried to an advanced stage followed by dehydration shrinkage and cracking.

In the writer's observation, earthy calcrete contains a much larger proportion of soil materials and is much more soil-like (or caliche-like) in appearance. Below depths of a meter or so it tends to display a crude layering, probably alluvial in origin, not to be confused with laminar pedogenic caliche above a plugged horizon, although secondary in situ pedogenic caliches are developed locally over valley calcrete.

a) Wall of slot No. 1 showing crenulated porcellaneous calcrete.
b) Porcellaneous calcrete with carnotite in slot No. 2.

c) Slickensides coated with carnotite from carbonatized clay-quartz beneath main calcrete, slot No. 1.
d) Partly carbonatized earthy calcrete with soil peds, slot No. 2.

"Superimposed on this range of physical properties between the porcellaneous and earthy varieties are a number of structural features which serve to compound the variability in gross appearance of the calcrete. For example, nodular textures are common in the upper transitional zone; they consist of either soil peds coated with carbonate or pisoliths of carbonate with prominent concentric growth patterns. Where strongly developed the carbonated horizon may have a rubbly or gravelly structure. In both the upper and lower transition zones, planar structures are developed to a greater or lesser extent; they may be carbonate rich zones, or rafts of clay-quartz preserved in a more carbonate rich matrix. Mammillary, swell, cavernous or cellular structures are common within the main part of the calcrete horizon.

"Opaline silicification is common, usually as veinlets, concretions, cavity filling, or a general impregnation. In extreme cases silica rich zones up to several metres in thickness have been formed.

"The lower transition zone marks the end of what is generally recognised as calcrete. With the gradual disappearance of carbonate, clay-quartz relicts become more dominant, the rock therefore darker in colour, carbonate occurs primarily as veins rather than as a matrix impregnation, and planar structures are in marked contrast to the somewhat cauliflower-like structures in the calcrete zone above. The thickness of the transition zone is variable. Sometimes the carbonated clay-quartz ends abruptly against a grit band within 20 cm of the base of the transition calcrete, but on the other hand, it may extend for up to 2 m." (Western Mining Corporation, 1975)

"Silicification may also be prominent in the Carbonated Clay-Quartz Unit.

"The final unit in the profile is the Clay-Quartz which contains no detectable carbonate and extends down to the basement; it is the original valley-fill material. It is a mixture of red-brown clay and detrital quartz grains, but with occasional grit bands which can be correlated on a local basis. Arkosic bands may also be present, particularly at the western end of the ore body and towards the bottom of the profile." (Cameron, 1976)

4.2.1.10 Calcrete Platforms and Mounds

The two excavated slots at Yeelirrie, particularly Slot No. 2 (Plates IV-6, IV-8), reveal a most interesting dome-like or perhaps diapiric structure within the mass of valley calcrete. These structures, composed of the porcellaneous variety of calcrete described above, have become known locally as "mounds." Cameron (1976) comments on them as follows:

"The overall structure [of the calcrete body] is planar, more or less parallel to the surface; this is seen on all scales, illustrated by the distribution of individual units, the rafts of loam, hardpan or clay-quartz, caverns developed in the porcellaneous calcrete or carbonated clay-quartz, and the distribution of grit bands in the clay-quartz. There is, however, one feature which breaks the continuity of this planar pattern. In both excavations, masses of porcellaneous calcrete can be seen truncating the higher units, and occasionally reaching the surface. Apart from the unusual discordant appearance of these masses, the most striking feature of them is the presence of low angle fault planes around the margins, sometimes highlighted by a coating of brilliant yellow carnotite."

Mabbutt et al. (1963, p. 53) used the term platform to describe segments of outcropping valley calcrete elongated with the valley and "typically up to 1/2 mile wide and 1-1/2 miles long . . . up to 10 feet high . . . flat crested or saucer-shaped . . . with rocky irregular rims . . . partly sand-masked." The platforms are separated by anastomosing alluvial floors. Large elongate structures which fit this description are visible on the ground and on aerial photographs of the Yeelirrie calcrete channel, particularly in the low gradient segment. Slot No. 2, for example, is excavated along the southwesterly margin of such a platform having a relief of about 3 m. The six porcellaneous calcrete mounds exposed on the southwest side of Slot No. 2 (Plate IV-6) and the three on the northeast side are a part of that platform.

The origin of the calcrete mounds is controversial. Since the base of the calcrete is not exposed, one cannot observe whether smaller mounds such as those shown on Plates IV-6 and IV-8 coalesce downward or laterally toward the central parts of the larger platforms or whether they project more or less deeply than the earthy calcrete. Sink holes, cavities, and collapse structures observed on several mounds in the Hinkler Well drainage (see below) and reported in many other valley calcretes indicate substantial vertical flow, perhaps upward at times, in those areas and, by analogy, at Yeelirrie also. The concept of local plumes of upwelling groundwater propelled by small hydraulic gradients and/or salinity or temperature differences is an attractive explanation. Increased loss of CO₂ from rising water would enhance carbonate precipitation. (For a description of "young" mounds or incipient mounds near the terminations of some calcreted drainages, some of which are composed of partly

Plate IV-8 YEELIRRIE MOUND STRUCTURE

Overlay showing apparent sagging of earthy calcrete and carbonated loam around a small mound of porcelaneous calcrete on the southwest face of Slot No. 2. Figures in parentheses are an average of cps U (Bi^{214}) from readings taken on three adjacent mounds, on surrounding earthy calcrete, carbonated loam, and on the surface.

carbonated mud, others of porcellaneous calcrete, several of which are radiometrically anomalous and some of uranium ore grade, see Hinkler Well Drainage and North Lake Way, 4.2.2 and 4.2.3.) Several exploration geologists in Australia favor the upwelling concept. Certainly, at Yeelirrie the bedrock constriction evidenced by the narrowing of the drainage and flattening of the gradient in the orebody zone accords with such a model. Presumably, the groundwater table would be at or close to the tops of the mounds, whereas today it lies 5 m or so below that level. Alternatively, Alan Mann of CSIRO (personal communication, 1976) has suggested growth of authigenic carbonate at the base of the mounds. This has the advantage of permitting continued growth during periods of relatively low water table.

Warping of layering (Plate IV-8) and fractures with slickensides in earthy calcrete around the mounds indicate differential vertical movement during or after their formation. It is not clear whether this is a result of settling of the more compactable earthy calcrete around competent porcellaneous calcrete or of actual expansion of the developing porcellaneous mass resulting from carbonate crystallization between grains in the manner suggested for caliche pseudo-anticlines (Jennings and Sweeting, 1961). Convolutions in crude layering in porcellaneous calcrete in Slot No. 1 (Plate IV-7) could be explained in this way and support the idea of forcible upthrusting. Erosional truncation of the higher mound summits, development of large caverns and of microcrystalline quartz films, veinlets, and concretions within the porcellaneous calcrete suggest that the growth of mounds may have ceased in the vicinity of the orebody.

4.2.1.11 Mineralogy

The only published systematic data on the mineralogy of Western Australian calcretes is that published by Western Mining Corporation on Yeelirrie as follows:

"X-ray diffraction and petrographic studies were carried out on diamond drill core as an adjunct to metallurgical testing. A summary of the mineralogical characters of each unit is given in Table [4.2]. As stated in the previous section, the profile is quite variable, and though the same broad sequence can be recognized, each

MINERALOGICAL COMPOSITION - IDEALISTIC & DIAGRAMMATIC
Figure 4.9

Table 4.2

Comparative Mineralogy

<u>HORIZON</u>	<u>UNIT</u>	<u>COMPOSITION</u>	<u>CLAYS</u>			<u>CARBONATES</u>		<u>Q.</u>	<u>FELDSPAR</u>
			<u>MONT.</u>	<u>ILLITE.</u>	<u>KAOL.</u>	<u>DOL.</u>	<u>CALC.</u>		
1. OVERBURDEN	a) Soil/hardpan	Variable clay-quartz and feldspar. Often significant calcite. Silica present in hardpan.	X	*	*		*	X	*
	b) Carbonated soil or hardpan	As above but with increasing calcite and montmorillonite	X	*	*	*	X	X	*
2. CALCRETE	a) Calcrete	Variable proportion of carbonates and montmorillonite. Quartz and feldspar minor or absent. Dolomite dominant. Carbonates up to 90% in extreme cases.							
	i) Earthy		X			X	X	*	
	ii) Porcellaneous		*			X	*	*	
	b) Transition calcrete	Retains high carbonate. Calcite important. Increase in quartz and kaolinite	*		*	X	X	*	
3. CLAY-QUARTZ	a) Carbonated clay-quartz	Dominant quartz and kaolinite. Carbonate decreasing - calcite often dominant	*	*	X	*	*	X	
	b) Clay-quartz	Essentially quartz and kaolinite with minor montmorillonite, illite and feldspar. Carbonate absent.	*	*	X			X	*

X = Major constituent

* = Minor constituent

section through the profile may differ in detail from the next. Fig. [4.9] therefore serves merely to illustrate bulk mineralogical composition, and trends from one unit to the next, in a diagrammatic and somewhat idealised way. The principal constituents are quartz, carbonate (dolomite and calcite), clays (montmorillonite, illite and kaolinite) and feldspar; gypsum and celestite may be locally abundant in restricted sections, but are not universally present." (Western Mining Corporation, 1975)

"For convenience, the Clay-Quartz Unit may be used as a reference for the changes through the profile. It consists simply of quartz and kaolin in varying proportions with minor illite, montmorillonite and feldspar. The average of several intersections is 45% kaolin, 33% quartz and with the three other components each about 7%. However, as is suggested by the lithological profile, quartz may be appreciably higher in grit bands and feldspar in the arkose.

"In the Calcrete Unit, quartz and kaolin are virtually eliminated, being replaced by carbonate and montmorillonite in proportions which appear to be reflected in the physical character of the calcrete-- as, for example, a relatively higher montmorillonite content in the earthy variety. The total carbonate content varies within wide limits, commonly averaging about 70% in the porcellaneous calcrete, but in some cases being over 95%. The distinctive feature of the calcrete is the presence of dolomite, which is commonly the dominant carbonate species, or may even be the only one present.

"As may be expected, the transition zones show intermediate characters, with increasing quartz and kaolin as the carbonates decrease, but it appears that there is one important difference. In the Calcrete Unit dolomite is the dominant carbonate whereas in the transition zones calcite becomes increasingly important, even though it may still be present throughout the calcrete.

"The Overburden varies in mineralogical composition with the nature of the surface material.

"Gypsum and celestite may be locally abundant in restricted sections. Gypsum tends to occur in the higher levels of the profile, especially in the Overburden, whereas celestite is more common in the Clay-Quartz Unit, sometimes concentrated into narrow bands of water-clear euhedra." (Cameron, 1976)

Microcrystalline quartz, commonly described as opal, is an almost universal accessory in Western Australian valley calcretes and commonly occurs in horizontal layers. This is not at all surprising in view of the ubiquity of hardpan in soils of the alluvial-aeolian plains, the paleodrainage itself, and even in very recent alluvium.

4.2.1.12 Uranium Mineralization

Carnotite is the only uranium mineral identified by the staff of Western Mining Corporation or reported by any other investigator at Yeelirrie. Thorium is absent. One of the interesting features of the carnotite is the greenish tint common to much of it; in some specimens it is almost olive green. Another is the very common presence of a thin film of microcrystalline quartz. In thin sections of the rich porcellaneous ore (Plate IV-9) the carnotite appears as euhedral to subhedral crystals 0.005 - 0.1 mm in diameter adjacent to carbonate walls of dehydration and solution cracks. The microcrystalline quartz forms a granular to prismatic crust over the carnotite, roughly 0.1 mm thick. It clearly protects the carnotite from dissolution, and it probably inhibits the loss of radon gas.

Cameron (1976) states that:

"The carnotite is clearly one of the last minerals to be deposited, forming a thin film on the walls of voids in the porcellaneous calcrete, dispersed through the earthy calcrete, coating quartz grains in the Clay-Quartz Horizon, and generally coating fracture plains. One of the more striking examples of this last type is carnotite on fault planes. Only minor amounts of clay and silica deposited in the voids of the porcellaneous calcrete are demonstrably later than the carnotite. At one locality, the porcellaneous calcrete has been extensively silicified at the surface; here, the carnotite is evenly dispersed through the silica instead of a surface coating which is the more usual mode of occurrence, but this appears to be a purely local feature.

"The [economic] mineralisation covers an area of approximately 6 km by 0.5 km, elongated parallel to the drainage; it occurs throughout the profile to an average depth of 8 m, but occasionally to 14 m. Though present throughout the profile, the bulk of the carnotite occurs in the carbonated units."

The epigenetic textural relationship of visible carnotite to calcrete is undeniable but may be largely due to remobilization. The balance between solution and precipitation of carnotite in this environment is delicate, and all of the chemical parameters which affect the balance have changed from time to time and from place to place. Present-day textures do not disprove contemporaneity of at least some carnotite and calcrete.

Brown carbonated clay-quartz below the main fully developed calcrete contains a very substantial fraction and quite probably the bulk of the total mineralization. Plate IV-7, showing carnotite on small slickensided surfaces, is from the lower unit. Similar material on the stockpile is

almost uniformly well mineralized. As shown in Figures 4.6 and 4.7, the carbonated clay-quartz unit is subjacent to the calcrete throughout. Earthy calcrete may also be very well mineralized, and carbonated loam above the calcrete may contain a little carnotite as well. Plate IV-8 shows the generalized Bi²¹⁴ gamma-ray response obtained by the writer from three adjacent mounds and surrounding earthy calcrete and carbonated loam, as well as from the soil and the surface above the soil along the southwest side of Slot No. 2. The highest reading (348 cps) is from a single location directly over a mound which does not reach up to the soil profile. Regional background on the sand plain surface outside the zone of mineralization is 1.8 cps on the Bi²¹⁴ channel. An analogous pattern was observed on the northeasterly side of the same slot, and a similar difference between earthy and porcellaneous calcrete was observed along Slot No. 1, except that readings were more variable. The writer does not know to what degree the pattern observed may reflect uranium-to-daughter-product disequilibrium. Cameron (1976) reports that disequilibrium studies have shown that "some samples were out of equilibrium, but it was found that disequilibrium is not a serious problem."

4.2.1.13 Radiometric Response

The following section and the succeeding section, 4.2.1.14 (on "Radon"), are taken in their entirety from Western Mining Corporation (1975).

"An airborne magnetic and radiometric survey of the general area was carried out by the Bureau of Mineral Resources (B.M.R.) in 1968 as part of its systematic regional reconnaissance programme (Gerdes et al. 1970). Recordings with a total count scintillometer were made from a DC3 on flight lines spaced at 1.6 km intervals, and at a mean terrain clearance of 150 m. [Plate IV-3], taken from the map published by the B.M.R., clearly shows the prominent anomaly over the Yeelirrie channel and the ore body in particular.

"The same pattern, though of course in greater detail, was obtained in the follow up ground survey carried out by W.M.C. (Fig. [4.5]), which illustrates the value of the B.M.R. reconnaissance scale flying in this particular environment. In the ground survey a McPhar TV5 integrating spectrometer was used on a 500 x 60 m grid; one minute scalar readings were recorded on three of the four channels--1.30, 1.63 and 2.50 MeV. The ore body is clearly defined on the > 1.63 MeV channel (U + Th) by the x2 background contour, corresponding to approximately 400 cpm. The survey also highlighted the absence of Th in the deposit, a fact confirmed by the limited analyses for Th which were carried out.

"Bore hole γ -logging is now standard practice at Yeelirrie. Several different makes of probe were used, all based on a 1/2" x 1/2", or 1" x 1/2" NaI crystal. Depending on the equipment, the results were obtained in either analogue or digital form and then converted to eU_{3O_8} using a computer programme based on that developed by the U.S.A.E.C. Initially, calibration was achieved simply by comparing logging results with XRF analyses, but this method was superseded by calibration in specially constructed pits. Since the value of γ -logging in grade estimation is dependent on the state of equilibrium, extensive studies were carried out both by comparing the γ -count from a sealed sample with the XRF analysis, and also by measuring the γ -spectrum of selected samples. It was concluded that there are no serious disequilibrium problems; together with the absence of Th, this makes bore hole γ -logging a particularly convenient technique for use in the evaluation stage."

4.2.1.14 Radon

"As an exploration technique, the measurement of Ra^{222} in soil gas is regarded in the industry with varying degrees of confidence and enthusiasm. In the calcrete environment it appeared to be particularly suitable in the search for concealed mineralisation, and an orientation survey was therefore carried out at Yeelirrie to assess its value.

"The instrument used was an Inax (Model 284) detector in combination with an improvised sampling system consisting of metal sampling tube, a small hand pump and a dust filter. The probe was inserted into a 130 cm deep hole drilled by a vehicle mounted auger, the top of the hole sealed with a wooden, conical plug, and approximately 15 litres of soil air pumped through the detector. Although correction for the α -decay of Ra^{220} was made, Th is not a problem in the Yeelirrie environment.

"The radon response over the ore body is pronounced, with readings frequently above x8 background (i.e. 10,000 cpm) over near surface, ore grade mineralisation. In general, drilling substantiated the results, but the anomaly strength could not be related to grade, thickness or depth due to the complexities introduced by the variability of ground conditions and the unknown extent of lateral migration of the radon.

"Though the orientation exercise confirmed the applicability of radon measurement as an exploration technique, it could not be tested to the limits of its capabilities, since the arid climate, poorly consolidated overburden, highly permeable host rocks, shallow mineralisation and large areal extent should offer ideal operating conditions. In the Yeelirrie situation the ore has some surface radiometric expression (Fig. [4.5]) which gives radon no benefit over a faster and cheaper radiometric survey."

4.2.1.15 Mining and Recovery

Handling the large volume of water appears to be the only serious technical problem in mining the orebody. Variable clay content introduces some difficulty in the leaching process, but there do not appear to be sufficient amounts of gypsum or other deleterious agents to cause major problems. The following is taken directly from a brochure on Yeelirrie prepared by Western Mining Corporation.

"Mining Plan: The deposit at Yeelirrie is similar in certain respects to some of the uranium deposits in the United States. The Yeelirrie ore, however, occurs in roughly horizontal but discontinuous layers whereas the U.S. open cut deposits in Wyoming, for example, form into 'roll fronts' which tend to concentrate the ore in discrete areas.

"The maximum depth for mining the Yeelirrie deposit will be about 9 metres and consequently the overburden to ore ratio will be low.

"Because of the manner in which the Yeelirrie deposit occurs, selective mining will be employed to control the grade of the ore extracted.

"Mining Method: It is expected that the mining method to be used will be along the following lines:

"(i) The mining area will be predrilled on a close pattern and radiometrically sampled.

"(ii) Large self-propelled scrapers with pusher bulldozer-rippers will remove the larger barren areas of material. Smaller self-elevating scrapers will remove the waste close to the ore layers. Generally the ground will only need ripping.

"(iii) The ore will be removed with hydraulic excavators used in either the back hoe or front loader configuration.

"(iv) From the pit the ore will be carted to a weighing and radiometric assaying tower to determine the tons carried and the grade of the load. The ore will then be transported to a storage area and dumped into variously graded stockpiles.

"(v) Larger long haul trucks will transport the ore from the stockpiles to the mill.

"PROCESSING - The principal steps to be used in producing yellow cake from Yeelirrie ore are depicted in the flowsheet and are explained in more detail below. The flowsheet shown includes a pre-roast of the ore prior to leaching and is one of three basic flowsheets being investigated at present.

"Crushing: Wet ore received from the pit will be blended to produce the required head grade and air-dried to 12-15% moisture in a stockpile area.

"Ore recovered from the stockpiles will be conveyed to a primary screen fitted with a 19 mm aperture screen. Screen oversize will be crushed in an impact crusher and returned to the primary screen. The -19 mm product will be conveyed to the fine ore bins.

"The fine ore will be extracted from the bins and fed to a rotary kiln drier for moisture elimination, followed by roasting at elevated

temperature to improve the ore settling characteristics. After roasting, the ore will be quenched in a spiral classifier and the sands fed to a rod mill.

"Grinding and Thickening: The grinding circuit will consist of rod and ball mills in series producing a final grind of -48 mesh. The ground pulp will be classified in cyclones and the cyclone overflow at about 25% solids pulp density thickened before feeding to the leaching circuit.

"Leaching: Thickened underflow will be fed to two parallel series of leach autoclaves and leaching carried out at around 50% solids pulp density in the presence of soda ash and caustic soda reagents. Leaching temperatures will be controlled at about 125°C by the addition of steam through heating coils in each leach vessel. Uranium extractions are expected to be in excess of 95%.

"Solid-Liquid Separation: After leaching, the pulp will be cooled in heat exchangers to about 50°C using pre-leach pulp and pregnant liquor as coolants.

"Counter-current washing in thickeners will be used for recovery of soluble uranium and reagent. Make-up liquor will be added at the final thickener and recarbonated barren liquor at the middle thickener. Final thickener underflow will be pumped to the tailings dam.

"Precipitation: Pregnant liquor taken from the first washing thickener will be clarified and heated to 80°C. Precipitation of uranium will be carried out in agitated tanks by the addition of caustic soda, and the resultant slurry thickened and filtered to produce a crude yellow cake. The latter will assay around 70-75% U_3O_8 , 5-6% V_2O_5 , together with smaller amounts of sodium, silica and other impurities.

"Barren solution will be recarbonated with waste gases from the process steam boiler plant and returned to the thickener circuit as wash water.

"Yellow Cake Refining: To remove vanadium, crude yellow cake will be repulped with sodium carbonate and roasted in a multi-hearth furnace. Roaster cake will be cooled, ground and agitated to leach the water soluble sodium vanadate. The slurry will then be filtered and washed for the recovery of low vanadium yellow cake, and the filtrate treated for the recovery of vanadium as red cake.

"For the control of sodium content, yellow cake will be dissolved in sulphuric acid, the solution clarified and then re-precipitated with ammonia. The purified yellow cake will be filtered, washed, dried and calcined in a multi-hearth furnace.

"The calcined product containing in excess of 90% U_3O_8 and meeting all other specifications required for subsequent conversion to natural uranium hexafluoride (UF_6), will be crushed to -6 mm before drumming for final dispatch.

"SAFETY AND HYGIENE - There will not be any health hazards associated with open cut mining operations at Yeelirrie. Hygiene regulations and facilities applicable to the uranium mining industry will be adopted wherever appropriate, in both the mining and processing operations."

Plate IV-9. CARNOTITE IN CALCRETE - WESTERN AUSTRALIA. a) Yeelirrie. Carnotite (black) in porcellaneous calcrete cavity with quartz overgrowth and later clay-carbonate b) Hinkler Well drainage, "young" mound. Anhedral-subhedral carnotite (disseminated crystals) mainly with coarser carbonate in dolomitic carbonated clay. c) North Lake Way "young" mound. Anhedral-euhedral carnotite (dark) in mottled dolomitic carbonate after clay d) North Lake Way, "young" mound. Disseminated to massive carnotite (dark) in mottled dolomitic carbonate after clay

4.2.2

HINKLER WELL DRAINAGE PROSPECTS

(Lat. 26° 50' - 26° 55' S; Long. 120° 05' - 120° 22' E)

4.2.2.1 Location, Distinctive Features, Discovery, and Present Status

The Hinkler Well drainage basin (Plate IV-2) is north of and contiguous with the Yeelirrie basin and, in many ways, a replica of it, though less than one-third as large. Two or possibly three areas along the main calcrete drainage contain some ore-grade uranium mineralization.[†] Of particular interest are several small apparently young or incipient calcrete mounds with strongly anomalous radioactivity in the calcrete delta area where the Hinkler Well drainage enters Lake Way (4.2.2.9 ff below). Three modes of carnotite mineralization are recognized. Important hydrogeochemical data have been supplied by the CSIRO.

The mineralogic occurrences in the main valley calcrete were discovered by ground scintillometry shortly after the announcement of the Yeelirrie discovery and were held in 1976 by Western Mining Corporation (upper drainage) and Carpenteria Exploration Company (lower drainage). The radioactive calcrete mounds in the delta area are of more recent discovery, and in 1976 much of that area was held by ESSO Exploration Company (Australia). No excavations, other than shallow road metal quarries, have been made in the calcrete, but there are some 20 wells and stock bores available for water sampling, and considerable uranium exploration drilling has been done along the calcrete in the last few years. No announcements have been made and no data are available as to grades or quantities of mineralized ground. The properties were inactive in 1976.

Hinkler Well itself is 32 km due south of Wiluna and 48 km northeast of Yeelirrie. The drainage runs 47 km easterly to the midpoint of the westerly shore of Lake Way and is 38 km wide at the widest part. The calcrete body includes 27 km in the axial part of the valley and 4 km of calcrete delta. Because the drainage encompasses many of the characteristics of a uraniferous valley calcrete basin, it has been selected by the CSIRO Division of Mineralogy at Perth as a study area

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[†]The term ore-grade mineralization is used here for reported occurrences in drill holes of a few hundred ppm uranium over large fractions of a meter.

(Mann and Deutscher, 1978). The work is in progress with financial support from Carpentaria Exploration Company. Alan Mann of CSIRO, leader of the research team, and David Crabb of Carpentaria Exploration spent four days in the prospect area in September 1976 with this writer and have made unpublished data available to him.

4.2.2.2 Hinkler Well Catchment Basin, Comparisons with Yeelirrie

Like Yeelirrie, the Hinkler Well basin is a broad, extremely flat valley on the "new plateau" with remnant patches of the "old Plateau" around it and partly filled with sediments internally derived except for airborne materials.

The area of the present catchment upstream from the uppermost occurrence of ore-grade mineralization is about 850 km^2 , less than one-third that of Yeelirrie, and it differs from the Yeelirrie catchment in several respects. The perimeter includes less than 30 km of active, inward-facing breakaway in granitic rock compared with about 180 km at Yeelirrie. Since breakaways on the south and the west shed into the Yeelirrie basin, sand plain extends right up to the rim of the Hinkler basin on those sides (Plate IV-2, cross profile B-B'). It is likely that the Hinkler drainage once extended further south and west prior to breakaway retreat. On the north side of the catchment basin, half of the perimeter is on Wiluna Greenstone Belt capped by Lower Proterozoic basalt and half on granitic rock with low inward facing active breakaways. Quartz veins are strikingly abundant in this latter area. The finger of greenstone at the headwater divide (Plate IV-2) probably impeded growth of the basin in that direction.

4.2.2.3 Relief, Gradients, Narrowing, and Flattening

No vertical survey control is available except for the contiguous contour map provided by Western Mining Corporation and one spot elevation (Mount Lawrence Wells 608 m; east of Mount Wilkinson). Cross profile B-B' was constructed by extrapolation from Wiluna (elevation 510 m) to Lake Way and by assuming a longitudinal gradient in Hinkler Well basin comparable with that of Yeelirrie basin.

As shown on Plate IV-2, the valley narrows in its lower reaches between outcrops of the Wiluna Greenstone Belt, and the long profile flattens in this area, too. Well developed valley calcrete and bodies of uraniferous calcrete begin to appear a few kilometers upstream from the presumed westerly boundary of the greenstone. Relief in the delta area simply reflects the distribution of calcrete, standing 1 to 3 m above present surface drainage lines, and the distribution of sand and gypsiferous dunes.

Again, there is neither evidence of a lake ever being present along the main body of valley calcrete, nor of rejuvenation of the basin.

4.2.2.4 Exposed Bedrock, Comparison with Yeelirrie

The general distribution of bedrock types was mentioned above and is shown on Plate IV-2.

Of a total perimeter of about 70 km, almost one third of the catchment upstream from the first ore-grade mineralization is in greenstone. Only 43% (30 km) of the perimeter is on active inward facing granitic breakaways (compared with 90% on the Yeelirrie catchment), and only some 134 km² of granitic lateritic profile is currently exposed to erosion (16% of the catchment compared with roughly 750 km² at Yeelirrie or 25% of that catchment).

Lateritic duricrust shown by Mabbutt et al. (1963, Maps, Geology) on greenstone and basalt along the northerly and southeasterly rims of the basin formerly extended across much of the drainage accounting for the lateritic sediment beneath some of the valley calcrete (Figure 4.10).

4.2.2.5 Clastic Sediments, Sand Plain, and Lateritic Alluvium

Again, a notable difference between Hinkler Well basin and that of Yeelirrie is the preponderance of sand plain over the entire southern and western flanks of the catchment and the implication that much of the sedimentary fill here has been air-sorted at least. Another is the presence of lateritic alluvium on the north flank of the basin and beneath at least some of the calcrete.

The steeper gradient on the north slope has allowed lateritic and greenstone-rich alluvial fans to extend right down to the calcreted valley axis. Relatively little newly eroded pallid zone or less weathered granite is available from either side.

4.2.2.6 Soils, Comparisons with Yeelirrie

This basin falls within the Wiluna Hardpan region (Figure 4.3), and all of the soils except for the calcrete itself are underlain by the red-brown hardpan just as are those of Yeelirrie. The essential differences are the dominance of red earthy sands over the sand plains of the southern and western flanks of the basin and of more stony earthy loams on sediments derived from the greenstone (Northcote, 1960-1968). All of these are coarse-textured, porous, well drained soils of neutral to acid pH, entirely devoid of soil horizon caliche or kunkar and in these respects fully similar to Yeelirrie.

4.2.2.7 Calcrete Distribution and External Form

Calcrete appears at the surface on the Hinkler Well drainage only 16 km downstream from the present headwater divide which is about half the corresponding distance for the main Yeelirrie drainage (though not less than the distance from Montague Range greenstone to the small body of calcrete in the southerly tributary drainage above the Yeelirrie orebody; Plate IV-2). Except for the delta the exposed calcrete is never wider than the narrower parts of the main Yeelirrie calcrete; about 1.5 km. Assuming an average thickness of about 4 m for the calcrete and up to 50 m for the sedimentary fill in the basin--a guess--the volume of calcrete including the delta would be $\frac{1}{2}$ to 1% of the volume of sedimentary fill, essentially the same proportion as at Yeelirrie.

The calcrete delta flares outward at the shore of Lake Way in response to the flattened gradient but whether the calcrete maintains its thickness or whether it thickens or thins lakeward is not known to this writer. The delta is fringed by a large sand dune as much as 8 m high and tens of meters across. Smaller gypsiferous kopi dunes are common both lakeward and landward.

OLD AND "YOUNG" MOUNDS

a) Karstic topography over valley calcrete mound
Hinkler Well drainage

d) Young mound on lower Hinkler Well drainage delta
Delta margin sand dune in background

b) Mound and collapse structure in valley calcrete
Hinkler Well drainage

e) Young mound on outer fringe of Hinkler Well drainage
delta Lake Way in background

c) Brecciated and recemented calcrete around collapse
Hinkler Well drainage

f) Young mound on newer delta at north Lake Way prospect

Both along the main drainage axis and in the delta portion, the calcrete is readily visible from the air and on air photographs because of the white outcrop, the scattered small clay pans and especially because of the vegetation as along the Yeelirrie channel. The entire calcrete is clearly shown on the maps of Mabbutt et al. (1963 and Plate IV-2 herein).

4.2.2.8 Lithology and Internal Structures of the Main Valley and Deltaic Calcrete: Mature Mounds

Mound structure is very well developed in Hinkler Well calcrete taking two forms: 1) mature mounds, commonly with caverns and collapse structures, in porcellaneous calcrete in the main valley portion and 2) smaller, very low, apparently young or incipient mounds in earthy, muddy--rarely more mature--calcrete around the outer parts of the calcrete delta.

Mature mounds composed of porcellaneous calcrete or dolocrete are very abundant, from a few tens of meters to a few hundred meters in diameter, crudely circular or oblate along the valley, and from one to three meters in relief (Plate IV-10 a, b, c). Collapse structures are usually near the centers of the mounds with cavities up to a meter or more in diameter and up to 1/2 m in depth. Brecciated calcrete around the edges of the cavities is commonly recemented with calcite in the manner of rockhouse caliche, and the cavities are lined with secondary laminar carbonate 1 cm or more thick, attesting to vertical groundwater flow. Some mounds are covered in part with detrital clay pan in which karstic topography has developed. Collapse depressions are apparently major groundwater recharge inlets to the very permeable calcrete aquifer. No detailed data are available to the writer on subsurface lithology or mineralogy.

In general appearance the calcrete is similar to that at Yeelirrie. It is not one homogenous mass but includes lenses and fingers of soil and sediment. The gradational carbonation of soil is seen here at several places, from dispersed and veinlet carbonate to soil peds floating in carbonate and their progressive rounding and apparent

replacement. Much of the mature calcrete has the open fractured-nodular "popcorn" texture as at Yeelirrie, but comparatively large areas are composed of massive buff-colored dolomite, in places brecciated and recemented by a network of fine chalcedonic veinlets. Opal is locally prevalent, seeming to be at greater depth than the chalcedonic veinlets (Mann, personal communication, 1976) and commonly in unmineralized calcrete. In one occurrence within a collapsed mound, however, porcellaneous calcrete with abundant epigenetic opal and cryptocrystalline quartz in layers, vugs, and fractures near the water table 4 - 5 m deep was 5 times background in radiometric response. Laboratory analysis of a specimen at the Bendix Field Engineering Corporation Laboratory in Grand Junction (BFEC) indicated 300 ppm eU and 400 ppm cU. Sepiolite $[\text{Mg}_4(\text{OH})_2\text{Si}_6\text{O}_{15} \cdot \text{H}_2\text{O} + 4\text{H}_2\text{O}]$ has been identified by Mann and was observed as veinlets in mature calcrete in the upper part of the delta.

4.2.2.9 Lithology and Structure of "Young" Mounds on the Fringes of the Delta

Mounds of the second kind, shown to the writer by Mann, are on the outer fringes of the delta. They are only a few tens of meters in diameter, and they stand only a few tens of cm at most above lacustrine and aeolian muds and sands (Plate IV-10 d, e). Typically, they are marked by nothing more than a lighter colored area with less sand or no sand cover and a change in grass or shrubbery. They do not show collapse or karstic topography. More than a dozen of these mounds were seen by the writer. They are essentially at lake level, both landward and lakeward of the large fringing sand dune, but they are all lakeward of the main delta of mature, raised, and largely porcellaneous calcrete. All are decidedly carbonate-rich and the carbonate is predominantly dolomite. Only two of those observed are composed of mature grey calcrete, and in these the carbonate is half dolomite and half calcite with little else. The remainder are medium to dark grey in color and predominantly dolomitized clay and silt. They are from approximately 100 - 1000 m apart, and roughly half of them are notably radioactively anomalous.

Figure 4.10

Sketch cross section through a calcrete mound midway in the valley calcrete of the Hinkler Well Basin. After Carpentaria Exploration Company.

Figure 4.11

Ground Radiometric Traverse in Hinkler Well Basin Calcrete
(800m east of figure above)

D. Carlisle, 1976

The impression that one gets, supported by microtextural relations described below, is that these low mounds around the edges of the delta are in early stages of development. For reasons not yet clear but perhaps dependent upon groundwater circulation or upwelling, these mounds are developing around centers of authigenic carbonate nucleation. Upwelling and consequent evaporation is to be expected where groundwater flowing lakeward through the very permeable valley and deltaic calcrete encounters relatively impermeable lacustrine clays and their more dense saline interstitial waters. Deltaic calcrete, and by analogy valley calcrete, may grow by the development and coalescence of such mound structures. Similar structures occur on the north shore of Lake Way, and these are also predominantly dolomite and radiometrically anomalous as described later.

4.2.2.10 Uranium Mineralization, Radiometrics, and Probable Syngenetic Carnotite

Carnotite, as at Yeelirrie, is the only uranium mineral identified in the calcrete. Gamma-ray spectrometry confirms the absence of thorium in the uraniferous calcrete even though the non-carbonated red sandy soils of the region typically contain roughly 10 ppm eTh along with 6 ppm eU.

Carnotite appears to occur in three recognizable modes: I) as minutely disseminated grains in muddy calcrete of the "young" mounds and deficient in gamma-ray producing daughter products, II) as films of recently deposited bright yellow powdery carnotite deficient in gamma-ray producing daughter products in mature calcrete, and III) as euhedral to anhedral grains within carbonate nodules along fractures and lining cavities, commonly in association with chalcedony, in mature calcrete and in near equilibrium with uranium daughter products. This last is the mode observed at Yeelirrie. Modes II and III are epigenetic to the calcrete as they now stand.

Mode I. Figure 4.12 shows diagrammatically a total count airborne radiometric traverse from the upper delta to the playa of lake way and ground gamma-ray spectrometry in specific areas. The maximum ground response on the most anomalous "young" mound, lakeward of the sand dune

Figure 4.12

RADIOMETRIC SUMMARY LOWER HINKLER WELL DRAINAGE

		Carborne Total Count cps.	Ground Spectrometry	
			Bi ²¹⁴ cps eU ppm	Tl ²⁰⁸ cps eTh ppm
Red sandy and clayey soil over apparently unmineralized calcrete	Valley Calcrete	80 (120-160 rare)	$\frac{1.88}{6.5}$	$\frac{0.97}{10}$
Unmineralized calcrete		80		
Sandy loam		90		
Unmineralized calcrete	Delta Calcrete	80 (70-95)		
Clay pan		110-280		
"Young" mound		320 560 480		
		120-300		
"Young" mound		150 240 160		
Sand dune		80		
		180		
"Young" mound		2980	$\frac{365}{1850}$	$\frac{21.2}{0}$
Salt bush flat Gypsiferous kopi dunes		160 75		
Playa	Playa L. Way	80	$\frac{1.63}{5.5}$	$\frac{0.81}{9}$

which fringes the delta, was 365 cps Bi²¹⁴ or roughly 1850 ppm eU, which is approximately 200 times background in eU. eTh was nil. This mound is roughly 15 m in diameter and composed of muddy, aphanitic, vaguely nodular calcrete, light grey on the weathered surface, brown-grey on the fresh. Visible carnotite is questionably present in rare filmy patches. X-ray diffraction analysis indicates approximately 85% dolomite, the remainder being mainly calcite, clay, and minor quartz. In thin section (Plate IV-9b), clots of carbonated clay with very sparse angular clasts of quartz and feldspar up to 9.4 mm compose almost the entire rock. Irregular veinlets and indistinct zones with more abundant carbonate and with crustiform carbonate transect the clots. Carbonate occupies desiccation cracks and rims quartz clasts and vugs up to 2 mm long. Sparse later quartz fills some vugs. Carnotite occurs as sparse anhedral to euhedral crystals from 0.02 to 0.1 mm long always in association with carbonate as described, the coarser the carbonate the coarser the carnotite. Carnotite grains appear to be most abundant in carbonate-rich areas on the edge of more distinct veinlets between clay clots. No carnotite is enclosed by quartz. Granting the uncertainties of textural interpretation, this paragenesis very strongly suggests contemporaneity of carnotite and authigenic carbonate, mainly dolomite, in a partly developed calcrete. Laboratory analysis (BFEC) of a sample reasonably representative of the richer mineralization on this mound gave the following: 1100 ppm eU, 1200 ppm cU. This analysis is given to illustrate the general nature of the mineralization, and no inferences can be drawn as to continuity beyond or between mounds. The anomalous radioactivity associated with some young mounds is said to extend downward only a meter or two (Crabb, personal communication, 1976), which is to say not far below the water table. On the other hand, within the playa itself one can find small areas of anomalous radioactivity, often associated with increased carbonate or gypsum, in which the radioactivity increases downward several fold over a meter or so below the water table. In one shallow hole a pebble of greenstone with a slight film of carnotite on one surface was found by the writer.

Mode II. Small road quarries in dolomitic porcellaneous calcrete adjacent to the Wiluna-Kalgoorlie highway near the head of the calcrete delta expose carnotite in extremely thin, bright yellow powdery films on fracture surfaces without any suggestion of an opaline coating. . The films do not extend deeply into calcrete nodules nor into interior "dehydration" fractures, and the calcrete does not yield the expectable radiometric response. Field spectrometry on an average-appearing, mineralized flat surface yielded 28 cps Bi²¹⁴, 1.8 cps Tl²⁰⁸ (190 ppm eU; nil eTh). Samples of this same material analyzed at the Bendix Field Engineering Corporation laboratory at Grand Junction (BFEC) were reported to contain 200 ppm eU, 400 ppm cU. Anhedral carnotite grains of mode III carnotite up to 0.15 mm across can also be seen in this section in this material usually at the center of carbonate nodules. Carnotite of mode II is thought to have been deposited more recently than that of mode III, the uranium being either newly derived from sediments or bedrock or remobilized from mode III occurrences updrainage.

Mode III. Mode III is represented by only scattered exposures, though it is probably dominant in the valley calcrete. Excavations are lacking. Figure 4.11 is a north-south ground radiometric traverse by the writer across well mineralized mature valley calcrete some 800 m east of the cross-section on Figure 4.10. The highest response, 149 cps Bi²¹⁴, is roughly 83 times background (1.8 cps Bi²¹⁴ on red earthy sand and clay loam away from mineralized areas in this drainage). Drill data along the line are not available, but high chemical uranium assays up to 800 ppm are reported to correlate with radiometric highs on the surface (Crabb, personal communication, 1976).

4.2.2.11 Hydrology and Groundwater Chemistry

In comparison with Yeelirrie drainage, only a small fraction of the surface water at Hinkler Well basin flows across exposed pediment. Vegetation patterns indicative of large recharge, as described in the section on Yeelirrie hydrology, are almost entirely downslope from the few inward facing breakaways and sediments.

Figure 4.13, with analytical data provided by Mann, shows water wells and bores and, for some of these, the approximate depth to water

Figure 4.13

Hinkler Well Basin

(Analyses from Alan Mann and Rex Deutscher, pers. comm., 1976)

Well or bore   20   Uranium analysis p.p.b.
                   3   Vanadium analysis p.p.b.

(18m)   Approximate depth to water table

////   Uranium mineralization

.....   Calcrete

—   Drainage divide

0   5   10 Km

Explanation same as on Plate IV-2

table in September 1976. Mann (1976 and personal communication) and Mann and Deutscher (1978) have shown that waters in the perimeter of calcrete basins typically contain in the range of 10 - 20 ppb U and 2 - 7 ppb V. Groundwaters in wells draining breakaway slopes can contain up to 50 - 60 ppb U with still less than 10 ppb V and relatively low salinities. The uranium increases down drainage by evaporation to values of 200 - 400 ppb and the vanadium to values of 14 - 50 ppb. Mann (1976) states:

"The site of deposition of carnotite appears to be more closely associated with the amount of vanadium in groundwater [than with exceptionally high uranium concentrations]. . . . Compared to uranium, vanadium is relatively abundant in the country rock and its derived material. Laterite, goethite-rich alluvium, basic rocks and granite all contain more than enough vanadium for precipitation of the uranium as carnotite. However, vanadium's availability to, and distribution in, groundwater appears to be restricted and governed by its adsorption and fixation on goethite and other iron oxides. Vanadium values in groundwaters are usually less than 10 ppb except in cases where the groundwaters are in contact with carnotite, where values of 50 - 60 ppb are found. It is possible that other oxidation states (viz. vanadium (IV)) play, or in the past have played, a part in the desorption of vanadium from iron oxides and its solubility in water. If this were so then the oxidation of vanadium (IV) to vanadium (V) by oxygenation of a groundwater moving closer to the surface could be the 'trigger' to the initial precipitation of carnotite.

Mann has pointed out (25th Int. Geol. Congress, field trip lecture) that the V/U ratio in groundwater reaches the point of stoichiometric proportions in carnotite approximately in that part of the drainage where carnotite is found in calcrete. Below significant carnotite deposits, the V/U increases beyond the point of stoichiometry, an observation which may be in fact a useful exploration tool. Apparently this occurs near Hinkler Well. Potassium and chlorine values increase by roughly an order of magnitude down the main drainage and by more than an order of magnitude at the salt lake margin. HCO_3 content increases two- to three-fold in the upper drainage, then declines slightly and irregularly toward the salt lake.

In situ pH values for groundwaters in the Hinkler Well drainage have not yet been published, but Mann (1974c) has presented a summary of values derived largely from this basin: "Groundwaters in contact with laterites and clays are invariably acidic, with some waters in contact with

laterites having pH's lower than pH = 4.5." He shows groundwater pH's in the lateritic profile and regolith of the breakaways and pediments ranging from pH 4.5 - 7.0. In the calcrete zones "almost without exception" the pH "never falls below pH = 7.0 and is usually in the range pH = 7.0 - 8.5." The same range pH = 7.0 - 8.5 is shown for salt lake brines. Using field probes, Mann (1974a, c, and personal communication, 1977) has determined that the Eh of present-day well waters is fully oxidizing throughout the Hinkler Well Basin, ranging from slightly above 0 to 0.5 volts. He has also shown that this range in Eh straddles the stability field boundary between V(IV) and V(V) in solution at relevant pH values. Vanadium is more soluble in the more reduced state, i.e., V(IV), either as $\text{VO}(\text{OH})^+$ or HV_2O_5^- ion, but is required in the oxidized state V(V), as H_2VO_4^- to induce the precipitation of carnotite. Mann finds that Eh values within the Hinkler Well drainage do suggest that vanadium transported in the V(IV) state at moderate depth has been oxidized to V(V) closer to the surface in proximity to carnotite mineralization.

Flattening and narrowing of the drainage mentioned in 4.2.2.3 above in relationship to the Wiluna Greenstone Belt and well developed valley calcrete may be inferred to have caused groundwater to have moved relatively surfaceward into a more fully oxygenated zone. The mounds within the valley calcrete and on the fringes of the delta imply a still more effective situation if these are, in fact, due to upwelling groundwater.

4.2.3

NORTH LAKE WAY PROSPECTS

(Lat. 26° 42' S, Long. 120° 6' E)

4.2.3.1 Introduction; Discovery

Ore-grade uranium mineralization in calcrete has been discovered in "young" mounds along the north shore of Lake Way near the termination of Uramurdah Creek and in calcrete along the floor of the creek itself (Millbillillie on Plate IV-1) and, just recently, in or beneath an older calcrete delta. The writer examined the prospects on September 8, 1976 in company with Alan Mann of CSIRO and John Allen, resident geologist. Strong similarities with aspects of the Yeelirrie mineralization, on the one hand, and with the mineralized "young" mounds at Hinkler Well delta add interest to the occurrences.

The original discovery was made by Delhi International Oil Corporation as a byproduct of nickel exploration in the early 1970s along the Wiluna Greenstone Belt. Airborne scintillometry had been recorded as a matter of course along with an aeromagnetic survey. Modest radiometric anomalies, given little attention at first, were eventually investigated on the ground, leading to the discovery. Initial down-the-hole percussion drilling on a grid pattern confirmed the mineralization but gave unsatisfactory logs or correlations between radiometric and chemical analyses. Sizeable areas with grades in excess of 0.05% U were indicated with some analyses up to 0.40% U. By the time of examination in September 1976 more than a dozen excavations, as deep as 5 - 6 m, had been made exposing carnotite in calcrete. A more detailed exploration program was in preparation by the company.

4.2.3.2 Location, Geomorphic and Geological Setting, Older and Newer Calcrete Deltas

The prospects are 17 km southwest of Wiluna adjacent to a large, raised, mature calcrete delta which spans the entire north end of Lake Way. This older calcrete delta has been built outward onto Lake Way from major paleodrainages in the north and northwest (Paroo) and is exactly analogous to deltas on Lakes Miranda, Maitland, and many others. Elevated a few meters above the present pan of Lake, this older, rubbly, deltaic

Plate IV-II
North Lake Way

Figure 4.14
Overlay of Plate IV-II
Showing North Lake Way Prospects

calcrete shows some evidence of mounding and some collapse structure, though not so obviously as on the Hinkler drainage. It is moderately dissected by recent drainage courses. Nearly 15 km of airborne radiometric traverse and several ground stations on this delta yielded only background readings (60 - 90 cps total count) on the calcrete surface. Recent drilling through the calcrete, however, has revealed three small areas of ore-grade mineralization (Figure 4.14 westerly occurrences) primarily in calcareous clay.

Paleodrainages leading into this older deltaic calcrete are predominantly on Wiluna Greenstone Belt and Lower Proterozoic rocks. Uramurdah Creek, however, drains 80 km² of Archean granitic gneiss and an equal area of sand plain before encountering the older calcrete delta on the east. It then flows southerly between the east margin of the delta and adjacent sand plain, cutting through a large sand dune to form its own partly calcreted delta at present lake level. This newer delta, it appears, is still in the process of formation. Lobes of variously carbonated gypsiferous silt are actively building southward into the barren playa of Lake Way (Plate IV-11 and Figure 4.14). Valley calcrete, more recent than the older delta but probably a little older than the outer lobes of the Holocene delta, extends an unknown distance up Uramurdah Creek.

The climate, soils, vegetation, and the gradients are essentially identical with those of analogous parts of Yeelirrie, Hinkler Well drainage, and Lake Maitland. Groundwater from a well collared in older calcrete on the west bank of Uramurdah Creek and about 2 km north of the northerly prospect is reported to contain 90 ppb U; another about 3 km further north contained 270 ppb U.

4.2.3.3 Mineralized Younger Valley Calcrete

The northerly prospect (Millibillillie) on Uramurdah Creek is in valley calcrete about 2 km upstream from Lake Way, above the large fringing sand dune and at creek level. Bulldozer cuts to below the water table (about 3 m) have exposed as much as 5 m of light gray transitional calcrete beneath about ½ m of soil and underlain by strongly carbonated dark clay. The transitional calcrete, midway in

its development between earthy and porcellaneous, has a nodular texture around relict clay clots, abundant dehydration fractures, and some visible carnotite.

The strongly carbonated clay facies is megascopically identical in color and texture with material from the "young" mounds described on the Hinkler Well delta. Bright yellow carnotite, without a silica coating, occurs on fracture and slickensided surfaces on this material just as on the carbonated clay below calcrete at Yeelirrie. Concentrations of carnotite were reported to have been seen at the calcrete-clay contact.

X-ray diffraction analysis indicates that both the light gray transitional calcrete and the strongly carbonated clay facies are roughly 50% dolomite, the remainder being clay and minor quartz and feldspar. Thin sections of the carbonated clay facies show sparse anhedral to subhedral carnotite grains up to 0.05 mm associated with zones of slightly more abundant carbonate.

Ground spectrometry measurements on irregular uncompacted material from one cut showed 89 cps Bi^{214} (450 ppm eU) and 24 cps Bi^{214} (120 ppm eU) and nil eTh in the clay-rich and transitional calcrete respectively. Laboratory analysis on the former indicated 400 ppm eU, 300 ppm cU. These analyses are not offered as representative of the mineralization in any way, but merely to illustrate the equilibrium relationships in material left standing in a dump for a few years.

Airborne radiometric anomalies over this prospect area are observed along the lower portion of the creek itself immediately north of the sand dune, including the area of the open cuts just described.

4.2.3.4 Mineralized "Young" Mounds on the Newer Delta

The southerly prospect consists of uraniferous calcrete and carbonated clay exposed in several open cuts on the salt bush flat covering the newer delta immediately lakeward (south) of the large sand dunes (Plate IV-11, Figure 4.14). All of the cuts seen by the writer contain transitional porcellaneous to earthy calcrete, carbonated clay, or both, and all are mineralized with at least some visible carnotite.

As seen on the surface of the delta flats, as exposed in the cuts

and also as described by the resident geologist, the more mature calcrete occurs as roughly circular mounds perhaps 20 - 70 m in diameter, with not more than a few 10s of cm of relief and without collapse structures. The writer observed perhaps a dozen such exposed mounds tens to hundreds of meters apart, continuing right out to the edge of the barren pan of the lake. In every respect, including lithology, they resemble the "young" mounds of the outer Hinkler Well delta. On the wall of one open cut just lakeward of the large sand dune, a transitional porcellaneous calcrete mound can be seen truncating carbonated clay. In this same cut, clusters of sepiolite spheres looking like candied puffed rice occupy voids in the calcrete.

One particularly interesting mound (Plate IV-10f) about 60 m in diameter and about half-way out on the new delta flat is composed of light gray, muddy calcrete and has near its center a lesser mound or blister about 0.7 m in diameter which is partly cavernous and unusually radioactive (200 cps Bi²¹⁴ or roughly 1005 ppm eU, nil eTh by field gamma-ray spectrometry). Laboratory analysis of a sample (BFEC) indicated 900 ppm eU and 900 ppm cU. X-ray diffraction analysis indicated roughly 85% dolomite, the remainder being mainly clay, calcite, and very minor quartz and feldspar. In thin section (Plate IV-9c, d), carbonatization is seen to have progressed far enough to have produced a finely mottled texture in the clay: voids and desiccation cracks make up about 5% of the mass. Around these and a fraction of the 1% or so of angular detrital quartz and feldspar grains, slightly coarser carbonate has formed. Late cryptocrystalline quartz fillings are very sparse. Carnotite occurs 1) as disseminated extremely fine grains less than 0.02 mm and clusters in the more carbonated mottles, 2) as subhedral to anhedral crystals and clusters up to 0.05 mm in the darker, less carbonated matrix, and 3) as irregular to amoeboid massive replacements up to 3 mm across of coarse and fine carbonate and clay. These latter carnotite bodies are clearly visible megascopically on a cut surface. Some carbonate and probably all the cryptocrystalline quartz is later than the carnotite. The writer's impression from the thin section is that much of the carnotite is contemporaneous to penecontemporaneous with the carbonate, which is to say with primary (?) dolomite. In outcrop the blister could well be imagined as an outlet for upwelling groundwater.

Further out on the delta, within 300 m of the barren lake pan, the mound calcrete is dark, strongly carbonated clay with crudely concentric desiccation cracks looking exactly like the "young" mounds at Hinkler Well delta. Carnotite occurs along fractures. Laboratory analyses of a dump sample (336 ppm cU by delayed neutron; 93 and 700 ppm cU by spectrophotometry; 850 and 1200 ppm eU by gamma radiometry) suggest variable mineralization and complex disequilibria. The calcrete here may be only 2 - 3 m thick and thinning lakeward.

Still further south on the gypsiferous rim of the modern delta and within 30 m of the barren lake pan, with the groundwater table at less than 1 m, a mound (?) of well carbonated mud exposed in a trench suggests incipient calcrete. Dolomite, the only carbonate, constitutes about 30% of the material. Nodular texture and desiccation cracks have developed and there are sparse films of carnotite on the cracks. Field gamma-ray spectrometry indicated 35 ppm eU and 7 ppm eTh; delayed neutron analysis--38 ppm eU (eTh not determined). The uranium content is about half as large and the thorium content is about the same as noncarbonated playa mud.

4.2.3.5 Radiometric Response on the Newer Delta

Airborne radiometric response is anomalous over the entire newer delta where mounds occur, diminishing gradually from the inner to the outer edges. A airborne traverse southerly from the large sand dune yielded total counts of 120 - 160 cps between mounds, which is twice the background observed over barren calcrete, and as much as 800 cps over mounds.

The writer is unable to provide information on the presence or lack of mineralization between mounds, but if nothing else, the mounds do provide a ready indication of modern calcrete-uranium mineralization.

4.2.4

LAKE MAITLAND PROSPECT

(Lat. 24° 09' S., Long. 121° 05' E)

4.2.4.1 Introduction

The writer had insufficient time to examine the uranium prospect on Lake Maitland and has had to rely primarily upon unpublished data. These include the abstract of a paper presented by J. Lorimer of ASARCO (Australia) as part of a symposium "Uranium in Australia" in Sydney, February 1973, discussions in September 1976 with Mr. David Crabb of Carpenteria Exploration Company, and quantitative data kindly supplied by Dr. W. N. MacLeod also of Carpenteria Exploration Company who now hold the property. The geological sketch map (Figure 4.15) was compiled from the published Sir Samuel map sheet (Bunting and Williams, 1975) and from the above sources.

The Lake Maitland prospect is considerably different from the Yeelirrie property or from others in valley calcretes because the mineralization of interest is entirely within the present-day salt lake beneath contemporaneous lacustrine saline clay and silt.

4.2.4.2 Location, Geomorphic and Geological Setting, Possible Source Terranes

The deposit is 105 km southeast of Wiluna and on the same calcreted paleodrainage and salt lake system as Lake Way, but some 60 km further along toward the Eucla Basin. The paleodrainage continues below Lake Maitland to Lake Darlot where it is joined by the Yeelirrie paleodrainage in its passage to the southeast.

The climate and the regional geomorphic and geological surroundings are very similar to those at Yeelirrie which is only 120 km to the west. The setting in detail, however, is considerably different. Unlike the Yeelirrie or Hinkler Well occurrences, this deposit is located far below the headwaters of the paleodrainage. Much of the sedimentary host, both the clastic and the chemical components, and the uranium may have traveled for some distance or have been reworked several times. Gradients are extremely low throughout the drainage and especially downstream from Lake Maitland through nearly 40 km of continuing salt lakes. No extensive breakaways developed on granitic lateritic profile are to

be found directly upstream from the occurrence for 100 km or so. In fact, the immediate surroundings and much of the exposed bedrock upstream is predominantly Archean greenstone.

Two tributary drainages immediately west and north, respectively, from Lake Maitland provide potential source areas in granitic rock. One is a broad basin extending for roughly 40 km westerly toward Mount Keith with scattered outcrops of granitic rock around its perimeter. Two isolated thin strips of calcrete (Plate IV-2) have been mapped by Churchward (1976) in this basin. They lead from the granitic terrane toward the Lake Maitland paleodrainage. However, there appear to be only a few kilometers of actively eroding breakaway facing inward around the basin. The size of the catchment is approximately 1000 km², the great bulk of it being sand plain and lesser alluvial plain. It is comparable in size, therefore, with the Hinkler Well drainage, but much less potential bedrock source is exposed to weathering. The other tributary drainage due north of Lake Maitland is roughly similar in size, geomorphic development, and granitic (gneiss) exposure, but has no exposed calcrete within it except on the very edge of Lake Maitland. It does happen to be directly in line with the trend of the mineralized zone of the prospect within the lake (Figure 4.15). Whether either or both of these tributary basins or other areas near or above Lake Way are the principal source regions for the uranium mineralization is not known. In any event, Lake Maitland is near the intersection of all three.

4.2.4.3 Clastic Sediments

The distribution of alluvial, lacustrine, and aeolian sediments at Lake Maitland, considerably simplified on Figure 4.15, is characteristic of Western Australian salt lakes in general. The lacustrine deposits, Q1, on the lake itself and overlying the mineralized zone are composed of clay and silt, variously saline and gypsiferous and without hardpan below the surface. Around the edges of the clay and salt pan, the lacustrine sediments merge with alluvium, calcrete detritus, or with aeolian sand in the so-called samphire flats (Q1a) with their specialized salt and gypsum tolerant vegetation. Kopi dunes (Qd), composed of gypsum and clay, and in part calcareous, have formed around the southeasterly margin. Younger dunes and sheets of white and yellow quartz sand (Qs)

Figure 4.15

Generalized Geology and Mineralization of the LAKE MAITLAND PROSPECT

Geology after Bunting and Williams, 1975; Churchward, 1976

Mineralization data from W N MacLeod,
Carpentaria Exploration Company
Personal Communication July 1977

marginal to the salt lake and the calcrete are generally silty and commonly mixed with alluvium; older quartz sand dunes and sheets of the outlying sand plains are reddish. The two are not differentiated on Figure 4.15; both may develop extensive hardpan in their lower soil profiles.

4.2.4.4 Deltaic Calcrete

An extensive body of well developed massive, nodular calcrete, in part opaline, occupies the paleodrainage for at least 20 km above Lake Maitland and lesser areas on the east side and further downstream below the lake. Examination of Figure 4.15 and Plate IV-2 indicates quite clearly that the larger exposed body of calcrete on the upstream (northwest) side of the lake is a calcrete delta, precisely similar in morphology and origin to those on the northwesterly ends of Lake Miranda and Lake Way except that in this case the delta has substantially usurped the bulk of ancestral Lake Maitland. The surface of the calcrete is undulating. Its present elevation above the salt pan, up to 5 m, is probably in part due to deflation of lacustrine sediments and, in part, perhaps, to their differential compaction.

The calcrete delta is not the host for known uranium mineralization, provides only a background radiometric response (Plate IV-3), and is reported to yield assays of less than 20 ppm uranium throughout. In this respect, also, this delta is similar to the elevated calcrete deltas at Lake Miranda and north Lake Way.

4.2.4.5 Uranium Mineralization

A second kind of calcrete occurs within the lacustrine section but is only encountered in drilling within the main body of the lake. Some 150 auger holes have been drilled on intervals of 50 m on lines 400 m apart following a surface scintillometer survey in which the anomalous areas were outlined. According to Dr. W. N. MacLeod (personal communication, 1977):

" . . . Significant uranium values over 200 ppm occur in an arcuate zone over a known length of about 4000 m and between 100 and 400 m wide. [see Figure 4.15] The deposit is open to the northwest . . . .

The mineralisation appears to be confined to the uppermost 4 m of the lake sediments in a zone between 1 and 2 m thick. Core drilling would be necessary for sharper definition. In the mineralised zone there is a wide variation in uranium values from less than 100 ppm to over 2000 ppm, with the majority in the range of 400 ppm - 1000 ppm.

Uranium values occur in both the upper calcrete layer in the sediments and also in the underlying clay and quartz sand layer. Again much more careful sampling would be required to appreciate the detailed distribution.

Carnotite is the sole uranium mineral recognised. Dolomite is the principal carbonate mineral with accessory quartz, kaolinite and halite. Heavy minerals include goethite, ilmenite, leucoxene and zircon. Strontium occurs in the mineralised zone in values up to 6% but the mineralogical form has not been identified."

Lorimer (1973) refers to "black and brown banded calcrete carrying the uranium mineralization [underlying] the lake sediments and . . . itself underlain by a nodular calcrete and an opaline calcrete with a white carbonate coating." This is reminiscent of the uraniferous calcrete which appears to be forming more or less concurrently at north Lake Way and at the termination of the Hinkler Well drainage. Apparently the darker calcrete is less mature, less well indurated and younger than the underlying calcretes. Although Lorimer indicates a close correlation between radiometric maxima and high uranium assays, he does not say that the uranium is in radiometric equilibrium. Crabb (personal communication, 1976), in fact, reports finding high chemical uranium analyses associated with only slight radiometric highs in the lake sediments above some of the richer mineralization found in the ASARCO drill holes. This, too, is suggestive of relatively recent deposition of uranium.

Another very interesting feature of this prospect is the Y-shaped pattern or trend of the mineralized zone in map view within the lake (Figure 4.15). The fact that this mineralized zone conforms in shape with the nose of the large calcrete delta and is crowded between the delta and the eastern shore of the lake very strongly suggests that the mineralization is more recent than the calcrete delta and, once again, therefore, relatively young. Without further information one cannot assume a flow of groundwater parallel to the mineralization trend as the term "buried channel" might be taken to imply. As suggested below, movement of groundwater, or at least of uranium, perpendicular to the trend is a distinct possibility.

4.2.4.6 Radiometric Response

The total count airborne radiometric response over Lake Maitland is shown in Plate IV-3 (taken from Australia Bureau of Mineral Resources, 1971). The survey was flown in 1967 at an altitude of 150 m above ground level on east-west lines spaced at 1.6 km and is not corrected for topography. The radiometric expression over Lake Maitland is distinctive and noticeably coincident with the known mineralization but is much weaker than that at Yeelirrie.

Ground radiometric survey is said to show a two-fold increase in total gamma-ray response on passing from the calcrete delta onto the fringing samphire flats and the salt lake. On the outer edge of the southeasterly tip of the delta an increase of five- to ten-fold has been reported. On the other hand, as noted above, Crabb has indicated that only a slight increase in response is commonly observed above mineralized drill holes toward the center of the lake.

4.2.4.7 A Very Speculative Genetic Model

Clearly the data are very incomplete, but the purpose of this report justifies some speculative comments on genesis particularly because of the differences between this deposit and those of Yeelirrie and the main Hinkler Well drainage.

The stratigraphy of the calcrete, the geometry in map view, and the apparent geomtery in section suggest that there has been a sequential development of calcretes beginning possibly when the salt lake was only minimally developed. The lowermost, opaline calcrete, may have formed before the paleodrainage became fully choked with sediment. Some time after ancestral Lake Maitland was fully developed, valley calcrete forming in the paleodrainage above the lake began to encroach on the lake itself. Authigenic precipitation of the carbonate may have been accelerated by upward deflection of water in the paleodrainage as it encountered the relatively impermeable clays of the salt lake or dense saline water in the lake sediments. In any event the newly forming calcrete continued to grow downstream and outward into the lake as a delta. Another small fringing delta apparently also formed on the northerly shore of the lake at the termination of the tributary drainage

mentioned above. Without question the lake sediments and their pore waters contained uranium in significant though far from economic concentrations. The calcrete in and upstream from the delta, now constituting the major aquifer of the paleodrainage, brought continuing supplies of water and of uranium farther and farther outward over the buried older sediments. Flow lines would be down-trending from the saturated calcrete delta standing higher than the salt lake pan and then upward toward the evaporative surface within the lake itself. The result would be a continual flushing of uranium from the calcrete delta along with introduction of newly supplied uranium and the growth of new lacustrine calcrete within the zone of upwelling and evaporating waters. Precipitation of carnotite, whether mainly due to immobilization of CO_3^{2-} ion through common-ion precipitation of CaCO_3 , oxidation, or evaporation (Section 4.3.5), would occur in or close to the calcrete. The locus of upwelling and the zone of strongest uranium mineralization would be subparallel to the nose of the delta as it is in fact. Continual dissolution and redeposition of the carnotite with seasonally changing groundwater chemistry would create the apparent epigenetic textural features of the carnotite and would enhance the observed radiometric disequilibrium.

David Crabb (personal communication, 1977) has speculated that the humic material in the southern part of the lake may also be important in this system perhaps as a focus for initial absorption of uranyl ion.

4.2.5

OTHER VALLEY CALCRETE URANIUM OCCURRENCES IN THE SALT LAKE DIVISION

4.2.5.1 Distribution

Forty-five calcrete uranium prospects are shown on Plate IV-1 in addition to those of the areas described above, and there are undoubtedly several more in Western Australia which have not come to the writer's attention.[†] Many of those shown are merely one of several near the area marked, and many have been drilled or reinvestigated more than once. As of the writer's visit in 1976, only Yeelirrie had announced ore reserves. All but one of the forty-five additional prospects are within the Salt Lake Division or Salinaland (i.e., east of the Meckering Line, Figure 4.2 and Section 9.2.6 below) but only in its northerly part. All are within the main valley calcrete region (Figure 4.1), the Wiluna Hardpan region (Figure 4.3), and, interestingly, within the Mulga (Acacia aneura) zone. All are within the region of most extreme and persistent soil water balance deficiency (Figure 4.4) and of erratic late summer precipitation. Potential evaporation exceeds precipitation by twelve- to twenty-fold. The great majority are within the northern half of the Archean Yilgarn Block, though the northernmost prospects are in calcretes resting on and apparently derived from Proterozoic rocks including metasediments and high grade metamorphic and granitic rocks.

The writer had insufficient time to visit these remaining prospects, so the following notes are not based upon personal knowledge but are from a variety of sources, parts of which were confidential and should be so interpreted.

4.2.5.2 Three Rivers Prospect

The Three Rivers prospect on the Middle Branch of the Gascoyne River (Plate IV-1) is only a short distance from the Meckering Line and in a Proterozoic terrane. Reportedly the area is down drainage from "hot" granite, and carnotite has been found in calcrete on outcrop. Airborne

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[†] During preparation of this report for printing, a map and description of 62 prospects within the valley calcrete region has been published by CSIRO (Butt et al., 1977) providing more detail but not changing the regional picture.

anomalies are detectible and ground radiometries show anomalies up to $2\frac{1}{2}$ times background over several hundred meters. Analyses up to 500 ppm U have been obtained, but to date insufficient ore-grade material has been discovered.

4.2.5.3 Rocky Dump Well Prospect

This is one of several prospects on the easterly side of Lake Austin. Calcrete 1 - 9 m below the surface, averaging 5 m thick, occurs in a brackish section of drainage upstream from a possible constriction in granitic bedrock morphology. Mound structure is present. Ground radiometric anomalies and uranium mineralization have been found in calcrete within 1 - 2 m of the surface.

4.2.5.4 Nulyercamer Well Prospect

Fifteen kilometers or so south of Rocky Dump Well extensive valley calcrete 5 - 6 m thick with mound and collapse structure occurs downstream from "hot" granite. It is above the salt lake and in part, at least, over a gneissic bedrock constriction. The sedimentary fill more than 45 m thick may also contain a deeper level of calcrete. Silicified (opaline) calcrete occurs in an extensive anomalous zone 1 - 2 m thick near the water table which is generally less than 5 m deep. Uranium-low disequilibrium in some of the mineralization is indicative of leaching after carnotite precipitation.

A point source airborne radiometric anomaly is shown in this vicinity on the maps of Gerdes et al. (1970), and two more in the area of a separate prospect south of Nulyercamer Well.

4.2.2.5 Limekiln Well Prospect

Limekiln Well is near the southwesterly tip of Lake Mason 195 km southwest of Yeelirrie. Paleodrainage from Archean granite to the west has given rise to deltaic and lake-margin calcrete in brackish sediments and now partly covered by sand. Anomalous radioactivity has been investigated, including areas of clay lakeward of the delta.

An airborne radiometric anomaly of restricted source is shown here on the map of Gerdes et al. (1970).

4.2.5.6 Depot Springs--Munjeroo

These areas are 120 - 150 km down the paleodrainage from Limekiln Well and well below Lake Mason. Valley calcrete up to 3 km wide is exposed along some 60 km of narrow north-south paleodrainage easterly of the Booylgoo greenstone belt. At Munjeroo a calcrete delta has been built southerly into a large east-westerly salt lake system which itself has several carnotite-calcrete prospects along it (Yuinmery, Bulga Downs, Moomong Well). There is no well marked present-day drainage in the lower half of this stretch, but lateral gradients from granitic breakaways on the east and greenstone on the west are steep enough to bring alluvial fans--and presumably relatively low salinity water--right down to the calcreted paleodrainage. Lateritic profile in the granitic rocks and hardpan in the soils are developed as at Yeelirrie and throughout this region. The massive valley calcrete is also similar with cavernous and karstic topography and with opaline silica near the water table. Earthy calcrete observed by the writer near Depot Springs along the margin of the main body was texturally and compositionally indistinguishable from many soil-horizon caliches or kankars. Waterworn calcrete pebbles and cobbles are reported from carbonated clay and sand beneath the calcrete, which is unusual to the writer's knowledge, but it does point up the possibility of calcrete formation under a different climate and the reality of calcrete and carnotite dissolution in these occurrences. Some groundwaters here are strongly anomalous in uranium, others are not. Traces of carnotite have been found at various levels in the calcrete, including the opaline silica zone and also in underlying or interlayered alluvium.

Radiometric maps directly over the prospects were not available to the writer. Those that are available beginning at latitude 28, less than 10 km to the north (Gerdes et al., 1970 and Sir Samuel SW Total Magnetic Intensity and Radioactivity sheet G51/B1-22-3) show no recognizable anomaly along the entire paleodrainage. Lake Mason, which shows a radiometric low, was filled with water at the time of the survey in 1968.

4.2.5.7 Lake Barlee, Gum Well, Segies Well, and Vicinity

At least a half-dozen calcrete uranium prospects have been investigated along the Lake Barlee-Lake Raeside paleodrainage. Gum Well and Segies Well are about midway in the trend. Valley calcrete as well as deltaic and lake-margin calcrete has formed in areas of very low gradient, both upstream from probable bedrock constrictions and from relatively less permeable and/or hypersaline lacustrine clays. Archean granitic rocks in the catchment basins are reported to contain 8 - 11 ppm uranium. Anomalous radioactivity and significant carnotite mineralization have been found in some places.

4.2.5.8 Thatcher Soak

Thatcher Soak is near Yamarna, an area in which unverified tyuyamunite has been reported as occurring as a dissemination in calcrete (Ryan, 1977). It is on a paleodrainage near the southeasterly edge of the main region of valley calcretes as shown on Figure 4.1. The following note appeared in the February 1977 issue of Mining Magazine:

"Wattle Gully Gold Mines has announced indicated reserves of 2.75 million tonnes of uranium ore averaging 1.6 lb/tonne at its Thatchers Soak uranium prospect in Western Australia. This announcement followed a preliminary report by the company's consulting geologist.

Following a request for clarification from the Melbourne Stock Exchange, the company stated that 33 holes were drilled, to almost 10 m, with mineralisation encountered in 3 - 4 m of calcrete above clay."

4.2.5.9 Some Other Prospects Associated with Airborne Radioactive Anomalies

Several of the remaining prospects shown on Plate IV-1 are associated with airborne total count radiometric anomalies shown on the maps of Gerdes et al. (1970) or on the Total Magnetic Intensity and Radioactivity maps prepared by the Australian Bureau of Mineral Resources (Plate IV-3), though none are nearly so distinct nor as large as the Yeelirrie anomaly.

Noteworthy among these is Nowthanna Hill, mentioned in connection with the history of Western Mining Corporation's discovery of Yeelirrie, and the site of a strong anomaly over uraniferous calcrete. Another

smaller anomaly and a point source anomaly are shown in the vicinity of the Yarrabubba prospects just to the south. A north-southerly trending moderate anomaly and a string of point sources are shown slightly further to the south over the prospects labeled Cogla Downs.

A weak anomaly is shown 12 km southeast of Yeelirrie Homestead on the calcrete delta of the small salt lake in the area reported to have provided the first discovery of carnotite in calcrete, and a somewhat larger anomaly is shown at the Boundary Well prospect on Lake Darlot. To the south of Yeelirrie, a conspicuous anomaly is shown at the Yuinmery prospects and a lesser one at Bulga Downs.

Airborne radiometric maps are not available to the writer for prospects not mentioned in the above discussion, but, taking the records of Yeelirrie, Lake Maitland, and north Lake Way into account as well, the discovery of carnotite-calcrete deposits in Western Australia appears to have been heavily dependent upon airborne radiometric surveys.

Distinct radiometric anomalies are also commonly associated with breakaways where regolith and sometimes kaolinitic granite have been stripped away. These are quite noticeable around the Yeelirrie drainage. Ground radiometrics combined with sample analysis suggests that uranium is appreciably leached from these areas and that thorium is in part responsible for the recorded total count anomalies. It is interesting that Gerdes et al. (1970) noted the commonly anomalous character of salt lakes--actually salt lake margins with associated calcrete--giving the Nowthanna Hill area as an example and repeating an earlier suggestion that the anomalies may be caused by K^{40} in the salt.

4.2.5.10 Carnotite in Soil Horizon Caliche (Kunkar) at Lake Moore

Although not unique (see also Section 7.0 herein on the southwestern United States), it is worth recording that carnotite has been found in soil profile caliche or kunkar as opposed to valley calcrete. An occurrence reported to the writer by Eric Cameron of Western Mining Corporation near Mourubra Homestead at Lake Moore and 50 km or more south of the valley calcrete region is marked on Plate IV-1.

4.2.6 DISSECTED VALLEY CALCRETES IN THE NORTHWEST

As can be seen on Figure 4.2, the main area of valley calcretes is split into two parts by the Meckering Line, the limit to which present-day coastal streams have eroded headward into the old and the new plateau of the Salt Lake Province. Calcretes to the east of the line occupy alluvium-choked paleodrainages and salt lake margins with their primary morphology essentially intact or at least with very little dissection, whereas valley calcretes west of the Meckering Line have been eroded and dissected by coastal streams. Their remnants are left as perched terraces as much as 10 m above present drainages of the Ashburton, the Gascoyne, and parts of other river systems of the northwest. Today those streams, though intermittent, run in deeper valleys on sandy alluvium or bedrock without development of valley calcrete in the main channels.

Elevation of the old permeable valley calcretes has subjected them to groundwater flushing and removal of uranium, much as appears to have been the case with older calcrete deltas in the Yeelirrie-Lake Way-Lake Maitland region. Nevertheless, carnotite has been reported in calcrete terraces west of the Meckering Line as far north as the Pilbara Block. The Mooloo Downs prospect on the Gascoyne River (Plate IV-1) is one such occurrence. To the writer's knowledge no economically viable calcrete uranium deposit has yet been found in this region.

4.2.7

OTHER URANIFEROUS CALCRETES IN AUSTRALIA

The valley calcrete distribution map (Figure 4.1) following Sanders (1973) shows two areas in easternmost Western Australia extending into South Australia and the Northern Territory respectively. Little is known about these areas, and the soils maps (Northcote, 1960-1968; Northcote et al., 1975) do not distinguish between calcrete and kunkar. Notes accompanying the maps, however, indicate the occurrence of "rubbly calcrete mounds," "stoney calcrete rises," and "platforms" in association with soil units in these regions. Northcote (personal communication, 1976) had brought these to the writer's attention, indicating that they are not uncommon in these areas, though covered in part with sand. Although a complete valley calcrete is never seen, he reports that the mounds do seem, in places, to conform with the drainage pattern or with vestiges of old drainages and that the occurrence of acacia might suggest the presence of dolomite below.

At least one calcrete area on a paleodrainage is said to have been drilled in western South Australia confirming the presence of uranium but apparently not in economic amounts. No details are available to the writer.

In the Northern Territory more than one valley calcrete has been prospected and drilled. An occurrence at Woola Downs north of Alice Springs is the subject of a final report filed with the Mines Department in compliance with regulations upon termination of an exploration license (O'Sullivan, 1973). Percussion and rotary drilling, following geological, carborne, and airborne surveys outlines an arcuate or sub-linear, irregular channel-like calcrete body conforming closely with Precambrian basement morphology. According to the report,

"Basement in the area consists of largely undifferentiated granites and gneisses . . . unconformably overlain by arenites . . . outcropping discontinuously along the northern edge of the Tea Tree Basin. The northern boundary of the Woola Downs calcrete virtually overlaps a large sub-crop of granite-gneiss. A Tertiary laterite profile developed on some of those older rocks is preserved in places. [The calcrete ranges from 8 - 14 km wide, 6 - 14 m thick in the main portions but thins westward on basement and eastward to an extended feather edge.] Surface calcrete horizons tend to be pink, impure and terrigenous, containing abundant grains of subangular iron-stained plutonic quartz together with scattered opaque (Fe)

grains and considerable silt. In depth the typically well developed calcrete is buff-white, compact, fairly pure with variable quantities of clear subangular quartz grains. Fine, pink calcareous silt veining with contained iron-stained quartz is common, as are larger solution cavities; smaller cavities (desiccation cracks?) are often replete with clear silica. Silicification increases downwards sometimes leading to the development of a distinct and discrete basal zone of major silicification. Profiles with such major silicification occur in the axial (thicker) calcrete area, probably a more mature and further development of the thinner calcareous profiles whereby incipient silicification in depth becomes dominant silicification in depth, finding expression in clear or milky chalcedony, opaline silica, and very occasionally in bottle green silica. Irregular silt-filled cavities are common, and remaining carbonate is of a massive variety."

The thick axial zone contains minor uranium enrichment. No visible uranium minerals were found within the calcrete or the underlying sediments. Chemical background in the calcrete is 1 - 3 ppm U. Analyses of 11 - 23 ppm U over 1 - 20 m are reported mainly from the zone of major silicification near the base of the calcrete approximately coincident with the current standing water table. Radiometric and chemical analyses were not in linear relationship.

Climadiagram for Wiluna

(From Australian Bureau of Meteorology, raw data)

* Evaporation data extrapolated from Meekatharra

Fig. 4.16) Mean monthly values for pan evaporation, temperature, and precipitation are plotted. Climadiagrams such as this were used for determination of seasonal rainfall dominance.

4.3 GENETIC CONTROLS OF CALCRETE URANIUM MINERALIZATION IN WESTERN AUSTRALIA

4.3.1 Climate and Inferred Soil Moisture Regimes

Of the hypotheses that have been suggested to explain the contrasting distribution of nonuraniferous pedogenic and uraniferous nonpedogenic calcretes (Section 4.1.4 ff) in Western Australia, the most likely rest either directly or indirectly on climate. Against this it may be contended that calcretes were formed under a climate different from that of today. This is almost certainly true, as was reasoned in Section 4.1.5 above. However, the pattern of climate, and specifically the existence of a large arid continental interior and a more humid coast, probably has not changed since the full separation of Australia from India and Antarctica. The size of the arid interior has merely enlarged and contracted through time leaving the Yeelirrie-Wiluna area always at the most arid center. Moreover, as contended earlier, valley, deltaic, and lacustrine calcretes are unquestionably no older than Pleistocene, most probably Late Pleistocene (< 25,000 B.P.), and some deltaic and lacustrine calcretes are apparently forming today. Valley calcretes are probably still undergoing dissolution and reprecipitation downdrainage. The same may be said for carnotite.

The pattern of present climate in Western Australia and several climatic features which are thought to be particularly relevant to calcrete genesis are shown on Figures 4.4, 4.16, 4.17, 4.18, and 4.19). Contrasts between climate and several related features south and north of the Menzies Line are summarized in Table 4.3.

The principal impact of climate on calcrete genesis is through the soil moisture regime, including vadose and groundwater (Figure 3.3), and indirectly through plants and micro-organisms. As precisely defined in U.S. soils terminology (Soil Survey Staff, 1975), the soil moisture regime "refers to the presence or absence either of groundwater or of water held at a tension < 15 bars in the soil or in specific horizons [within the soil moisture zone] by periods of the year. Water held at a tension of 15 bars or more is not available to keep most mesophytic plants alive."

VEGETATION IN RELATION TO CALCRETE

a) Phreatophyte *Eucalyptus camaldulensis* on margin of deltaic calcrete Hinkler Well drainage

d) Mulga (*Acacia aneura*) trees in a valley calcrete region

b) Melaleuca tree characteristic of some valley calcrete margins

e) Mulga (*Acacia aneura*) brush with spinifex grass in valley calcrete region

c) *Causuarina crestatata* (buloke) a characteristic phreatophyte commonly restricted to valley calcrete

f) Mallee habit of *Eucalyptus* growth south of Menzies Line

Some Contrasts between Uraniferous and Nonuraniferous
Regions on the Yilgarn Block

Generally south of the <u>Menzies Line</u>	Generally north of the <u>Menzies Line</u>
CALCRETE: Pedogenic calcrete, soil-horizon carbonates, caliche, kunkar. Nonuraniferous.	Nonpedogenic, valley, deltaic, lacustrine calcrete. Locally with carnotite.
CLIMATE: Rainfall, annual (P_a): 200 - 500 mm (over 1000 mm in southwest). Relatively consistent pattern of predominantly winter rainfall from anti-cyclonic frontal rains or indefinite rain season.	170 - 250 mm. Highly variable and episodic summer to fall rains from local thunderstorms, sporadic tropical cyclones and occasional frontal showers. (Figure 4.17a,b; 4.19d)
Potential Evaporation, annual (E_a): < 3300 mm	3300 - 4200 mm (Figure 4.17c)
Ratio E_a/P_a : < 6 - 16	12 - 20
Water Balance $E_a - P_a$: < 3000 mm	> 3000 mm (Figure 4.18)
Temperature, mean annual: < 19°C	> 19°C (Figure 4.17d)
SOIL MOISTURE REGIME: Aridic to Xeric Moderate to low drought incidence.	Strongly aridic and distinctive ("Wiluna type," Figure 4.4; 4.16, and text). Moderate to severe drought incidence (Figure 4.19c).
SOILS: Alkaline calcareous grey, brown, and red earths (calcareous aridisols, U.S.) are common. Neutral, alkaline, and acidic soils in more humid southwest.	Acidic earthy loams with Wiluna Hardpan, a red-brown siliceous hardpan (duripan, U.S.), are ubiquitous. Calcareous only on or near calcrete.
VEGETATION (Plate IV-12): Mallee habit of eucalyptus dominates plant communities.	Mulga (<i>Acacia aneura</i>) dominates plant communities
GROUNDWATER: Extensively saline and nonpotable in wells or bores.	Good potable water high on the drainages in alluvium and some calcrete. Saline downdrainage.

The general nature of a soil moisture regime can be estimated roughly from the kinds of climadiagrams shown on Figures 4.4 and 4.16. If the capacity of the soil to hold water is also known, the periods of water surplus, utilization (by plants), deficit, and recharge can be inferred and added to the diagram. The fundamental concept and first step in estimating soil moisture regime from climate, therefore, is to make a simple arithmetic comparison of average monthly precipitation and average monthly potential evapotranspiration. One seldom has the requisite field water capacity measurements for soils over a large area to determine the exact onset of soil moisture deficit or surplus, and certainly we do not for Western Australia. But even without this data the climadiagrams are nevertheless usefully indicative of the general soil moisture regime. Specific classes of soil moisture regimes are precisely defined by the Soil Survey Staff and illustrated by distinctive climadiagram patterns. The patterns shown on Figure 4.4 are very comparable with examples presented by the Soil Survey Staff for Xeric, Aridic, and Ustic regimes, the three major classes which we have inferred for Western Australia. From south to north these are:

- 1) Inferred Xeric--characteristic of a Mediterranean climate where winters are moist and cool and summers are warm and dry. The moisture coming in winter when potential evapotranspiration is at a minimum, is particularly effective for leaching.

- 2) Inferred Aridic--characteristic of an arid climate, less commonly semiarid. The soils are hot and dry on average or never moist for long periods. Potential evaporation and temperature are usually high during rainy periods.

- 3) Inferred Ustic--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.

The climadiagrams shown on Figure 4.4 have been prepared by straightforward plotting of raw meteorological data (precipitation and evaporation from standard, class A, evaporation pans) supplied by the Australian Bureau of Meteorology and using the same format as the Soil Survey Staff (1975). We have then developed a subdivision of the three major

regimes by using additional criteria which we believe to be significant to calcrete genesis.

The first criterion, pointed out to the writer by CSIRO geologists and probably the most important, is the intensity, variability, and seasonal distribution of rain (Figure 4.17a,b). The boundary of interest separates the area of distinct summer-to-autumn episodic rain which characterizes the valley calcrete region (Aridic Wiluna, A_w on Figure 4.4) from the region of indeterminate rain season (Aridic Kalgoorlie, A_k). It closely approximates the Menzies Line. It is, in fact, a consequence of the interplay of the main rain-bearing factors shown on Figure 4.17a and corresponds with several other climate-related variables illustrated on Figures 4.18 and 4.19. The second criterion is derived from a comparison of ratios and arithmetic differences between annual evaporation and annual precipitation as shown on the caption to Figure 4.4. This criterion reaffirms the boundary between A_w and A_k and further outlines the approximate westerly and northerly boundaries of the valley calcrete region delineating a third aridic subregime, A_n , in the area including Nullagine. The last criterion is based upon the fact that the loss of water from a desiccating soil is not simply an arithmetic function of the potential evaporation as determined on standard meteorological evaporation pans, but is a complex function of the soil properties and especially of the dryness of the soil. It has been suggested (Prescott, 1949) that the rate of evapotranspiration from an agricultural soil may be approximated by an exponential function of the form E^m , where E is the monthly pan evaporation rate and m is dependent upon soil type and crop. In the absence of an empirical or theoretical model specific to calcretes, but noting that the top 10 cm of soil tend to lose a fifth to one-half the moisture which evaporates from a free water surface over the time between wetting by rain and drying (Trumble, 1948), we have arbitrarily selected the term $E^{0.75}$ to make additional comparisons with monthly precipitation, to define further the limits of the aridic regime, and to subdivide the Xeric and Ustic zones as shown on the caption to Figure 4.4. The nine examples of climadiagrams shown on the figure have been selected from 60 plots as most representative of the regimes.

Figure 4.17 Western Australia, Main Climatic Factors

a) These factors explain the low and extremely variable rainfall of the interior. Frontal rains tend to be long duration and low intensity, but are rare and extremely weak in the valley calcrete region. Monsoonal rains occur as localized high intensity, short duration falls. Tropical cyclones bring extremely high intensity rains but occur infrequently in the interior in late summer and fall. Local convectional storms occur in the interior during the summer.

b) Seasonal maxima represent the center of rainfall peaks of 3 months or greater on climadiagrams. The month of maximum rainfall has highest mean rainfall irrespective of position within the year.

c) Evaporation from the free water surface of an evaporation pan probably represents an upper limit of evaporation from the soil (see Prescott, 1949; Prescott et al., 1952). Evaporation rates vary significantly within the year (see Figure 4.16) but much less between years.

d) The high mean values and simple zonal distribution of values reflect the low latitude, year-round warm offshore waters, and subdued topography.

Figure 4.18 Western Australia, Water Balance

a) The average annual water balance defined as the arithmetic difference between evaporation and precipitation ($E_a - P_a$) suggests the annual net flux of water through the soil moisture zone.

b) Periods during which precipitation (P) exceeds evaporation (E) allow recharge of soil moisture. The function $E^{0.75}$ is used to reflect the fact that soil evaporation is less than pan evaporation (see text). Under either model, interior Western Australia is an area of perennial water deficit based upon mean monthly data. Plots of daily data would reveal short-term surpluses.

c) & d) Mean pan evaporation minus near precipitation ($E - P$) suggests a water balance deficit much greater than that computed using $E^{0.75}$ as a model for soil evaporation. The nonparallelism of the contours is the expression of the fact that the exponential function $E^{0.75}$ reduces higher values proportionally more than low values.

c) Summer Water Balance/January
An area of net surplus under both models exists in the monsoonal north-east, while the interior experiences extreme deficit due to extreme evaporation rates (see Figure 4.16).

d) Autumn Water Balance/March
The diminution of monsoonal rains is evident while the interior is receiving its peak rainfall during a period of decreasing evaporation.

Figure 4.19 Climate Classification, Drought and Rainfall Variability

b) The length of the pastoral growing season is an actualistic measure of soil moisture regime. The season in the Yeelirrie area begins in February or March indicating that sufficient moisture exists in at least the uppermost portions of the soil to allow grasses to grow but lasts for only 10 - 12 weeks.

c) The ratio of the range of the lower half of the distribution of annual rainfall totals (50th percentile minus 10th percentile) to the 30th percentile value is suggested as an indicator of agricultural drought incidence by D. Gaffney (1975). High values for this index reflect inherent variability of rainfall, non-gaussian rainfall total distribution, and the rainfall totals involved.

d) The ratio of the range of annual rainfall totals (90th percentile minus 10th percentile) to the 50th percentile presented here tends to emphasize variability of low rainfall areas. Additional indices of variability, developed by the writer such as the ratio of the range of mean monthly rainfall in the three maximum rainfall months to the largest mean, the ratio of the maximum recorded 24-hour fall to the annual total, and the probability of a dry month during the three wettest months, reinforce the variability shown here. Data required to generate detailed distributions of these factors were not available to the writer.

It is our contention that the soil moisture regime is useful in predicting the occurrence and the characteristics of calcretes because it is, in fact, a representation of the conditions existing at various times of the year within the zones of potential carbonate deposition (Section 3.3 above). It is indicative of the rate of leaching and illuviation, on the one hand, and of evaporation and loss of CO_2 , on the other. The congruence of the area of the A_w soil moisture regime with the region of valley calcretes is a rather remarkable confirmation of that contention.

The empirical correlation between soil moisture sub-regimes and the occurrence of pedogenic and nonpedogenic calcretes does not in itself explain their distribution, however. The lack of carbonate horizons in soils of the valley calcrete region suggests that something more complicated than excessive rates of evaporation and CO_2 loss is involved in their genesis. The regional congruity of occurrence of siliceous hardpan and valley calcretes underscores the problem and is considered next.

4.3.2 The Wiluna Hardpan

In Australia, "hardpan"[†] refers both to a soil horizon which may be relict or forming currently and also to massive bodies of soil, colluvium, and alluvium up to 15 m thick which are strongly and pervasively cemented and replaced by opaline or chalcedonic silica (Teakle, 1936, 1950; Stephens, 1956; Litchfield and Mabbutt, 1962; Mabbutt *et al.*, 1963; Brewer *et al.*, 1972; Bettenay and Churchward, 1974; Northcote *et al.*, 1975).

The coincidence of soils containing or underlain by hardpan and the

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[†]Hardpan as a soil horizon is equivalent to "duripan" in U.S. soils terminology (Soil Survey Staff, 1975, p. 41). Ferruginous and minor calcareous cements are commonly present. Silicification in a true hardpan is strong enough that dry fragments from some parts of it do not slake in water or HCl. Much of the cement is insoluble in HCl but is soluble in KOH, other strong base, or alternating acid and base. Opal or chalcedony is commonly visible. In the United States, duripans are known to form in both arid and Mediterranean climates. Thus, they are not uncommon in the northern San Joaquin Valley and parts of Southern California, for example, as well as parts of Arizona and Nevada. The Soil Survey Staff believes that duripans are restricted largely to areas of volcanism or former volcanism, and that ash has been the principal source of silica.

main region of valley calcretes (Bettenay and Churchward, 1974; Figures 4.1, 4.3) is truly impressive. Recent mapping near the Western Australia - South Australia border has revealed hardpan in that area of nonpedogenic calcrete also (Firman, 1976). Except for small areas in north central South Australia, southwest Queensland, and far west New South Wales, these are the only known occurrences of hardpan in all of Australia. Bettenay and Churchward (1974) have formerly proposed the name Wiluna Hardpan for the occurrences in the main region of valley calcrete.

In Australia, hardpan occurs only in the most arid zones. Its silica is unquestionably derived from the lateritic profile through groundwater transport or indirectly through lateritic detritus and soil. Where well developed the hardpan has a hard, brittle, rocklike consistency and displays laminae 2 - 30 cm thick, only poorly developed secondary cleavage, and irregular vertical partings containing chalcedonic silica or rare carbonate (Bettenay and Churchward, 1974). Normally it contains a sandy to gritty skeletal fraction and a finer-grained groundmass and, in places, includes fluvial sands and gravels as well as soils. It is "very pervious when wet" (Sanders, 1972). Hardpan occurs almost universally beneath alluvial plains and sand plains of the New Plateau down to valley axes where it may alternate with or give way to calcrete. It commonly forms in residual soils on lower pediment slopes but tends not to occur on poorly drained saline flats nor on strongly lateritic upper surfaces of the Old Plateau. The depth to hardpan on alluvial plains is typically 0.1 - 0.8 m in open areas but increases to as much as 1.5 m in the areas of strong surface water recharge (Litchfield and Mabbutt, 1962, see "R" on key to Plate IV-5). In other places, the upper limit of hardpan may be determined by texture-permeability changes brought about by coarser layers in the soil in the same way that pedogenic and nonpedogenic calcretes are at times delimited.

Soils above the hardpan are porous earthy loams which are freely permeable and well drained (Yeelirrie, Section 4.2.1.6). They are nonsaline, acidic, and low in organic matter and in base exchange capacity. They are unique to the valley calcrete region (Figure 4.3), and they contrast markedly with the commonly alkaline, commonly carbonate-rich,

sometimes saturated soils of southern and west central Western Australia outside that region. Both Wiluna Hardpan and valley calcrete overlie laterite, postdating incision of the Old Plateau and Late Tertiary arid alluviation. West of the Meckering Line both calcrete and hardpan occupy dissected terrace remnants, the calcrete occurring along old drainage axes flanked by hardpan. Hardpan is also found in soils formed on the youngest alluvial deposits and almost certainly continues to form today.

Microscopic studies (Litchfield and Mabbutt, 1962; Brewer et al., 1972) and geomorphic and stratigraphic relations (Teakle, 1936, 1950; Bettenay and Churchward, 1974) show that the Wiluna Hardpan has formed through the alternate illuviation of clay and deposition of silica cement. The facts that it is generated in a near-surface soil horizon and that it lies at a greater depth beneath areas of surface water recharge indicate that evaporation must be an essential factor in precipitation of the silica.

4.3.3   Genetic Connections between Wiluna Hardpan, Valley Calcrete, and Carnotite Mineralization

The writer suggests that Wiluna Hardpan, valley calcrete, and carnotite mineralization are related genetically in Western Australia.

North of the Menzies Line 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 of the runoff from pediments encounters recharge areas on upper alluvial plains and infiltrates deeply enough to be more or less safe from evaporation and loss of CO₂. A fraction of the rain infiltrates rapidly into fractured and permeable mottled or pallid zone rocks on the breakaways and pediments. Some sinks into open-textured earthy loams above the hardpan. The permeability of hardpan is apparently sufficient when wet to facilitate downward movement of the water and the fact that soil surface temperatures are at a maximum in summer and appreciably higher than at depth results in downward transport of soil water vapor as well (Schoeller, 1959).

In summary, 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 carbonate by CO_2 loss prior to evaporative 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. As observed in the field, the soils are nonsaline and nonalkaline, and water which reaches the groundwater zone tends to be potable, at least high on the valley flanks.

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 sulfate, phosphate, hydroxyl, neutral carbonate or, if pH rises, dicarbonate or tricarbonate complexes, is free to migrate with groundwater toward the calcreted valley axis.

We may conclude that the entire succession of secondary deposits from siliceous hardpan on the valley flanks to calcrete in the axes of the valleys and gypsum and halite on the shores and flats of salt lakes is a consequence of evaporative concentration, and in the case of calcrete, loss of CO_2 from a flowing reservoir of sub-surface water.

The question is why this same arrangement does not prevail south of the Menzies Line where salt lakes, lateritic profiles rich in clay and silica, and climates arid enough for the development of pedogenic soil-horizon calcretes are also found. The answer, according to the writer, is that in that area the evaporative sequence is developed in large part within the soil itself, specifically in the soil moisture zone. South of the Menzies Line, 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 salts within the soil. The rain tends to be more persistent, and the soil is wet or actually at field capacity over long periods. Even between rains, since surface temperatures are lower or no higher than sub-soil temperatures, there is no tendency for water vapor to migrate downward, but rather upward in the direction of increasing soil moisture tension.

P_{CO_2} is comparatively high in the organic soil moisture zone but decreases toward the surface and between rains. As a consequence, calcium carbonate tends to precipitate directly in the soil primarily by loss of CO_2 . As calcium carbonate precipitates, soil moisture pH values increase toward a theoretical maximum value of 9.9 for a de-aerated solution in contact with calcite (Garrel and Christ, 1965, p. 86 ff). This in turn enhances the solubility of silica. With time, evapotranspiration becomes increasingly important and salinities rise, but silica saturation is not necessarily reached. Groundwater recharge through the vadose zone, when it does occur in this soil moisture regime, is likely to produce waters which are saline and perhaps nonpotable, even on valley flanks (Table 4.3).

With strong desiccation and appropriate amounts of vanadium, potassium, and uranium in the soil or transported into it, carnotite may conceivably accumulate in certain parts of the caliche horizon or in contact with clays as it does in the valley calcrete environment. If it does it would be widely dispersed and noneconomic.

4.3.4 Alternative Hypotheses for the Menzies Line

Other regional differences may contribute to the widespread occurrence of pedogenic carbonate horizons in the soils south of the Menzies Line and the possible diffuse precipitation of uranium. One of these is the large and continuing supply of calcareous dust from exposed limestone and calcareous soils on and around the Nullarbor Plain. Powdery calcareous loams and calcareous earths with kunkar visible in the A horizon extend across the entire plain and for thousands of square kilometers to the north and west.

A second possible source of calcium are remnants of Cretaceous to Eocene marine limestones which are known to have been deposited on the Old Plateau surface almost as far north as Kalgoorlie. Conceivably, outliers of these units may yet be discovered even further north through drilling deeper valleys of the ancient river system.

Sanders (1972, 1973) has suggested that the greater part of the calcium and magnesium carbonate in the valley calcrete region north of the Menzies Line has been derived from dolomites of the Proterozoic

Bangemall Group, now exposed only north of Wiluna (Figure 4.1), but which he believes to have once extended at least as far as 180 km south of Wiluna. Mafic and ultramafic rocks of the Archean greenstone belts are an equally probable source. The dolomitic character of many valley, deltaic, and especially lacustrine calcretes fits either suggestion. In fact, the proportion of carbonate in valley calcretes, 1/2 - 1% of the total volume of valley fill at Veelirrie (Section 4.2.1) and Hinkler Well Basin (Section 4.2.2), for example, may be less than the proportion of carbonate in the sheets of pedogenic calcrete or kunkar in many drainage basins south of the Menzies Line.

The greater salinity of groundwaters south of the Menzies Line may reflect in small or large part greater proximity to the ocean and derivation of marine salt from anticyclonic frontal rains. Rain-precipitated salts, predominantly NaCl, appear to be related to distance from the coast, intensity and direction of wind, and rainfall (Teakle, 1937; Hingston, 1958; Morgan, 1972). Morgan notes that the groundwaters are less saline in summer rainfall areas, i.e., north of the Menzies Line, than in comparable regions with misty winter rains and ascribes this to the marine source. Similar relationships have been observed in many other parts of the world, including the Namib Desert discussed below, and in the United States where Smith (1976), for example, has suggested that large amounts of the sodium, chlorine, and bromine in Searles Lake may have been derived from atmospherically transported sea salts.

Terrestrial salt, however, from windblown dust, and especially from dry lakes and barren plains, is also a major source of sodium and chlorine in inland parts of Australia (Hutton and Leslie, 1958; Hutton, 1977; Patterson, 1977) and, as noted above, of calcium carbonate as well.

The remote possibility that uranium may have been concentrated along or near the former southerly extension of the Archean-Proterozoic unconformity over the region of uraniferous valley calcretes was implied in Section 4.1.2. Apart from this, no information is available to the writer to suggest that the Archean basement south of the Menzies Line is any less uraniferous than north of the line.

Schematic Models for Calcrete Uranium Mineralization, Western Australia

4.3.5

Carnotite Precipitation

Figure 4.20, modified from Mann (1974c), and 4.21, by the writer, show features of the valley calcrete and deltaic-lacustrine environments and zones in which carnotite mineralization may be expected to occur in carbonate or in carbonated clay. Mann has presented seven hypothetical mechanisms for carnotite precipitation in these environments as follows:

1. Separate uranium, 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 [oxidation of vanadium to five-valent state].

Mention is also made of the probable absorption of uranium on clays, hydrated iron oxides, or fine-grained carbonate and of the complexities that may be introduced by colloidal phenomena and organic activity.

The importance of P_{CO_2} in carnotite precipitation arises from the fact that the solubilities of the uranyl dicarbonate and tricarboxylate complexes $[UO_2(CO_3)_2 \cdot 2H_2O]^{2-}$, $[UO_2(CO_3)_3]^{4-}$ are enormously greater than that of the simple uranyl ion UO_2^{2+} or $UO_2(OH)^+$ in an alkaline hydrous solution (Hostetler and Garrels, 1962). Thus, in a carbonated groundwater containing K^+ , vanadium in the five-valent state as $H_2VO_4^-$, and uranyl ion, the dissolution-precipitation of carnotite can be represented by the following reactions:

In a solution containing only the above components, removal of CO_2 drives all these equations to the right and decreases the solubility of carnotite. With $CaCO_3$ added, however, some amount of CO_3^{2-} , HCO_3^- , or H_2CO_3 is always present in solution and available to form the uranyl carbonate complexes (including the less soluble neutral complex, $UO_2CO_3^0$). Removal of CO_2

increases pH and the ratio $\text{CO}_3^{2-}/\text{HCO}_3^-$, making CaCO_3 less soluble (Section 3.3.2). Depending upon the magnitude of the pH change which accompanies the CO_2 loss, carnotite may become more or less soluble. This introduces a problem in explaining the spatial and temporal association of calcite and carnotite in calcretes.

The actual situation in a calcrete environment must be infinitely more complicated than the ideal systems suggested by the above, though these are complicated enough. Very little is known about the effects of impurities, of a variety of possible surface reactions with soil materials (particularly montmorillonitic clays), of grain size, polymorphism (e.g., observed aragonite), or other physical differences. Varying reaction rates and nonequilibrium reactions further obscure the picture. The role of bacteria or other organisms in a calcrete environment is little understood. Uranyl ion, moreover, forms complexes with OH , SO_4 , PO_4 , F , Cl , and other ligands (Langmuir, 1977). Clearly the application of carbonate and carnotite equilibria to this complicated situation is very speculative. It may be less indicative of favorability criteria, in fact, than observed geological relationships.

In the following, there is a slight reordering of mechanisms from those of Mann (1974c), some differences in emphasis, and, in the next section, two added considerations, the need for reconcentration and for stabilization of precipitated carnotite.

4.3.5.1 Addition of Vanadium- or Potassium-enriched Waters

Local additions of sufficient dissolved potassium or vanadium can unquestionably induce precipitation of carnotite from uraniferous waters. Proof of this special circumstance in the vicinity of a valley calcrete uranium deposit, however, has not been demonstrated to the writer's knowledge. The mechanism would not in itself explain the concentration of carnotite in subhorizontal layers close to the ground surface or near present or former water tables. On the other hand, carnotite precipitation due to potassium enrichment at salt lake margins is a distinct possibility discussed below in connection with evaporative concentration.

Vanadium, whose abundance is often cited as an important factor, is widespread in laterite, clay, and mafic igneous rocks associated with Archean greenstone belts. Some have questioned whether vanadium from the finger of greenstone due north of the Yeelirrie orebody (Plate IV-2) or the Wiluna Greenstone belt near Lake Way may have influenced carnotite concentration in those areas. The writer is more inclined to emphasize the geomorphic effect of resistant greenstones on valley gradients and groundwater flow. Two vanadium deposits of economic interest do occur in greenstone belts not far from carnotite deposits in the Yarrabubba area (Plate IV-1) southeast of Meekatharra (Jones, 1965). Vanadium is present in many granitic rocks in amounts sufficient to precipitate the contained uranium as carnotite. The occurrence of carnotite in breakaways illustrates that vanadium, as well as potassium, can be mobilized to at least some degree from the lateritic profile.

4.3.5.2 Carnotite Precipitation with pH Change

A mechanism may be hypothesized for precipitating carnotite in calcrete dependent upon change in pH toward the solubility minimum which, for waters of average CO_2 content, is near neutrality (Mann, 1974b; Langmuir, 1977). This might be expected, for example, where acidic uraniferous groundwaters from the valley flanks enter the calcrete environment. One would expect this mechanism to concentrate carnotite in areas where the acidic uraniferous waters enter zones of near-neutral pH on the margins of the calcrete. Further into the calcrete the pH would rise as the waters tended to equilibrate with calcite, and carnotite would redissolve. As Mann points out, the situation would become complex as calcrete continued to form updrainage or downdrainage or was redissolved. Carnotite, unless protected by a coating of silica, for example, would tend to be reworked from areas of high pH to others near neutrality.

In reality, carnotite is strikingly concentrated within calcrete itself or in carbonated clays adjacent to calcrete with $\text{pH} \geq 7.5$. Areas of neutral pH outside the calcrete environment are not significantly uraniferous.

4.3.5.3 Change in Partial Pressure of CO₂

Direct loss of CO₂ into the atmosphere or indirectly into soil air is a plausible hypothesis because of the observed relationship between drainage channel morphology, zones of near-surface or upwelling groundwater, and significant carnotite mineralization. As noted in Section 3.3, subsurface waters can become enormously enriched in CO₂ from pore vapors in organic layers of the soil containing up to hundreds of times the atmospheric concentration of CO₂. If pH were held at or near some neutral or alkaline value, e.g., by CaCO₃ in the soil, the consequent increase in CO₃²⁻ ion activities would cause greatly enhanced solubility of carnotite due to formation of uranyl carbonate complexes. Where such a groundwater containing uranium, vanadium, and potassium is forced closer to the surface, especially in a hot climate, accelerated loss of CO₂ at or near the given pH would reverse the process and facilitate precipitation of carnotite. It would appear that the postulate requires a pH buffer not yet identified, and without which, in a calcrete environment, the expected consequence of CO₂ loss would be increased pH and CO₃²⁻ ion activity leading to precipitation of more calcite and solubilization rather than precipitation of carnotite.

Further evaporation, once P_{CO₂} had fallen to a value in equilibrium with the atmosphere, would increase salinity (i.e., the concentration of all components other than total carbonate in solution), which will in itself reduce the solubility of CO₂. Calcite will continue to precipitate by evaporative concentration of Ca²⁺, and, depending upon several factors including the rate of CO₂ exchange with soil air, CO₃²⁻ ion activity may fall, leading to carnotite precipitation at or before complete desiccation. This brings us to the next mechanism.

4.3.5.4 Carnotite Precipitation by Evaporative Concentration

In many places simple evaporative concentration of uranyl and other ions is known to produce coatings and efflorescences of carnotite or sulfates and carbonates such as schroekingerite, bayleyite, zippeite, or other soluble uranium minerals on or near exposed surfaces toward which water can migrate (Bell, 1956). Carnotite on breakaway faces is one example.

Such occurrences are only rarely of economic interest, as may be the case with the schroekingerite occurrences of the Red Desert in Wyoming.

Data gathered by Mann and Deutscher on the Hinkler Well Drainage (Section 4.2.2, Figure 4.13), by Western Mining Corporation at Yeelirrie (Section 4.2.1), by Dall'aglio et al. (1974), and others indicate that dissolved K, V, U, and Cl or total dissolved solids (TDS) increase irregularly and disproportionately down the valley portions of the drainages by about an order of magnitude due to evaporation. Dissolved potassium, chlorine, and TDS increase by another order of magnitude or more between the lower valleys and the salt lakes, but uranium and vanadium do not, or they behave in a complicated way below carnotite ore deposits, and HCO_3 decreases. It is reasonable to believe that although vanadium is somewhat of a problem, the combined activities of potassium, vanadium, and (decarbonated) uranyl ion may on occasion have reached values high enough to cause precipitation of carnotite.

However, the mineralogy, texture, morphology, and distribution of calcrete uranium occurrences do not fit a simple in situ or lacustrine evaporite model. Carnotite is not necessarily most abundant where salinities are greatest. In fact, it is not at all abundant in salt lakes except where it is associated with calcrete, as at Lake Maitland or in the "young" mounds of recent deltas.

Mixing of trunk valley drainage waters carrying some uranyl ion, vanadium, and potassium with hypersaline, potassium-rich waters of a salt lake is a much more attractive model because it would explain observed concentrations of carnotite near the margins of the lakes. Potassium concentration may in itself trigger carnotite precipitation. Again, however, carnotite mineralization at the margin of salt lakes is in carbonate mounds, and these are typically slightly updrainage from or spatially above the most hypersaline waters (Figure 4.21). Further explanation is required to account for the close association of carnotite and carbonate.

Mann and Deutscher (1978) have doubted that the evaporative mechanism can be applied to valley calcretes since there is little or no evidence that salt lakes have extended for any appreciable distance up the valleys

and certainly not as far as the Yeelirrie orebody. On the other hand, as indicated by minor amounts of gypsum in association with mineralized valley calcretes, evaporative concentration in the soil moisture zone and particularly in areas of retarded groundwater flow or of upwelling along trunk valley drainages is quite capable of producing hypersaline waters. Even though ephemeral, high potassium concentrations in these hypersaline waters could induce precipitation of carnotite upon mixing with incoming uraniferous waters. Evaporative concentration plays a unique role in all forms of calcrete uranium genesis because it builds up the concentrations of all of the components in solution except carbonate species which, in theory, remain substantially controlled by ambient P_{CO_2} . It provides a means of getting around the contradictory effect of CO_3^{2-} ion concentration on the precipitation of carbonate and carnotite. This brings us to the next mechanism.

4.3.5.5 Carnotite Precipitation through Common-ion Precipitation of Calcite or Dolomite

Precipitation of calcite or dolomite from a carbonated solution containing appropriate amounts of six-valent uranium, five-valent vanadium, and K^+ by additions of Ca^{2+} or Mg^{2+} which are in solution with other anions, and without access to CO_2 , will decrease the concentration of CO_3^{2-} ion and promote destabilization of uranyl carbonate complexes which in turn will lead to precipitation of carnotite. This common-ion effect, not to be confused with carbonate precipitation by CO_2 loss, might be expected wherever carbonate-rich waters encounter waters strongly enriched in calcium sulfate, chloride, or other anion. This will occur at the entrance to salt lakes, where precipitation of carnotite is further enhanced by the high concentrations of potassium and possibly of uranium and vanadium discussed above.

In this event, carnotite and carbonate should be contemporaneous as indeed appears to be the case in the incipient and partly carbonated "young" mounds on the outer, newer deltas of the Hinkler Well Drainage (mode I carnotite, Section 4.2.2.10) and north Lake Way. Furthermore, the carnotite should be finely disseminated throughout the carbonate but

always associated with it, as is observed in thin sections from those young deposits. Subsequent reworking of the primary carnotite with changes in groundwater regime by alkaline carbonated waters accounts for the epigenetic concentrations along fractures and other open spaces presently observed in older calcretes (modes II and III, Section 4.2.2.10). Radiometric equilibrium measurements and textural relationships between carnotite and chalcedonic films, cited in detailed descriptions of the deposits, support these contentions.

Even in the main or trunk portions of valley calcrete drainages, i.e., the Yeelirrie environment, highly evaporated waters can develop in the capillary fringe or the soil moisture zone, locally approaching the ionic concentrations in salt lakes. Strongly carbonated uraniferous waters moving into these domains may similarly precipitate both calcite by common-ion effect and carnotite by carbonate ion depletion.

4.3.5.6 Carnotite Precipitation through Oxidation

Mann (1974c) has pointed out that because the concentrations of vanadium and uranyl ion which can be carried concurrently in waters with potassium is significantly greater if vanadium is in the four-valent state, either as $\text{VO}(\text{OH})^+$ or HV_2O_5^- , depending on the pH, than in the five-valent state, as H_2VO_4^- , which is required for the precipitation of carnotite, a powerful mechanism can be postulated for transporting uranyl ion in slightly reducing waters and precipitating carnotite through oxidation as groundwaters approach the surface (Hostetler and Garrels, 1962). Moreover, the oxidation of V(IV) to V(V) has been shown experimentally to occur more readily in an alkaline environment.

The model suggested by Mann has U(VI) and V(IV) initially dissolved in neutral to slightly acidic and only mildly oxidizing ($< 0.2\text{v}$ at pH7) or slightly reducing groundwater. Upwelling induced by a constriction of some sort causes an increase in oxygen content, oxidation of V(IV) to V(V), and consequent reduced solubility of carnotite. Mann and Deutscher (1978) have recently accumulated new data in support of this model in the area of the north Lake Way prospects. By in situ Eh-pH probe measurements in drill holes they have shown that the redox boundary between V(IV) (in deeper waters) and V(V) (in shallower waters) does occur today at a few meters' depth. The boundary is deepest beneath

Uramurdah Creek itself, as might be expected. Thus, it is distinctly possible that vanadium from a distant or proximal source beneath the newer calcrete is transported largely in the tetravalent state until upwelling water (Figures 4.20, 4.21) carries it across the redox boundary. Precipitation of carbonate, possibly by the common-ion effect, causing further decline in CO_3^{2-} ion activity and precipitation of five-valent vanadium in carnotite would produce the young mounds of the newer delta and the finely disseminated contemporaneous mineralization observed in thin section.

An attractive feature of this model is that it provides a means of solubilizing vanadium from bedrock or from adsorption sites on laterite or clays at depth in the present climate. The likelihood that vanadium has become less mobile since the early Tertiary periods of laterization and the comparatively low V/U ratios in upper catchment groundwaters (Figure 4.13) has been cited as a problem in carnotite genesis. Once again, however, the occurrence of carnotite on breakaways indicates that some vanadium, at least, is available under present arid conditions.

4.3.5.7 Adsorption and Nucleation on Clay or Other Minerals

Some of the richest carnotite mineralization in the "calcrete" deposits and, in places the greater part of it, is associated with carbonated clay immediately adjacent to the calcrete itself. This is true of some earthy calcrete in upper parts of the Yeelirrie orebody which may contain as much as 50% montmorillonite. It is especially true of clay-quartz below the main calcrete at Yeelirrie containing up to 45% kaolinite and minor illite and montmorillonite. The greater part of the mineralization at North Lake Way is also in mottled calcareous clay subjacent to the calcrete (Brian Lancaster, personal communication, 1977). Uranium and vanadium have also been shown to accumulate on pellets of pure calcium carbonate placed in waters of Lake Way for a period of several weeks (Mann and Deutscher, 1978).

Nucleation of precipitates from solution is almost always initiated in a heterogeneous manner at the surfaces of solids already present. Clays and other finely divided materials, because of their large surface area

and associated surface free energy, enable nucleation to take place with a smaller free energy of activation than would be required for homogeneous nucleation throughout the body of a saturated solution. The rate of heterogeneous nucleation is proportional to the surface area of the impurity which catalyses the transformation. Dall'aglio et al. (1974) quote work by Muto et al. (1965) indicating that the adsorption of uranium by kaolinite shows a minimum uranium concentration in solution at pH 6 of 10^{-8} moles, which is an order of magnitude less than the minimum concentration of uranium in equilibrium with carnotite at the same pH.

Although the mechanisms and quantitative relationships are very poorly known, the observed capacity of clays, particularly montmorillonite, and of organic and other materials with large specific surface to adsorb metal ions and to catalyse precipitation may be a significant factor in calcrete uranium genesis (see also 4.3.6 below). The same clays without carbonate, however, are not uraniferous.

4.3.5.8 Comparison of Possible Mechanisms of Precipitation

Table 4.4 is a summary with crude subjective evaluations of the individual mechanisms suggested. In reality, the effects of the mechanisms are complex and not easily separated. Thus, forced upwelling of groundwater near a bedrock constriction or lacustrine clay barriers, for example, stimulates mechanisms 3), 4), 5), and 6). P_{CO_2} and pH are intimately related. The importance of evaporative concentration, both in itself and also as a prerequisite for common-ion precipitation of carbonate, is consistent with the observed climatic control of calcrete-carnotite distribution.

Table 4.4

Carnotite Precipitation Mechanisms in Western Australia

Mechanism	Possible Effectiveness for Carnotite Precipitation in Calcrete
1) Addition of vanadium- or potassium-enriched waters	Theoretically important but not demonstrated for valley calcrete orebodies. Applicable to salt lake margins and analogous situations.
2) pH change	Possibly effective on a small scale only.
3) Change in P_{CO_2}	Requires a pH buffer until extreme evaporation where decline in CO_3^{2-} ion activity becomes possible and very important.
4) Evaporative concentration	Strongly effective. Calcrete ores are not simple evaporites, but evaporative concentration of K may help precipitate carnotite in 1), 3), 5), and 6). Evaporative concentration makes 5) possible.
5) Common-ion precipitation of calcite or dolomite	Strongly effective in areas of strong evaporative concentration. Yields contemporaneous carnotite and calcrete.
6) Oxidation	Very strongly possible.
7) Absorption and surface catalysis	Possibly a factor.

4.3.6

Reconcentration and Stabilization

Although substantial concentrations of very finely disseminated carnotite apparently contemporaneous with carbonate occur in "young" mounds and recent calcrete deltas, workable deposits of this variety have not yet been proven. At Yeelirrie and other occurrences large amounts, if not all, of the megascopic carnotite is in open spaces and along fractures or slickensided surfaces. These epigenetic concentrations occur in the same areas where contemporaneous precipitation of carnotite and carbonate would be expected, i.e., where groundwater is shallow or upwelling. They extend below the calcrete in carbonated clay. Radiometric equilibrium analyses reported in 4.2.1, 4.2.2, and 4.2.3 suggest, though inconclusively, that they range in age. Groundwaters in their vicinity and downdrainage from known deposits contain strongly anomalous amounts of uranium and vanadium, implying dissolution now. At the same time, much larger areas of calcrete contain little or no uranium. It seems highly probable, therefore, that early carnotite has been subject to both lateral and downward reworking into smaller, most favorable locations. Even there it is vulnerable to further dissolution, but in a few places, perhaps due to changes in the groundwater regime, it has remained. At Yeelirrie, large proportions have been protected by films of microcrystalline quartz. Clays, because of their absorptive capacity, may help to stabilize carnotite precipitation. On the other hand, in regions of marked stream rejuvenation, e.g., west of the Meckering Line, dissolution far exceeds precipitation, and earlier occurrences are dispersed.

The importance of reworking and of stabilization will be apparent again in the calcrete deposits of South West Africa.

5.0

URANIFEROUS CALCRETE AND GYPCRETE DEPOSITS
OF SOUTH WEST AFRICA

5.1

GEOGRAPHIC, GEOLOGICAL, AND GEOMORPHIC SETTING

Uranium associated with calcrete, gypcrete, and weathered bedrock has been widely reported from the Namib Desert region of South West Africa, commonly as carnotite though locally as soddyite. Carnotite has been found in deposits from the Angolan border in the north to the Kuiseb River in the south, and from the Atlantic coast to as much as 100 km inland and 1000 m above sea level. As with the Australian occurrences it is again relevant to preface discussion of the Namib calcretes and gypcretes with an evaluation of the environmental setting, while also acknowledging that much research remains to be conducted in this presently remote region before the nature and origins of the uraniferous deposits can be fully understood.

5.1.1

General Physiography and Geographic Setting

South West Africa covers approximately 825,000 km², one-fifth of which constitutes the Namib Desert which stretches for 1,360 km along the Atlantic coast in a belt 80 to 150 km wide. The total length of the Namib Desert from Mossamedes, Angola, in the north to the mouth of the Olifants River, Cape Province, in the south is some 2,000 km. In the north and center of the region the Namib Desert extends eastward to the foot of the Great Escarpment, atop which more humid lands prevail. In the south a more gradual transition merges the Namib with the Kalahari and Karroo Deserts of the interior. The Namib region as a whole falls within what several authors recognize as the Marginal Lands of southern Africa, the commonly terraced or sloping terrain that is separated by the Great Escarpment from the Plateau Lands of the interior.

Within the borders of South West Africa the Namib Desert has been divided into five principal regions: the Skeleton Coast, the Kaokoveld, the Central Namib, the Dune Namib, and the Southern Namib. The Skeleton Coast comprises a 50-km-wide belt of gravel terraces, sand dunes, and low hills extending south from the Cunene River to the Ugab River. The Kaokoveld, a 150-km-wide zone paralleling the Skeleton Coast farther inland, is mainly

Plate V-1. LANDSAT PHOTOGRAPH, MAIN REGION OF CALCRETE
AND GYPCRETE URANIUM OCCURRENCES ON NAMIB DESERT.

Main Region of Calcrete and Gypcrete Uranium Occurrences in the Namib Desert

(Topography mainly from Gemini V photograph)

Figure 5.1

broken country with steep-sided mesas capped by Karroo lavas, intervening basins half-filled with fluvial debris, and rugged hills underlain by granite, gneiss, and quartzite. The Central Namib, between the Ugab and Kuiseb Rivers, comprises a broad bedrock or gravel-strewn platform (the so-called Namib Platform) rising from sea level to about 1000 m at the foot of the Great Escarpment 100 to 200 km from the coast. The platform is locally disrupted by deep canyons and ridges of more resistant metamorphic rocks of the Damara Orogen. Water-laid gravels are commonly cemented with gypsum near the coast and calcium carbonate inland, and it is here that the principal known uraniferous calcrete and gypcrete deposits occur. South of the Kuiseb River a great thickness of sand mantles the Namib Platform creating an enormous dune field, the Dune Namib, that extends 400 km southward and 100-150 km eastward from the coast to the Great Escarpment. South of the Koichab River, the southern Namib comprises a series of rocky ridges paralleling the coast and, farther south, a series of gravelly marine terraces. Of these southern regions all but the northern tip of the Dune Namib lie within the restricted Diamantgebied or Sperrgebied.

The physiography of the area of greatest interest for this report was recorded on a well-known Gemini V photograph and on Landsat reproduced as Plate V-1. Figure 5.1 is an overlay of the Gemini photograph. Much of the area and several of the calcrete-gypcrete uranium deposits lie within the Namib Desert Park. Gobabeb, the Namib Desert Research Station, is near the southern edge of the park on the Kuiseb River. Walvis Bay, a shipping port and commercial fishing center with railroad and highway access, is within an enclave which is part of the Republic of South Africa. Swakopmund, population about 10,000, is a residential, business, and summer resort center much in favor among South West Africans. The Rössing uranium mine, roughly 60 km northeast of Swakopmund, has recently become a major source of income and employment. Intensive exploration has resulted in several additional bedrock uranium discoveries along the high metamorphic grade axis of the Damara Orogen. Farming on a small but locally intensive scale is restricted to the lower parts of major rivers, notably the Kuiseb and Swakop. Water supply is a continuing problem both for farmers and miners. The calcretes, quite unlike those of Australia, are not good aquifers.

5.1.2 Regional Geology, Potential Source Rocks

The dominant basement rocks of the Namib Desert and adjacent regions are those assigned to the Damara System sensu lato, considered to be Proterozoic in age. Radiometric age determinations obtained from regional metamorphic and granite pegmatite minerals associated with sediments in the Damara orogenic belt suggest an age of 450-500 million years for the most recent orogenic event affecting these rocks, the Damaran Orogeny (Clifford, 1967). The Damara rocks and their igneous associates have been subdivided by Martin (1961) into a miogeosynclinal Outjo (Otavi) facies and a eugeosynclinal Swakop (Damara) facies. The Outjo facies contains mainly chemical sediments, principally dolomite and limestone, in association with fairly well-sorted detrital sediments, mainly shales, quartzites, as well as some tillites. These rocks are comparatively gently folded, little metamorphosed, and outcrop primarily inland from the Kaokoveld to the Otavi Mountains, south and west of the Etosha Pan. The Swakop facies comprises schist, quartz-schist, and greywacke in association with other poorly sorted detrital sediments, and metamorphosed basic and ultrabasic rocks of igneous origin. These rocks are strongly metamorphosed, intensely folded, and, over large areas, granitized. They outcrop extensively in the Kaokoveld and in the Central Namib region. In the latter area, the rocks range from almost pure biotite muscovite schists to micaceous quartzites, striking commonly ENE and ranging from sea level to over 1500 m in the Khomas Hochland. The more arenaceous members, represented mainly in the basal Nosib Group, and calcareous units of the Karibib Formation resist weathering more than the schists, giving the terrain a corrugated aspect. Langer Heinrich, 1152 m (Figure 5.1), is a prominent hill of quartzite within the general outcrop of the Damara System, assigned by Jacob (1974) to the Nosib Group and lying stratigraphically below schists, gneisses, hornfelses, and thin meta-tilloids of his "Damara" Group, or Swakop Group in current terminology (Table 5.1). Marbles and calc-silicate hornfels of the Karibib Formation compose the Husabberg on Welwitschia Flat and the Witpoortberge across the Swakop River. The same marble, clearly visible on the Landsat and Gemini photographs, continues southwesterly on the Damara trend as sinuous ridges across the entire Namib Desert Park.

Table 5.1 Summary of lithologies of the Nosib and Swakop Groups
(Modified from Jacob, 1974)

		Formation	Lithology
SWAKOP ("DAMARA") GROUP	Khomas Subgroup	Witpoort and Tinkas	<u>Witpoort</u> : pelitic and semipelitic migmatitic biotite schist and gneiss containing cordierite, K-feldspar, sillimanite, almandine; migmatite; minor calc-granofels. <u>Tinkas</u> : biotite schist containing muscovite, cordierite, andalusite, sillimanite, almandine, staurolite, hornblende; calc-granofels; marble; para-amphibolite.
		Karibib (Husab)	Pelitic schist; calc-granofels; calc-silicate gneiss; dolomitic and calcitic marble.
		Chuos	Schistose diamictite containing inclusions of igneous and sedimentary origin. Meta-tilloid.
	Unconformity		
	Hakos	Rössing	Pelitic schist and gneiss containing cordierite, K-feldspar, sillimanite, almandine; marble; quartzite; conglomerate; calc-granofels.
Para- and unconformity			
NOSIB GROUP	Khan		Hornblende-biotite schist and gneiss; migmatitic banded and mottled quartz-K-feldspar-plagioclase-clinopyroxene-hornblende gneiss.
	Etusis		Quartzite; conglomerate; quartzofeldspathic gneisses containing sillimanite, cordierite, biotite; banded quartzofeldspathic clinopyroxene-hornblende gneiss; migmatite; pelitic schists; minor marble.

A summary of the formations and lithologies of the Nosib and Swakop Groups in that part of the Namib Desert of greatest relevance to the present report is given in Table 5.1, modified from Jacob (1974) and discussed again in connection with the calcrete uranium deposit at Langer Heinrich. Note the abundance of calcareous rocks and the paucity of ultramafic rocks in comparison with the Yilgarn Block of Western Australia.

Ultrametamorphic or anatectic and magmatic granitic rocks which underlie major portions of the Central Namib are excellent candidates as uranium source rocks. These are shown on the explanation to Figure 5.6 and mentioned again in discussions of the deposits which follow. Ultrametamorphic equivalents of the Nosib and Swakop Groups, the Red Granite-Gneiss and the Salem Granite respectively, are both anomalously radioactive locally. Six late tectonic to post-tectonic granites have been recognized. The Bloedkoppie granite is anomalously radioactive and of especial interest at Langer Heinrich. The alaskitic, pegmatitic G_4 granites, ranging somewhat in age and contact relations but including the major host rocks at the Rössing uranium deposit, occur as small intrusives and veins, as does the Horebis granite. The Achas and Gawib granites occur as stocks; the Donderhoek granite is batholithic. Early syntectonic to post-tectonic pegmatites, both homogeneous and inhomogeneous, layered and zoned, number in the many thousands and are found transecting every rock type. Many contain uranium minerals (Martin, 1965).

The northeasterly trending Damara orogenic belt occupies a broad swath through the Central Namib, including the general area of the Swakop-Khan River system. Axially within this belt, passing through Karibib and projecting beneath Walvis Bay, is a median geanticline, the Abbabis Swell, with the oldest exposed Precambrian Abbabis Formation at its core. This structure corresponds closely with the belt of maximum metamorphic grade (viz. Clifford, 1967), and in turn, more or less, with a bedrock uranium province which includes the Valencia, Ida, and Rössing structural domes. Uranium-anomalous granitic rocks are not restricted to this central belt, however, nor are the calcrete-gypcrete deposits, though some of the richest of these superficial occurrences are along the flanks of the belt. Jacob (1974) favors a single prolonged period of metamorphism, the Damaran orogenic episode, falling mainly in the range 450-500 million years.

Post-Damara rocks include the horizontally disposed sandstones, shales, and limestones of the Nama System, which in South West Africa extend in a broad belt from the Naukluft Mountains south of Windhoek southward across the Orange River, but mainly inland from the Namib Desert. Within the desert region proper, post-Damara rocks consist mainly of the Karroo System (Upper Carboniferous to Triassic), of which the largest outcrop is represented by the Stormberg basalts north of the Ugab River.

Post-Karroo (Post-Triassic) time in South West Africa, as over much of southern Africa, has been characterized by a predominance of erosion which has served to unroof much of the basement complex. Sedimentary deposits are primarily found as wedges of debris around the margins of southern Africa, thickening seawards across the present coastline, or as veneers of terrigenous debris in interior basins such as the Kalahari Desert. There are no known Jurassic sediments in South West Africa, and the Cretaceous is represented by a small patch of marine debris on the coastal strip of the Sperrgebeid lying on Precambrian schists near Bogenfels. The Cenozoic Era is represented in the stratigraphic record by fluvial and marine terrace formations of highly variable thicknesses and probable late Tertiary age along the coast and major river valleys and by a mantle of dune sand. The marine terraces have been variously ascribed to epochs of the Tertiary Period, but it seems likely that the majority are of Quaternary age.

5.1.3 Geomorphic History

The paucity of the post-Karroo sedimentary record poses serious problems for the interpretation of the geomorphology of the Namib region, and suggestions regarding the origins of the various surfaces and duricrusts must remain speculative at this stage. Present understanding of global tectonics suggests that the erosional development of the Namib region probably began in Jurassic times with the fracturing and separation of Karroo and older rocks along the margins of the African plate. Evidence exists for marginal marine transgressions in Upper Cretaceous time and perhaps again in the Eocene Epoch, for uplift in the Miocene or Pliocene, and for intermittent structural movements during late Tertiary and Quaternary times.

Weathering and erosion during Cenozoic times presumably reduced the region to its present configuration, leaving inselbergs of older rock mainly along the inner edge toward the Great Escarpment while the remainder of the region was sculptured into a series of erosion surfaces, mostly subaerial in origin with concomitant accumulation of extensive calcretes and gypcretes. Evaluating the geomorphic evidence in the light of his belief in scarp retreat and pediplanation, King (1967) has tabulated a sequence of post-Karoo events for southern Africa as follows:

1. Gondwana planation (Jurassic)
2. Post-Gondwana dissection (Early Cretaceous)
3. African planation (Late Cretaceous - Middle Tertiary)
4. Epeirogenic uplift (Miocene) [cf. Pliocene, below]
5. Valley-floor planation (Miocene and Pliocene)
6. Gorge cutting (Quaternary)
7. Minor differential movement (Quaternary)
8. Coastal submergence (intermittently through Quaternary)

Whether or not the fragmentary field evidence completely sustains King's proposed sequence and his belief in almost rhythmic alternations of prolonged subaerial erosion separated by periodic uplift, landforms attributable to each phase, especially since mid-Tertiary times, may be identified in the Namib and adjacent regions (Mabbutt, 1952; Korn and Martin, 1957).

In the Central Namib Desert, the area of interest, the deeply weathered and eroded "African" surface with characteristic inselbergs and broad valleys was apparently formed by earliest Tertiary times (Mabbutt, 1952). Tertiary climates, ranging from periods with rainfall greater than today through extreme aridity but even then characterized by summer rains and dry winters (Korn and Martin, 1957), became preponderantly arid toward the end of the period. As a result great volumes of sediment accumulated on the "African" surface. Perhaps half or more than half of the old topography in the Namib was overfilled with gravels and sands, and a great plain, the ancestral surface of the present Namib Platform, was formed. One drill hole on the Tumas River (Section 5.2.2) midway between the Escarpment and the ocean penetrates 107 m of alluvium. Similar thicknesses are reported on the Ugab River (Mabbutt, 1952). These thick alluvial sediments must have been converted to calcrete by the end of that

period because pronounced uplift of the central continent at the end of the Tertiary coupled with pluviation of the Pleistocene resulted in intense rejuvenation of major rivers and deep incisions which transect these calcretes for tens of meters. The margins of dissection, the so-called "gramadullas" (Rust and Wieneke, 1974), are sharp edges supported by resistant conglomeratic calcrete, hardly ever more than 3 - 4 km from the river and clearly visible on satellite photographs (Plate V-1). Wide expanses of the old platform--the Welwitschia, Tumas, and Tinkas Flats for example--underlain by thick calcrete conglomerate have been left virtually untouched by this major rejuvenation. Mabbutt (1952) presents detailed evidence for Tertiary calcification of the "Main Terrace" gravels on the Ugab River. Netterberg (1969c) and Goudie (1972) also suggest a Pliocene age for calcification of the gravels and a probable correlation with the great Kalahari Limestone deposit of the Kalk Plateau. These calcretes are much older than the valley calcretes of Western Australia.

Various wet periods during the Pleistocene have caused lesser terraces to be formed within the ancestral surface of the Namib Platform and within the incised valleys. Several of these can be approximately dated and related tentatively to Middle and Upper Pleistocene cultural units (e.g., Mabbutt, 1952; Korn and Martin, 1957; Netterberg, 1969c). The present Namib Platform (Logan, 1960) is thus a compound surface. As arid climates returned, new thin sheet calcretes and, within the fog belt, gypcretes have formed across all of the surfaces excluding only active stream beds. These are purely surficial and pedogenic in origin. They overlie the older calcreted gravels unconformably and are draped over the shoulders of incised river valleys.

Slope gradients on the Namib Platform are surprisingly greater than one's impression of the vast expanse would lead one to believe. In the Namib Desert Park area, which includes Langer Heinrich and the Tumas River gypcrete occurrences, gradients range from 0.75 percent near the ocean to 1.3 percent near the base of the Great Escarpment. North of Swakopmund in the area of the Klein Spitzkoppe prospects gradients range from 0.4 percent to 1.5 percent. The contrast with gradients in the Yeelirrie region of Western Australia, ranging from 0.02 percent near the Yeelirrie orebody to 0.4 percent near the headwaters of that drainage and averaging about 0.1 percent along the stretches of valley calcrete, is illustrated in Figure 7.13.

Figure 5.2 Southern Africa, Climatic Factors

Mean Annual Total Precipitation (millimeters)
(After Schulze, 1972; Nagel, 1962)

a) The extreme aridity of the Namib Desert is illustrated by the annual rainfall total at Gobabeb of 18.8 mm. The dotted line represents the general inland limit of precipitating fogs. The amount of fog precipitation increases southerly from the equivalent of 15 mm of rainfall in the North (Walvis Bay) to greater than 300 mm around Cape Town (Nagel, 1962).

Mean Annual Temperature °C
(After Schulze, 1972)

c) The relative isotherm in South West Africa in the vicinity of the Namib Desert are diagrammatic due to the small body of data available.

Average Annual Potential Evaporation (millimeters)
(After Schulze, 1972)

b) Evaporation totals from the class A pan are presented. The distribution illustrated is somewhat diagrammatic in South West Africa due to the paucity of data. The high

Annual Water Balance, Evaporation Minus Precipitation (mm)
(Derived from published precipitation and evaporation data)

d) The annual water balance presented is the arithmetic difference between annual class A pan evaporation and annual precipitation ($E_A - P_A$). Fog precipitation was

5.1.4

Present Climate

The desert character of the Namib region is attributable in part to the influence of the cold north-flowing Benguela Current which generates heavy sea fogs but little rain, and in part to the broader atmospheric circulation patterns of the South Atlantic Ocean which, among other things, produce strong onshore and alongshore winds capable of moving large quantities of sand. The main climatic factors of southern Africa (Figures 5.2, 5.3) have a strong topographic bias exhibiting steep gradients across the coastal escarpments and more gradual changes through the interior plateau. On the Namib Desert itself three well-marked climatic zones parallel to the coast can be recognized (Besler, 1972) with corresponding soils or duricrusts.

1. Coastal Namib: an ocean-dominated, cool, foggy desert 20 - 30 km wide, with gypcrete, sand, and salt.
2. Middle Namib: alternating hot, dry, and foggy desert 20 - 30 km wide, including Gobabeb with ubiquitous gypcrete and the more important (nonpedogenic) gypcrete uranium deposits.
3. Eastern Namib: a warm desert below the escarpment with summer rains and ubiquitous pedogenic and nonpedogenic calcrete, including the Langer Heinrich deposit.

On the Coastal Namib in the Walvis Bay area precipitating fogs occur on an average of 200 days per year (Jackson, 1951). Rainfall is extremely sparse, some 10.7 mm annually, but fog precipitation is commonly sufficient to "wet the ground to a depth of two to three inches" (Jackson, 1941). Nagel (1962) reports annual fog precipitation equivalent to 130 mm of rainfall at Swakopmund in 1958 and similar amounts for 3 km inland, in contrast to a mean annual rainfall of only 17.9 mm. As far inland as Gobabeb, fog precipitation contributes twice as much moisture to the soil profile as rainfall. Deposition of salt from the atmosphere is very substantial (Goudie, 1972). While exceedingly rare, large rainfalls do occur in the coastal Namib; they are less frequent and probably of lower intensity than at locations further inland. A surficial gypcrete crust is pervasive except for active dunes and innumerable small salt pans.

Explanation for Figure 5.3

Soil Moisture Regimes of Southern Africa

Inferred from Climadiagrams

Aridic Regimes:

- A_h Hyperaridic regime. Dry climate. Extremely sparse rainfall.
 $E_a/P_a > 25$ (64 at Gababeb)
 $E_w/P_w > 11$
 $E_a - P_a > 3000$ (3559 at Gababeb)
- A_{hm} Marine hyperaridic regime. Marine dominated coastal strip. Cool and subject to frequent fogs.
 $E_a/P_a > 20$
 $E_w/P_w > 10$
 $E_a - P_a > 2500$
- A Aridic regime. Hot dry climate. Soil never moist for long periods. Mean monthly precipitation never exceeds evaporation (E) or $E^{0.75}$.
 $E_a/P_a > 13$
 $E_w/P_w > 9$
 $E_a - P_a > 3000$
- A_s Subaridic regime. Episodic isolated convective storms in late summer and autumn. Precipitation exceeds $E^{0.75}$ in one to five summer months.
 $E_a/P_a = 5-10$
 $E_w/P_w = 2-4$
 $E_a - P_a = 2000-3000$

Subustic Regime:

- U_s Subustic. Broad midsummer precipitation peak. Orographic rain on the eastern escarpment and storms on eastern plateau.
 $E_a/P_a = 2-4$
 $E_w/P_w = 1-2$
 $E_a - P_a < 2000$

Xeric Regimes:

- X Xeric regime. "Mediterranean" type climate. Frontal winter rains and fog. Precipitation exceeds evaporation in three to five months.
 $E_a/P_a < 5$
 $E_w/P_w < 0.6$
 $E_a - P_a < 1500$
- X_s Subxeric regime. "Mediterranean" climate but with lower rainfall. Seasonality decreasing toward East.

(a = annual; w = wet month)

Figure 5.4

Climadiagrams for South Africa

The Middle Namib is also subject to morning fogs, but these commonly dissipate and are followed by much higher temperatures and lower humidities later in the day. Nevertheless, Seely and Stuart (1976) recorded a yearly mean fog precipitation of 35.2 mm at Gobabeb in contrast to a mean rainfall of only 16.8 mm. Analysis of fog water collected at Gobabeb in 1968 by Goudie (1972) indicates that fog waters are alkaline, sulfate is a major component, and TDS is in the range of 100 - 1000 ppm. Daily and yearly temperature and humidity ranges are larger than at the coast. The near coincidence of the inland limit of surficial gypcrete and the limit of fogs attests to the effects of fog precipitation on soil moisture and soil chemistry.

The Eastern Namib below the escarpment receives more rainfall than the Middle Namib but is beyond the influence of the fogs. The barren ground of the Middle Namib gives way to grasses and low shrub which support ostrich and antelope. Winds warmed by their descent down the escarpment bring thunderstorms in late summer. In winter dry and hot winds of only a few days' duration, the so-called Berg winds, can bring temperatures greater than 90° F to the Eastern and Middle Namib.

The distribution of surficial (pedogenic) gypcrete and calcrete in the Namib is closely related to the present climate. The inland limit of sulfate-bearing fogs marks the boundary of surficial gypcrete. Surficial calcrete is strongly developed with increasingly available moisture towards the escarpment. Goudie (1972) notes the preferential development of calcrete in shallow drainages where soils would at times be moister than in surrounding areas. Owing to a lack of data (essentially the Gobabeb records, Seely and Stuart, 1976), the Middle Namib - Eastern Namib boundary appears simply as a dotted line within the inferred "hyperaridic" soil moisture regime of Figure 5.3.

Above the Great Escarpment the western and southwestern interior plateau has a desertic climate and an inferred aridic soil moisture regime on Figure 5.3 comparable with the Wiluna - Yeelirrie area of Western Australia: mean annual precipitation is less than 250 mm, average annual evaporation is greater than 3000 mm, and rainfall is at its peak in late summer or autumn (of cf. climadiagrams for Upington, Figure 5.4, and Wiluna, Figure 4.16). The correlation of this inferred aridic regime with Netterberg's area of ubiquitous calcrete of all types (Figure 5.5) is impressive.

Figure 5.5. Distribution of calcretes in Southern Africa in relation to climate. From Netterberg, 1971.
Reproduced by courtesy of the author and CSIR.

5.1.5

Calcrete Uranium Host Rocks

The two ages of calcrete described above need to be clearly distinguished. The uppermost and younger of the two encompasses the crusts of purely surficial sheet calcrete of probably Middle Pleistocene to Recent age. Seldom over 3 m thick, it is a true duricrust in the sense of Goudie (1973) and others. It covers the entire present Namib Platform, except for Holocene stream gravels and active erosional surfaces, from the Great Escarpment seaward to the fog belt where exactly analogous crusts of gypcrete cover the surface. The surficial calcrete unconformably overlies the thick calcreted gravels, sands, and silts of the earlier age, overlapping terraces at several levels and extending over the shoulders of rejuvenated river valleys. It has formed after the deep rejuvenation and stream incision which followed end-Tertiary uplift and early Pleistocene pluviation. Often replete with laminar and rockhouse structures, it illustrates several generations of calcrete dissolution and reprecipitation, and it is, with rare exceptions, barren of significant uranium mineralization.

The calcrete of interest here, and the host rock for calcrete uranium deposits, is the underlying unit which has formed in gravels, sands, and silts deposited before Pleistocene stream rejuvenation. These are sediments which choked and filled the valleys on the Late Cretaceous - Early Tertiary "African" erosion surface after the onset of arid to extremely arid climates in the Late Tertiary.

Unlike the paleodrainages of Western Australia, the valleys of the "African" surface were overfilled with sediments and calcreted throughout (Figure 3.1). Moreover, the headwaters were strongly elevated, the gradients, in comparison with Western Australia, were steep, and there were neither closed basins nor internal drainages. Consequently, there are no salt lakes and no deltaic or lacustrine calcretes. The source terrain contained much more limestone, much less mafic rock, and was not so intensely and deeply weathered as in Australia. Hence, the detritus is coarse, unsorted, and fresh; the cement is calcareous and extensive. As noted by Gile et al. (1966), coarse texture facilitates carbonate cementation.

The resulting calcrete is much like concrete in that it consists of an aggregate of coarse detrital fragments held together by a calcite cement.

It does not have abundant shrinkage cracks nor open solution cavities, as does the Australian calcrete, and is not a good aquifer though it is appreciably permeable (Section 5.2.1). Sedimentary structures such as bedding, graded bedding, cross bedding, and scour and fill are well preserved. But soil carbonate profiles or discrete horizons of calcified and noncalcified sediment produced by alternating alluviation and pedogenic carbonate deposition are lacking. However, post-depositional solution structures and calcitic replacement bodies, some of them mineralized with carnotite (Figure 5.8, Plate V-3, Section 5.2.1.5), are common.

All of these characteristics, as well as the terrain, the size and steepness of the catchment areas, the climate, and the aggrading alluvial profile, suggest to the writer that these calcretes have been formed mainly by laterally flowing groundwaters. One may visualize the situation in valleys of the old "African" surface as they filled with alluvium in the later Tertiary. Even in the driest of climates the groundwater table in an alluviating valley will tend to rise progressively as the sedimentary fill thickens. With an adequate supply of Ca^{2+} and CO_3^{2-} , deposition from the capillary fringe at moderate depth (Section 3.3.4.3) during successive periods of prolonged desiccation could cement the entire profile from bottom to top. It is not necessary to appeal to downward reworking of surficial calcrete by means of a progressively falling water table (Netterberg, 1969b, 1971) since lateral supplies of Ca^{2+} and CO_3^{2-} in infiltrative water from the Great Escarpment and the easterly highlands would be very substantial. Downward reworking and precipitation from the gravitational water zone is not precluded, however, and is, in fact, the undoubted cause of the solution and replacement structures mentioned. Carnotite concentrations in these structures have probably also been reworked from uraniferous calcrete since vadose meteoric water alone would not supply new uranium. After the deep Pleistocene stream incision, uranium leached from bedrock or from later calcrete deposits has been carried directly to the ocean where much of it has accumulated in organic muds, especially in the vicinity of Walvis Bay (Meyer, 1973).

5.1.6

Gypcrete Uranium Host Rocks

The crusts of gypcrete within 50 - 60 km of the Atlantic coast on the Namib Desert are thought by the writer to be analogous to the surficial sheet calcrete higher on the Platform. They are typically only a fraction of a meter to 1 m thick and in a few places contain as much as 90 percent gypsum (Martin, 1963). They rest unconformably on thicker conglomeratic gypcrete, calcrete, or bedrock itself (Plate V-5, Figure 5.10). They are porous, commonly puffy in appearance, and essentially devoid of uranium mineralization.

The underlying conglomeratic and sandy gypcrete is more compact and quite analogous to the calcreted Tertiary gravels last described, though there are differences in lithological detail (see Tubas Grant Prospects, 5.2.2, below). Where the Tertiary gravels are thick, only the upper part is gypcrete--perhaps 5 to 25 m--and the lower part is calcrete. The contact is gradational over a narrow zone. Elsewhere the lower gypcrete rests directly on bedrock.

Martin (1963) has advanced an ingenious hypothesis for the origin of the gypcrete, invoking metasomatic replacement of pre-existing calcrete by sulfur derived from marine biogenic H_2S which has been transported inland on fogs and mists. He cites the remarkable phenomenon of near-shore H_2S eruptions which occur seasonally near Walvis Bay. Marine life which teems in the area due to the nutrient effect of upwelling cold Antarctic waters, the Benguela Current, is periodically decimated by incursions of warm saline Atlantic waters and consequent blooms of phytoplankton followed by oxygen depletion. The accumulation of dead matter in the sediments yields great quantities of H_2S . At times the gas erupts violently and drifts inland for tens of kilometers. The hypothesis has been questioned by many, partly because SO_4^{2-} is a far more persistent component of the marine fogs than is H_2S . Gypsum and other salts are deposited from marine fogs elsewhere.

Sulfur isotope analysis by Ms. Barry Wall at UCLA of 16 surficial gypcretes collected by the writer yielded a $\delta^{34}S$ ranging from +14.7 to +17.6 (average +15.8). Eight samples collected from the older gypcrete unconformably below the surficial crust had $\delta^{34}S$ ranging from +12.9 to +17.7 (average +15.9). Samples of black organic-rich mud from Sandwich Harbour

south of Walvis Bay yielded $\delta^{34}\text{S}$ of -10.96 and -8.2, and one sample of fog water provided by Hambleton-Jones yielded $\delta^{34}\text{S}$ +13.41. These results do not confirm the Martin hypothesis. Nevertheless, his evidence for preferential gypsiferous replacement of calcrete near vertical fissures within a meter or so of the surface and close to the ocean does support a meteoric origin. In his hypothesis Martin does not differentiate between the younger gypsum crusts and the underlying gypcreted gravels. For what it is worth, the identical $\delta^{34}\text{S}$ values for purely surficial gypcrete and for the unconformably underlying gravelly and sandy gypcrete, which is the host for gypcrete uranium, might be taken to suggest a similar genesis but during an earlier time. Or it may merely indicate downward migration of sulfate replacement. The occurrence of workable quality salt deposits beneath gypsum layers at depths of 1 1/2 - 12 m or more in calcreted gravels near Swakopmund (Gevers and van der Westhuyzen, 1932) might be similarly explained by mist transport of marine salts followed by illuviation of both halite and gypsum.

The only gypcrete carnotite mineralization on the Namib Desert known by the writer to be of ore grade as of 1976 (see Tubas Grant Prospects, 5.2.2 below), is in the lower gypcrete.

5.2   DESCRIPTIVE GEOLOGY OF SOME SPECIFIC OCCURRENCES IN
                 SOUTH WEST AFRICA

5.2.1   LANGER HEINRICH

(Lat. 22° 49'S; Long. 15° 20'E; Elev. 600 - 750 m)

5.2.1.1   Location, Discovery, and Present Status

The Langer Heinrich orebody 90 km east of Swakopmund is the best known and most thoroughly explored calcrete uranium deposit in South West Africa. Although ore reserves have not been announced as of this writing, a note in Engineering & Mining Journal of July 1977 states that "a major new uranium mine is on the horizon in South West Africa (Namibia). Geological and technical investigation at the Langer Heinrich Mountain near Swakopmund has indicated that a profitable mine can be established, according to Dr. Wim de Villiers, chairman of General Mining and Finance Corp." When placed in operation this would be, for South West Africa, the second after Rössing, some 40 km to the northwest, though not of the same order of magnitude.

The deposit is in the northeasterly part of Namib Desert Park about 10 km south of the Swakop River and about one-half as far (40 km) from the base of the Great Escarpment as from the ocean. It is thus further from the ocean and at a higher elevation than any of the other calcrete or gypcrete deposits of significance in this region.

The exposures are not actually on the platform of the Namib Desert, but in a more recently incised east-westerly valley formed where the Gawib and Tinkas Rivers have worked their way headward from the deeply rejuvenated Swakop River (Figures 5.1, 5.6). With Langer Heinrich Mountain rising to 1152 m directly to the north and the Schieferberg-Bloedkoppie immediately on the south, the mineralized calcrete is confined to a zone about 1/2 km wide and 13 km long in the axis of this "Langer Heinrich" valley.

Discovery of carnotite in this area probably goes back 20 years. A. von Stryk, a local miner working pegmatites in the Langer Heinrich area for gem tourmaline, is said to have seen the yellow mineral in the late 1950s and had it identified as carnotite by a German geologist.

Figure 5.6
Generalized Geology of Langer Heinrich
(After General Mining and Finance and Jacob, 1974)

The Kleins (father and son) of Swakopmund also saw the carnotite, had walked over it, and flown over it with a scintillometer observing anomalous radiation. The first claims were staked apparently during a period of government closure precipitated by a rush of applications following the discovery of Rössing and were held invalid. Very early in the 1970s the State undertook an aerial radiometric and magnetic survey of the desert region which includes Rössing. The survey was not published nor made generally available, but all the anomalies were evaluated, grouped into concession areas and awarded to six consortiums comprising all applicants for concessions. Ground scintillometer surveys confirmed the airborne surveys in several places. General Mining Corporation, heading the consortium which received the Langer Heinrich concession, began a percussion drilling program in early 1974. Holes were put down to 30 m on average and within two days, it is said, a million tons of well-mineralized calcrete had been found. Within a month ten times that amount could be estimated, and twelve months later the present reserves were essentially established with the expenditure of less than one-quarter million dollars. In all, some 1500 percussion drill holes and over 100 diamond drill holes have been placed through the water table and mostly to a depth of 30 m. In addition, 36 rectangular pits or shafts 1 X 2 m have been sunk by drilling and blasting to an average depth of 15 m, maximum 20 m, in nine sets of four on 100 m corners, and spaced from one end of the orebody to the other. Cyclone percussion drill samples agreed very closely with shaft samples; diamond drill core samples were a little low.

At the time of the writer's visit in September 1976, no plant other than that required for test sampling and storage had been erected. J. Fouché of General Mining and Finance Corporation has indicated that metallurgical and recovery tests have been completed and that there are no unusual problems. The clay-sized fraction, which is present throughout the calcrete and tends to increase with depth or in local areas, is a source of slimes but can be handled effectively. As much as 5 - 10 percent of the ore may be in gypsiferous calcrete. Water supply is as much of a problem here as elsewhere in this desert region. The calcretes are not cavernous and not good aquifers.

Figure 5.7

Diagrammatic Cross Sections Showing the Relationship of Mineralized Calcrete to Bedrock, Terraces, and Fans at Langer Heinrich

ALONG THE GAWIB RIVER

QUATERNARY ~~~~~ Surficial sheet calcrete

TERTIARY { Valley calcrete
Zone of carnotite mineralization ($>0.01\% \text{U}_3\text{O}_8$)

ACROSS THE GAWIB RIVER

The writer is especially appreciative of the cooperation of General Mining and Finance Corporation Limited for arranging his visit to the property. Mr. J. Fouché, Manager: Exploration & Geology for General Mining and Finance Corporation, provided information in Johannesburg; Mr. Klaus Linning, Divisional Geologist in Windhoek, provided additional data, lengthy discussions, and much logistical help; and Dr. J. W. O. Hartleb, resident geologist, guided the author on the property. Prior to the writer's visit to South West Africa, both Dr. von Backström and Dr. Hambleton-Jones provided literature and valuable insights to the occurrences there.

The writer takes full responsibility for any quantitative estimates in the following descriptions. No program of representative sampling or detailed mapping was undertaken. Except where quotations are indicated or credit is given, the inferences drawn are those of the writer.

5.2.1.2 Bedrock Geology and Potential Source Rocks

The bedrock geology shown on Figure 5.6 and diagrammatic cross sections on Figure 5.7 are taken from data provided by General Mining and Finance Corporation, incorporating the work of Jacob (1974) as does much of the following description. A summary of the lithology of the Proterozoic formation is shown in Table 5.1.

The immediate area is dominated by an east-northeasterly trending structural dome centered on Langer Heinrich Mountain immediately north of the deposit. The dome is a medium-sized representative of many similar structures in this part of the Damara Orogen, including the better known Rössing and Ida domes, both of which are associated with bedrock uranium mineralization. Quartzite, conglomerate, and quartzofeldspathic gneiss of the Nosib Group (Etusis Formation) crop out over the entire mountain. Red granite gneiss, an anatectic and migmatitic equivalent of Nosib Group rocks, may lie at the core of Langer Heinrich but is not exposed. The dome is mantled by steeply foliated Swakop Group ("Damara Group" of Jacob) rocks, including meta-tilloid Chuos Formation and the much more extensive biotite schist, calc silicate rock, quartzite, and marble of the Tinkas Formation. The Schieferberge,

which borders the calcrete deposit on the south, takes its name from this lithology. Neither the late Nosib Group Khan Formation nor the Swakop Group Rössing Formation have been mapped around this dome as they have in uraniferous parts of the Rössing and Ida Domes. The Tinkas Formation schists are intruded, with demonstrable cross-cutting relations and strong marginal coarse feldspathization--dent de cheval--directly east of Langer Heinrich by porphyritic and, in places, gneissic Salem granite, assertedly a granitized equivalent of Swakop Group rocks. Salem granite is reported by local geologists to have strongly anomalous uranium contents in some areas, but no Salem granite is exposed updrainage from mineralized calcrete on the Gawib or Tinkas Rivers. It may well occur to the east, however. The Etusis and the Tinkas Formations contain only 4 - 6 ppm U, but the schists of the latter are appreciably anomalous in vanadium, containing as much as 100 ppm (Hambleton-Jones, 1976 and personal communication). Visually dominating the headwaters of the Gawib River and the easterly end of "Langer Heinrich" valley is the strikingly attractive red weathering dome of the Bloedkoppie, elevation 857 m. The post-Swakop Bloedkoppie granite stretches in a northeasterly belt for at least 20 km and up to 5 km wide across the present headwaters of the Gawib and Tinkas rivers. The rock is medium-grained granite with accessory biotite, containing aplitic phases and subsequent thin pegmatite veins and is reported to contain uranium in anomalous amounts. Hambleton-Jones (1976 and personal communication) has suggested a figure of 5 - 12 ppm on average and as much as 20 ppm U in the vicinity of pegmatities and aplites. A specimen of weathered Bloedkoppie collected by the writer contained 7 ppm U measured by delayed neutron analysis. Post-Damara Gawib and Horebis granites, not known to be anomalously radioactive, crop out to the west of the Schieferberge and northeast of Langer Heinrich beyond the "Langer Heinrich" valley catchment. The alaskitic and pegmatitic metasomatic G_4 granite, famous because of its association with Rossing uranium mineralization, has not been mapped near Langer Heinrich. Later aplite and pegmatite veins do crop out in abundance, however, not only within the Bloedkoppie granite but also throughout the Tinkas Formation, and these are reportedly as radioactive as the Bloedkoppie, or more so.

Plate V-2 LANGER HEINRICH

a) View northwesterly across ore zone in "Langer Heinrich" valley on Gawib River to barren calcreted fan and Langer Heinrich Mountain.

d) Calcitic tubules in barren valley calcrete. Gawib River.

b) View easterly along ore zone, barren calcreted fan and Langer Heinrich Mountain on left.

e) Coarse angular clasts in Langer Heinrich calcrete ore, west end of zone.

c) View westerly across possible mound structure to Gawib Flat terrace.

f) Outcropping calcrete with carnnotite, middle of Langer Heinrich ore zone.

Weathering of bedrock in this area does not approach that of the tens-of-meters thick lateritic profile of Western Australia, but is about as intense, judging by appearance, as in the granitic rocks of much of the Mojave Desert or of southern Arizona, for example. Honeycomb surfaces, case hardening exfoliation, the formation of tafonis--cavernous hollows with interiors larger than entrances--and granular disintegration (Goudie, 1972) indicate mechanical and chemical processes quite adequate to release a large fraction of the contained uranium.

The anomalous uranium content of the Bloedkoppie granite and its position relative to the Langer Heinrich deposit have led to its postulation as the source rock. A rough calculation tends to discredit this one occurrence, however, as the sole source for Langer Heinrich, unless essentially every bit of the uranium likely to have been released during weathering and erosion since the start of calcrete formation were trapped in this one valley. Moreover, uraniferous calcrete is known to occur near Onanis 20 km or so east and upslope from Langer Heinrich on a dissected portion of Tinkas Flat.

5.2.1.3 Tertiary Calcrete Morphology

Excluding the surficial sheet calcretes of Pleistocene to Recent age, the calcrete units at Langer Heinrich belong to the Late Tertiary assemblage (Section 5.1.3) and are in three geomorphic settings.

- 1) Great masses of calcrete underlying the plains and terraces of the once-continuous Gawib and Tinkas Flats and the upper Namib Platform generally. These are up to many tens of meters thick, composed of poorly sorted fluvial gravels where exposed, filling in the old topography and capped by reworked pedogenic calcrete or, towards the ocean, gypcrete. The calcretes of Gawib Flat at the west end of the known Langer Heinrich deposit are of this setting, left standing as a terrace by headward erosion of the Gawib River. The terrace surface stands 10 - 15 m above the present bed of the river (Plate V-2c). Calcrete in the upper part of this terrace is seemingly barren of significant mineralization, and, since it blankets radioactivity and adds to the overburden on possible ore, it has apparently discouraged drilling to the west.

- 2) Calcreted fan gravels, on the southern flank of Langer Heinrich Mountain. The fan surfaces are elevated about 10 - 15 m above the Gawib River bed and without doubt once merged with the calcreted plains described in 1) above. They are truncated by the Gawib River on the northern margin of the uranium deposit (Figures 5.6, 5.7, Plate V-2a). Fanglomerate clasts are exceptionally coarse, unsorted, angular, and of local derivation, i.e., mainly Nosib quartzite and Tinkas schist. This calcrete also is barren of significant uranium mineralization.
- 3) Langer Heinrich Calcrete. Calcrete exposed along "Langer Heinrich" valley by Gawib River erosion, including the mineralized zone, is, in fact, the lower part of the calcrete described in 1) above and not a younger valley fill. Hambleton-Jones has recognized this relationship and proposed the name Langer Heinrich Calcrete Formation for the lower part and Gemsbok Calcrete Formation for the overlying part on the fans and terraces, basing the distinction on the presence of an unconformity between them. The whole calcreted section is replete with scour and fill and intraformational erosion surfaces at many levels, however, and the two-fold subdivision may not hold. Nevertheless, it is only this deeper calcrete that hosts appreciable uranium mineralization. But it is also only within "Langer Heinrich" valley that it does so. Judging from exposed bedrock topography and the sporadic occurrences of bedrock knobs along "Langer Heinrich" valley, highly variable thicknesses of calcrete are to be expected. Apparently ore-grade calcrete is not known to be deeper than 30 m.

The present-day gradient on the mature terrace surface, i.e., from Tinkas Flat to Gawib Flats, is 0.9 percent, which is 9 - 12 times as steep as that of the central Yeelirrie channel and 45 times as steep as the gradient through the Yeelirrie orebody. What fraction of this steeper gradient might be tectonic is not known. The gradient on the Gawib River itself is more than 1 1/4 percent but has nothing to do with uranium mineralization, in the writer's opinion.

Langer Heinrich Exploration Pit Profiles

(After J.W.O. Hartleb, General Mining and Finance Corp., Ltd.)

Figure 5.8

Near the west end of the Langer Heinrich mineralized zone, a low erosional dome of mature calcrete (Plate V-2c) stands 3 - 4 m above surrounding calcrete and alluvium midway between knobs of outcropping Tinkas schist and granitic dikes 200 - 300 m to the north and south. Carnotite is obvious in this area, and it is also the center of a marked radiometric anomaly. The impression of the writer, after seeing the Australian deposits, is that here perhaps is the South West African counterpart of a mound resulting from the constraining of groundwater flow between bedrock highs and its forced upwelling. Even though upwelling occurred beneath an appreciable thickness of overlying gravels, the forced rise would have brought the capillary fringe much closer to the ground surface and thus enhanced carbonate precipitation.

5.2.1.4 Conglomeratic Calcrete Lithology

The mineralized host sediment ranges from torrential stream channel fill to quieter water deposits. Sedimentary structures and textures very different from those of Western Australia have been recorded on meticulous pit profiles prepared by J. W. O. Hartleb, resident geologist (Figure 5.8).

The sedimentary clasts are of nearby bedrock, with little or no sorting, rounding, or weathering. The smaller clasts, grit- to sand-sized, are largely of granitic derivation (Plate V-3a), including sharply angular, less commonly subrounded, very fresh rock and crystal fragments dominantly of calcic to potash feldspars, quartz, and fresh biotite flakes as well as amphiboles, pyroxenes, and other accessory minerals. Fragments of quartzite, schist, and smokey, radiation-damaged pegmatitic quartz are quite common.

The carbonate cement is also very different from that of the Western Australian uraniferous calcretes. Instead of the extremely fine-grained irregularly mottled clusters and obscure veinlike areas representing calcitic and dolomitic replacements of clay which typify the Australian host rocks, one most commonly sees clear crystalline mosaics of nonmagnesian sparry calcite. These strongly resemble the calcite of nonpedogenic groundwater caliches developed in coarse alluvium and unrelated to a soil profile. Calcite ranges widely in abundance

Plate V-3 EPIGENETIC STRUCTURES, CALCRETE. S.W.A.

a) Langer Heinrich Cut slab of high grade ore showing irregular calcite replacement bodies in calcrete Darker areas marked (c) are massive carnotite

b) Calcrete-gypcrete west of Klein Spitzkoppe Calcareous tubule with massive carnotite (c) and later fine-grained barren calcitic shell (s)

but averages around 20 - 25 percent. Finer varieties occasionally vein and push apart sedimentary clasts, but there is also both megascopic and microscopic evidence (below) for metasomatic replacement of the clasts on a local scale. Gypsum may constitute up to roughly 2 percent of the cementing material in the upper 3 - 4 m of the calcrete but only in patches, since Langer Heinrich is at the extreme inland edge of coastal fogs and of gypcrete. Secondary quartz or opal is not seen, and this, too, is strikingly different from the Australian occurrences.

The calcrete is dense and tough, requiring drilling and blasting, but it is not impermeable. In one exploration shaft surface water which had risen an additional 5 m after a rain is reported to have drained back to its normal level in 5 months (one-quarter to one-third of the return could be ascribed to evaporation).

5.2.1.5 "Clay"-rich Calcretes

As shown on Figure 5.8, "clayey conglomerate, clayey grit, clayey sandstone, and clayey siltstone" is increasingly abundant with depth or in local areas. Within the main calcrete there are mixed "clay"-carbonate cemented layers. One exploration pit near the east end of the deposit is in micaceous "clayey" silt, moderately calcified throughout its entire 12 m depth, while pits within 100 m are strongly calcreted.

In thin section the "clay" is seen to be a mica-rich clay-sized to silt-sized variant of the same fluvial sediments found elsewhere in the calcrete. Fresh angular quartz and feldspar make up about 30 percent of the rock, biotite and muscovite make up about 20 percent, and almost-clear calcite as prisms, mosaics, and, in some areas, replacements of mica and feldspar make up roughly 50 percent. An impalpable matrix is present, but X-ray diffraction analysis failed to indicate any definite clay mineral. Carnotite is present throughout the "clay"-rich pit and is visibly abundant on some specimens. The pit is said to be of good grade.

5.2.1.6 Solution and Replacement Features

Superimposed on the primary sedimentary features are some important structures developed by solution and refilling and/or replacement of the calcrete (Figure 5.8, Plate V-3a).

- 1) Most important are irregular amoeboid or fingerlike bodies or mottled areas. These bodies may be up to several centimeters in length and characteristically have shells of lighter colored, finer-grained calcite cement which transects the main calcrete and its coarse-grained calcite. They may have very abundant carnotite in interior parts or they may be completely barren. In hand specimen and in thin section, carnotite can be seen replacing the finer-grained calcite, and both may be replaced in turn by still finer-grained barren calcite (Plates V-3, V-4). Similar structures occur in calcretes elsewhere in South West Africa.
- 2) In the coarse calcrete are rare, more or less vertical, irregular pipelike bodies up to 1/3 m in diameter and 3 m long, filled with weakly cemented sand and, in a few places, abundant carnotite. These can create problems in evaluating drill data.
- 3) In the "clayey" calcrete, vertical pipelike or irregular bodies up to 1/2 m by 3 m filled with hard, cemented calcareous grit and sand occur at random. These may or may not contain carnotite.
- 4) Very rare concretions of nearly pure calcite are also seen. These are barren to the writer's knowledge.

5.2.1.7 Mineralization

Uranium mineralization of economic interest, i.e., greater than 0.01 percent U_3O_8 , forms an irregularly discontinuous, undulating layer within the lower (Langer Heinrich) calcrete (Figure 5.7). The favorable zone is from 5 - 15 m thick in general, as much as 30 m deep at the maximum, and extends over an area of at least 13 km X 1/2 km. According to unconfirmed estimates grades are mainly in the 0.02 - 0.05 percent U_3O_8 range, averaging 0.04 percent, but several times that concentration can be found locally. The lower boundary is fairly well marked. Overburden averages about 8 m thick. Carnotite in lesser concentrations occurs sporadically above and below the economic layer and, according to K. Linning (personal communication, 1976), has been observed to extend downward into schist bedrock by as much as 4 m with no obvious carbonate cementation.

Plate V-4 CARNOTITE IN CALCRETE AND GYPCRETE, S.W.A.

a) Langer Heinrich. Host Calcrete showing fresh angular granitic detritus and sparry calcite cement.

d) Calcrete-gypcrete west of Klein Spitzkoppe. Carnotite grains in fine-grained secondary calcite (right) transected by gypsum (left) which is itself mineralized mainly along grain boundaries.

b) Langer Heinrich; high grade. Euhedral carnotite (dark) in irregular stringers and lining cavity with still later calcite in medium-fine grained secondary calcrete.

e) Tubas Grant; gypcrete mineralization. Carnotite (black) in gypsum around margins of quartz and feldspar grains, in irregular replacements and along cleavages.

c) Langer Heinrich; high grade. Euhedral carnotite (dark) in medium-fine secondary calcrete and along border with late very fine grained barren calcite.

f) Tubas Grant; gypcrete mineralization. Enlargement of part of e) showing subhedral to euhedral carnotite.

Megascopically, the carnotite is in local concentrations, centimeters to meters apart and from a few specks to areas of 5 - 10 cm in diameter. It may appear to coat aggregate clasts, but slips and fracture planes with carnotite coatings are not found here as they are in Australian calcretes. There may be some tendency for higher uranium values to occur in coarser phases of the calcrete, and, within a given exploration pit, mineralization may tend to concentrate in one or a few strata (Figure 5.8); but in general there is no obvious correlation between grade and gross lithology, nor does the amount of megascopically visible carnotite correlate directly with chemical analyses. Richer material may be at any level within the economic layer.

5.2.1.8 Calcite - Carnotite Relations (Plate V-4)

Three general ranges of calcite grain size are characteristic of specimens collected by the writer and they appear, in thin section and hand specimens, to represent a sequence from older (coarse) to younger (fine) as follows.

- 1) Irregular mosaics of 0.05 - 0.5 mm sparry calcite grains, occurring in undisturbed and unreplaced calcrete which is well packed with noncarbonate clasts. The fabrics strongly suggest recrystallization (aggrading neomorphism) of the primary cement (Bathurst, 1975). In places spotty, coarse, loosely bound carnotite may be associated with this calcite.
- 2) Irregular mosaics of 0.01 - 0.05 mm sparry (recrystallized?) calcite grains, commonly in the interior parts of the irregular amoeboid or fingerlike bodies or mottled areas (Section 5.2.1.6 above) and transecting the undisturbed calcrete. These can be replaced by abundant euhedral to subhedral carnotite (Plate V-4b).
- 3) Masses of indistinguishable grains less than 0.002 mm in size in the same bodies as 2) and transecting and replacing both the calcrete and the carnotite, if present. This is barren of carnotite in thin section (Plate V-4a) or as seen megascopically in the field.

The sequence has occurred at various levels and places within the body of the calcrete and is not related to an exposed weathering surface or soil profile of uniform depth. The solution-replacement bodies are quite irregular in size, orientation, and distribution. They demonstrate reworking of the calcrete most likely by gravitational water, and they imply substantial remobilization of carnotite. Carnotite is exclusively associated with and has grown at the expense of calcite; relationships with other minerals are fortuitous. Carnotite grains are distinctly euhedral to subhedral, and from 0.001 - 0.1 mm across. Crystals of the larger grain size have commonly grown along very irregular stringers, minute solution cracks, or cavities within the calcite mosaic and are commonly succeeded by a later coarse calcite filling (Plate V-4b). Finer-grained carnotite is characteristic of more pervasive replacements of finer-grained calcite.

The evidence for metasomatic attack on quartz and feldspar mentioned earlier is particularly clear in areas described under 2) above where these minerals commonly show serrate and corroded edges against calcite. Moreover, in these areas the proportion of clasts decreases with successively finer calcite replacements. It would be difficult to credit this latter feature solely to crystallization expansion since the bodies are surrounded by competent calcrete. The corrosion of quartz and feldspar implies strongly alkaline solutions during these latter stages of carbonate and carnotite emplacement. Again, highly carbonated gravitational water moving slowly enough to reach near-equilibrium with calcite is a likely agent. Garrels and Christ (1965) show that rainwater, having equilibrated with atmospheric CO_2 , descending and reacting with calcite in the subsurface without further loss or gain of CO_2 , will tend toward a theoretical equilibrium pH of 9.9 and $[\text{Ca}^{2+}]$, $[\text{CO}_3^{2-}]$, $[\text{HCO}_3^-]$, and $[\text{H}_2\text{CO}_3]$ activities of $10^{-3.9}$, $10^{-4.4}$, 10^{-4} , and $10^{-7.5}$, respectively. Such a solution could carry substantial uranium as carbonate complexes plus vanadium and potassium. There is no doubt that appreciable carnotite has been reconcentrated in the replacement bodies by this process and also that appreciable amounts have been redissolved and transported away.

The identification of carnotite has been confirmed by X-ray diffraction

(BFEC) of specimens of representative mineralization collected by the writer from Langer Heinrich.

5.2.1.9 Probable Tertiary Age of Mineralization

Several features suggest that the carnotite mineralization is of considerable age, and probably Late Tertiary:

- 1) Analysis of carnotite-bearing specimens by radiometric and chemical methods (BFEC) indicated essential equilibrium between uranium and gamma-ray producing daughter products. A rich calcrete specimen yielded 5.50 percent cU and 5.91 percent eU. A sample of "clayey" carbonated silt yielded 0.14 percent cU and 0.16 percent eU.
- 2) Paragenetically, as described, the carnotite precedes very fine-grained calcite along irregularly shaped replacement features deep within the lower calcrete.
- 3) Mineralization of economic interest is restricted to an undulating layer within the lower calcrete which appears to reflect bedrock morphology in a general way and not the present-day groundwater table.
- 4) The suspected mound structure, described above, is possibly a very good example of mineralization consequent to upwelling of groundwater at a time when upwelling would place the sedimentary depositional surface within reach of capillary transport and evaporation.
- 5) Mineralization appears clearly to have preceded early Pleistocene stream rejuvenation and headward erosion by the Gawib and Tinkas Rivers into "Langer Heinrich" valley. Calcrete along the lower stretches of these rivers outside "Langer Heinrich" valley is barren. Uranium mobilized after Pleistocene incision would be largely transported to the ocean.

There is evidence, discussed below in relation to the Tubas Grant prospects (Section 5.2.2), that a period of even greater aridity occurred during the latter stages of alluviation which preceded the Pleistocene rejuvenation. Alluviated, wind-blown sands appear in the upper part of

the alluvial section on the Tubas Grant and, incidentally, are the richest and most consistent hosts for uranium mineralization. The Langer Heinrich area, being further inland and adjacent to the Highlands, probably continued to be slightly wetter than the lower Namib Desert at this time, as it is today, and continued to experience calcretion of accumulating coarse debris.

It seems not unlikely that carnotite mineralization at Langer Heinrich and on the Tubas Grant took place during this Late Tertiary period of extreme aridity.

5.2.1.10 Groundwater

Some references have been made above to groundwater, and very little more information is available. The original exploration holes were essentially all drilled through the present water table. Groundwater stands in a few of the pits today. In general, the depth below the surface ranges from about 10 m in the easterly part of the mineralized zone to 7 m near the center and is deeper than the pits (15 m) at the west end. Gawib River has perhaps 6 - 8 m of unconsolidated sand in its bed. The calcrete is not a major aquifer.

Carnotite occurs above and below the present water table. According to company geologists, it has been observed to have migrated in surface washes after the very rare rainfalls. Uranium content of one groundwater sample from the mineralized zone was reported to be 1000 ppb. Samples from water bores north of the Swakop River are said to contain from roughly 10 - 350 ppb (Hambleton-Jones, personal communication, 1976).

5.2.1.11 Radiometric Expression

A distinct airborne radiometric anomaly outlines the mineralized zone at Langer Heinrich (Figure 5.6). It would not be detectable, however, if it were not for exposure of the mineralized calcrete by headward erosion of the Gawib and Tinkas Rivers. Capillary transport could not have brought sufficient uranium from more than 10 m depth to the surface of the original calcrete to produce a detectable anomaly. Uranium, if present at all in pedogenic calcretes, tends to concentrate in the lower parts and commonly at carbonate-clay interfaces.

5.2.1.12 Radon

Ra²²² detection by α -track counting on appropriate film from buried containers has been experimented with and is reported to give positive results with the overburden thickness described.

5.2.1.13 A Probable Catchment Basin, Bedrock Constraint, Capture and Exposure -- a Speculative Model

Figure 5.1 and the inset map on Figure 5.6 represent interpretations of the Gemini and Landsat photographs (Plate V-1) of the region followed by ground reconnaissance. Before Pleistocene rejuvenation and deep dissection by the Swakop, the Khan, and the Kuiseb Rivers and their innumerable short tributaries, Tinkas Flat, directly updrainage from Langer Heinrich, would have received water from many hundreds of square kilometers of what is now Swakop catchment. This water would have drained not through the Tinkas and Gawib Rivers to the Swakop, but westerly into the Tumas River drainage. Headward erosion by the Gawib and Tinkas Rivers has pirated the ancestral Tumas River catchment at the very point where it had been constrained between Langer Heinrich Mountain and the Schieferberge-Bloedkoppie.

Deposition of coarse clastic sediments during the Tertiary accompanied or followed by calcrete cementation had preceded that capture. Ancestral Tumas River groundwater draining the escarpment was funneled through the narrow Langer Heinrich valley on its way to the lower desert where it would have been forced closer to the surface and where precipitation of both calcite and carnotite would have been facilitated. Coarse sediments are more easily converted to calcrete than fine-grained ones. The decreasing permeability would have offset the comparatively steep gradient. Since that time some of the calcite and much of the carnotite has been reworked by vadose waters resulting in the solution-refilling and replacement structures described in Sections 5.2.1.6 and 5.2.1.8 above.

The Gawib and the Tinkas Rivers have now cut into those calcretes, leaving the old surface as a terrace 10 - 15 m high and exposing the deeper carnotite-bearing calcrete in Langer Heinrich valley. As in Western Australia, the constraining of groundwater flow between bedrock highs and its consequent upwelling appears to be most favorable for carnotite precipitation.

5.2.2

TUBAS GRANT PROSPECTS

(Approx. Lat. 22° 55'S, Long 15°E, Elev. 300 - 400 m)

5.2.2.1 Location, Discovery, and Present Status

Specimens of carnotite can be found in gypcrete in several places on the Namib Desert, and uraniferous calcrete prospects on the Namib commonly have gypsiferous facies. On the Tubas exploration concession, being prospected by the Anglo American Corporation of South Africa, gypcrete is the main host for what may become a viable deposit. The occurrences are on the central part of the Tumas River drainage 40 - 50 km east of Walvis Bay or about midway between Langer Heinrich and the ocean. This is within the fog belt and the zone of almost daily accretion of marine salts.

The original discovery of rich carnotite mineralization in gypcrete in the grant area was apparently made in a prospective gypsum operation in gypcrete (Martin, 1963) opened by the same A. von Stryk who is credited with the discovery of carnotite at Langer Heinrich. Disseminations and sporadic concentrations of carnotite are very evident beneath the superficial crust in several of his shallow open cuts and in a shaft 5.5 m deep in gypcrete. The discovery is on the northerly edge of what is now recognized as an irregularly shaped patch of ground several kilometers in length underlain by grades of 0.01 percent U_3O_8 or higher over thicknesses of at least 1 m (Figure 5.9).

The exploration program of Anglo American Corporation, as of 1976, covers several hundred square kilometers within the concession area. Airborne radiometry has been of limited value. According to information given to the writer, anomalies are detectable but are not strictly definitive. Ground radiometry is useful locally, but the barren capping of gypsum and overbuden from 1 - 15 m thick limits its applicability. Soil sampling has not been effective. Radon mapping with α -track sensitive film was being used routinely at the time of the visit as a guide for drilling. Films were being buried at 250 m separation on lines spaced 1 km apart, and broad anomalies were being obtained which were usefully indicative of the pattern of mineralization determined by subsequent drilling on the same spacing, though in some areas radon anomalies and

the drilling results do not superimpose. Air track drilling has been employed to depths as great as 50 m, but current practice has been to drill only to the water table, which in this area is usually in the vicinity of 15 m. Some sporadic values were originally found below the water table but no significant mineralization and no visible carnotite. Exploration is being continued on the grant.

The writer is especially appreciative of the efforts of A. B. McKerron, D. A. M. Smith, Henk Gewald, and G. F. Wagener for arranging access to the deposits and for logistical support as well as useful discussions. Mr. Clive Kirk, resident geologist, kindly provided guidance in the field.

5.2.2.2 Geomorphic and Surficial Geological Setting on the Tubas Grant

There are marked differences but also similarities between the geological-geomorphic setting of the Langer Heinrich and Tubas Grant deposits.

One's first impression of the area is that of a desolate, windswept plain with so little vegetation that survival of the ostrich population and the many lesser birds and animals seems incredible. Precipitation from the fog, the only reliable source, exceeds that from the rain by up to many fold but is only 1/100 of the potential evaporation. Yet this is a cool desert except for those few days in winter when the hot, dry Berg or East Wind blows. Except for rare low ridges of metamorphic rock the surface is strewn with desert pavement and a seemingly pervasive gypsum crust. Traveling across it, however, one sees appreciable relief, commonly up to several meters along the current Tumas River and tens of meters on knobs and ridges of marble. Beneath the dominant, mature surface, probably correlative with the Main Terrace surface of Mabbutt (1952), as many as 6 or more terrace surfaces, only meters apart vertically, indicate minor rejuvenations of the drainage. On each of these surfaces a capping crust of recent brittle, open-textured surficial gypcrete or of soft gypsiferous sand from a fraction of a meter to 1 m thick has formed and continues to form today, the older and higher the terrace surface, i.e., the longer the surface has remained stable, the thicker the gypcrete. These gypcrete crusts do not project into the

hillside beneath overlying terraces--as proven by drilling--and in this respect their origin and morphology and their role in conserving terrace surfaces is analogous to that of pedogenic caliches on fan and terrace surfaces in many parts of the world. They are generally barren of carnotite; the uranium content of 19 samples taken by the writer ranges between 2 - 7 ppm except for one crust directly over carnotite-bearing gypsiferous sand which contained 16 ppm U. As at Langer Heinrich, the ore host is an older formation unconformably beneath the capping crust except that here, rather than being calcrete, it is composed of compact mature gypcrete, or importantly, gypsiferous sand lenses within gypcrete lying below the surficial crusts and stratigraphically below the dominant Main Terrace surface. For reasons noted in the regional discussion (Section 5.1.3) the older alluvial fill is thought to be Tertiary in age.

The present Tumas River drainage is entirely on the Namib Platform, heading some 30 km to the east on Gawib Flats and on southern Tinkas Flat (Figure 5.1). Lacking a major catchment in the Highlands, it has incised the platform sediments only very weakly in comparison with the Kuiseb and Swakop-Khan systems, and it fails to reach the ocean. But, as hypothesized in the Langer Heinrich discussion, the ancestral Tumas River was a larger system, heading above the Great Escarpment, part of it flowing through "Langer Heinrich" valley and out onto the ancestral Namib Desert to the Atlantic. Gypcrete occurrences on the Tumas River were downdrainage from Langer Heinrich during the period of Late Tertiary alluviation and development of the Namib Platform. The succeeding period of deep incision by all the major rivers was initiated by uplift at the end of the Tertiary and by Pleistocene pluviation. The Swakop River, with large catchments in the Khomas Hochland, cut downward more rapidly than most and, by means of its tributaries, the Tinkas and the Gawib, pirated a major part of the catchment of the ancestral Tumas River. The hypothesis has gained support from the diamond core holes drilled by the Anglo American Corporation showing that the depth to bedrock along the course of the Tumas River is more than 100 m, while on valley sides much lesser depths are found.

The topographic gradient on the Namib Platform and on the Tumas River

FIGURE 5.9
SKETCH MAP OF A PART OF THE TUBAS GRANT

FIGURE 5.10
DIAGRAMMATIC SECTION OF THE NAMIB PLATFORM AT THE TUMAS RIVER

today in the area of the Tubas Grant is 0.76 percent. This is 8 - 10 times as steep as the gradient on the central Yeelirrie channel and 40 times the gradient at Yeelirrie orebody itself. A considerable fraction of the Namib gradient, however, could be tectonic and may postdate both the host sediments and the uranium mineralization.

5.2.2.3 Bedrock Geology on the Tubas Grant

The area is only 10 - 20 km southwesterly along the Damara structural trend from very well exposed sections of highly metamorphosed Nosib and Swakop ("Damara" of Jacob, 1974) Group rocks, their anatectic equivalents, and post-Swakop intrusives described by Jacob in the Swakop gorge. The basement beneath the Tubas Grant undoubtedly includes all of these. A leucocratic granite encountered in one core hole resembles the G₄ granite of Rössing fame. Particularly noticeable on the landscape, and important in terms of bedrock morphology and probably in terms of gypcrete uranium mineralization as well, are long ridges of Karibib (Husab) Formation marble extending from the Husaberg north of the Swakop River southwesterly along the Witpoortberge south of the river and continuing intermittently in folded outcrop pattern across the entire Namib Desert Park to the Kuiseb River. These are very evident on the Gemini and Landsat photographs (Figure 5.1). At least one occurrence of folded Karibib marble creates a bedrock constriction where it crosses the Tumas River drainage, and this appears to be related to significant carnotite mineralization on the Tubas Grant.

5.2.2.4 Calcreted and Gypcreted Tertiary Alluvium and Mineralized Sand (Figure 5.10)

The thick alluvial gravels and sands which accumulated in the valleys and the irregularities of the old "African" erosion surface beneath the Tubas Grant are generally similar in composition to their counterparts near Langer Heinrich but are much better sorted and more rounded. Radiation-damaged smokey pegmatite quartz is a common constituent.

Five diamond core holes have been drilled through the older alluvium to basement. One along the course of the Tumas River penetrated 2 m of barren surficial gypcrete; 9 m of gypsiferous red sand with spotty carnotite;

91 m of unmineralized calcrete containing gray silty sand, medium to bouldery gravel, and silt; and, finally, 10 m of weathered regolith resting on bedrock schist. Another, also in the valley, penetrated 1.7 m of gypcrete crusts, 5.5 m of red-brown alluviated aeolian sand with gypsum and minor calcite, and 100 m of calcrete containing pebble conglomerate and sand before encountering granite directly beneath well-rounded gravel. Still another, to one side, reached granitic basement in only 37 m after passing through 25 m of gypsiferous sand and 12 m of gypsiferous granitic alluvium, without any calcrete. The enormous volume of alluvial fill plus the sorting and the rounding of the clasts lends credence to the hypothesis that the ancestral Tumas River had a longer course.

Gray and red-brown aeolian sands in the upper 25 m or less of the fill may indicate a period of increased late Tertiary aridity. The sands seem not to have dune morphology but have been incorporated into the fluvial section as beds, fingers, and lenses meters to tens of meters in dimension. Almost exclusively quartz and feldspar, the sand grains are mainly 0.05 - 0.5 mm in diameter, frosted, and well sorted for the most part but not particularly well rounded. Even where variably cemented with gypsum and minor carbonate, the sands appear to have remained very permeable, and they are the most consistent hosts for carnotite mineralization.

Both the sands and the coarse alluvium integral to the Late Tertiary alluvial fill underlie the Main Terrace surface and are transected by Tumas River pluvial (?) erosion. Their contact with overlying (and unmineralized) gypcrete caprock which is readily seen in outcrop is, therefore, an erosional unconformity of appreciable time span (Plate V-5). In other words, the relationship of surficial gypcrete to the main body of gypcrete in this area is exactly analogous to the relationship of surficial pedogenic calcrete to the main body of calcrete in the Langer Heinrich area.

The contact between gypcrete and underlying calcrete in this old alluvium may or may not coincide with the base of the sand. In the first diamond core hole mentioned above, the contact is within the sand; the

gypcrete mineralized with spotty carnotite above 10 m, the calcreted gray silty sand, unmineralized, below. In the second, it does coincide with the base where gypsiferous red-brown sand with minor carbonate gives way to light gray calcreted pebble conglomerate at 7 m. In the third, 25 m of sand and 12 m of granite regolith are entirely converted to gypcrete with only minor carbonate and no real calcrete. In outcrop, channel fillings of quartz-rich gypcreted pebble conglomerate commonly occur within the gypcreted sand section.

Nevertheless, the appearance of alluviated aeolian sands and the implication for more extreme aridity (or a climate approaching that of today) does seem to correspond broadly with the change from calcrete to gypcrete cementation. Is it unreasonable to believe that conditions which create gypcrete today within reach of ocean mist and fog might not have existed in the Late Tertiary? And might not the formation of gypcrete occur directly both then and today rather than as a replacement of pre-existing calcrete? Martin (1963) reports that surficial gypcrete in von Stryk's prospect area may contain more than 80 percent of gypsum, whereas the lower conglomeratic varieties average only 33 - 65 percent gypsum.

Goudie (1972, p. 20) has observed that

"In the vicinity of the marble ridges and inselbergs the gypsum contains above average quantities of CaCO_3 , and three samples from Swartbank had CaCO_3 contents of 44.5, 21.6 and 35.1 per cent, thus showing the local effects of the highly calcareous marble (96 per cent CaCO_3). The mean calcium carbonate content of the most calcareous horizon in 25 localities sampled by myself between Walvis Bay and just beyond Gobabeb, and by Scholz (1963) between Walvis Bay and his station Namib 7, was 12 per cent."

An observation will be reported next which suggests that the original carnotite mineralization in gypcrete, like that in the Langer Heinrich calcrete, predates the Pleistocene pluvials and deep incision into the Tertiary alluvial fills.

5.2.2.5 Mineralization on the Tubas Grant

The most consistent host for carnotite on that part of the Tubas Grant seen by the writer, i.e., essentially the central portion along and adjacent to the Tumas River, is red-brown (hematite coated) gypsum-cemented

Plate V-5. TUBAS GRANT PROSPECTS

- a) View easterly up Tumas River on Middle Namib Desert. Foreground, Karabib Limestone. Center, riverbank cut location below surficial-sheet gypcrete.
- b) Surficial-sheet gypcrete unconformably over valley gypcrete, Tumas River.
- c) Riverbank cut, knife at lower limit of red-brown gypsiferous sand. (white = pick marks)
- d) Conglomeratic ore-grade gypcrete with abundant carnotite, von Strykes's shaft.

sand. In several places, including von Stryk's shaft and in a vertical "riverbank" cut above the present Tumas River bed (Plate V-5), red-brown hematite-rich gypsiferous sand is underlain by gray gypsiferous sand at a depth of 2 - 4 m below the surficial gypsum cap. The change takes place along a fairly sharp horizon unrelated to sedimentary structures, suggesting a fossil groundwater table. The concentration of uranium mineralization drops markedly below this horizon. In the riverbank cut, the horizon is about 2 m above the present stream bed and perhaps 10 - 15 m above the permanent water table encountered in exploratory drilling. The tenor of mineralization in samples collected quickly by the writer drops from 0.06 percent cU and 0.06 percent eU (BFEC) above this horizon to one-third of that figure below it. In von Stryk's shaft the same color change is observed, and the horizon corresponds quite closely with the upper surface of rounded pebble conglomerate; massive and spotty carnotite mineralization is visible throughout the upper 3.5 m of red-brown gypcrete above the horizon but is only sparsely present in gray gypcrete below. Laboratory analysis (BFEC) of a richer specimen from above the horizon showed 1.27 percent cU and 1.25 percent eU.

The writer's observations are limited, of course, but the apparent relationship of mineralization to a fossil water table suggests that the carnotite was emplaced prior to the present deeper groundwater regime and, inferentially, prior to rejuvenation of the Tumas River, however slight that has been. The measured equilibrium relationship between uranium and daughter product gamma-radiation indicates an appreciable age. Taken in conjunction with observations cited in the discussion of Langer Heinrich mineralization, there seems to be support for the writer's belief that initial carnotite mineralization tended to coincide with a period of increased aridity in the Late Tertiary.

Clive Kirk, resident geologist, pointed out during the visit that gypsum cementation results in a noticeably greater permeability than does carbonate cementation. This probably reflects crystallization expansion pushing sedimentary grains apart as the gypsum grows by atmospheric accretion as well as the cleavage and the solubility of gypsum and perhaps of entrained salt as well. This, too, raises the possibility,

he suggests, that gypcrete formation and carnotite deposition may have been more or less contemporaneous.

Microtextural relations (Plate V-4b,c) place the presently visible carnotite later than gypsum cementation, though not necessarily much later since there are no massive replacements nor veins of carnotite cutting the gypsum. Euhedral carnotite crystals 0.001 - 0.01 mm in diameter are arranged in clusters on the margins of quartz and feldspar grains and in interstices where they have partially replaced gypsum and also, less abundantly, within the gypsum where there is a tendency to preferential alignment along cleavages. Some quartz and feldspar clasts are clearly corroded in areas of intense carnotite replacement.

Figure 5.9, a diagrammatic sketch map, illustrates an apparent relationship between carnotite mineralization and bedrock morphology. The resistant marble unit is the outcropping, southwesterly trending ridge of Karibib Formation mentioned earlier and clearly visible on the LANDSAT photograph (Figure 5.1). Drill data indicate that the marble continues beneath the Tumas River in the roughly 2 km gap between exposures. The riverbank exposure and von Stryk's shaft discussed above are in an irregular zone within the gypcrete which is thought, on the basis of exploratory drilling, to contain at least 0.01 percent U_3O_8 over depths of at least 1 m. Grades very much higher than this are obtainable within the zone, but the distribution is said to be patchy and to reflect the occurrence of the red-brown sand. The marble ridge constitutes a bedrock constriction and does affect the water table. But whether the distribution of significant carnotite mineralization should be credited primarily to the effect of the constriction on the water table and consequent evaporation, CO_2 loss or increased Eh or primarily to its control over the original distribution of sand layers and lenses during sedimentation is a moot point in the light of information available to the writer.

The relationship of significant mineralization to the present-day water table, i.e., its restriction to the vadose zone, was mentioned above in connection with exploratory drilling practice. It is not clear to the writer whether this in itself indicates remobilization of the uranium or whether the present-day water table is simply always a few

meters below the controlling (?) fossil water table. Remobilization of carnotite is evident locally. In one trench along the Tumas River bank a vague band of carnotite continues from sandy gypcrete into gypsiferous colluvium. In another area gypsiferous and carbonaceous soil contains carnotite locally.

According to Kirk (personal communication, 1976), carnotite is the only secondary uranium mineral identified from samples taken by the company.

5.2.3 CALCRETE URANIUM PROSPECTS IN THE KLEIN SPITZKOPPE AREA

(Lat. 21° 53'S, Long. 15°E, Elev. 800 - 1000 m)

5.2.3.1 Location and Geomorphic and Geologic Setting

Brief visits were made to these interesting properties on September 30, 1976. They illustrate some of the features of Namib Desert deposits already seen and a new one only briefly mentioned in connection with Langer Heinrich, namely the occurrence of carnotite in significant amounts in weathered bedrock schist.

The area is on a continuation of the Namib Desert Platform 100 km northeast of Swakopmund, 70 - 90 km east of Henties Bay on the Atlantic coast and 100 km northerly from the areas just described. The climate, the degree of bedrock weathering, and the development of gypcrete and calcrete are virtually identical with those of the region containing the Tubas Grant and Langer Heinrich. Drainage is mainly to the Omaruru River which is less deeply incised than the Swakop-Khan drainage but otherwise bears the same relationships to bedrock, to the Tertiary post-"African" alluvial fill, and to the calcretes and gypcretes. The Proterozoic bedrock is just on the northerly flank of the northeasterly trending belt of highest metamorphic grade within the Damara Orogen. Swakop Group metamorphic rocks and post-Damara anatectic and intrusive granites, including tin and gem topaz-bearing pegmatites, crop out mainly on pediments and low ridges. The sharply pointed Klein and Gross Spitzkoppie (Figure 5.1) are composed of Mesozoic Karroo or post-Karroo granitoid rocks. West of Klein Spitzkoppe is a large resistant Karroo dolerite dike forming a northeasterly trending ridge, the Swartberge. Beginning at the coast a gypcrete crust covers all of the stable sedimentary surfaces, becoming mixed with calcrete near the prospects and giving way completely to calcrete further inland.

5.2.3.2 Bantu Mining Corporation Prospect near Klein Spitzkoppie-- A Bedrock Constriction

Two separate properties are involved. The easterly, discussed first, is under exploration by the Bantu Mining Corporation, a public company incorporated to assist in the development of native African territories and

Figure 5.11
KLEIN SPITZKOPPE AREA

technical training. It is entirely within a Damara Homeland. The writer was taken to a mineralized area immediately east of Klein Spitzkoppe by Mr. van der Merwe, resident geologist, and Mr. Dippenaar, chief mineral technician. Subsurface exploration up to that time had been entirely by percussion drilling, and only one trench 2 m deep was available in which the carnotite mineralization in calcrete could be examined. Drilling has been done to as much as 50 m depth but is mainly only to the groundwater table at a lesser depth.

The area visited is centered approximately on the trench, and it appears to be a classical example of calcrete uranium mineralization directly updrainage from a bedrock constriction. As shown on Figure 5.11, it lies along the course of the Spitzkoppe River, a tributary of the Omaruru with its bed only a few meters below the uppermost calcrete surface. A north-southerly arcuate line of granitic hills, of which Klein Spitzkoppe is the northernmost and highest member, crosses the course of the river 2 - 4 km west of the prospect. In the prospect area east of this arcuate line the present-day slope gradient on the river has been decreased to less than 0.5 percent. Immediately downdrainage from the constriction it increases again to 1.5 percent. The flattening of gradient above the constriction must have been even greater prior to complete alluviation, and the retarding effect on subsurface groundwater flow through the developing calcrete commensurately greater. The uraniferous area is precisely where maximum impoundment and closest approach of the groundwater table to the surface would be expected to have occurred. In the trench, irregularly distributed carnotite concentrations can be observed throughout the calcrete below a thin, reworked, surficial caliche crust. The calcrete is a moderately well cemented, open-textured, and permeable pebbly grit. In thin section angular, unsorted, and unweathered crystals and rock fragments entirely of granitic derivation, including sparse muscovite and biotite, are cemented by 40 - 50 percent of almost-clear calcite crystals up to 1.5 mm in mosaics, as at Langer Heinrich, and as incrustations. Minor gypsum rims both calcite grains and sedimentary clasts. Carnotite, again the only uranium mineral, is associated with the calcite, coating grains adjacent to open spaces and along grain boundaries. X-ray

fluorescence analysis indicates 2 percent MgO.

No evidence could be seen during the brief visit that a lake had actually formed above the constriction, and nothing resembling lake beds was found. Nor was there anything suggesting a calcrete mound as was the case at Langer Heinrich. The writer estimates that perhaps 3 m of overlying calcrete has been eroded by Spitzkoppe tributaries in the prospect area.

Both airborne and ground radiometric anomalies can be detected on this prospect over an area of at least 1 km by 0.5 km.

Two other anomalous calcrete uranium areas, one to the northwest, the other to the southeast, were pointed out on a geological map and air photos and described to the writer. One, at least, appears to be in the same geomorphic situation, that is to say, immediately updrainage from a bedrock constriction.

5.2.3.3 Calcrete-Gypcrete Prospect West of Klein Spitzkoppe--Carnotite-Sand Tubules--Bedrock Constriction

The second property visited in the area is 8 km west of Klein Spitzkoppe on Farm Marenica. Discovery by scintillometry from a light aircraft has been credited to Mr. Klein of Swakopmund. At the time of the visit the property was being explored by Goldfields Consolidated Corporation. No drilling had yet been done, but resistivity, hammer-seismic, and gravity surveys had been run, and the first two had provided correlative data on depth to bedrock. Exposures consisted of several small open cuts and fairly lengthy trenches. The writer was conducted to two very interesting but quite different carnotite-rich showings by Mr. J. A. Pinna, resident geologist.

The first showing is in a gypcrete-calcrete and again appears to illustrate the importance of bedrock morphology and constriction of groundwater flow. It is located (Figure 5.11) along a network of closely spaced intermittent streams which head near Klein Spitzkoppe and flow toward the ocean. While these are merely present-day drainages, they illustrate the most likely course of groundwater flow from the highlands in the east toward the ocean during calcification of the alluvium and emplacement of the carnotite. The impediment to that flow was provided

in part by the resistant dolerite ridge, Swartberg, mentioned earlier, and in part by granite and schist which crop out a few hundred meters to the southwest. These are the only obvious outcrops west of Klein Spitzkoppe, and both are downdrainage from the showing.

The calcrete-gypcrete, exposed in a pit 2 1/2 m deep, is a well-cemented pebbly grit containing angular, poorly sorted, and unweathered granitic material as at the Bantu property. The calcite is in almost-clear mosaics with a range of grain sizes as at Langer Heinrich. There is very mild corrosion of some quartz clasts. Gypsum is mainly late, filling horizontal fractures, the cores of some tubules, and sporadic interstices.

Sand-filled calcareous tubules essentially identical with several of those described at Langer Heinrich, and in places spectacularly mineralized with carnotite, are of special interest (Plate V-3b). The tubules are abundant, making up 10 percent or more of the calcrete in some places. They range from 1 - 5 cm in diameter and up to 10 cm in length, having a tendency to lie in the horizontal plane but randomly oriented within it. They are compound, as are those at Langer Heinrich, having an outer shell of finer-grained calcite with very few clasts which truncates both the calcrete grit outside the tubule and the calcrete grit and the carnotite, if present, inside the tubule. The character and abundance of grit fragments appears to be the same inside and outside most tubules, which argues against open space filling of solution cavities by sand. Gypsum with sparse sand occupies the inner core of a few tubules, both replacing and replaced by carnotite (Plate V-4d).

The tubules appear to have been formed initially by dissolution and reprecipitation of calcite without disturbing the gritty aggregate. Carnotite emplacement apparently occurred contemporaneously or after this tubule-filling calcite but before generation of the latest finer-grained calcite shell by replacement.

In the exposure seen by the writer carnotite is the only visible uranium mineral, occurring preponderantly in the structures just described and associated mainly with calcite.

The mixture of calcrete and gypcrete in a property of this type does constitute a metallurgical problem since neither an alkaline nor an acid leach is optimal.

5.2.3.4 Carnotite in Bedrock Schist

The second showing on the westerly property is on a schist pediment, apparently a portion of the old "African" surface exhumed by erosion of former calcrete-gypcrete deposits near the Spitzkoppe River. The area is close to a point where the Spitzkoppe River is forced to funnel through a break in the Swartberg. Several long trenches about 1.5 m deep have been excavated into weathered bedrock on the showing.

Many obliquely inclined granitic pegmatite veins less than 1 m thick transect the schist in this area, and both rock types are strongly weathered to perhaps 4 - 6 m, judging from resistivity and hammer seismic data. The pegmatites are much more fractured, however, and therefore are apparently more permeable than the schist.

Carnotite occurs down to a depth of 1.5 m mainly as disseminations over several centimeters along the hanging wall margins of the pegmatites, but also as thin coatings on fractures in the schist.

Discontinuous thin films of calcite can be found in some of the carnotite-bearing fractures in the schist, and a carbonate reaction can be obtained with acid on carnotite-bearing pegmatite fragments. The association suggests, but hardly proves, precipitation of calcite and carnotite by the same mechanism, namely loss of CO_2 and water into soil air. Introduction of excess vanadium from the schist would not in itself explain the localization along pegmatite hanging walls. Nor are the pegmatites large enough in themselves to have been the uranium source. The relationships to the weathered surface and to permeable zones imply supergene transport of uranium in alkaline carbonated groundwater from once-overlying calcrete.

5.2.4

OTHER OCCURRENCES IN SOUTH WEST AFRICA

5.2.4.1 General Observations

Neither the time nor the opportunity was available to locate all of the calcrete-gypcrete occurrences in South West Africa. Dr. von Backström (1974) has stated that "over a hundred localities have been traced by aerial spectrometer survey." Numerous exploration concessions have been granted, and carnotite in associations similar to those described have been found from the Kuiseb River to Cape Cross and reportedly almost to the Angolan border.

Hambleton-Jones (personal communication, 1976) has also identified the yellow oxide-zone uranium silicate soddyite $[(\text{UO}_2)_5(\text{SiO}_4)_2(\text{OH})_2 \cdot 5\text{H}_2\text{O}]$ in calcrete uranium occurrences on the Namib Desert at locations not specified. To the writer's knowledge, all of the occurrences of potential economic interest found to date are on the Namib Desert. They are within the region for which, based on climatological data, the writer has postulated a "hyperaridic" or "marine hyperaridic" soil moisture regime (Figure 5.3). The ratio of annual potential evaporation to precipitation, including mist and fog water, is greater than that of the uraniferous calcrete region of Western Australia by as much as three-fold and remains as high throughout the year as the driest month in Western Australia. Figure 5.3 also shows a large area on the Plateau of South West Africa extending through Upington in the Republic of South Africa in which the climadiagrams suggest aridic soil moisture regimes very comparable with those of the valley calcrete area of Western Australia. The implications of this comparison are interesting. Calcretes of all types abound throughout this part of southern Africa (Mountain, 1967; Netterburg, 1971, Figure 5.5), as must adequate source rocks as well.

5.2.4.2 Other Occurrences in Bedrock Schist with Pegmatites--Uis Tin Mine

Occurrence of carnotite in bedrock schist, such as that described from the prospect west of Klein Spitzkoppe, are worth a little more discussion because of their affiliations with and differences from calcrete-gypcrete occurrences. None are known to approach economic scale to the writer's knowledge.

Additional occurrences similar to the one described are reported from the area south of the Spitzkoppes. These, too, are on parts of the old "African" surface from which overlying calcrete has been eroded. Several more occurrences can be seen north of the Kuiseb River west of Gobabeb, in this case not only in weathered Khomas schist but in Nösib quartzite as well. These are mostly overlain by small patches of calcrete or have patches nearby and invariably are accompanied by fillings of calcite along the fractures. The relationship is the same as that reported to have been found beneath ore at Langer Heinrich.

A particularly instructive set of occurrences was shown to the writer at the Uis tin mine by Mr. Tom Richards, chief geologist. The Uis mine is in a Damara reserve 170 km north-northeast of Swakopmund and is operated by ISCOR. It lies along a northeasterly trending Sn-Li-Be-Nb-Ta simple pegmatite belt in Khomas schist. The pegmatites, up to 100 m wide and 3 km long, occupy tension fractures within a major north-southerly shear and are inclined at large angles to the foliation in the schist. They are in part metasomatic.

Calcrete up to 10 m thick has formed in the lower parts of some narrow valleys in the mine area, overlying at least one pegmatite dike. Weathering extends to perhaps 10 - 50 m deep. Weathered pegmatite and immediately adjacent schist is more strongly fractured than the main body of schist. Films of carnotite occur within the weathered and fractured pegmatite and the schist up to 10 m from the contact in both directions and up to 20 m below the present erosion surface. Those seen by the writer were on the hanging wall contact of the pegmatite.

Carnotite also occurs along fractures entirely within the weathered schist in association with "vein" calcrete and gypcrete, i.e., sandy fracture fillings up to a few centimeters thick cemented with calcite or, less commonly, gypsum.

The occurrence is virtually identical with the one described west of Klein Spitzkoppe but with much larger pegmatites. Again the mineralization is unquestionably supergene and apparently dependent upon the same mechanisms. The occurrences are not known to approach economic grades.

Well water obtained for tin concentration in the mine area is warm, much too saline to be potable, and contains, in one sample collected by the writer, 100 ppb U.

5.3   GENETIC CONTROLS OF CALCRETE AND GYPCRETE URANIUM
MINERALIZATION IN SOUTH WEST AFRICA

5.3.1   SIMILARITIES WITH WESTERN AUSTRALIA

A diagrammatic representation of the physical setting and geometry of Namib calcrete and gypcrete uranium deposits is shown on Figures 5.12a and 5.12b.

In spite of many differences, important similarities between the uranium mineralization in the calcrete deposits of Western Australia and the calcrete and gypcrete deposits of South West Africa provide support for the main generalizations from the Australian study. There can be little doubt, for example, that the initial carnotite concentrations result from lateral transport of uranium in groundwater over appreciable distances. The localization of mineralization in a narrow valley at Langer Heinrich can only be explained in this way. Recognition of an earlier large catchment area, the restriction of significant carnotite to an undulating zone deep within the calcrete (related apparently to bedrock morphology), and the possibility of a mound structure or at least a culmination on the ore zone between bedrock highs adds to this conviction. It seems clear that bedrock barriers or constrictions which narrow the channel of subsurface flow or which act as sills and thus force the groundwaters close to the land surface where it is subject to oxidation and evaporation greatly favor the formation of uraniferous calcretes. This is probably true in all of the uranium properties mentioned above. The term evaporatic uranium deposits which is applied to these by some industry people seems apt in several respects, though, as in Australia, they are not simple evaporites.

A "Menzies Line" concept separating uraniferous valley calcretes from nonuraniferous pedogenic calcretes cannot be applied in South West Africa because the two varieties differ widely in age and geomorphic setting. Nonpedogenic Holocene or Pleistocene calcretes apparently have not been described in southern Africa, though the notable similarity of climate and inferred soil moisture regime in the Wiluna-Yeelirrie region and the western High Plateau of South Africa and South West Africa suggests further study. Some calcretes of unknown age on upper Molopo

Figure 5.12

DIAGRAMMATIC GEOMORPHOLOGY AND SURFICIAL GEOLOGY, NAMIB DESERT PARK REGION, AND MODELS FOR URANIUM DEPOSITION

and Limpopo River tributaries in southeastern Botswana appear to be localized along sluggish paleodrainages and to have the general morphology of valley calcretes. They bear investigation.

Some possible mechanisms for carnotite precipitation are considered next in the same order as they were for Western Australian deposits and shown in part on Figures 5.12c and 5.12d. In each case the presence of uranium as uranyl ion, potassium, and vanadium in solution is assumed. Lack of geochemical data on Namib Desert waters as well as the much older age of the mineralization makes these models even more speculative than those for Australia.

5.3.2

CARNOTITE PRECIPITATION

5.3.2.1 Addition of Vanadium- or Potassium-enriched Waters

As in Western Australia, this mechanism is difficult to evaluate, and the lack of data on water geochemistry on the Namib Desert adds to the difficulty. Both potassium and vanadium are available in this terrane in amounts adequate for carnotite deposition, but no exceptionally rich sources are apparent adjacent to the known deposits nor are there concentrations of clay minerals or hydrated iron oxides which might serve as cation-exchange sinks for them.

Vanadium concentration, especially, is a matter worth considering in the context of a specific exploration program since, as Hostetler and Garrels (1962) have pointed out, "carnotite stability is very sensitive to changes in ionic activity rather than changes in Eh and pH (except for distinctly reducing conditions); its precipitation is critically controlled by the amounts of uranium, vanadium and CO_2 in solution."

5.3.2.2 Carnotite Precipitation with pH Change

Neutralization of acidic uraniferous groundwaters was suggested as a possible minor or contributory mechanism in Western Australia. Acidic groundwaters, pH 5 or less, may not have developed, however, on any scale in South West Africa during the late Tertiary and Pleistocene as they have in the lateritic profiles of Western Australia. Carnotite does not occur preferentially at the upper (easterly) edges of the calcreted Namib Platform. Instead, the deposits occur at various distances below the Great Escarpment, though, admittedly, Langer Heinrich is within 30 km.

The reverse mechanism, neutralization of alkaline waters, might be applied to gypcretes. A situation may be visualized on the Namib Platform where carbonated, rather strongly alkaline uraniferous groundwaters, having come to near-equilibrium with calcite in a calcrete, e.g., pH 7.0 - 8.5, migrate into gypcrete with a neutral or very slightly acidic pore water. On the Tubas Grant prospects, where a groundwater sample with pH 6.5 (191 ppb U) was obtained, known carnotite mineralization was said to be present only in the lower gypcrete, as this mechanism would

demand, not in the underlying calcrete. The mineralization, moreover, appears to be related to a former groundwater table above which sulfate-rich, carbonate-rich vadose water would be expected to retain uranyl ion in soluble complexes. On the other hand, we have no evidence for appreciably acidic waters. Goudie (1972) found fog waters to be alkaline.

The absence of acidic groundwaters appears to rule out the mechanism of carnotite precipitation demonstrated by Bethke (1953) in which acidic (pH 4) uraniferous sulfate waters were reacted with calcite to form gypsum. Decrease in SO_4^{2-} ion promotes destabilization of uranyl sulfate complexes $[\text{UO}_2\text{SO}_4^0, \text{UO}_2(\text{SO}_4)_2^{2-}]$ and near-contemporaneous deposition of carnotite. The mechanism has been advanced to explain the occurrence of carnotite, sabugalite $[\text{HAl}(\text{UO}_2)_4(\text{PO}_4)_4 \cdot 16\text{H}_2\text{O}]$, and autunite in the basal 25 feet of interbedded gypsum, limestone, and dolomite in the gypsiferous Brule formation in Nebraska (Dunham, 1955).

5.3.2.3 Change in Partial Pressure of CO_2

As in Western Australia, direct loss of CO_2 into the atmosphere or indirectly into soil air is an attractive hypothesis because of the apparent relationship between bedrock morphology and significant carnotite mineralization, but, again, short of extreme evaporation, it requires some mechanism not yet identified to buffer pH at or near a given neutral to alkaline value.

The epigenetic solution-deposition tubules and replacement bodies with carnotite in the Langer Heinrich and the Klein Spitzkoppe calcretes have resulted from acidic attack on calcite by gravitational waters followed by one or more stages of calcite redeposition and precipitation of carnotite and this followed in turn by emplacement of barren calcite shells or mineralized gypsum fillings (Plates V-3 and V-4). Meteoric waters initially at equilibrium with atmospheric P_{CO_2} would have a theoretical pH of 5.7. Upon descent and reaction with calcite, in the absence of free CO_2 , they would dissolve relatively little calcite and reach a theoretical pH of 9.9 (Garrels and Christ, 1965). With organic sources of CO_2 in the soil, very much more calcite would dissolve, and the equilibrium pH would be lower. Reprecipitation of calcite and

carnotite in these structures is apparently the result of CO₂ loss followed by desiccation. Corrosion of quartz and feldspar related to the late carnotite emplacement implies strongly alkaline pH.

5.3.2.4 Carnotite Precipitation by Evaporative Concentration

The textures and structures of uraniferous calcrete or gypcrete deposits are not those of simple lacustrine evaporites. Carnotite is not concentrated in uppermost soil layers. Nor are the gypcretes themselves normal evaporites in the sense of being residual concentrations from a standing body of water. Instead, they are half-aeolian chemical sediments. The anomalous gypcrete soil analysis reported earlier (16 ppm U) from above an ore-grade gypsiferous sand indicates upward capillary transport of uranium during evaporation, but, apart from this, the superficial crusts of calcrete and gypcrete are barren not only at the surface but also throughout whatever "soil" horizons may have developed within them. Postulated mechanisms of carnotite deposition dependent upon upward transport of uranium by capillary-evaporative process through tens of meters are not favored by the writer. Capillary transport is limited (Section 3.3.1), becoming decreasingly effective as the soil dries out and is countered, moreover, by the illuviating effects of vadose water.

One can only guess that, during mineralization, concentrations of uranium, vanadium, and potassium probably increased downdrainage, owing to evaporation as they do in Western Australia, and that this facilitated carnotite precipitation by one or more triggering mechanisms. Without internal drainages, the very high concentrations of potassium and other ions detected in Australian salt lakes may not have developed, but substantial concentrations could have been expected in areas of impeded groundwater flow. Carnotite mineralization in the deeper gypcrete appears to be related to a former groundwater table and also to more permeable sands through which evaporative concentration would be more effective.

5.3.2.5 Carnotite Precipitation through Common-ion Precipitation of Calcite

Decreased CO_3^{2-} ion activity caused by common-ion crystallization of carbonate following evaporative concentration was emphasized as a probably most effective mechanism in Western Australia where it is supported by the apparent contemporaneity of finely disseminated carnotite and carbonate in "young" mounds. On the Namib Desert, marine-aeolian gypcrete substitutes for gypsum concentrations in salt lakes or constricted valley drainages. At the confluence of uranium-bearing, calcium carbonate-saturated groundwater from higher calcreted portions of the Eastern Namib platform with gypsum-saturated waters on the Middle Namib, CaCO_3 precipitation by the common-ion effect will immobilize CO_3^{2-} ions and facilitate precipitation of carnotite. Textures of carnotite in gypcrete are accordant with this mechanism.

On the upper part of the platform, gypsum is present in small amounts today as far inland as Langer Heinrich (Section 5.2.1.4), suggesting that the mechanism may have been operative during initial mineralization of the calcrete deposits.

5.3.2.6 Carnotite Precipitation through Oxidation

Oxidation of V(IV) to V(V) in areas of upwelling uraniferous groundwater appears as likely here as in Western Australia, though no Eh data are available to the writer. It must be considered as an important contributory mechanism, particularly where calcite deposition ensures a high pH. Data are particularly needed in the gypcrete environment to assess the magnitude of the effect.

5.3.2.7 Adsorption and Nucleation on Clay or Other Materials

In view of the scarcity of clay minerals, no special case can be made for adsorption or surface catalysis as a mechanism for localizing carnotite. The favorability of gypsiferous, well-sorted, sandy layers on the Tubas Grant is very likely a consequence of their greater permeability.

Ghelinsor

Figure 6.2

SOMALIA

GEOLOGICAL SKETCH MAP OF URANIUM PROSPECTING
IN MUDUGH PROVINCE

5.3.2.8 Summary of Possible Mechanisms

Table 5.2 is a summary and evaluation of the mechanisms suggested. For calcretes, the comments are similar to those for Western Australia (Table 4.4). The postulated mechanisms may be slightly less effective in the gypcrete environment and the mineralization correspondingly more diffuse. In both environments, movement of groundwater towards the evaporative surface is thought to be the major mechanism in precipitation of carbonate and carnotite. Carnotite with calcite in weathered schist along fractures and zones permeable to both oxygenated waters and escaping CO₂ may indicate several of the mechanisms and perhaps the greater abundance of vanadium in the schists as well.

Table 5.2

Carnotite Precipitation Mechanisms on the Namib Desert

Mechanism	Possible Effectiveness for Carnotite Precipitation	
	in calcrete	in gypcrete
1) Addition of vanadium- or potassium-enriched waters	Theoretically important but not demonstrated	same
2) pH change	Acid to neutral pH change is unproven as a mechanism at the major scale	Decreasing pH is a possible mechanism except that acidic waters not demonstrated
3) Change in P_{CO_2}	Requires a pH buffer until extreme evaporation Very important in solution-recemen- tation of calcrete carnotite	
4) Evaporative concentration	Strongly effective. The ores are not simple evaporites, and, although con- ditions during mineralization are not known, evaporative concentration was important as in Australia	
5) Common-ion precipitation of calcite	Strongly probable	Very strongly probable near the calcrete- gypcrete inter- face
6) Oxidation	Very strongly probable	Very strongly probable
7) Absorption and surface catalysis	Uncertain	Uncertain

5.3.3 Reconcentration and Stabilization

We have seen that visible carnotite is sporadic and commonly in small solution and replacement structures at Langer Heinrich and near the Spitzkoppes. The most likely cause of these structures is gravitationally and laterally moving carbonated water reacting with the calcite, then stagnating and becoming strongly alkaline as the profile dries out, as carbon dioxide escapes, and as calcite reprecipitates. Carnotite appears to have moved with the calcite. Some of that epigenetic carnotite has been redissolved and replaced by still later calcite. Some is found in bedrock cracks beneath calcrete and former calcrete. At the same time the grade of uranium ore at Langer Heinrich is reported not to correlate directly with megascopically visible carnotite. Richer mineralization may be at any level within the economic layer. The broad relationship of the occurrences to bedrock morphology suggests that penecontemporaneous carnotite may have been deposited as a protore in areas of favorable groundwater regime. As in Australia, therefore, reworking of carnotite from large primary occurrences into smaller concentrations is a logical inference and may be an essential step in the development of an orebody. On the Namib Desert carnotite has not been stabilized by silica coatings, but perhaps the extreme aridity exceeding even that of the valley calcrete region of Australia has been the fortuitous factor in preservation of the secondary enrichments.

6.0 OTHER OCCURRENCES OF CALCRETE URANIUM IN AFRICA

Carnotite-bearing calcrete deposits have been reported in Angola, Mauritania, and Somalia (e.g., Premoli, 1976). Political conditions did not permit visits by the writer, but some data are available on the deposits in Somalia.

6.1 PROBABLE CALCRETE URANIUM DEPOSITS IN SOMALIA

During the Uranium Geology Working Group Discussions at the 25th International Geological Congress in Sydney in August 1976, Dr. James Cameron of the Division of Nuclear Power & Reactors of the International Atomic Energy Agency presented some data on occurrences of carnotite associated with near-surface limestone, gypsum, bentonitic clay, and sands within an extensive area of anomalous radioactivity in Mudugh Province of central Somalia. The occurrences are within a broad north-southerly valley some 240 km in length and 15 km in width but with not much more than a few meters of relief. Sheets of solid limestone caprock occur along the valley margins. The richest mineralization is more than 2 1/2 m but less than 10 m deep and is notably related to the groundwater table. The region is extremely arid.

In 1974 (Dall'aglio et al., 1974, discussion), Dr. Cameron commented on the great similarities of the Yeelirrie and Mudugh deposits as follows:

"At Mudugh carnotite is present interstitially and in cracks and cavities in calcrete, marls, clays and bentonite in the near-surface zone, and is apparently limited to the zone of the narrowly fluctuating seasonal water table. The uranium seems to occur from the surface to about 5 - 8 m depth, and none is at present known to occur below the lower level of the water table."

Dr. Cameron has kindly made extracts of his earlier report on these occurrences available to the writer, and these are reproduced here verbatim.

Cameron on Somalia:

Excellent and full co-operation by the Project Manager, Mr.K.Nabiev and members of his staff is gratefull acknowledged. All necessary documentation was made available and discussions with Mr.Nabiev, Mr.K.Agamalian, Exploration Geologist, Mr.P.J. J.Labuschagne, Chemical Analyst, Mr.Y.Skornjakov, Associate Expert, Mr.E.Niva, Associate Expert/Driller and with the Somali geologists and geophysicists concerned with the project, particularly Mr.A.M.Nalaye, provided the facts on which this report is based.

Having reviewed all the available information, the writer concluded that apart from recommendations for future work, the most useful contribution of the consultant mission would be a preliminary economic assessment of the deposits. This report is therefore orientated towards that objective.

Location and Access

The location of the uranium area in the Mudugh Province is indicated on Figure No.1. The uranium occurrences and radiometric anomalies extend over a narrow, north-south orientated zone, some 240 kilometres in length and 15 kilometres in width. The principal population centres are the towns of El Bur at the southern end and Dusa Mareb, near the centre of the zone. These are approximately 300 and 400 kilometres respectively N to NNE of Mogadiscio. The main project activities and the field office are at the town of Dusa Mareb. Access from Mogadiscio to Dusa Mareb is firstly, by a hard top road, mainly in good condition, northwards for approximately 400 kilometres through the town of Bulu Burti to near Belet Uen. From this point, access is by bush track northeast for approximately 150 kilometres to Dusa Mareb. Total travelling time by Land Rover is approximately 10 hours.

The Belet Uen-Dusa Mareb section is presently under reconstruction and a hard top road will eventually run from the Mogadiscio-Ethiopia highway northeast, through Dusa Mareb, and Galcaio to the north. When completed it will have considerable advantages for any further exploration or exploitation of the Mudugh uranium area.

A primitive air-strip exists at Dusa Mareb but it is subject to flooding during the rainy period. Because of the flat topography it should not, however, be difficult to locate or prepare an all weather landing strip to service any future activities.

Cameron on Somalia (cont.):

Topography

In general, the Mudugh area is a flat monotonous plain covered with open scrub bush. The area is semi-arid with sand and exposed rock between the bush. Physiographic variations are very slight and difficult to note on the ground. The uranium occurrences are reputed to follow a very shallow depression which can be identified from aerial photographs, and although the writer found some difficulty in identifying this feature during the brief field visit it would be in accordance with regional structural trends and drainage patterns. The project geologists identify limestone boundaries to the depression and a gypsum crust covering most of it.

General Geology

In central Somalia, including the Mudugh uranium area, a series of continental-lagoonal and off-shore sediments overlies older rocks. These sediments are reputed to be of Miocene age and have been referred to as the Merca series which is subdivided into lower and upper beds. The lower beds include clayey sandstone and marl with lenses of limestone and gypsum, showing features of continental sedimentation and commonly rest on a weathered basalt of about 25-30 metres thickness. The upper series consists of a light-grey limestone of cryptocrystalline texture with breccia and sand.

In the areas of the uranium occurrences, gypsum, sepiolite, marl, limestone, chert, conglomeratic limestone, clay, sand and sandstone are represented.

The general tectonic pattern of Somalia and of the Mudugh Province may play some part in the location of the uranium occurrences. The N-S or NNW-SSE East African fault trend which the Scebeli River follows may be the most significant. The other structural trend is the NE-SW fault system which defines the Mogadiscio coast line.

Summary of Earlier Work

The original discovery of radioactivity was made in 1969 by the Phase I Project Manager, Dr. A. I. Katskov during a flight in which a gamma-ray spectrometer was carried.

This was followed by a scintillometer airborne reconnaissance survey along N-S cut lines about 15 kilometres apart. More

Cameron on Somalia (cont.):

detailed ground survey scintillometer surveys on 500 metre grid lines followed and certain areas were then covered on a 100 metre grid. A semi-systematic aerial scintillometer survey on an approximate 5.0 kilometre lines spacing was also done mainly at the north end of the zone. Pitting and drilling was started on the principal anomalous areas.

As of March 1971 eighteen anomalies covering an area of about 200 square kilometres had been found and partly explored. From north to south the principle areas are Ghelinsor, Adado, Mirig, Dusa Mareb, Wabo, Bulhale, Hamur, Wamoley and El Bur Nos. I, II and III. The location of the areas on this Ghelinsor-El Bur zone are illustrated on Figure No.2.

Three reports, describing work up to the first half of 1971 were made available to the writer.

1. "Interim Report - Mineral and Groundwater Survey Phase II" (issued by the United Nations in 1972 but describing operations up to 3 March 1971).
2. "Report of Mission to Somali Democratic Republic Project SOM-130-101-SF: Study of Sedimentary Uranium Deposits" by Franc R. Joubin D.Sc., Consultant, April 16 to May 13, 1971. This report includes an appendix "Report on Laboratory Testing of Wabo Sample" by Technical Service Laboratories, Toronto, Canada dated 20 July 1971.
3. Mission Report by Mr. A. Khilkoff Choubersky and Mr. B. Alvarado on their visit to the Project, dated 26 May 1971. This report detailed the exploration work which it was recommended should be done on the radioactive areas during Phase III of the project.

Material from these reports has been utilized in the preparation of the present report and repetition is avoided as far as possible. The Figures 1 and 2 from the Interim Report 1972 are relevant and are utilized here.

In mid-1971 the uranium ore reserves were reported as approximately 2,000,000 tons of ore averaging 0.12% U_3O_8 having a content of 2,400 tons U_3O_8 . This tonnage related only to the Wabo area and no assessments were made for the other areas then investigated.

Cameron on Somalia (cont.):

REVIEW OF GEOLOGY AND MINERALOGY

The most striking general feature about the occurrences is their marked north-south alignment; not only do the occurrences follow one alignment for 240 kilometres but most of the individual expression of surface radioactivity are narrow and aligned in the north-south direction, e.g. the Bulhale occurrence is some 5 kilometre long and only a few hundred metres wide. Similarly, the Wamoley occurrence is 7 kilometre long and again only a few hundred metres wide.

The association of the uranium occurrences with a physiographic depression feature, presumably a drainage channel, which may itself be defined by a regional tectonic structure, seems to be acceptable as a possible ore control feature.

The second notable feature is the very great extent of the expression of surface radioactivity covering an area of at least 200 square kilometres combined with the fact that this is apparently more extensive than the sub-surface uranium mineralization. Some of the surface expressions of radioactivity are not related to any occurrence of uranium in the sub-surface. This might suggest a surface flow of uranium bearing waters with possibly marked disequilibrium in the soil. However ore sample of radioactive soil taken from the surface near the centre of the Wabo occurrence gave an inconclusive result as shown by the following figures:-

	<u>% U_3O_8</u>	<u>Equilibrium Rated %</u>
+ 46 mesh	0.017	95
- 46 mesh	0.007	85

The near surface area is composed mainly of limestone, marls, limey clay, sepiolite, bentonite, sands, gypsum and breccias.

A true definition of the age of these near surface rocks is difficult and although they have been designated as of Miocene age, it seems probable to the writer that much more recent, Quaternary formations are also represented. Many of the near surface formations in which the uranium mineralization occurs are probably

Cameron on Somalia (cont.):

due to recent reworking of material and the deposition of the gypsum and limestone is probably due to tropical surface weathering and re-deposition processes. It was not clear to the writer that a distinctive ore bearing formation and barren formation can be distinguished as suggested on page 24 of the 1971 Interim Report. The uranium which occurs as carnotite (see Appendix I "Mineralogical Report") is located in cracks or appears as spots or stains on surfaces in the near surface rocks. Immediately under the soil the marls, clays and limestones are impregnated with gypsum and although the carnotite may also occur sporadically this layer averaging about $2\frac{1}{2}$ metres thick is frequently near barren of uranium mineralization. The principal mineralization zone occurs immediately below this and extends down to the water table which in the occurrences near Dusa Mareb is at about 6 metres below the surface. For example, in the No.5 trench at Wabo the surface soil is radioactive but immediately below there is a $2\frac{1}{2}$ metres thickness of pink clay and gypsum which shows only low radioactivity. Below this, white lime-clay with some bands of pink clay continues for a further $3\frac{1}{2}$ metres down to the water table. This material is liberally impregnated with carnotite in cracks. Below the water table the mineralization diminishes and disappears. The carnotite also occurs in the marls, sandstones and in the bentonite clays but there appears to be little doubt that the white clay-limestone is the most favourable host. All existing evidence tends to indicate that there is no non-oxidized (black) uranium mineralization below the water table. It, therefore, appears that the uranium occurrence is due to precipitation and evaporation from waters at the contact of a fluctuating ground water table and that there is probably a chemical preference for the lime type host rock. Analysis of the ground waters (Dr. Joubin's report 1971) revealed that the waters are alkaline and are strongly saline. Very little work has been done to determine any uranium content in these waters, but the project laboratory reports that one sample tested contained a low concentration of uranium.

The possible origin of the uranium is unclear. It may be related to several stages of solution and precipitation. A source could lie at some considerable distance from the present deposits, e.g. igneous rocks in Ethiopia. Such uranium may well have been transported and deposited in other favourable horizons and gone through several stages of solution, transport and deposition before finding its way in near surface waters to the present location where chemical and evaporation conditions caused re-deposition. There is also a possibility of the uranium being of hydrothermal origin more directly related to the tectonic

Cameron on Somalia (cont.):

north-south fault systems, which cross Central Somalia, one of which may, underlie the north-south orientated channel in which the occurrences now exist.

Insufficient evidence exists about the structure and geology of the rocks underlying the area. It was noted that, at about a 100 kilometre west of Dusa Mareb one drill hole penetrated a grey sandstone of the Jesomma formation with carbonaceous trash and pyrite at a 120-150 metres depth. Although there has been no opportunity to check for uranium in this sandstone, its stated characteristics are of a type known to be favourable for uranium and such formations would have to be tested in future.

In the writer's view the Mudugh deposits are expressions of near surface precipitation and evaporation of uranium bearing waters of unknown origin at a fluctuating water table surface. The uranium concentrations are likely to lie immediately above the water table and it is unlikely that greater concentrations or non-oxidized black ore will be found immediately below the known deposits. This does not, however, remove the possibility of occurrences at greater depths in more favourable horizons.

Cameron on Somalia, Appendix I

PETROGRAPHIC REPORT
LUCIUS PITKIN, INC. PETROGRAPHIC-MINERALOGICAL LABORATORY

1 August 1973

TO: Ben Bowyer, Assistant Director, RD, AEC

FROM: James R. Farris

URANIFEROUS SAMPLES FROM SOMALIA

Sample Location: Wabo, Mudugh Area, Somalia, Africa

AAI 400 Coarse to medium calcareous sandstone: submature quartzarenite

General Description

Sample AAI 400 and 401 contain the secondary uranium mineral carnotite. Trace amounts of uraninite were noted in Sample AAI 400.

Sample AAI 400 is basically a submature sandstone containing quartz and calcareous granules cemented by calcite and trace amounts of limonite. A chlorite-like mineral coats quartz and carbonate grains and portions of the calcite cement. Sample AAI 401 is a clastic limestone composed primarily of crystalline calcite enclosing minor amounts of carbonate sand-sized grains, biotite and medium to silt-sized quartz grains. Illite is present in trace amounts.

Detailed Petrographic Description

Sample AAI 400 is composed primarily of subangular to subrounded composite quartz, most of which is highly fractured, recrystallized metamorphic quartz and single quartz grains which are possibly volcanic in origin.

Interclasts of microcrystalline calcite are subordinate to quartz. Microspar and sparry calcite surround most of the interclasts. The sparry calcite exhibits grain growth and interlocking crystal mosaic. The microspar and sparry calcite constitute the primary cementing agents. Calcspathization has also occurred within micro-fractures in quartz grains and solution pores in interclasts.

Cameron on Somalia, Appendix I (cont.):

X-ray diffraction analyses revealed the absence of clay minerals in the sample, although a trace amount of a chlorite-like mineral was noted.

Minor amounts of limonite were observed coating quartz grains and interclasts.

Reflected light microscopy revealed extremely fine-grained uraninite occurring in trace amounts and filling solution pores in microspar and interclasts; however, carnotite is the principle uranium mineral present. See Tables I, II, and III. Carnotite occurs as both grayish-yellow fine grained masses and coarsely crystallized aggregates which coat quartz and carbonate grains and fill micro-fractures in quartz grains.

AAI 401 Clastic limestone -- Slightly sandy, silty Intramiclutite

Sample AAI 401 is basically a coarse calcilutite containing minor amounts of interclasts and medium crystalline sparry calcite. The interclasts are loosely packed and primarily cemented with sparry calcite. Illite acts as a secondary cementing agent.

The terrigenous portion consists of a trace amount of biotite, silt-sized and medium sand-sized quartz grains of both plutonic and possibly volcanic origin.

Light yellow carnotite was the only uranium mineral identified. See Tables I, II and III. Carnotite occurs primarily as a fine grained, dull to earthy coating on quartz and carbonate constituents; however, an anomalous concentration of vanadium was also noted within the clay fraction.

James R. Farris, Sr. Petrologist

Cameron on Somalia, Appendix I (cont.):

Table I

X-RAY DIFFRACTION DATA

AAI 400 <u>Carnotite</u>		AAI 401 <u>Carnotite</u>		ASTM File Card Number 8-317 <u>Carnotite</u>	
<u>d/A</u>	<u>I/I₁</u>	<u>d/A</u>	<u>I/I₁</u>	<u>d/A</u>	<u>I/I₁</u>
6.50	100	6.51	100	6.56	100
5.10	20	--	--	5.12	10
4.60	20	4.49	20	4.53	5
4.25	40	4.23	40	4.25	30
3.52	40	3.51	40	3.53	50
3.24	25	3.23	25	3.25	30
3.11	60	3.11	55	3.12	70
2.70	20	2.69	10	2.715	10
--	--	2.60	10	2.594	5
2.55	20	2.55	15	2.571	20
--	--	2.47	10	2.475	10
2.13	30	2.15	30	2.156	30
--	--	2.07	20	2.032	10
--	--	--	--	1.998	10
1.94	20	--	--	1.942	20
--	--	1.90	15	1.914	10
1.81	10	1.84	15	1.831	10
--	--	--	--	1.784	10
1.67	10	--	--	1.678	10

Cameron on Somalia, Appendix I (cont.):

Table II

SEMIQUANTITATIVE EMISSION SPECTROGRAPHIC ANALYSES
Secondary Uranium Mineral Only (CARNOTITE)

<u>Element</u>	<u>AAI 400</u>	<u>AAI 401</u>
Al	.5000	1.0000
B	.0030	.0020
Ca	6.0000	9.0000
Cr	.0080	.0040
Cu	.0020	.0050
Fe	.1000	.6000
Ga	.0001	.0001
K	2.0000	1.0000
Li	.0100	.0100
Mg	1.0000	2.5000
Mn	.0030	.0050
Na	.2000	.3000
Ni	.0010	.0040
Pb	.0100	.0050
Rb	.0100	0
Si	10.9999	10.9999
Sn	0	.0010
Sr	.0050	.0050
Ti	.0300	.0800
U	1.9999	.5000
V	2.0000	1.0000
Y	.0010	0
Zn	.0200	.0100

Elements looked for but not found: Ag, As, Au, Ba, Be, Bi, Cd, Ce, Co, Cs, Dy, Er, Eu, Gd, Ge, Hf, Hg, Ho, In, Jr, La, Lu, Mo, Nb, Nd, Os, P, Pd, Pt, Re, Rh, Ru, Sb, Sc, Se, Sm, Ta, Tb, Te, Th, Tl, Tm, W, Yb, Zr

Cameron on Somalia, Appendix I (cont.):

Table III

CHEMICAL ASSAY DATA

	<u>U₃O₈</u>	<u>eU₃O₈</u>	<u>V₂O₅</u>
AAI 400	.14	.13	.04
AAI 401	.13	.17	.06

7.0

CALCRETE OR GYPCRETE URANIUM FAVORABILITY
IN SOUTHWESTERN UNITED STATES

Criteria for uranium favorability deduced from the Australian and South West African studies have been applied to the southern Basin and Range Province of the United States. LANDSAT and selected U-2 and low level air photographs, a variety of published geological maps and reports, soils maps, and private communications have provided initial guidance. Many areas were visited and the more interesting ones are described briefly in Section 7.3 below. Some geological mapping, ground radiometric spectrometry, a limited amount of sampling and delayed neutron analysis, a very small amount of alpha-track radon detection, and a similarly very small amount of pit excavation was done. The primary objective has been to search for areas in which nonpedogenic calcrete or gypcrete may have developed and where additional study or exploration might be justified. A systematic exploration for uranium has not been undertaken. Many pedogenic calcretes, some gypcretes, and some lacustrine limestones were examined with the thought that some combination of processes or favorable circumstances perhaps not represented in Australia or South West Africa might yield a uranium concentration or might at least reveal more information on transport, deposition, and preservation in a calcrete environment. Nevertheless, the study can only be considered preliminary.

7.1

GENERAL FAVORABILITY CRITERIA FOR ECONOMIC
CALCRETE URANIUM OCCURRENCE

Given an ample source terrain and solubilization of uranium, vanadium, and potassium, ore formation requires that diffuse (noneconomic) precipitation of uranium does not take place during lateral transport toward areas of groundwater convergence. Since carnotite precipitation in the calcrete environment goes almost hand in hand with deposition of carbonate, the likelihood of ore genesis is greater if the climate, soil moisture regime, and chemistry are such that calcrete is not generated throughout the whole catchment basin but only in the groundwater convergence area. Dissolved potassium and five-valent vanadium must be in adequate supply at that point to precipitate carnotite.

Contemporaneous or penecontemporaneous carnotite even in a valley calcrete may not be of ore grade. Therefore, reworking into small, most favorable parts of the calcrete or adjacent clay without excessive loss downdrainage is probably essential. Finally, since carnotite is very soluble in an alkaline carbonate-rich environment, it must be stabilized or protected from further dissolution in some way. Conditions of gypcrete uranium ore genesis are apparently analogous and may not be unique to the coastal Namib Desert.

Genetic prerequisites and favorability criteria may be summarized as follows:

1. Adequate source terrain, deeply weathered. Yilgarn granites contain < 2 - 25 ppm U. Damara metamorphics and post-Damara granitics are comparable but locally much richer. Schists, granites, "greenstones," and derived sediments yield V. Preexisting ore-grade deposits are not known to be sources.

2. Anomalous groundwater uranium and vanadium contents. Present-day groundwaters updrainage from calcrete contain 10 - 60 ppb U; 1 - 12 ppb V; 10 - 35 mg/liter K.

3. Large catchment area. Yeelirrie 3000 km². Hinkler Well Basin 850 km². Langer Heinrich many hundreds km². Present flow or storage may be large, 1 1/4 million U.S. gallons/day (4500 m³) at Yeelirrie slot, but possible less during mineralization.

4. Low drainage gradients. Yeelirrie 0.1 to 0.02% in calcrete, 0.3% above. Namib Platform 1.3% to 0.73%.

5. Very limited runoff. No permanent streams. Runoff only during short sporadic summer storms and very little sedimentation.

6. Nonpedogenic calcrete. Indicative of subsurface (vadose and groundwater) flow into a trunk aquifer where carbonate precipitates.

7. Absence of soil carbonate deposition or other uranium fixing processes in the catchment area. Essentially true in valley calcrete region of Western Australia where siliceous soil horizons ("hardpan" = duripan) develop instead of calcrete. Apparently true of Khomas Hochland. Not true for gypcrete on Namib Platform which is downdrainage from calcrete.

8. Evaporative concentration of uranium, vanadium, and potassium downdrainage. Roughly 10-fold on Hinkler Well Basin excluding salt lakes where K increases by another 10-fold. TDS increases from < 750 ppm near breakaways to 20,000 ppm at Yeelirrie orebody. U and V also increased by dissolution of carnotite (191 ppb Tubas, up to 1000 ppb Langer Heinrich). V/U may exceed carnotite stoichiometry below ore.

9. Constricted, shallowing, or upwelling groundwater flow within the valley calcrete area due to bedrock or impermeable sediment constraints resulting in:

Rising Eh: oxygenated near-surface water converts V(IV) to V(V).

Loss of CO₂: into soil air above capillary fringe or warm upper soil moisture zone.

Abundant carbonate deposition: in capillary fringe and soil moisture zone which may overlap.

Accelerated evaporation: further concentrating ions.

Contemporaneous - penecontemporaneous precipitation of carnotite.

10. Reconcentration of carnotite. Dissolution of early carnotite and reprecipitation as epigenetic fillings and replacements in smaller area.

11. Stabilization of carnotite. By overgrowth with silica at Yeelirrie. By desiccation at Langer Heinrich and Western Australian occurrences.

12. Moderate to low relief and tectonic stability. Very little sedimentation to prevent deep burial. No topographic rejuvenation and consequent leaching of carnotite.

Climate enters into at least seven of the criteria listed. Tectonic stability and its influence on topography and subsurface morphology is a

major factor. Comparisons of the southwestern United States with known occurrences in terms of these criteria and some of the complications introduced by differing sequences and ages of deposition are briefly reviewed next.

7.2

FAVORABILITY IN COMPARISON WITH
WESTERN AUSTRALIA AND SOUTH WEST AFRICA

7.2.1

Geological History and Tectonic Stability

Table 7.1 summarizes the main steps in the genesis of Australian and South West African calcrete and gypcrete uranium deposits and the comparatively rather complicated geological history of the southwestern United States. Continued tectonic instability during the Cenozoic and consequent rapid sedimentation or dissection is probably the single most critical factor in evaluation of calcrete-uranium potential in the western United States. The search will have to be concentrated in areas where this effect is minimal. However, if the inference made earlier as to the timing of major mineralization in Western Australia is roughly correct (25,000 B.P. and probably 18,000 - 16,000 B.P., yet old enough for carnotite to have reached approximate radiometric equilibrium in quartz-sealed fillings at Yeelirrie), then the period of mineralization need not be excessively long, and surfaces as ancient as those of Australia and South West Africa may not be essential. Mineralization of Late Tertiary to Pleistocene age is an appropriate target in view of the evidence and the uncertainty about the stability of calcrete-carnotite in older or buried occurrences.

7.2.1.1 Old Geomorphic Surfaces

Ancient surfaces of low relief are present in the southwestern United States. They occur principally as erosional remnants at higher elevations fringing mountain ranges or as terraces along principal drainage courses, but they may also be extensive in some areas in the subsurface, buried by younger fans and valley and lake sediments. Their geomorphic configuration and well-developed soil profiles imply that they were once extensive and stable for relatively long periods. In contrast with Western Australia, where only two surfaces are present, four or five surfaces of Quaternary, or as old as late Tertiary, age are common in the U.S., attesting to repeated rejuvenation, alluviation, and soil formation (see Figure 3.2, e.g.).

In southeastern California at least four surfaces (pediments, piedmont alluvial fans, and pediment terraces) are considered older than

Table 7.1

Synoptic History of Calcrete (Gypcrete) Uranium Mineralization

VALLEY CALCRETE REGION
WESTERN AUSTRALIANAMIB DESERT
SOUTH WEST AFRICA

SOUTHWESTERN UNITED STATES

Figure 7.1
Areas with Geomorphic Surfaces More Than 15,000 B.P.
(After Shlemon and Purcell, 1976)

Holocene or approximately 15,000 years B.P. (Shlemon and Purcell, 1976):

- 1) the youngest of these lies on Colorado River deposits dated by uranium-thorium from a Mammoth tusk at about 100,000 years B.P.;
- 2) a surface below the radiometrically dated Colorado River deposits with broad distribution is believed to have developed during a climatically controlled epoch of regional alluviation, probably "Illinoian" pluviality, between 100,000 and 200,000 years B.P.;
- 3) older still are surfaces estimated to be at least middle Pleistocene in the order of 200,000 to 500,000 years B.P.;
- and 4) the oldest identified surfaces are believed to be greater than 500,000 years B.P. and possibly older than 2,000,000 years B.P. (Shlemon and Purcell, 1976). Older Colorado River deposits of reversed polarity (Matuyama) appear to interfinger with the upper remnants of the oldest surface deposits, indicating an age of greater than 700,000 years. Some older surfaces are perhaps Late Tertiary in age. The map of Shlemon and Purcell (1976) implies that roughly one-third of the 10,000 km² (4,000 mi²) area studied in southeastern California east of the Salton Sea is covered by remnants of the four geomorphic surfaces greater than 15,000 years old (Figure 7.1). Essentially all of these surfaces are underlain by soils with a large percentage of pedogenic calcrete in various stages of development.

Although regional dating of surfaces throughout the Mojave Desert has not been accomplished, a comparable geomorphic history implies that ancient surfaces are similarly widespread. On the basis of relief alone, the westernmost wedge between the San Andreas and Garlock Faults has been the most stable part of the Mojave Desert. Widely separated topographic highs rise mostly less than 700 m (2000 ft) above a gentle undulating plain.

7.2.1.2 Seismicity

The value of seismic records as indicators of long-term stability is uncertain. However, the broad patterns illustrated on Figure 7.2 tend to confirm geomorphic and geological evidence for comparative Holocene stability over 1) much of south central and western Arizona and adjacent parts of southeastern California and southernmost Nevada and 2) the Mimbres-Columbus-Las Cruces region of south central New Mexico (Section 7.3.5). At Las Cruces, nevertheless, five distinct surfaces with pedogenic calcrete record mid-Pleistocene to Holocene rejuvenation (Figure 3.2), the last not more than 5000 years B.P.

Figure 7.2

Probabilistic Estimate of Seismic Activity

Maximum probable horizontal bedrock acceleration
(expressed as percent of gravity) with 90 percent
probability of not being exceeded in 50 years. (After
Algermissen and Perkins, 1976.)

7.2.1.3 Quaternary Fault Frequency

Another approach to evaluation of tectonic stability is to plot the abundance of Quaternary faults.

Figures 7.3, 7.4, and 7.5 present the evidence for surface structural lineaments in the Lower Colorado valley between Lake Mead and the Gulf of California. This evidence is based upon a photogeologic interpretation of LANDSAT panchromatic and color infrared imagery at a scale of 1:500,000. The lineaments reflect a variety of situations in which linear elements occur in the landscape, namely as joints, outcrop limits, bedding planes, faults young and old, and related ridge crests, valley troughs, and other topographic features. Only a portion of this population consists of faults and, of this smaller set, only those faults thought to be of Quaternary age are shown by a thickened line. These latter have been checked in the field and/or from published and unpublished sources.

Figure 7.6 identifies Quaternary faults of the Lower Colorado valley within their broader regional setting. From this diagram, it will be seen that there is a paucity of observable evidence for surface faulting in a broad belt of country straddling the Lower Colorado valley between Lake Mead and Yuma, and that this belt of limited or negligible Quaternary tectonism extends eastward into central Arizona. In contrast, relatively intense tectonism appears in the northwest and southeast of the region and, to a lesser extent, around Lake Mead.

In the northwest area, displacement of Quaternary deposits occurs along several faults, most notably the Sierra Nevada fault zone, the Panamint Valley fault zone, the Death Valley fault zone, and the Furnace Creek fault zone, all of which trend approximately north-northwest to south-southeast. In some places, both normal and strike-slip displacement of considerable magnitude has taken place, and Holocene deposits have been involved in movement. The area of most active displacement ends southward, however, in the Garlock fault zone which imposes its own significant strike-slip components on the structure and relief across the northern margin of the Mojave Desert. Although north-northwest to south-southeast fault traces occur to the south of the Garlock fault, for example as the Blackwater and Harper faults and as similarly trending structures around Baker, they are less persistent, and the magnitude of

Figure 7.3: Structural lineaments in the Las Vegas area
 (Source: A. R. Orme, for Fugro Inc.)

Figure 7.4: Structural lineaments in the Neelands - Kingman area (Source: A. R. Orme, for Fugro Inc.)

Figure 7.5: Structural lineaments in the Blythe - Yuma area
(Source: A. R. Orme, for Fugro Inc.)

Figure 7.6: Quaternary faults in the Lower Colorado valley and vicinity (Source: A. R. Orme, for Fugro Inc.)

their displacement is less. Quaternary basin fills become more widespread, and the relief features that are such conspicuous elements of active tectonism north of the Garlock fault zone diminish in elevation. Some weak trends continue toward the Cadiz Valley and Pinto Basin, but the magnitude of Quaternary dislocation weakens generally southward and eastward.

A second area of intense Quaternary tectonism occurs in and around the Salton Trough. It is associated with recent displacements along such major faults as the Mission Creek, Banning, San Jacinto, Coyote Creek, Elsinore, and San Andreas. Some movements related to this activity appear to extend east into the Pinto Basin and southeastward across the Colorado River into the Gila Mountains, but no comparable northwest - southeast trending structures parallel to the Salton Trough trends occur beyond the Pinto Basin and Yuma areas.

A third area of comparatively minor activity occurs in the vicinity of Lake Mead. Although a few scattered north-northwest by south-southeast trending structures extend for a short distance down the Colorado valley, such activity seems to die out in the vicinity of Needles and is not a conspicuous feature of west central Arizona.

The significance of these observations is that areas affected by prolonged instability continuing through the Quaternary Period rarely provide conditions conducive to the development and/or survival of thick caliches and other duricrusts. This is because structural instability periodically freshens topographic contrasts, and the subsequent erosion both disrupts existing land surfaces and provides alluvial debris which mantles downstream slopes and basins. In contrast, areas of comparative stability, reflecting less Quaternary tectonism, frequently provide topographic stability of sufficient duration to promote thick caliche development. It is in these latter areas that we might reasonably expect the survival of significant duricrusts. Field observations confirm this reasoning, though exceptions to the rule occur where local structural or topographic controls render such generalizations misleading.

7.2.2

Comparative Climates

7.2.2.1 Present-day Climate

Climates under which calcrete uranium deposits appear to be still forming in Western Australia are characterized by the following:

1. Low annual precipitation (P_a)
250 mm (10 in) or less
2. High annual potential evapotranspiration (E_a)
3500 - 4000 mm (140 - 160 in)
3. High annual evaporation ratio (E_a/P_a)
15 or greater
4. Large soil moisture deficit ($E_a - P_a$)
3500 mm (140 in) or more
5. High summer temperatures
30°C (85°F). Perhaps less critical than other factors. Namib gypcrete environment is cool. Freezing is experienced at Yeelirrie currently.
6. Aridic to hyperaridic soil moisture regime
Arid climate with rainfall concentrated in summer to autumn storms during periods of high temperature and high evaporation.
7. Episodic rainfall
Highly variable incidence of summer to autumn storms.

Deposition may have been initiated in Western Australia and South West Africa under even more arid conditions.

The degree to which these conditions are approximated currently in the southwestern United States is illustrated in Figures 7.7, 7.8, and 7.9 and in Tables 7.2, 7.3, and 7.4. Note the areas of large soil moisture deficit (large $E_a - P_a$), but recall that these are for present-day climates and that they represent annual means (cf. Köppen classification, Figures 7.10 and 4.19). Rainfall seasonality in relation to temperature and potential evaporation, thought to be a very important criteria for valley calcrete uranium mineralization in Western Australia, has been estimated by visual inspection of mean monthly precipitation and potential evaporation totals on the climadiagrams, taking into account the lengths of periods without precipitation as well. Rainfall episodicity in the arid parts of the study area is large both within and between years (Pyke, 1972), much as it is in central Western Australia. The coefficient of variation of annual rainfall, defined as the ratio of the standard

Figure 7.7

Climadiagram for Boulder City, Nevada

a

b

c

d

Explanation for Figure 7.9

Soil Moisture Regimes of the United States

Ustic Regimes: Broad midsummer precipitation peak.

U Ustic proper. Easternmost region receives good rains in all months.

$$E_a/P_a = 2-4$$

$$E_w/P_w = 2-3$$

$$E_a - P_a < 1500 \text{ mm}$$

U_f Frigid Ustic. High elevations.

$$E_a/P_a \sim 5$$

$$E_w/P_w \sim 3$$

$$E_a - P_a < 1400 \text{ mm}$$

U_s Subustic.

$$E^{0.75}_a/P_a > P \text{ 1-5 months}$$

$$E_a/P_a = 5-6$$

$$E_w/P_w = 3-4$$

$$E_a - P_a = 1500-2000 \text{ mm}$$

U_s-X_s Subustic - subxeric. Uplands which receive good precipitation in both winter & summer.

$$E_a/P_a = 3-5$$

$$E_w/P_w = 1-2 \text{ summer, } < 1 \text{ winter}$$

$$E_a - P_a = 1200-1600 \text{ mm}$$

Aridic Regimes: Dry climates. Soil never moist for long periods of time. Mean monthly precipitation never exceeds mean monthly evaporation.

A Aridic proper.

$$E_a/P_a = 10-15$$

$$E_w/P_w = 5-10$$

$$E_a - P_a = 2000-2500 \text{ mm}$$

A_y Aridic Yuma type.

$$E_a/P_a > 20$$

$$E_w/P_w > 20 \text{ (summer rain)}$$

$$E_a - P_a = 2500-3000 \text{ mm}$$

A_m Aridic Mojave type. Very hot, very dry regions.

$$E_a/P_a > 20$$

$$E_w/P_w = 6-10 \text{ (winter rain)}$$

$$E_a - P_a = 2500-3000 \text{ mm}$$

A_c Cold Aridic regime.

$$E_a/P_a = 10-15$$

$$E_w/P_w = 4-10$$

$$E_a - P_a = 1500-2100 \text{ mm}$$

A_s Subaridic regime. Semiarid regions which may receive both summer and winter precipitation. (Superscript s = summer rain; superscript w = winter rain.)

$$E_a/P_a = 6-10$$

$$E_w/P_w = 6-8$$

$$E_a - P_a = 1700-2000 \text{ mm}$$

Xeric regimes: "Mediterranean" type climate. Hot, dry summers and cool, wet winter.

X Xeric proper.

$$E < P \text{ in winter months}$$

$$E_a/P_a = 0.7-7$$

$$E_w/P_w = 0.07-2$$

$$E_a - P_a < 1900 \text{ mm}$$

X_s Subxeric regime.

$$E_a/P_a = 4-18$$

$$E_w/P_w = 0.7-2$$

$$E_a - P_a = 1600-2600 \text{ mm}$$

FIGURE 7.9

From soils maps of Arizona, New Mexico, and inferred from climadiagrams, vegetation maps, and topography. Climadiagrams from data of U.S. Weather Bureau, 1964; Green and Sellers, 1964; Brown, 1973; Maker *et al.*, 1974; U.S. Dept. Agriculture, 1975.

Table 7.2

PRESENT CLIMATE PARAMETERS IN WESTERN AUSTRALIA,
SOUTHWESTERN AFRICA, AND SOUTHWESTERN UNITED STATES
(mm and °C)

	E_a	P_a	E_a/P_a	$E_a - P_a$	Rainfall Seasonality	Rainfall Variability	T of 3 hottest months
<u>Western Australia</u>							
Kalgoorlie	2770	242	11.4	2528	indefinite	moderate to high [†]	25.0
Wiluna	3967	249	15.9	3718	S-A	high [†]	29.4
Nullagine	3553	334	10.6	3219	S	moderate to high [†]	31.3
<u>Southern Africa</u>							
Gobabeb	3540	19 rain 35 fog	65.5	3486	indefinite	70%*	24.1
Swakopmund	2466	18 rain 130 fog	16.7	2318	indefinite	80%*	19.3
Windhoek	3382	370	9.1	3012	S-A	40%*	23.2
Upington	3805	204	18.7	3601	s-A	55%*	27.1
<u>S.W. United States</u>							
Mojave	2950	116	25.4	2834	W	40% [§]	26.7
Boulder City	2940	137	21.5	2813	s and w	30% [§]	22.5
Yuma Citrus Sta.	2983	83.3	35.8	2900	A and W	60% [§]	31.9
Sacaton	2727	234	11.7	2493	S and W	30% [§]	30.1
Tucson	2134	277	7.7	1857	S and w	30% [§]	28.9
Sierra Ancha	1902	635	3.00	1267	S and W	30% [§]	24.5
Las Cruces	2455	214	11.5	2241	S	35% [§]	25.5
Alamogordo Dam	2776	265	10.5	2511	S	40% [§]	25.3

[†]Gaffney, 1975 and Figure 4.19d.

*Schulze, 1972. Values are (%) (mean deviation/mean)

[§]Hershfield, 1962. Values are (%) (standard deviation/mean). Note: values probably represent minimums for stations in the western Mojave and Colorado River valley due to the small body of data used.

Table 7.3

COMPARATIVE LISTING BY CLIMATE PARAMETERS

Stations are listed in descending order.

<u>Ea</u>	<u>Pa</u>	<u>Ea/Pa</u>	<u>Ea-Pa</u>	<u>T of 3 hottest months</u>
WIL.	Sr.An.	Gob.	WIL.	Nul.
Up.	Wind.	Yuma	Up.	Yuma
Nul.	Nul.	Moj.	Gob.	Sac.
Gob.	Tuc.	Bdr.C.	Nul.	WIL.
Wind.	Alm.D.	Up.	Wind.	Tuc.
Yuma	WIL.	Swak.	Yuma	Up.
Moj.	Kal.	WIL.	Moj.	Moj.
Bdr.C.	Sac.	Sac.	Bdr.C.	Las C.
Alm.D.	Las C.	Las C.	Kal.	Alm.D.
Kal.	Up.	Kal.	Alm.D.	Kal.
Sac.	Swak.	Nul.	Sac.	Sr.An.
Swak.	Bdr.C.	Alm.D.	Swak.	Gob.
Las C.	Moj.	Wind.	Las C.	Wind.
Tuc.	Yuma	Tuc.	Tuc.	Bdr.C.
Sr.An.	Gob.	Sr.An.	Sr.An.	Swak.

Table 7.4

SEASONALITY OF PRECIPITATION RELATIVE TO POTENTIAL EVAPORATION
(millimeters)

		E_a	P_a	E_a/P_a	$E_a - P_a$	
SUMMER-AUTUMN RAIN DOMINANCE ↑	Little or no winter rain. Evaporation declines during wet season.	Windhoek	3382	370	9.1	3012
		Ghanzi (Bots.)	3305	446	7.41	2859
		Nullagine	3553	334	10.6	3219
	Late Summer-Autumn rain with evaporation high.	Upington	3805	204	18.7	3601
		Wiluna	3967	249	15.9	3718
	Bimodal rainfall Autumn-Winter.	Yuma Cits. Sta.	2983	83.3	35.8	2900
		Boulder City	2940	137	21.5	2813
		Tucson	2134	277	7.7	1857
		Sacaton	2727	234	11.7	2493
		Las Cruces	2455	214	11.5	2241
		Alamagordo Dam	2776	265	10.5	2511
Lee's Ferry		2285	151	15.1	2134	
Indertiminate rain- fall seasonality.	Gobabeb	3540	19 rain 35 fog	65.5	3486	
	Kalgoorlie	2770	242	11.4	2528	
WINTER RAIN DOMINANCE ↓	Winter rain.	Mojave	2950	116	25.4	2834
		Eyre	1465	289	5.1	1176
		Esperance	1837	679	2.7	1158
		Perth	1688	889	1.9	799

deviation to the mean expressed as percent, is greater than 60% in the Yuma area (Hershfield, 1962). Court (1974) reports that annual rainfall totals at Yuma have a distinctly non-Gaussian distribution, and median annual rainfall is less than 25% of the arithmetic mean.

Soil moisture regimes (Figure 7.9) have been derived directly, in part, from soil maps of New Mexico (Maker et al., 1974) and Arizona (U.S.D.A., 1975) and inferred, in part, from climatic data, from a vegetation map of Arizona (Brown, 1973), and from studies of precipitation variability and seasonality by Jurwitz (1953), Bryson and Lowry (1955), Hershfield (1962), and Pyke (1972). Eleven representative climadiagrams are illustrated out of a total of over 100 complete and partial diagrams plotted in and near the study area. In contrast with the rather simple distribution patterns in Western Australia, and slightly more complex patterns in southern Africa, the situation in the southwestern United States is extremely complicated, illustrating marked topographic effects and pronounced seasonal changes. Court (1974), for example, reports an increase in precipitation of approximately 20 cm for each km increase in elevation in the Colorado River Basin.

In the northwestern Mojave Desert (A_m on Figure 7.9), which is analogous in several aspects of present-day climate with areas well south of the Menzies Line in Western Australia, summer storms are largely absent, and soaking frontal rains or snows of winter are the dominant components. All other areas experience significant summer rain.

Extreme southeastern California, essentially all of Arizona, and much of New Mexico have two distinct rainy seasons (Pyke, 1972; Jurwitz, 1953), unlike the Western Australian and South West African calcrete regions. Summer rainfall tends to be more pronounced in the southern and eastern portions of the study area as incursions of warm moist air from the Gulf of Mexico or Gulf of California generate local thunderstorms. In addition, rare but copious rainfalls accompany the passage of tropical cyclones. Court (1974) suggests that about one-fourth of the rainfall in the southeastern California deserts comes from tropical autumn storms. Crown King, Arizona, approximately 87 km north of Phoenix, received a 24-hour rainfall total of 135 mm and a five-day total of 344 mm, during rainfalls associated with a tropical cyclone in 1951 (Jurwitz, 1953). In this

respect, southeastern California and southwestern Arizona resemble the Wiluna region. They are different in that winter frontal rains from the West Coast extend into the area as well. Presumably these create the soil moisture conditions much like those south of the Menzies Line in Western Australia, i.e., saturation of the soil moisture zone followed by drying and formation of pedogenic calcrete. Nevertheless, in terms of climate seasonality and variability and, if the reasoning earlier has been correct, this region labelled A_y on Figure 7.9 probably has greater potential for valley calcrete of the Western Australian variety than any other in the southwestern United States study area. Areas labelled A have perhaps slightly less potential.

7.2.2.2 Comparative Climate Summary

1) Total annual evaporation is lower in southwestern United States, and both winter and summer evaporation rates are lower than those of valley calcrete areas in Western Australia and South West Africa.

2) In several parts of the study area and especially at higher elevations, air and soil temperatures are significantly lower than in Western Australia or southern Africa, and the seasonal range of temperature is greater. Yuma is an exception in that both the values and range of mean monthly temperature there are essentially the same as that at Wiluna, Western Australia, and Upington, South West Africa. Freezing ground temperatures and snow occur in some areas (U_f Figure 7.9).

3) Total precipitation for the U.S. stations is also generally lower than calcrete regions except for Gobabeb on the Namib Desert, but that station is drier than Langer Heinrich and much drier than slopes on the Great Escarpment immediately updrainage from Langer Heinrich.

4) The ratio E_a/P_a is appreciably greater at several southwestern United States stations than at Wiluna, but the total soil moisture deficit ($E_a - P_a$) is less.

5) Two regions, along the lower Colorado River and the Rio Grande in New Mexico are most comparable to the Western Australian and southern African uraniferous calcrete areas:

a) Eastern Southern California, southwestern Arizona, and the southern tip of Nevada (A_y on Figure 7.9). This region is the most

arid part of the study area: mean annual evaporation totals > 3000 mm, summer mean temperature > 30°C, and mean annual precipitation totaling < 200 mm. The climadiagram for Yuma Citrus Station is strikingly similar to that for Wiluna. Where soils have been mapped, pedogenic calcrete (caliche) of moderate maturity appears to underlie perhaps 10% of the area (Plate VII-1). It is distinctly limited to the more stable geomorphic surfaces.

b) The valley of the lower Rio Grande in New Mexico. This area of extensive pedogenic calcrete is somewhat less arid; mean annual evaporation totals > 2500 mm, summer mean temperatures > 25°C, mean annual precipitation < 300 mm. Precipitation reaches a peak in late summer, but is distributed through the year much more than at Wiluna. Pedogenic calcrete (caliche) of Stages 1 to 4 of Gile et al. underlie 20% or more of the area.

In calcreted portions of the Basin and Range Province, coarse gravels and steep gradients such as those which characterize valley calcretes of the Namib Desert variety are more likely to be found than fine-grained hosts of the Western Australia variety. The nature of Late Tertiary climates which produced Namib valley calcretes are not fully clear, but apparently were very arid. Calcretes probably analogous to the Namib variety have developed on a small scale in carbonate host sediments in the Jean-Sloan area near Las Vegas, Nevada (Section 7.3.2).

6) Other regions labelled A on Figure 7.9, notably south central Arizona, are comparable to the lower Rio Grande valley in the wide extent of pedogenic calcrete (caliche) development (up to 25% of the area locally). Regions labelled A_s, largely in southeasterly Arizona and southwestern New Mexico, have slightly less pedogenic calcrete than A but more than A_y. Both A and A_s areas have a significant component of winter rain which results in greater similarities with Kalgoorlie and Nullagine in Western Australia which are outside the uraniferous valley calcrete region.

7) Areas labelled U_f or U_s - X_s are largely elevated. They have little to no pedogenic calcrete and also low favorability for valley calcrete uranium deposition.

Figure 710

Köppen Climate Classification of Southern Africa (After Schulze, 1947)

a

b

8) The western Mojave Desert, labelled A_m, contains Stage 1 to Stage 3 pedogenic calcrete beneath more stable geomorphic surfaces but has a dominance of winter rain and should, in theory, be less favorable for valley calcrete formation.

7.2.2.3 Pleistocene Climate

All of the above inferences have been drawn on the basis of present-day climates. Whereas Western Australia was even more relentlessly arid during glacial maxima than today (Section 4.1), southwestern United States was much wetter. The difference, if as pronounced as Bowler (1976) infers, is a serious one especially in terms of carnotite preservation.

The most recent glacial maximum, Tioga stage in California, occurred some 15,000 - 20,000 years ago, causing many basins in the Mojave Desert and Great Basin which are now occupied by bajadas and playa lakes to fill with water. Lake Bonneville last overflowed its basin about 14,000 years ago. Analysis of tree ring data from the La Brea tar pits in Los Angeles (Templeton, reported by Stout, 1977) suggests that precipitation over a 40-year cycle about 14,000 years ago was more than twice the present mean annual precipitation in Los Angeles and occasionally 5 times as large.

Whether filling of Great Basin lakes was solely due to greatly increased precipitation or in part to reduced evaporation during the colder glacial maxima, conditions for uraniferous calcrete development must have been much less favorable than today. It then becomes a question of whether deposits perhaps formed during arid interglacial or preglacial times can have been protected from excessive burial or dissolution. The general pattern of climatic favorability, i.e., the relative distribution of aridity, across the study area has probably remained about the same throughout the late Cenozoic.

Figure 7.11

Calcrete-Gypcrete Uranium Project Study Area, Southwestern United States

Showing the general distribution of igneous and metamorphic rocks

7.2.3

Source Terrain

Yilgarn granitic rocks, reported to contain up to 25 or more ppm U, and Damara and post-Damara rocks, locally very uraniferous, may be richer on average than Precambrian rocks in southwestern United States (2.0 - 4.5 ppm U, Malan, 1972) or plutonic rocks in general in that region (< 1 - 5.0 ppm, Marjaniemi and Basler, 1972). Actually, insufficient data are available to make a meaningful comparison. Uranium-anomalous granitic and metamorphic rocks are present in the Southwest, though only a few are reported in the published literature. In addition, Cenozoic intermediate to silicic volcanic rocks provide a source of labile uranium in the Basin and Range Province which does not have counterparts in Western Australia or South West Africa (Coates, 1956). Vitreous tuffs are especially favorable candidates: the Erie Tuff (Section 7.3.2) in southernmost Nevada contains 5 - 14 ppm uranium.

Figure 7.11 is a very generalized plot of igneous and metamorphic rocks in the study area which might be expected to be sources for supergene uranium. Areas of unusual interest include:

- 1) The "Needles Region," including the junction of Nevada, Arizona, and southeastern California. Anomalous Precambrian rocks are reported by Malan (1972) in the McCullough Mountains, southern Clark County, Nevada (up to 13.7 ppm U and confirmed by ourselves at 15.2 ppm eU), in the Black Mountains, Mohave County, Arizona (up to 12.7 ppm U), the southern Big Maria Mountains, Riverside County, California (up to 13.2 ppm U), and southern Marble Mountains, San Bernardino County, California (up to 10.9 ppm U). We have demonstrated values of 5.2 to 14 ppm eU in 20 samples of Erie Tuff near Jean-Sloan, Nevada and suggested a correlation with comparable rocks extending several tens of miles to the south. We have confirmed anomalous values, < 8 ppm eU, in Precambrian granitics of the Hualapai Mountains in Mohave County. Numerous minor uraniferous veins occur in this region (Walker and Osterwald, 1963). In addition, the occurrence of prospective to ore-grade carnotite deposits in Tertiary lacustrine sediments in the Date Creek-Artillery Peak region of Arizona is evidence in itself of substantial source terrain and effective groundwater uranium transport. Anomalous granitic rocks in this area have given a Mesozoic age (Mary McNeil, personal communication, 1977).

2) Southeastern Arizona, portions of Santa Cruz, Pima, and Cochise County. Marjaniemi and Basler show a group of anomalous intrusives in southeastern Arizona containing up to 23.4 ppm U. This is also a region of numerous minor vein uranium occurrences. Prospective uranium occurrences in Pliocene to Pleistocene lacustrine sediments in San Simon Valley indicate surficial mobilization of uranium.

3) Sierra Ancha Region, Gila County, Arizona, and central Arizona Precambrian Belt. Numerous well-known occurrences of vein type uranium mineralization in the Dripping Springs Quartzite of the Apache Group suggest an anomalous source region. However, the paucity of visible secondary minerals has been taken to indicate very little groundwater mobilization from these deposits.

Minor vein occurrences are known throughout the Precambrian belt below the Mogollon Rim from southeastern Arizona through the Bagdad and Wallapai Districts. Noneconomic carnotite mineralization in Pliocene or Pleistocene lacustrine limestone of the Verde Formation in Verde Valley and similar rocks north of Lake Pleasant and in the vicinity of Horseshoe Dam again indicate surficial mobilization of uranium. Anomalous calcrete (28.3 ppm eU) was found in the latter area during our study.

4) Silver City Region, New Mexico, Burro Mountains. Precambrian granitoid rocks containing 3 - 6.4 ppm cU (delayed neutron, UCLA) and more than two dozen vein occurrences, some with mineralization $> 0.10\% \text{ U}_3\text{O}_8$ and two with a record of production, suggest a significant source terrain.

5) Mesozoic Granitic Rocks in General. In spite of the low average uranium contents shown in published literature for Mesozoic granitic rocks in the southern Basin and Range Province, the fact that Sierran granitics provided supergene uranium for the small but workable fracture fillings and lake bed deposits of the Kern River, Rosamond, and Coso Districts of California demonstrates the mobility of uranium from these sources during weathering. Minor enrichments (up to 293 ppm cU) in caliche in granitic terranes of the western Mojave Desert were examined during the present study.

The character and intensity of weathering over much of the southern Basin and Range Province appears generally comparable with that on the Namib Desert. The main part of the pallid zone in Western Australia is much more intensely weathered, of course, but less weathered outcrops on lower pediment slopes in that area are not greatly different from weathered granitic rocks in parts of the southwest.

7.2.4 Groundwater Uranium Contents and Evaporative Concentration

Groundwater contents of 10 - 60 ppb U, 1 - 12 ppb V, and 10 - 35mg/liter K, increasing 10-fold downdrainage or 100-fold for K in salt lakes are characteristic of Western Australian uraniferous calcretes. The results of extensive hydrogeochemical surveys currently under contract in the Basin and Range Province of southwestern United States are not yet available as of this writing, and no systematic water sampling program was undertaken in connection with the present calcrete/gypcrete research. We offer no favorability rating in this regard, therefore.

Some two dozen reconnaissance samples analyzed by Dr. Emil Kalil using the delayed neutron technique at UCLA show several domestic wells and some flowing streams in or near the study area, including the Amargosa and Mojave Rivers, to contain 2 - 4 ppb U. Values from irrigation waters have been in the range 8 - 28 ppb except from a small area of groundwater convergence and constriction in southern New Mexico where values of 76 ppb and 288 ppb were obtained (Section 7.3.5). Evaporative concentrations up to 339 ppb were obtained from waters in equilibrium with NaCl in a small salt lake (Soda Lake) in the Temblor Range of California. Knauss et al. (1974) report values of 0.2 - 29 ppb in wells of the Mojave region.

These results illustrate that appreciable solubilization of uranium has occurred in many parts of the study area. They also illustrate the effect of evaporative concentration and the caution that must be exercised in the interpretation of uranium analyses from evaporative waters.

Interpretation of hydrogeochemical data in relation to calcrete uranium mineralization is in its infancy. This is a result largely of persistent uncertainties about the chemical mechanisms of uranium and vanadium transport and carnotite precipitation in the calcrete environment. It is also partly due to the paucity of well-controlled surveys. Systematically arranged sampling points have not been available. Opportunistic water samples from wells, bores, and a few open pits are of limited reliability in terms of ion content, Eh, and pH even with in situ testing. A great deal of caution will need to be exercised in interpretation of hydrogeochemical surveys.

Progressively rising U and V contents along a drainage due to evaporation is a favorable circumstance in the calcrete environment. In Western Australia total ion content or conductivities increase, and HCO_3^- contents at first increase and then decline in the zone of valley calcrete deposition. Dall'aglio et al. (1974) show V content declining along with HCO_3^- in the lower part of a small basin. But this is contrary to the observations of Mann (personal communication, 1976) and Mann and Deutscher (1978) who found variable increases in V and V/U ratio below carnotite mineralization in Yeelirrie-like basins. These authors believe that they have been able to achieve considerable success in predicting the locus of carnotite precipitation in the Western Australian delta-salt lake environment by calculating a carnotite solubility index:

$$\text{SI} = \frac{\log[\text{UO}_2^{2+}]^2 [\text{H}_2\text{VO}_4^-]^2 [\text{K}^+]^2}{[\text{H}^+]^4 K_{\text{s.p.}}}$$

where $K_{\text{s.p.}}$ is the solubility product of carnotite from the equation:

and is taken to be $10^{-13.7}$ (Hostetler and Garrels, 1962). Uranyl ion concentration in the calculation is derived from measured total uranium, bicarbonate, and pH values according to data provided in the paper by Hostetler and Garrels. An SI equal to or greater than zero indicates that carnotite precipitation is possible with very large caveats, of course, about the validity of the assumptions and the thermochemical data upon which the several equilibrium values are based. Mann and Deutscher found a single positive value at a salt lake margin. Attempts to relate ion ratios other than those of K, U, and V to carnotite mineralization in Western Australia have not been successful to the writer's knowledge. Mann and Deutscher also point out that an Eh in excess of 0.2 volts at pH 6 1/2 - 7 is required to ensure the oxidized state of vanadium as V(V) requisite for carnotite precipitation.

The investigation of $^{234}\text{U}/^{238}\text{U}$ ratios undertaken by Russian, American, and Japanese investigators (Osmond and Cowart, 1976) especially in relation to sandstone uranium deposits may be a fruitful line of research.

7.2.5   Pedogenic Calcrete (Caliche) in
                          the Southwestern United States
                          by Oded Kolker

7.2.5.1   The Caliche Distribution Map

General county soil maps are available over almost all of the study area, the main exceptions being in southeastern California. These have been used to prepare a map (Plate VII-1) showing the occurrence of near-surface caliche on a regional scale. The county soil maps are reliable guides to the distribution of soil associations, the basic mapping units, but cannot in general be used to locate the caliche-bearing soils within an association. Their major limitations are: 1) caliche more than 5 to 6 feet below the surface is not recorded; 2) it is not always possible to determine the presence and degree of development of immature caliche from the profile descriptions and the soil taxonomy; and 3) when several maps are combined, discrepancies and mapping-unit discontinuities appear. The last two limitations can be partially overcome with the help of field reconnaissance and independent sources (e.g., references in the literature, statewide soil maps) and by considering environmental variables such as climate and lithology. Nevertheless, any attempt to map caliche over an extensive area from general soil maps suffers from their incomplete coverage (to date), varying intensities, and nonuniform terminology. (See also Section 3.2.2 re in situ calcrete.)

Silcretes do not occur in the study area, but duripans--siliceous hardpans--containing both silica and calcium carbonate cement are widespread in parts of Arizona and are here designated silcalcretes.

Geomorphic processes have been active in the study area in modern times, and, since caliche development requires prolonged surface stability, the mapped caliche bodies tend to occur in a few characteristic geomorphic situations. Aside from bedrock slopes in mountain masses, these are mostly abandoned depositional surfaces. Most are in alluvial fans dissected as a result of base level lowering by drainage integration. Many caliche associations in the map represent a relict fan surface in various stages of dissection and destruction. Others represent multi-level relict fan surfaces along major streams which were incised

episodically. These are called valley-border surfaces. Some associations represent incised basin floors of fluvial construction, and some are basin floors of lacustrine origin. Thus, a classification of caliches into five surface types is possible. Each caliche type is seen to be distinctive in certain profile properties. Mountain hillslope caliche is a thin, dense laminar cap over bedrock. Proximal fan caliche is essentially a cemented fan conglomerate, high in cobble but low in carbonate content, of intermediate thickness and moderately steep slope, and with vertically variable cementation. Distal fan caliche is thicker and higher in carbonate content and more gently sloping. It has variable gravel content, and hence morphology, and is also vertically discontinuous. Basin floor caliches fall into two categories, mesa (fluvial) and valley (lacustrine) types. Mesa caliche is distinctive for having the greatest thickness, carbonate content, vertical continuity, and areal extent of all. Valley caliche is thinnest and most fine-textured, with moderate carbonate content and frequent vertical discontinuity. Eighty caliche profiles have been analysed to establish statistical correlation between major profile properties and the surface type.

This classification of caliches is meaningful because the geomorphic surface is a convenient surrogate for two important determinants of caliche profile properties: age and the textural composition of the host sediment. It must be emphasized, however, that the data set is relatively small, and the dispersal about the category means is usually large, so that the surface type does not automatically connote a suite of specific caliche properties. It should also be noted that this classification does not reflect modes of genesis--e.g., relative vs. absolute carbonate accumulation, vertical vs. lateral transport, downward leaching vs. capillary rise. All caliches examined appear to be of pedogenic origin by downward carbonate movement, but, with the exception of the mountain type which clearly formed by in situ weathering of calcareous bedrock, this cannot be ascertained without analysis of properties not considered here, such as orientation of pebble coatings and micromorphology.

Silcalcretes appear to be essentially caliches with a variable admixture of silica cement. They are thinner and less gravelly than indurated caliches, with greater tendency toward structural development

but a comparable content of carbonates. These differences reflect the lithology from which they develop and the properties of silica cementation.

7.2.5.2 Uranium Favorability; Implications of the Caliche Map

The Caliche Distribution Map (Plate VII-1), based largely on county general soil maps, shows only surficial caliches, for soil surveyors do not dig deeper than 60 inches. Some of the caliche bodies extend beyond this limit to an undetermined depth, and there are also some deeply buried caliches which do not show on the soil maps at all nor on Plate VII-1. Thus, the map does not directly indicate subsurface conditions at the depth of lateral groundwater flow in which uranium and vanadate ions would be transported. However, since arid soils generally become increasingly calcareous at depth, the subsoil material is highly unlikely to be acid where near-surface caliche occurs. The caliche-free areas include some soils with pH of 5 to 6. These are in areas of recent alluvium from noncarbonate rocks where carbonate accumulation by eolian or fluvial agencies has not progressed very far. The soil surveys indicate that even in such cases the subsoil and substratum are usually calcareous with neutral to alkaline pH.

Silcretes are not found in the study area. There are, however, duripans--siliceous hardpans--which invariably contain an admixture of calcium carbonate cement and are here referred to as silcalcretes. They are restricted to parts of Arizona and to an area north of the map limits in Lincoln County, Nevada. Because of the lithology from which they are derived, duripan soils would be expected to be acidic. The presence of carbonate cement shows, however, that even here conditions were sufficiently alkaline at least periodically to allow precipitation and accumulation of calcium carbonate, probably from eolian sources. The relative amounts of silica and carbonate cement in silcalcretes is variable. Two samples were examined microscopically, one from Nevada and one from the Willcox Playa area, Arizona. In the former, calcite comprising about 35% of the volume surrounds discrete masses of opaline silica amounting to < 10% and containing fresh quartz phenocrysts. The silica may be primary (volcanic) rather than secondary (pedogenic). At Willcox Playa, small calcite crystals comprising 10 - 15% of the total

volume are embedded in an opaline silica groundmass occupying 35% of the volume. The carbonate deposition may thus be earlier or later than the precipitation of silica, or the two may have occurred in alternating sequence, suggesting short-term fluctuations in soil chemistry. In any case this would allow carbonate ion to have been transported by lateral flow of subsurface waters through such material at least periodically, and along with it, uranyl carbonate complexes. The uranium favorability of calcreted lower valleys in silcalcrete areas would thus be greater.

All the caliches mapped here appear to be pedogenic. There is no known occurrence of Western Australia-type valley calcretes. Even the valley-bottom caliches (associations 9a, 12, and 22) are very thin and sheetlike and are in fact associated with lakebeds undergoing in situ alteration near the surface.

All caliches in the study area are of Quaternary age, most dating from the middle or late Pleistocene, and some are even early Holocene. This is because of the high rates of geomorphic process in the region, with resulting burial or erosional destruction of ancient surfaces. Hence, the map does not give any clues to the possible presence of uraniferous calcretes, now buried, which may have formed in ancient times when the surrounding slopes from which subsurface drainage was derived were noncaliche bearing.

Most mapped caliche bodies developed in thick, permeable alluvium in the structural basins, on alluvial fan slopes, or on stream terraces. The bedrock floor is usually hundreds or even thousands of feet below the surface, and the surficial layers in which the pedogenic caliche develops thus cannot be affected by groundwater. One exception to this is the mountain hillslope caliche, denoted by a separate symbol on the map. It is a thin laminated crust resting on the bedrock, which probably formed by lateral spreading of meteoric water infiltrating to the impervious lithic contact. Only on limestone does it attain a thickness of more than several inches. Otherwise, it occurs chiefly in mountain masses of basic to intermediate volcanic rocks. The Cherioni soil (association 2 in southwestern Arizona), however, which features a silcalcrete crust over the bedrock, develops on rocks of more granitic

composition which are more likely to be source rocks of uranium.

Elsewhere, caliche which developed in shallow alluvium over a bedrock floor is found in pediments between mountain fronts and the thickening fan sediments. Here also there is an opportunity for the calichified layers to be impregnated with laterally moving subsurface waters in which uranium ions may be transported. Only association 13 in southeastern Arizona is of this type, but it may occur in other associations near the fan heads. In general, caliche bodies at a shallow depth above the bedrock floor, as in the small uraniferous fan at Sloan, Nevada (Section 7.3.2), are not extensive enough to appear on the soil maps.

Patterns on the map and the "Explanation" refer to the degree of caliche development as follows:

Soft caliche (s): earthy or powdery carbonate deposit, in material low in coarse clasts; soft to hard lime masses or nodules may be present, but not continuously cemented layers.

Soft to weakly cemented caliche (s-w): lenses or laterally discontinuous layers of weak cementation in soft caliche.

Weakly cemented caliche (w): contains a nearly continuous layer of weak cementation, a few inches to several feet thick; friable and breakable by hand; softens upon wetting.

Indurated or mature caliche (i): has a continuous hard layer a few inches to many feet thick; samples can be removed only with a hammer; does not slake in water; lenses or strata of weaker cementation may be present.

Bedrock caliche (br): thin (few mm to few cm) caliches developed directly on carbonate or noncarbonate bedrock, mainly in situ on mountain hillslopes.

"Percent of map containing caliche" has been estimated from descriptions of soil series within associations as shown on the "Legend."

Figure 7.12. Map of the Mojave region and adjacent areas, showing lakes and drainage during a part of Pleistocene time (probably the Tahoe age). From Blackwelder, 1954.

7.2.6 Catchment Areas, Gradients, Groundwater Constrictions,
and Salt Lake Margins

The orebody at Yeelirrie lies in the upper part of the drainage only 60 km below the present headwaters. Examples of present-day drainages which are longer than 50 km, which have catchments comparable with that of Yeelirrie or that inferred for Langer Heinrich, relatively low relief at least along the trunk stream, and either end in playas or become saline along some part of their course include Jornada del Muerto basin, Tularosa basin, Playas Lake basin, and Mimbres River basin, New Mexico; San Simon Valley, Sulphur Springs Valley, Salt River drainage, Whitewater Draw, Gila River, vicinity of Coolidge in Pinal County, Sacramento Wash, Bouse Wash, Centennial Wash, Arizona; Las Vegas and Pharump Valleys, Nevada; and Amargosa River, Mojave River, California. Bouse Wash, which would fall into the median size range for these drainages, has a length, for example, of over 100 km (65 miles) and a catchment area of over 3000 km² (1300 mi²).

In southern Arizona, several former internal drainages have become integrated into the Gila and Colorado River system during Quaternary time. In contrast, it has been inferred that in California the now separate Owens, Amargosa and Mojave Rivers were part of a single system during some of the Pleistocene (Figure 7.12) which flowed southeastward through Cadiz, Danby, and Chuckwalla valleys to the Colorado River (Blackwelder, 1954). Such ancient drainages provide potential sites for valley calcretes in addition to the present drainages.

Uraniferous valley calcrete slope gradients fall into two categories (Figure 7.13):

- 1) The very low gradients (0.02 - 0.4%) characteristic of valleys with calcreted clays, silts, sands, and rare gravels in Western Australia and
- 2) Gradients steeper than 1) by an order of magnitude or more (0.7 - 1.3%) which characterize surfaces underlain by unsorted to poorly sorted gravelly calcretes and gypcretes of the Namib.

The greater ease with which coarse, unsorted alluvium is calcified and the comparative abundance of limestone in the Namib source terrane apparently make up for the steeper gradient. Coarse carbonate-rich fanglomerate beneath a similarly steep or steeper surface has been converted to mature, indurated calcrete in the Jean-Sloan area, Nevada (Figure 7.13 and Section 7.3.2).

Figure 7.13

Comparison of Longitudinal Gradients

Vertical Exaggeration 20x
Gradients to Scale in Percent

Yeelirrie, Western Australia

Langer Heinrich - Tubas Grant, South-West Africa

Mimbres Drainage, New Mexico

San Simon Valley, Arizona

Bouse, Arizona

Whitewater Draw, Arizona

Hidden Valley, Nevada

Jean Sloan, Nevada

Salt lakes or playas have been logical exploration sites in many countries with very limited success. If the target is a uraniferous calcrete then attention should be given to the geometry of the model illustrated in Figure 4.21. Sharp increase in K^+ ion concentration and conditions likely to favor upwelling of groundwater with consequent rise in Eh, increase in temperature, loss of CO_2 , and evaporation are most probable at the point of groundwater entry along the margin of a salt lake. Lake Maitland in Western Australia is an interesting exception.

7.3

SPECIFIC AREAS IN SOUTHWESTERN UNITED STATES

7.3.1 Preliminary Selection of Areas; Remote Sensing Imagery

Since very little information was available at the outset on the overall distribution of calcrete in the southwestern United States and nothing at all on nonpedogenic calcrete, areas were selected for reconnaissance and some for slightly more detailed study on the basis of:

1) known or rumored occurrences of uranium mineralization in what might be calcrete, gypcrete, or a near analogue. The Jean-Sloan area and three smaller areas in the western Mojave Desert were known to contain uraniferous calcrete. Some other carbonate units with carnotite or known uranium anomalies and with a distribution suggesting valley calcrete turned out to be lacustrine limestones (e.g., Verde Formation, San Simon Valley lake beds).

2) probable uraniferous source rocks.

3) strongly arid climates and, as the distribution of caliche became better known (Plate VII-1), the occurrence of calcrete itself.

4) most importantly geomorphology and geology, especially in the hope of testing a large catchment area with low gradients, minimal dissection or alluviation, and a possible groundwater constriction.

Owing primarily to the large areas involved, regional geological and topographic maps and especially small-scale imagery were found particularly useful at the preliminary stage which the present investigation represents. Table 7.5 compares the scale and approximate spatial resolution of the small-scale imagery utilized.

Sensor	Scale	Approximate Spatial Resolution (m)	Swath Width (km)
LANDSAT multispectral scanner imagery	1:1,000,000	80	185
Skylab 190A and Gemini photography	1:715,000	30-40	163
Skylab 190B photography	1:500,000	10-20	109
U-2 and RB-57F photography	1:130,000	1-3	27

Table 7.5. Scale, resolution, and coverage of images utilized. The LANDSAT image scale is for an 18 x 18 cm (7 x 7 in) format; all other scales are for 23 x 23 cm (9 x 9 in) format.

LANDSAT color composites of the entire study area provided synoptic views of large areas (ca. 26,000 km² or 10,000 mi² per frame). Dominant characteristics of the drainages, viz. length, width, topographic constrictions, and size of the watershed are generally apparent in LANDSAT imagery, and gross aspects of vegetation cover or lack of it furnish a clue to regional climate. Some information on the nature and extent of valley fill can be interpreted. Bouse Wash, Centennial Wash, Buck Mountain Wash, and the Mimbres drainage, for example, were singled out for closer evaluation from the study of LANDSAT images. LANDSAT is limited by the low resolution and lack of stereo, although multispectral data extractable from computer compatible tapes may be applicable to calcrete mapping (briefly discussed later in this section).

The higher resolution Skylab 190A and 190B photography is appropriate for a closer inspection of selected target areas. Natural color is superior to color infrared or single band photographs for mapping broadly distributed surficial deposits. The photogeologic map of San Simon Valley (Figure 7.14) was prepared from Skylab 190B natural color stereoscopic photographs enlarged to a scale of 1:250,000. In stereo, older terrace deposits are separable from younger alluvial fan and floodplain deposits by virtue of their higher elevation and relative dissection. The white lake beds can be distinguished from recent alluvial deposits of yellow-brown hues. Gemini photographs, being oblique, are not well suited for geologic mapping but were useful in visualizing regional geologic relationships in South West Africa.

For more detailed geologic mapping, including the differentiation of bedrock lithologies and identification of faults, folds, and other structural features, the U-2 and RB-57 photos or conventional aerial photography are required. Both U-2 color infrared and conventional black and white aerial photographs were utilized as an aid to field mapping in the Jean-Sloan, Nevada area (Section 7.3.2).

Calcrete itself is sometimes identifiable from its light tone on sensing imagery. LANDSAT imagery as well as air photographs have been utilized in early stages of exploration for uraniferous valley calcretes in Australia (Premoli, 1976) and in southern Africa. Lattman (1973) used air photographs to distinguish pedogenic calcretes near Las Vegas, Nevada

and Mountain (1967), among others, has described locating calcrete for construction materials from air photographs in southern Africa. Large areas of stripped pedogenic calcrete on the McCollough fan south of Las Vegas are readily apparent on U-2 photos of the area, as are isolated patches, interpreted to be remnants of the same geomorphic surface, in nearby Hidden Valley (Section 7.3.2).

Although not utilized in this investigation, multispectral data from LANDSAT can aid in distinguishing calcareous deposits from certain other highly reflective alluvial deposits. A particularly applicable technique is a computer-generated image formed by the subtraction or ratioing of the red and green bands (Merifield et al., 1975). White or light gray materials such as calcrete, caliche, pure limestone or marble, and calcareous-alkaline soils have a similar reflectance in the two bands. In the subtraction or ratio image, the radiance values cancel out and the material appears dark, nearly as dark as clouds or snow. Alluvial deposits generally possess hues of yellow, yellow-brown, brown, or red-brown; they have a higher reflectance in the red band than the green band and therefore appear brighter in the subtraction or ratio image.

Pedogenic calcretes within the U. S. study area are commonly mantled by darker material, commonly as desert pavement and varnish. White calcrete is commonly distinctly visible from above in spite of this. Fringes of white pedogenic calcrete may be detectable near the tops of escarpments and along drainage courses, but only in relatively high-resolution imagery. Other things being equal, age of geomorphic surface is correlative with thickness of underlying pedogenic calcrete (Section 3.4.1). Shlemon and Purcell (1976) found that thick petrocalcic horizons are most characteristic of early Pleistocene to late Tertiary surfaces. The older surfaces are distinguishable from younger surfaces in air photographs by their 1) higher elevation--they form a margin around the base of mountain ranges, 2) darker color owing to a greater development of desert varnish and desert pavement, 3) comparative lack of vegetation, and 4) greater degree of dissection.

7.3.2   The Jean-Sloan Area, Clark County, Nevada

7.3.2.1   Introduction

The Jean-Sloan area of south central Clark County, Nevada was selected for a more detailed investigation because of known carnotite occurrences in calcrete (Hewett, 1923; Barton and Behre, 1954; Garside, 1973) in the vicinity of Jean and Sloan, 20 - 45 km (13 - 28 miles) south of Las Vegas along the Union Pacific railroad (T. 23, 24, 25 S., R. 60 E.). The area is underlain by Tertiary volcanic rocks ranging from basalt to rhyolite, Paleozoic limestones and dolomites with subordinate red beds and sandstones, and Precambrian gneisses, granites, and schists. Pedogenic and nonpedogenic calcretes of at least two ages occur above older bedrock surfaces and in valley fill. Carnotite occurs in most of the cuts along the railroad from a point 3 km (2 miles) northeast of Jean to a point 5 km (3 miles) north of Sloan. It appears: 1) within the calcrete as bright yellow to greenish yellow extremely fine-grained films and specks on joints and cavities and partly coating occasional pebbles (Barton and Behre localities 3 and 4); 2) along joints and bedding surfaces in the Bird Spring Limestone and along minor fractures within the sandstones and red shales of the Supai and Toroweap Formations (localities 1, 2, 6, 8, and 18 through 27); 3) along fractures in the Erie Tuff (localities 7, 1 - 13, 17, and 18); and 4) in the pre-Erie Tuff gravels and sediments (localities 5, 14, 15, and 16). The excellent detailed descriptions of the occurrences by Barton and Behre are not repeated here.

During the present study carnotite was discovered in calcrete of a slightly greater age and different setting in Hidden Valley some 6.3 km (4 miles) east of Erie. The regional distribution of the Erie Tuff, a strongly potential source rock, has been extended far to the south.

7.3.2.2   Calcrete and Contained Uranium

The Jean-Sloan area includes Pleistocene - Holocene (?) calcrete of at least two ages developed beneath surfaces of 1 - 3% gradient. Sparse carnotite mineralization occurs in both.

Sloan Calcrete: The calcrete occurrences described by Barton and Behre are in the younger of the two units, shown on the northwesterly half of Plate VII-2 as the Sloan Calcrete (Qs1), and consisting of strongly and pervasively cemented boulder fanglomerate derived from the Paleozoic terrane. The unit encompasses several fans composed predominantly to almost exclusively of carbonate detritus, minor chert, and sandstone and in some places basalt and andesite boulders. Exposed thicknesses are commonly in excess of 5 m (16 ft) along the railroad track. Pedogenic horizons are lacking. Crude sedimentary layering is, in places, reflected by varying degrees of induration, though all of it has reached stage 4 maturity of Gile et al. (1966) or "hardpan" of Netterberg (1971). The cement is calcite and lesser dolomite with rare gypsum. Steep gradients on the fans, from 1.7 to 3.0%, have unquestionably facilitated appreciable lateral groundwater flow. Cementation is apparently from groundwater in the capillary fringe and in part from gravitational water with some lateral component. Though each occurrence and each catchment area is measured only in kilometers to tens of km² at most, the coarse gravelly to bouldery texture, the wholesale cementation, and the steep gradients create a strong physical resemblance with the Namib Desert variety of groundwater calcrete. The predominance of carbonate clasts within the framework is a major chemical difference.

Visible carnotite occurs sparingly as thin films on fractures, as coatings on pebbles, and as specks in the cement at variable depths in the calcrete. Slightly greater abundances in areas of jointing may indicate reworking of earlier precipitates. The carnotite appears as tiny rounded blebs and crusts without obvious crystal form even under high magnification. Contemporaneity of some carnotite and carbonate is conceivable. At Barton and Behre's locality 3, a railroad cut about 1.6 km north of Sloan, carnotite films on carbonate pebbles occur in gypsiferous clayey calcrete and friable crystalline gypsum. Carnotite is visible only in artificial exposures. Neither the mineral nor anomalous radioactivity has been detected on natural exposures of weathered calcrete. Field gamma-ray spectrometry has failed to detect thorium. Laboratory analyses (BFEC) of two hand samples gave 22 ppm cU, 40 ppm eU and 42 ppm cU, 60 ppm eU. Possible downdrainage enrichment in the area of fanglomerate

and groundwater constriction about 2 miles east of Sloan has not been tested.

Hidden Valley Calcrete: The older calcrete unit, shown as Qh (Hidden Valley Calcrete) on Plate VII-2, is well exposed as cliff cappings in an area of recent stream piracy at the north end of Hidden Valley (NE 1/4 Sec. 8, T. 24 S., R. 61 E). It may be equivalent to the McCullough Fan calcrete described by Cooley et al. (1974), though slightly less mature. From one to three individual calcrete layers reach a maximum combined thickness of 5.4 m (18 ft) in the axial portion of the prepiracy drainage along Hidden Valley, each apparently thinning to a feather edge on the valley flanks. The lower meter or so of the calcrete is weakly cemented with gypsum and carbonate and is underlain by 3 - 4 m of uncalcified fan gravels and an unknown thickness of playa lake beds. Surface gradients in the area of exposed calcrete prior to stream piracy are from 1 - 1.5%, decreasing uniformly toward the small playa in southern Hidden Valley (Figure 7.13). A minor bedrock constriction between outcrops of biotite trachyte is possibly present 300 - 400 m southeast of the exposures.

Each calcrete layer or cycle shows a well developed pedogenic profile with a massive plugged horizon overlain by variably developed laminar caliche and local rockhouse structure at the surface. Angular pebbles and cobbles are sparse to abundant, the vast majority being moderately anomalous biotite trachyte derived from the hypabyssal center 2 - 3 km to the west-northwest (Tt on Plate VII-2). Illuvial transport of solubles probably including uranium is indicated by the occurrence of gypsum and other more soluble salts in the lower part of the calcrete by roughly vertical tubular, prismatic, and stalactitic structures and by the characteristic pedogenic sequence. On the other hand, the notably greater thickness of calcrete in the axial swale of the prepiracy valley and the localization of visible calcrete there indicates appreciable lateral flow and concentration of ions along the valley axis. The Hidden Valley calcrete appears to be hybrid: a pedogenic calcrete modified by nonpedogenic lateral solution transport toward the very gentle valley axis.

Carnotite, confirmed by X-ray, occurs as bright yellow to slightly greenish yellow films on fracture surfaces in the lowermost few centimeters of the middle (1.2 m thick) calcrete and the upper half of the lower (3 m thick) calcrete. It has been observed over an exposed length of 10 m or so near the valley axis. Radiometric response is extremely weak, reaching a maximum of 3.5 cps Bi²¹⁴, 1.5 cps Tl²⁰⁸ (13 ppm eU, 16 ppm eTh) by field spectrometry, decreasing to about one-third to one-half of that value on calcrete along valley flanks. The thorium content results from included fragments of biotite trachyte, fresh occurrences of which yield values of about 8.0 ppm eU, 27 ppm eTh by field spectrometry, and 4.0 ppm cU by delayed neutron analysis. Laboratory analysis (BFEC) of two samples of carnotite-bearing calcrete gave 700 ppm cU, 600 ppm eU and 44 ppm cU, 30 ppm eU, the latter being more characteristic of the occurrence.

The apparent catchment area updrainage from these carnotite showings prior to stream piracy is a mere 8 - 10 km². In lower Hidden Valley, where the calcrete is buried by recent alluvium and playa silt, the catchment would be 8 - 10 times as large. It includes large areas of biotite trachyte. If the ridge of basalt (Tmb) barring the southwest end of Hidden Valley postdates the valley itself, uranium released by weathering may have accumulated at one time on the margin of Jean Lake.

7.3.2.3 Stratigraphic Lithology and Possible Source Rocks

The geological map (Plate VII-2) and descriptions of the following geological units are abstracted from the work of Martin Kohl (1977), graduate student at UCLA.

Field work at intervals during 1977 consisted of mapping and sampling Tertiary volcanic and younger rocks. The distribution of Paleozoic units is from Barton and Behre (1954), Hewett (1956), and Longwell et al. (1965), supplemented by air photo interpretations. Quaternary units and geomorphic surfaces were mapped largely with the aid of aerial photographs.

Precambrian rocks crop out in the extreme southern part of the study area and represent the northerly extension of the rocks composing the higher parts of the McCullough Range lying to the south. They consist

largely of gray quartzofeldspathic biotite gneiss intimately intruded by foliated biotite granite, aplites, and pegmatites. Two delayed neutron uranium determinations from this complex yielded 1.5 and 15.2 ppm for specimens of reddish aplite and gray biotite gneiss, respectively. Malan (1972) reports Precambrian gneiss from the McCullough Mountain containing 1.6 - 13.7 ppm uranium. Large volumes of rock having up to 15 ppm could provide a very substantial source for later supergene mineralization.

Paleozoic rocks dominate the northwestern portion of the study area comprising the Devonian Sultan Limestone, the Mississippian Monte Cristo Limestone, the Mississippian through Permian Bird Spring Formation, and the Permian Supai, Toroweap, and Kaibab Formations. These rocks appear to be radiometrically impoverished in almost all localities examined, yielding a total gamma count of only 20 - 40 cps at the surface. One exception is a red clayey shale bed thought to lie within the Sultan Limestone at the railroad pass about 1.5 km (1 mile) northeast of the quarries at Sloan. Here the shale reaches 5.7 cps Bi^{214} or roughly 25 ppm eU. Visible carnotite is present in a sandy horizon at the top of the Toroweap Formation near Jean, but is not sufficiently abundant to greatly affect the radioactivity of the area (Barton and Behre, 1954). These authors believe that the uranium is the result of enrichment from much younger volcanic rocks. Radioactivity of the sandy horizon decreases to background levels characteristic of surrounding limestones as it is traced about 6.5 km (4 miles) northward. This is ascribed to the probable thinning of the tuff as well as a greater depth of posttuff erosion.

Tertiary rocks shown on Plate VII-2 and in part in Table 7.6 include:

- 1) Sporadic basal gravels, fanglomerate, and sand up to 100 m thick, not in itself uraniferous but containing very locally sparse supergene carnotite (Tal).
- 2) Porphyritic basalt-andesite flows similar to some of the Patsy Mine Volcanics of Bingler and Bonham (1972) of 18.6 to 14.5 m.y. age (Anderson et al. 1972). Analyses of three samples indicate only 2.79 - 2.99 ppm cU (Tpb).

- 3) Erie Tuff (Te) discussed below.
- 4) Biotite trachyte (Tt) discussed below.
- 5) Mount Davis Volcanics (Tmr, Tme, Tmb) discussed below.
- 6) Aphanitic latite flows (Tl) totaling 50 - 120 m thick and overlying Mount Davis Volcanics, biotite trachyte, and other rocks to the north and east. The unit contains only about 3 ppm cU.

Of these, the Erie Tuff is distinctly anomalous in uranium content. The biotite trachyte and parts of the Mount Davis Volcanics are moderately uraniferous.

Erie Tuff (Te): The widespread and uraniferous Erie Tuff forms the second oldest major volcanic unit. The tuff, up to some 80 m (260 ft) thick, is universally porphyritic with between 3 and 10% sanidine, and one-half to one-fifth as much sodic plagioclase, and auxiliary magnetite, biotite, pyroxene, and sphene in a fine-textured vitroclastic groundmass. Pinkish brown to maroon dense compact varieties, largely welded, typically alternate with less compact grayish or purplish white material vaguely defining several separate cooling units on the order of 5 - 20 meters thick. It is an alkali-rich rock of intermediate composition similar to that of quartz latite (Table 7.6) and considerably enriched in the lithophile trace elements, particularly boron and the light rare earths which are present at 10 times the concentrations commonly seen in granites (Barton and Behre, 1954). Analyses of 20 samples by delayed neutron technique range from 5.2 to 13.9 ppm U. Field gamma-ray spectrometry indicates 8 - 15 ppm eU and 45 - 70 ppm eTh. This is 1 to 2 times that of typical granite. Values vary erratically both horizontally and vertically within the tuff and show no evidence of covariation. Analysis of very fresh tuff and weathered tuff from the same horizon in a railroad cut gave 7.63 ppm cU and 6.68 ppm cU respectively, a difference of 12 1/2%. Remobilized uranium in the form of sparse carnotite, typically accompanied by gypsum, celestite, or dull gray calcite, occurs sporadically in and around fractures, especially in disturbed areas. Radiometric readings in these areas indicate up to triple the rather high backgrounds characteristic of the tuff.

The Erie Tuff can readily be correlated with the Tuff of Bridge Spring (Bingler and Bonham, 1972) which lies to the south in the Highland

Spring Range. Specimens taken from the hills south of Hidden Valley and over 12 miles farther to the southeast in the Highland Springs Range were examined in thin section and found to be almost identical. The Tuff of Bridge Spring is equivalent to at least part of Longwell's older Golden Door Volcanics (Anderson et al., 1972) which Longwell (1963) mapped along the Colorado River over a distance of 100 km (66 miles). The tuff is thought to have been essentially continuous at one time over the entire area which now contains uraniferous calcrete. However, because its relationship to the biotite trachyte which surrounds northern Hidden Valley is not yet known, one cannot conclude that it was ever exposed in the catchment area of the Hidden Valley Calcrete. It may lie at depth.

No source or vent for the Erie Tuff was found in the area. The most likely source region would lie to the south and east, the direction in which the tuff becomes thicker. Concordant ages of 14.5 and 14.4 m.y. were obtained from specimens of this unit from the Eldorado Mountains east of Nelson by Anderson et al. (1972). Although these ages are probably reliable and are closely bracketed by the K-Ar dates from the underlying and overlying rocks, the presence of considerable relief within lower cooling units and, in places on underlying surfaces, indicates a substantial interval of time during which the Erie Tuff was being laid down.

Biotite Trachyte (Tt): The northern half of Hidden Valley is surrounded by an extensive series of trachyte domes and flows of unknown thickness forming a heterogeneous series of bodies showing variable color, texture, flow banding, and degree of fracturing, but with only slight variations in modal mineralogy and uranium content. A small subcircular collapse feature with central latite plugs occurs in Sec. 6, T. 24 S, R. 61 E. Colors range from near-white through shades of gray to black, as well as purplish, orange, and reddish brown. The most conspicuous diagnostic feature is the presence of numerous elongate biotite flakes, constituting 1 - 3% of the rock along with 1 1/2 - 4% plagioclase (An₅₅) plus accessory magnetite, sphene, and apatite in an aphanitic to altered glassy groundmass. Although it is not particularly enriched in uranium (3 - 5 ppm cU), it must be regarded as a potential source rock for the Hidden Valley calcrete carnotite occurrence.

Mount Davis Volcanics (Tmr, Tme, Tmb): Stratigraphically above the Erie Tuff and of unknown relation to the biotite trachyte are heterogeneous volcanic rocks correlated with the Mount Davis Volcanics (Bingler and Bonham, 1972) of 14.6 to 11.8 m.y. age (Anderson et al., 1972). Olivine basalt dikes, cones, and extensive flows are common in and around the southern part of Hidden Valley along with rhyolitic dikes, plugs, flows, and widespread epiclastic and tuffaceous layers totaling some 200 m in thickness. The basalt contains about 3 ppm uranium (Table 7.6).

The rhyolite is strongly silicic (Table 7.6), containing very few phenocrysts of sanidine and sodic plagioclase with accessory quartz, sphene, biotite, and magnetite in a glassy or aphanitic groundmass. Approximately 5 ppm uranium make this a possible though not very rich source rock. The epiclastics presently contain only 3 or 4 ppm uranium, but whether this is due to original poverty, penecontemporaneous depletion, or recent leaching has not been determined.

7.3.2.4 Genesis and Favorability

Identification of the Erie Tuff by Barton and Behre (1954) as the most likely source for supergene carnotite in the Sloan Calcrete and other rocks in the Jean-Sloan area is entirely reasonable. It may not be the source for uranium in the Hidden Valley calcrete, however. The age of the Erie Tuff in relation to biotite trachyte domes and extrusions in northern and northwestern Hidden Valley is not known, but may very well be greater, as Barton and Behre suspect. In this event the biotite trachyte is the almost certain source. Weathering in the trachyte is not intense but neither is it in the Erie Tuff; analyses quoted above suggest a loss of one-eighth of the contained uranium on weathering of the tuff. Vanadium content of the Erie Tuff reported by Barton and Behre is 5 - 10 times the uranium content.

Precambrian granite and gneiss are fertile sources of uranium in this region but are nowhere updrenage from known mineralized calcrete occurrences.

If the volcanic rocks are indeed the uranium (and vanadium) sources, lateral groundwater flow is implicit to both the Sloan and Hidden Valley

calcrete uranium occurrences. Both are younger, and both lie down-drainage from outcrops or preexistent outcrops of the source rocks.

Precipitation of carnotite would seem to be a consequence of CO_2 loss coupled with evaporative concentration of other ions in solution, perhaps of common-ion precipitation of carbonate in small soil domains, and probably of absolute desiccation. The absence of carnotite or detectible uranium on weathered calcrete surfaces and its concentration along late fractures is evidence of reworking and perhaps some reconcentration. Desiccation is the sole factor tending to protect precipitated carnotite.

The occurrence of visible carnotite in calcrete in such small catchments with such apparently small components of lateral groundwater flow and with only moderate weathering of the source terrane is fairly encouraging in terms of calcrete uranium favorability in the southwestern United States. Gradients are steep in comparison with those of texturally comparable calcretes in Australia and South West Africa. Areas of groundwater constriction or salt lake margins have not been tested.

Table 7.6

Analysis of the More Important Cenozoic Igneous Rocks
Jean-Sloan Area

	1	2	3	4	5	6	7	8	9
SiO ₂	55.3	67.9	66.95	63.4	66.81	75.6	51.6	60.0	71.2
TiO ₂	1.45	0.425	0.52	0.71	0.35	0.5	1.47	0.77	0.16
Al ₂ O ₃	14.7	14.3	15.01	17.2	16.16	12.4	15.7	17.8	12.5
Fe ₂ O ₃	7.99†	2.09†	1.93	4.22†	2.01	0.93†	8.96†	5.85†	1.14†
FeO	—	—	0.41	—	1.25	—	—	—	—
MnO	0.112	0.062	0.08	0.093	—	0.066	0.140	0.098	0.066
MgO	6.45	0.467	1.16	1.79	0.72	0.087	6.53	2.05	1.01
CaO	7.60	1.53	1.45	3.36	2.62	0.705	9.18	4.47	1.55
Na ₂ O	2.86	4.08	4.04	3.54	3.42	3.60	2.68	3.78	2.78
K ₂ O	2.96	5.22	5.83	4.99	5.66	4.38	1.95	4.03	4.45
H ₂ O	—	—	+1.89 -0.61	—	+0.48 -0.10	—	—	—	—
P ₂ O ₅	—	—	.08	—	—	—	—	—	—
	99.42	96.08	99.97	99.303	99.58	97.92	98.21	98.85	94.86
ppm U*	2.91	8.20	10.0	3.90	—	4.91	2.29	2.85?	—

†Total iron computed as Fe₂O₃.

—Not analyzed at this time and not included in sum.

*Uranium determinations not necessarily made on same or same number of specimens as major element analyses.

1. Olivine--Augite basaltic andesite from Patsy Mine Volcanics. Average of four analyses on three specimens.
2. Erie tuff--average of six analyses on five specimens from different cooling units.
3. Erie tuff--average of four analyses on four specimens, from Barton & Behre (1954).
4. Biotite trachyte--average of seven analyses on six specimens.
5. Biotite trachyte--analysis of "latite" from Hewett (1956).
6. Rhyolites of Mt. Davis Volcanics. Average of seven analyses from six specimens of chilled glasses and flows from separate intrusions.
7. Basalts of Mt. Davis Volcanics--average of six analyses of four specimens from different flows.
8. Dark aphyric latites--average of nine analyses of eight specimens, except for SiO₂ percentage which is taken from the one value obtained by the maximum-dilution technique.
9. Quaternary rhyolite ash--average of two samples.

7.3.3

San Simon Valley

7.3.3.1 Introduction

San Simon Valley, in Cochise and Graham counties, Arizona, was selected for closer study primarily because airborne radiometric anomalies had been reported in the Quaternary valley fill. The soils maps indicated caliche in the soils; drillers' logs reported caliche at shallow depth; and San Simon Valley, one of Arizona's longest drainages (160 km, 100 mi), is located in a semiarid, tectonically relatively stable environment.

A 55-year record at San Simon indicates an average precipitation of 20.14 cm (7.93 in) and an average temperature of 15°C (60°F). Temperatures above 38°C (100°F) are common between May and September, with an average for these months of 25°C (77°F). Nearly 50 percent of the rainfall occurs in July, August, and September as sudden thunderstorms. Snowfalls are infrequent, and snow rarely remains on the ground for more than a day.

Artesian water, discovered in 1910 about midway in the valley, stimulated agricultural development. Many of these wells were left flowing for decades and provided surface water to San Simon Creek (Cushman and Jones, 1947).

7.3.3.2 Geology and Geomorphology

The geology has been described by Knechtel (1936), Gilluly (1956), Gillerman (1958), Wood (1959), Clay (1960), Davidson (1961), and Cooper and Silver (1964).

San Simon Valley lies in a large structural trough extending in a northwest direction from the vicinity of Rodeo, New Mexico to the vicinity of Globe, Arizona. The trough was formed by normal faulting beginning in middle Cenozoic time and continuing through late Cenozoic. The Peloncillo Mountains on the northeast consist primarily of intermediate to basic volcanic rocks of late Cretaceous and Tertiary age, but Paleozoic and Cretaceous marine sediments and Precambrian granite are exposed in fault blocks bounded by steeply dipping northeast-trending faults. On the southwest the Chiricahua Mountains are composed mainly of Tertiary rhyolite, and the Dos Cabezas Mountains are made up of Precambrian granite,

Figure 714

Photogeologic Map of San Simon Valley, Arizona

gneiss, and schist, Paleozoic and Cretaceous marine sediments, and silicic to intermediate Cretaceous and Tertiary volcanic rocks. Laramide igneous events contributed intrusive breccia and dark aphanitic magmatic bodies, followed by Paleocene quartz diorite and quartz monzonite stocks, Eocene basaltic dikes, middle Tertiary andesitic and dacitic dikes, granodiorite stocks, and quartz dikes. About 60 percent of the Dos Cabezas Mountains are made up of granitoid intrusions and metasediments. The Pinaleno Mountains, also on the southwest, are composed almost entirely of Precambrian gneiss, schist, and granite.

The San Simon trough served as the depositional site for a thick sequence of Cenozoic alluvial deposits and lake sediments. The older valley fill, distinguished as terrace deposits and lake beds on the photogeologic map (Figure 7.14), have been called the Gila conglomerate by earlier workers (Gilbert, 1875; Knechtel, 1936) and range in thickness to over 600 m (2000 ft) in the central part of the valley (White, 1963). The lake beds occupy the central part of the trough and consist of light-colored clays and silts which are gypsiferous in places and locally contain tongues and lenses of sand, tuff, and carbonates. They inter-finger outward with a coarser facies of buff or gray-colored conglomerates composed of subangular to angular pebbles, cobbles, and boulders derived from the adjacent mountain ranges. Upper Pliocene fossils have been described from the lake beds (Knechtel, 1936). Younger deposits of silt, sand, and gravel underlie the active alluvial fan surfaces, the Gila River, and San Simon Creek and their tributaries.

The main physiographic features and present drainage were established by late Cenozoic time, according to Cooley (1968). During the Pliocene, the San Simon Valley was impounded and occupied by a large lake; similar enclosed basins were present in much of Arizona during the Tertiary. The Gila and San Francisco Rivers probably flowed into this basin. In late Pliocene or early Pleistocene time, the Gila River system became integrated, and incision of the older valley fill began, progressing up San Simon Valley. The upper terrace bordering the Gila River near Safford is continuous with the floor of San Simon Valley, whereas Knechtel (1938) observed that the lower terrace extended 24 km (15 mi) up San Simon Valley.

7.3.3.3 Hydrology

Groundwater in the San Simon Valley is confined primarily to the older valley fill which is underlain, at irregular and poorly known depths up to 600 m (2000 ft), by volcanic tuffs and breccias and overlain in places by a veneer of alluvial fan deposits and recent fill along present stream channels. Contained aquifers are frequently artesian in nature or show considerable artesian pressure. They occur as lenses of sand and gravel 0.3 to 15 m (1 to 50 ft) thick separated by clay strata beneath 18 to 60 m (60 to 200 ft) of alluvial fill and up to 180 m (600 ft) of impermeable bluish clay. Wells in this unit can generally produce 1900 to 7600 liters/min. (500 to 2000 gallons/min.) and are able to sustain aggregate yields in the neighborhood of 12 to 18 million cubic meters per year (10 to 15 thousand acre-feet per year). Recharge of the deep aquifers is thought to occur beneath the upper ends of the fans, where clays and other beds of lacustrine origin finger out against the coarser marginal sediments, giving descending waters free access to most of the permeable layers.

Nonartesian groundwater occurs in sands and gravels above the blue clay at relatively shallow depths in aquifers interbedded with clays or silt from 18 to 46 m (60 to 150 ft) below the surface. The water is derived directly from rainfall seepage, streamflow, agricultural waters, lateral underflow into the basin, and leakage, both natural and artificial, from the underlying aquifers. A major source is at San Simon Cienega, 27 km (17 mi) southeast of San Simon, where large quantities of northward-traveling groundwater are forced upward to the surface due to some obstruction, later to sink back down to the shallower levels. Generally, the nonartesian shallow waters are somewhat mineralized, subject to depletion, and do not constitute a reliable supply. According to White (1963), pressure gradients found to exist in the lower artesian system and surface gradients in the upper water table cause the water in both systems to flow slowly northwestward to the Safford Valley of the Gila River.

Cushman et al. (1947) stated that the artesian groundwaters in the San Simon Valley display chemical variations controlled by the composition of the rocks with which they have been in contact. Waters pumped from

areas of valley fill derived from the granitic hills to the west are low in hardness but relatively high in fluoride. The largely volcanic mountains to the east seem to be reflected in greater hardness but lower concentrations of fluoride. Nonartesian groundwaters do not show a similar pattern, perhaps because of data insufficiency, but in general they tend to be more highly mineralized than the deeper waters.

Chemical analyses of well waters (White and Smith, 1965) imply only marginal differences in hardness between the two sides of the valley. Of seven deep wells on the northeast side for which data are available, dissolved solids ranged from 610 to 252 ppm and averaged 347, while the 66 available wells on the southwest side averaged about 286 and ranged from 550 to 159 ppm. Fluoride ranges from 14 to 1.6 ppm, averaging 4.9 on the northeast and from 20 to 0.4 ppm, averaging 4.5 on the southwest, suggesting local rather than regional control.

7.3.3.4 Soils and Caliche

The soils of San Simon Valley are the product of a continental, arid to semiarid climate with light precipitation totals, large temperature changes, and low humidity. They have been grouped into twelve general associations for broad interpretive purposes (U.S.D.A, Soil Conservation Service, 1971, 1973, 1976; see also Caliche Distribution Map, Plate VII-1).

In summary, the soil surveys indicate that ten of the twelve soil associations contain calcium carbonate accumulations in degrees ranging from calcareous soil to continuous but immature pedogenic calcretes, the latter being the Stewart soils of the Gothard-Crot-Stewart association. The Stewart soils are described as having an indurated calcareous and siliceous continuous "hardpan" 15 - 38 cm (6 - 15 in) thick at a depth 25 - 30 cm (10 - 12 in). Field observations of Stewart soils near Willcox revealed these to be immature accumulations and not petrocalcic horizons.

Plotted on Figure 7.14 are areas where drillers' logs of water wells in San Simon Valley indicate subsurface caliche, predominantly between depths of 3 and 30 m (10 and 100 ft). Although drillers' logs are not generally reliable for lithologic descriptions, the shapes of

the reported caliche areas are intriguing and could be interpreted as lying along former courses of San Simon Creek. It is tempting to speculate on the presence of a valley calcrete, but data are insufficient to go further.

7.3.3.5 San Simon Anomaly

In addition to the Whitlock Mountains Anomaly described by Burgett and Zollinger (1976a), these authors (1976b) reported another airborne radiometric anomaly in San Simon Valley about 16 km (10 mi) east of Bowie (Figure 7.14). The area is underlain by white to gray lacustrine calcareous and tuffaceous clays. Our ground radiometric reconnaissance revealed activities about three times background approximately one mile S 32°E of West Well. Typical readings from the Geometrics Gamma Ray Spectrometer are given in Table 7.7.

Table 7.7. Ground radiometric data southeast of West Well, San Simon Valley. Values are counts/sec.

Location	Total Count	Bi ²¹⁴ (U)	Tl ²⁰⁸ (Th)
0.9 mi. S 54° E of West Well	120	1.4	2.0
~ 1 mi. S 32° E of West Well	175 173	5.6 6.1	1.5 2.5
Creek west of West Well	86	1.7	0.7

Fresh exposures of lake beds at the Union Carbide Zeolite Pits (Sec. 20, T. 11 S, R. 29 E, Bowie, Arizona 15-minute U.S. Geological Survey Quadrangle, 1949) were also examined. Radiometric measurements taken on the zeolite beds, as well as subjacent and superjacent beds, showed low uranium activity (1.6 to 3.5 cps). By comparison, the Whitlock Mountains Anomaly provided ground radiometric uranium counts of 21.6 to 48.6 cps.

7.3.3.6 Conclusions

The thin surficial calcrete exposed in the axial parts of San Simon Valley is not a valley calcrete in the sense used in this report. It appears to have developed mainly above calcareous clays of the Pliocene lake beds by in situ and pedogenic processes. The calcrete (caliche) is not in itself uraniferous although locally the underlying units are mineralized. In 1976-77, exploration drilling in the lake beds was underway.

7.3.4

Bouse Wash, Arizona

7.3.4.1 Introduction and General Setting

Bouse Wash, in Yuma County, southwestern Arizona, possesses several characteristics comparable to the drainage at Yeelirrie. Its total length is on the order of 117 km (65 mi), it lies in a relatively stable tectonic setting with an arid to semiarid climate, and it drains large areas of potential uranium source rocks. Drainage is primarily subsurface, and many of its tributaries disappear before intersecting the main wash. Study of LANDSAT images and topographic and geological maps reveals the presence of a constriction formed by outcropping bedrock in the vicinity of the town of Bouse (Figure 7.15).

Upper Bouse Wash drains a region underlain primarily by Cretaceous volcanic rocks of andesitic to rhyolitic composition and Quaternary basalt. Tributaries of the central segment of Bouse Wash drain areas of Paleozoic and Mesozoic sedimentary rocks, Mesozoic granitic rocks, and Cretaceous andesitic rocks. Cunningham Wash, the major tributary of Bouse Wash, drains the 48-km- (30-mi-) long Butler Valley, bordered primarily by Precambrian granite gneiss.

Late Cenozoic lacustrine clays and silts, interbedded with alluvial sands and gravels, underlie Bouse Wash in the vicinity of the town of Bouse. They indicate that a fairly large lake was impounded behind the constriction formed by Bouse Hills and the Plomosa Mountains northwest of the town of Bouse. The constriction was subsequently breached, and Bouse Wash became integrated into the Colorado River drainage system.

7.3.4.2 Calcrete

A comparatively significant accumulation of calcium carbonate for this part of Arizona was noted about 0.8 km (0.5 mi) south of Bouse along an easterly tributary of Bouse Wash. The tributary originates about 13 km (8 mi) to the east in the Bouse Hills, composed of Mesozoic granite and Cretaceous andesite.

In an attempt to determine the geometry and distribution of the calcrete, six trenches up to 3 m (10 ft) deep were excavated by backhoe, mainly to the east of Bouse Wash over a 4 km (2.5 mi) stretch south of Bouse.

Figure 7.15

GENERALIZED GEOLOGIC MAP, BOUSE WASH, ARIZONA

(After E. D. Wilson, 1960)

The excavations exposed green silty clay interbedded with brown to red-brown sand and gravel within which the calcrete appears as filaments, veinlets, and nodules up to 5 cm in diameter disseminated through 1 m or more of the clay or in coarser materials at contacts of zones of differing permeability. In some places calcium carbonate constitutes about 80 percent of the sediment. Locally, the nodules coalesce into a layer about 0.3 m thick. Individual beds as well as calcareous horizons could not be traced between excavations, 60 to 90 m (200 to 300 ft) apart.

The morphology of the calcrete suggests that it is primarily pedogenic. However, it appears to be restricted for the most part to the area of calcareous silty clay lake beds exposed along the tributaries of Bouse Wash which drain the east side of the basin. Moreover, the nodules are most abundant within 3 m (10 ft) or so of the banks of the washes, although observations were limited to a few minor tributary washes. Apparently the strongest calcium carbonate development is related to ephemeral flow in washes entering from the east as a result of favorable source rocks, primarily the lake beds and beyond that the andesitic terrain. If this is the case, its origin resembles gully bed cementation (Section 3.2.2), and it does represent some lateral transport of calcium carbonate. The lake beds themselves are a consequence of the topographic constriction at Bouse.

It is interesting to note that caliche is forming in the area today as evidenced by its presence in artificial fill placed along Bouse Hills Wash to protect the railroad. Calcium carbonate coats grains and pebbles and forms soft, friable nodules up to 2 cm (0.75 in) in diameter in discontinuous layers one nodule thick. A weak surface cementation of white, powdery calcium carbonate is also present on the fill as well as on recent alluvium at other locations.

7.3.4.3 Uranium

Groundwater from three wells within the calcrete area yielded only 2 to 4 ppb uranium by delayed neutron analysis. Twenty-eight delayed neutron analyses were run on samples of nodular calcium carbonate and associated noncalcareous sediments. Values for nodules ranged from about 2 ppm to 23 ppm uranium and, for noncalcareous sediments, from 3 ppm to

5 ppm uranium. In partly carbonatized clay the uranium concentration is proportional to the abundance of nodules. Some large nodules containing 13 to 23 ppm U were almost twice as rich as immediately adjacent clay. Relations between concentration and depth are ambiguous or correlative with calcium carbonate or carbonaceous matter. Lake beds contain about 3 ppm U.

Twenty-six ground radiometric measurements were made with the Geometrics GR410 gamma-ray spectrometer. Bi²¹⁴ gamma-ray responses ranged from 1.4 to 3.3 cps within a 4 km (2 1/2 m) radius of Bouse. One measurement taken for comparison 10 miles south of Bouse along Highway 72 yielded 2 cps Bi²¹⁴. No significant trends or anomalies are indicated.

7.3.4.4 Conclusions

Sufficient field data were collected to establish that a valley calcrete is not present at shallow depth on the upstream side of the topographic constriction in Bouse Wash. Calcium carbonate accumulations occur locally, primarily in lake beds. Uranium values were found to be somewhat higher in the nodules than in noncalcareous sediment, but no significant uranium concentrations were discovered.

7.3.5

Mimbres-Palomas Basin, New Mexico

A reconnaissance study of the Mimbres-Palomas Basin in Luna County, New Mexico (Figure 7.16) was prompted by the existence of very large, relatively stable catchments containing three major groundwater constrictions in an area favorable to calcrete deposition and with a known uraniferous terrane in the headwaters.

The basin is part of a large region in southwestern New Mexico and Chihuahua characterized by extremely broad internal drainages; a region described by Hawley (1969, 1975) as the Bolson subsection of the Mexican Highland section of the Basin and Range Province. Through much of the late Quaternary long periods of landscape stability and soil formation in the bolsons have been interrupted by brief episodes of relatively mild but widespread erosion and sedimentation on fans and valley floors. During glacial maxima basin floors were commonly flooded. In the Mimbres-Palomas drainage this resulted in Pluvial Lake Palomas (Reeves, 1969), covering a length of nearly 200 km in the state of Chihuahua and extending into Luna County in the area of interest. An even larger lake, Cabeza de Vaca, occupied this area in Early and Middle Quaternary. Today Lake Palomas is largely a region of alkali flats and remnant playas. In the Bolson subsection generally, according to Hawley (1975), "Quaternary bolson fill, rarely more than 100 m (330 ft) thick, overlies late Tertiary bolson deposits (lower Santa Fe and Gila Group equivalents) that locally exceed 1000 m (3300 ft) in thickness." The Quaternary surficial fill consists of 1) fans and piedmont alluvium forming aprons around isolated mountain groups; 2) fine-grained alluvium and lake and playa sediments along the basin floor; 3) fluvial sands and gravels of very restricted occurrence in ancient rivers; and 4) eolian sand.

Pedogenic calcretes are associated with soils and paleosols related to at least five periods of relative stability in the adjacent Las Cruces area and along terraces of the Rio Grande River (Gile et al., 1970). In the Mimbres-Palomas area terrace exposures are not present, but calcrete is particularly evident in older piedmont gravels around the Florida and Tres Hermanas Mountains. Nonpedogenic (gravitational water and capillary fringe) carbonate deposition in the Las Cruces area has been described by Ruhe (1967).

Darton (1915, 1916) observed that the depths of groundwater in wells came within less than 25 ft of the surface in three areas of constricted subsurface flow: 1) along the Mimbres drainage east of Deming between the northerly tip of the Florida Mountains and the Cookes Range, 2) along the Palomas Arroyo near Waterloo (also known as Seventysix Draw) between the Florida and Tres Hermanas Mountains, and 3) along the Palomas and Mimbres drainage southeast of Columbus between the Tres Hermanas and West Portillo Mountains. Although there is no evidence of a valley calcrete at the surface in any of these areas, well drillers have reported encountering "caliche" at various depths.

The size of the catchment updrainage from the first Mimbres constriction is in the order of 2500 km²; it is something less above the Palomas constriction at Waterloo and roughly three times as large above the Palomas-Mimbres constriction near Columbus. Anomalous amounts of uranium occur in Precambrian granitics and associated dikes, shear zones, and veins in the Big Burro Mountains in the westerly headwaters of the catchment (Gillerman, 1953). Minor production has been obtained from some of the veins containing oxide zone minerals in the White Signal District. Lesser anomalies have been observed in the Mimbres Mountains (Chenoweth, 1976).

The three areas of constricted subsurface flow and shallow groundwater were visited briefly on three occasions in 1976 and 1977. Nine water well samples gave the following results by delayed neutron analysis:

	ppb U
Upper Mimbres drainage near Spalding	18
Deming municipale water	N.D.
Waterloo-Palomas constriction area (T26S, R8W)	
Shallow nonsaline well (NW1/4, Sec.5)	2
125' deep saline well (N1/2, Sec.8)	288
250' deep saline well (N1/2, Sec.8)	76
Irrigation well, nonsaline (NW1/4, Sec. 22)	60
Irrigation well, nonsaline (W1/2, Sec. 22)	90
Pancho Villa Park, Columbus	N.D.
Columbus, Irrigation Well (NW1/4, Sec. 11, T29S, R8W)	53

Seven backhoe trenches were dug in the same Waterloo-Palomas constriction area to a maximum depth of 11 ft in the hope of finding some evidence of nonpedogenic calcrete. Authigenic carbonate as filaments, stringers, nodules, and, in one case, massive caliche was found in four of the trenches but only mud and sand, in part gypsiferous, in three trenches along the lowest part of the draw. The carbonate, up to 4 ft thick, is clearly pedogenic and would correspond to stages 1, 2, and, less commonly, 3 of Gile et al. (1966). Uranium contents of samples by delayed neutron analysis range from 2.7 to 6.2 ppm, being highest in gypsiferous mud or sandy clay loam and not clearly related to carbonate content or depth. Surface samples here and elsewhere including exposed caliche tend to fall in the range of 1 to 3, rarely 4, ppm U.

These reconnaissance data are inadequate to support or eliminate the possibility of nonpedogenic calcrete occurrences at greater depths in the areas of groundwater constriction.

7.3.6

Western Mojave Desert

Predominantly pedogenic calcrete with anomalous amounts of uranium are known in at least three locations in the western Mojave Desert:

- 1) High Vista area,
W 1/2, sec. 18, T. 8 N., R. 7 W. (S.B.B.M.) on the Kramer SW
7½-minute quadrangle, U.S. Geological Survey.
- 2) M & R Ranch prospect,
Sec. 30, 31, T. 31 S., R. 39 E. (M.D.B.M.) on the Castle Butte
15-minute quadrangle, U.S. Geological Survey.
- 3) Kramer Junction area,
Sec. 14, 22, 23, T. 11 N., R. 7 W. (S.B.B.M.) on the Boron
15-minute quadrangle, U.S. Geological Survey.

7.3.6.1. High Vista Area

The prospect, drawn to our attention by Mr. Tom Mitchel of BFEC, is in a small alluviated basin, not more than 3 to 4 mi² in area, near the headwaters of an ephemeral stream draining northwesterly into Rogers (Dry) Lake. The stream has slightly dissected a very gently sloping older fan and pediment above Mesozoic granitic bedrock. Granite containing dikes of pegmatite and aplite occupies low hills within one-quarter to one-half mile south, west, and north of the prospects. Background radiometric response increases from 100 cps total count over the granite to 150 cps over pegmatite-aplites, which are upslope from the prospects. Quartz monzonite one-half mile north of the prospect yields up to 35 ppm eU and 25 ppm eTh very locally by ground gamma-ray spectrometry. The granitic rocks are rather deeply weathered, and adjacent alluvium is entirely decomposed granite.

Pedogenic calcrete (caliche) reaching stage 4 of Gile et al. (1966) is exposed from approximately 1 to 5 ft depth in three small open cuts within decomposed granitic detritus of the older fan. Radiometric readings and chemical uranium contents invariably increase downward from the A soil horizon through the entire 4 ft or so of calcrete. In the westernmost cut a maximum spectrometer reading of 70 cps Bi²¹⁴, 4 cps Tl²⁰⁸ was obtained in the lowermost part of the calcrete (360 ppm eU, nil Th). A sample of this calcrete contained 293 ppm cU by delayed neutron analysis. Weathered granite immediately beneath the calcrete

contained 178 ppm cU. A sample of the calcrete taken by Tom Mitchel (personal communication, 1977) was reported to contain 203 ppm eU, 200 ppm cU. An increase in gamma-ray response on the surface by as much as 1 1/2 times background in the vicinity of the cuts may be natural to the area. No uranium minerals were observed, and calcrete is not evident at the surface outside the cuts.

The occurrence appears to be an example of uranium fixation in pedogenic carbonate on the alluvial flanks of a catchment area, albeit a very small one. Some lateral transport of uranium in subsurface water from neighboring granitic hills is likely, but the wholesale fixation of both carbonate and uranium in pedogenic calcrete, if this is what has happened, would greatly diminish the possible generation of ore-grade nonpedogenic calcrete lower in the drainage system.

7.3.6.2 M & R Ranch Prospect

The prospect has been very briefly described by Bales (1956). The northwestern Mojave Desert in this area is a gently rolling upland draining to the northwest into Koehn (Dry) Lake at gradients as low as 1%. There are scattered monadnocks of Mesozoic granitic and Tertiary volcanic rocks. One such hill of weathered quartz monzonite containing northwesterly shear zones and rare pegmatite-aplite dikes rises some 400 to 500 ft above the main desert surface in the prospect area. Discontinuous patches of pedogenic calcrete up to stage 4 of Gile et al. (1966) and at least 2 1/2 ft thick are exposed in remnants of a dissected older fan on the westerly and southwesterly lower flanks of the hill.

Total gamma-ray response in the region has a background value of 60 cps, increasing two-fold over outcropping quartz monzonite and up to 3 or 4 times background over shear zones and pegmatite-aplite dikes. Anomalous values of up to 650 cps total count, 40 cps Bi²¹⁴, and 4 cps Tl²⁰⁸ are confined to trenched exposures of calcrete. Samples of the calcrete from 1 and 3 ft depth in one trench contained 43 and 35 ppm cU respectively. No uranium minerals were observed.

Again this occurrence appears to be an example of uranium transport over a very short distance from weathering granitic rocks and fixation in a predominantly pedogenic calcrete. As in the High

Vista area the extremely low thorium (Th^{208}) response indicates chemical rather than detrital transport of the uranium.

7.3.6.3 Kramer Junction Area

The area is in a broad alluviated portion of the western Mojave Desert draining southeasterly at gradients of 1/2 to 1% into Harper Dry Lake. Older and younger alluvium overlies Miocene and Pliocene (?) sedimentary and minor volcanic rocks, including borate beds of the Tropico Group. Upper units of the Tropico Group, including fanglomerate, sandstone, tuffaceous shale, and minor limestone, crop out in sections 14 and 15 on the northern edge of the area of interest. Secondary uranium minerals including uranophane (?) are exposed in numerous prospect pits in the shaley and limy units and some overburden (Bowes, 1955). Weathered Mesozoic quartz monzonite containing dikes of coarse pegmatite and aplite crops out extensively in a broad pediment and large ridge forming the northerly border of the eroded Tertiary basin. Several of these granitic rocks are anomalously radioactive, exceeding those of the M & R Ranch area in total radiometric response. Pre-Mesozoic gneiss and metavolcanic rocks occur to the southwest.

Pedogenic carbonate (caliche) of stage 1 to 3 maturity (Gile et al. 1966) is common in the areas of older alluvium, and in a few scattered open cuts a very slight increment in radiometric response over background can be detected in the carbonate. In one open cut the uranium content increased from 2.6 ppm cU in the uppermost carbonate horizon to 5.0 ppm in carbonate two feet below and 6.0 ppm in weathered granite with veins and nodules of carbonate at a depth of 4 1/2 ft.

Very irregular stringers, lenticular veins, and pods of carbonate have been deposited in the gravitational water zone in sandy and clayey gravels immediately downslope from the bedrock uranium occurrences in Tropico Group sediments mentioned above. Radiometric response is very slightly enhanced in some of the carbonate areas, in some cases along their margins, and in these areas delayed neutron analyses indicate contents of from 5 to 24 ppm cU. These weak concentrations are thought to represent both physical transport by soil creep and alluviation and chemical transport by laterally moving subsurface water.

7.3.7 Southeastern Mojave Desert, California and Arizona

Shlemon and Purcell (1976) report calcium carbonate accumulations in older alluvial deposits of the southeastern Mojave desert. The oldest alluvial deposits, estimated to be middle Pleistocene to late Tertiary in age, commonly possess carbonate K-horizons in their soil profiles and carbonate seams extending to depths greater than 1.2 m (5 ft), according to these authors. These older surfaces occur at higher elevations fringing the mountain ranges composed of nongranitic rocks but are largely buried by grus shed from granitic terrain. They are deeply dissected by the larger drainages and are characterized by surfaces of well-developed desert pavement and desert varnish (patina).

The Chocolate, Chuckwalla, and Orocopia Mountains, the principal ranges of southeastern California, are underlain chiefly by Precambrian metamorphic and granitic rocks, Mesozoic granite, and Tertiary volcanics (largely andesitic to rhyolitic in composition). In southwest Arizona between Yuma and Quartzsite and west of Highway 95, the Trigo and Chocolate (Arizona) Mountains are predominantly Cretaceous andesite. The Dome Rock Mountains west of Quartzsite consist of Mesozoic schist, gneiss, and locally metamorphosed sedimentary rocks and Mesozoic granite. As a whole, the region has been comparatively stable tectonically during Quaternary time. The climate is arid, with precipitation of from 7.6 cm (3 in) in the lowlands to 25 cm (10 in) in the mountains, occurring mostly with winter cyclonic storms from December to March and summer convection from July to September. Access is severely limited by the Yuma Test Station, Chocolate Mountains Gunnery Range, and Dunlap Artillery Range, which cover a large portion of the region, but access to narrow corridors is provided by Interstate Highway 10 between Indio, California and Quartzsite, Arizona, Highway 95 between Quartzsite and Yuma, and Highway 78 between Brawley and Palo Verde, California.

The older alluvial deposits reported by Shlemon and Purcell (1976) were examined in numerous places along these highways as well as in the Chocolate Mountains at the north edge of the Dunlap Artillery Range and the Mine Mountains west of Palo Verde, California. Most commonly the calcium carbonate occurs as seams or nodular horizons 2.5 - 7.6 cm (1 - 3 in) thick within the upper ten feet of fan conglomerate and generally comprises less than 25 percent of the total deposit.

However, an exceptional accumulation of calcium carbonate was encountered during a rapid reconnaissance at the head of a deeply incised wash two miles west of the Colorado River on the southeast flank of Palo Verde Mountain (sec. 21, 22 T. 10 S., R. 21 E., Cibola 7½-minute quadrangle, U.S. Geological Survey). Beneath a gently undulating surface with a well-developed desert pavement is four feet of tan pebbly silt underlain by a discontinuous plugged horizon up to 15 cm (6 in) thick of calcium carbonate. The underlying 2 m (6 ft) is a weakly cemented fanglomerate composed of fifty percent pebbles and cobbles of intermediate volcanic rocks in a matrix of sand and silt cemented with calcium carbonate. The subjacent 2.7 m (9 ft) is a similar fanglomerate except that it is much more thoroughly cemented and properly designated a pedogenic calcrete. It supports vertical walls along the wash and a prominent ledge on its upper surface. In places, discontinuous horizons are predominantly hard, clast-free calcium carbonate. The cemented fanglomerate, however, is not as well indurated as those in the Las Vegas, Nevada area; chunks can be broken from the outcrop by hand.

Ground radiometrics were not obtained, but five samples from this locality yielded 1.9 ppm uranium to 2.9 ppm uranium by delayed neutron analysis; no relation between the uranium concentration and the lithologic horizons described above is indicated.

Another sample was collected from a hard calcium carbonate lens exposed in a roadcut on Highway 95, 4.8 km (3 miles) south of Stone Cabin, Arizona. The lens reaches a maximum thickness of 0.3 m (1 ft) and occurs within fanglomerate with pebbles to cobbles of light-colored rhyolitic (?) rock. Calcium carbonate also occurs as discontinuous, soft, white, one-inch layers. The sample from the hard lens yielded 4.0 ppm uranium.

A sample from soft calcium carbonate seams in fanglomerate typical of the region, collected on the north flank of the Chocolate Mountains, California 21 km (13 mi) south of Interstate Highway 10 near Skylark Ranch, gave a value of 1.4 ppm uranium.

Generally speaking, calcium carbonate accumulations in the southeastern Mojave desert are not comparable in development with those of the Las Vegas, Nevada area. True pedogenic calcrete was observed only at Palo Verde Mountain, although it undoubtedly occurs elsewhere in the region.

7.3.8

Gypsum Wash, Nevada

Gypsum Wash, a south-flowing drainage emptying into Lake Mead, lies 24 km (15 mi) east of Las Vegas, Nevada. Attention was drawn to the area by radioactive airborne anomalies approximately located in NE 1/4 sec. 10, SE 1/4 sec. 10, W 1/2 sec. 12, and NW 1/4 sec. 14, T. 20 S., R. 63 E., Frenchman Mountain 7½-minute quadrangle, U.S. Geological Survey. The reported anomalies are described as follows: "Four airborne radioactive anomalies were reported in the Gypsum Cave area, east of Sunrise Mountain. Anomalous areas are reportedly underlain by a coarsely crystalline granite which may cut Tertiary (Miocene?) lacustrine deposits" (Garside, 1973, citing Barrett and Mallory, 1955). The mention of granite is inconsistent with Longwell et al. (1965), whose geologic map shows no granite in this area.

The reported anomalies are located in the northeastern extension of the Frenchman Mountains. Bedrock in the vicinity consists of late Paleozoic and Mesozoic sedimentary rocks, primarily limestone and dolomite. Stratified gypsum, which presumably is the source of younger gypsiferous deposits, is abundant in rocks of Pennsylvanian and Permian age. Fringing the eastern edge of the Frenchman Mountains and underlying Gypsum Wash is the Tertiary Muddy Creek Formation, which also contains abundant bedded gypsum intercalated with nonmarine red-brown fanglomerate, sandstone, siltstone, shale, and mudstone. In addition to white or yellow fine-grained stratified gypsum, coarsely crystalline gypsum occurs as lenses in the Muddy Creek Formation and in cavities of the older carbonate rocks. Selenite crystals up to 0.3 m (1 ft) in length occur in Gypsum Cave at the extreme northeast end of the Frenchman Mountains.

Overlying tilted Muddy Creek strata and stretching across Gypsum Wash is an extensive deposit of flat-lying gypcrete, currently being dissected by Gypsum Wash and its tributaries. Where well exposed by down-cutting drainage courses, the gypcrete is 3.7 or 4 m (12 or 13 ft) thick. In most places it appears to be nearly pure gypsum, varying from friable powder to coarsely crystalline rock. In excellent exposures at Gypsum Springs, in the south-central part of section 14, it is best described as a gypsiferous conglomerate with pebbles and cobbles of gray and brown limestone and dolomite cemented by gypsum. East of Gypsum

Wash the gypcrete is extracted in large strip mines for the manufacture of wall board.

Locations of the reported anomalies are underlain primarily by gypcrete. A ground radiometric reconnaissance was made with a Geometrics total count scintillometer in the NE 1/4 sec. 14, W 1/2 sec. 12, and NE 1/4 sec. 11, which are easily accessible. Most readings were in the range of 20 to 50 cps and are considered background. Readings in the 60 cps to 120 cps range were obtained in the N 1/2 of the NE 1/4 sec. 14 on gypcrete mantled by a thin veneer of desert pavement consisting of patina-surfaced carbonate pebbles and cobbles. Readings in Muddy Creek redbeds averaged 50 cps to 60 cps.

Delayed neutron analyses were run on seven gypcrete samples collected outside as well as inside the reported anomalous areas. Six of the samples ranged from 0.2 ppm to 0.9 ppm uranium. An analysis of 3.0 ppm uranium was obtained on a seventh sample 213 m (700 ft) south of Gypsum Cave (SW 1/2 sec. 12). Ground radiometrics at this location were 100 cps. A single sample in mudstone of the Muddy Creek formation yielded 3.625 ppm uranium.

Uranium concentrations as well as ground radiometric measurements are all very low within the area investigated, and the uranium concentrations of the gypcrete are not higher than the mudstones of the Muddy Creek Formation.

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CALICHE DISTRIBUTION

SOUTHWESTERN UNITED STATES

Compiled by O. Kolker

EXPLANATION	
DEGREE OF CALICHE DEVELOPMENT	
Type i	50-100%
INDURATES OR STRONGLY CEMENTED	25-40%
	15-25%
Type w	40-80%
WEAKLY CEMENTED	30-35%
	15-25%
Type s	40-100%
SOFT AND WEAKLY CEMENTED	15-35%
Type br	40-50%
BEDROCK	20-25%

LEGEND: Series name (degree of caliche development), % of mapping unit

- 1a. Pinal (i) 25%, Rillito (s-w) 35%, Gualtich (s-w) 25%
- 1b. Pinal (i) 70%
2. Charcoal (br) 40%
3. Cave (i) 20%, weakly to strongly cemented series (Rillito, Continental, Whitlock, Pinaleno, Nickel) 35%
4. La Palma (i) 20%, Toltec (w) 75%
5. Cavett (i) 35%, Gualtich (s-w) 40%, Rillito (s-w) 15%
6. Caberton and Cross (i) 25%
- 7a. Sonotita overlying Palos Verdes (w) 15%, Pinaleno (s-w) 12%, Eba (s-w) 8%
- 7b. Sonotita overlying Palos Verdes (w) 25%, Palos Verdes (w) 10%, Pinaleno (s-w) 10%
- 8a. Palos Verdes (w) 30%, Pinaleno (s-w) 30%, Nickel 25%, Eba (s-w), Rillito (w) and Tres Hermanos (s-w) 5% each
- 8b. Pinaleno (s-w) 40%, Nickel (w) 30%, Eba (s-w), Rillito (w) and Tres Hermanos (s-w) 5% each
- 9a. Eba (s-w) 25%, Nickel (s-w) 15%, Pinaleno (w) 10%
- 9b. Caliche (Rillito, Karro, Latene, etc.) (w) 25%
- 9c. Nickel (w) 35%, Upton (i) 30%
- 10a. Pastura (i) 35%, Polay and Partel (w) 35%
- 10b. Pastura (i) 50%
- 10c. Pastura (i) 10%, Polay (w) 25%, Map (s-w) 15%
11. Turner (br) 25%
- 12a. Stewart (i) 20%
- 12b. Frye (i) 25%
13. Cave (i) 10%, Kimberlough (i) 55%
14. Nickel (w) 65%, Pinaleno (s-w), Continental (w) and Cave (i) 5% each
15. Cruces (i) 65%
16. Continental (w) 40%, Cave (i) 5%, Pinaleno (s-w) 5%
17. Eba (s-w) 70%
18. Cave (i) 50%, Whiskel (i) 15%, Nickel (w) 15%
- 19a. Rillito (s-w) 40%, Gualtich (s-w) 30%
- 19b. Gualtich (s-w) 50%, Rillito (s) 20%
20. Gualtich (s-w) 50%
21. Pinaleno (w) 50%, Cave (i) and Continental (i) 45% each
22. Karro (i) 60%
23. Nickel (w) 35%, Tencoe (i) 20%, Del Norte (i) 15%, Upton (i), Terino (i), Turner (w), Dona Ana (s-w) 15% each
24. Nickel (w) 30%, Caliza (s-w), Tencoe (i) and Upton (i) 15% each; also exposed caliche
25. Caliche (i) 20%—lower elevations, Pinaleno (s-w) 20%—upper elevations, Map (s-w) 15%, Simona (i) 10%, Nickel (w) and Caliza (s-w) 15% each
26. Caliza (s-w) 15%; also exposed caliche
27. Berino (s) 30%, Simona (i) 15%, Dona Ana (s-w) and Caliche (i) 15% each
28. Berino (w), Simona (i) and Nickel (w) 25% each
29. Caliche (i) 50%, Wink (w) 5%, Jal (s), Dona Ana (s), Berino (s) 5% each
30. Simona (i) 55%, Caliche (i) 25%, Tencoe (i) 5%, Cruces (i), Dona Ana (s), Berino (s) and Wink (w) 15% each
- 31a. Berino (w) 40%, Dona Ana (s) 30%, Turner (w) 10%, Jal (s) and Simona (i) 15% each
- 31b. Turner (w) 60%, Berino (s) and Dona Ana (s) 20%
32. Nuevo (i) 15%, Wink (w) 20%, Simona (i) and Dona Ana (s) 15% each
33. Sallido (s-w) 30%
34. Polay (w) 15%; also exposed caliche
35. Litolio Caliche (s) 30%, Ustulio Haptagide (s-w) 30%, Litolio Ustulio Caliche (s) 10%
36. Typic Caliche (s-w): a. 35% and b. 20%
37. Litolio Caliche (s) 35%, Ustulio Caliche (s) 15%, Ustulio Caliche (i) 5%
38. Litolio Caliche (s) 35%, Typic Caliche (s-w) 5%
39. Simona (i) 20%, Wink (w) 30%, Litolio Caliche (s) 10%
40. Adalento variant 45%, Sunrise 10%, both (i)
41. Sunrise (i): a. 85% and b. 40%
42. Moapa Valley remnant surface a. 100%
43. Bernese (i): a. 30% and b. 20%
44. Del Norte (i): a. 70% and b. 25%
45. Cavett (i) 25%
46. Caliche (i) 15%
47. Ajo (i) 20%
48. Ponsell (i) 20%
49. Mormon Mesa (i): a. 100%; b. 40%; c. 25%
50. Tencoe (i) 70%
51. Nepe (i) 25%
52. Skyhaven (i): a. 50% and b. 20%
- 53a. Cave (i) 35%
- 53b. Cave (i) 35%, Goodsprings (i) 30%, Las Vegas (i) 25%
54. Pittman (w) 27%
55. McCullough Fan surface: a. upper (i) 80%; b. middle (w) 80%; c. lower (s) 80%
56. Kyle Canyon Fan surface: a. 1 and 2 (i) 80% and b. 3 (s) 50%

Silicified: the following series contain silicified caliche, Pinal (1a, 1b), Charon (2), La Palma, Toltec (4), Cavett (5), Stewart (12a), Frye (12b)

0 10 20 30 40 50 Miles
0 10 20 30 40 50 Kilometers

Geology of the Jean - Sloan Area, Clark County, Nevada

119°15' 119°30' 119°45' 120°00' 120°15' 120°30' 120°45' 121°00'

Plate IV-3

AERIAL RADIOMETRIC OVERLAY FOR PLATE IV-2
(Geology of the Yeelirrie Region)

(Aerial radiometric contours from Gerdes et al., 1970; Bur. of Min. Res. Australia, Maps AS:G51/BI-22-1,3,4,1971)

Plate IV-2 GEOLOGY OF THE YEELIRRIE REGION SHOWING SOME LANDFORMS AND REGOLITH

Base from Australia 1:250,000 series, Wiluna, Glenargy, Sandstone and Sir Samuel topographic map sheets
Geological contacts from Mobbitt, et al., 1963; Churchward, 1976; Bunting and Williams, 1974; Western Mining Corp., 1976; and air photo interpretation
Compiled by Donald Carlisle, 1977

EXPLANATION

- Breakaways (scarps) on granitic rock.
Hachures on pallid zone pediment.
- Present day intermittent drainages
(in areas of interest).
- Boundary between predominant to subdominant
outcrop and alluvial or sand plain.
- Boundary between sand plain and alluvium.
- Yeelirrie orebody (W.M.C., 1976).
- Extensive calcrete exposed.
- Some calcrete exposed. Includes drainage floors,
clay pans and sand plains with calcareous and
red sandy and clayey earths and hardpan.
- Salt lakes and dunes with saline clays and
calcareous and gypsiferous earths.
- Sand plain, aeolian and fluvialite, red earths
and extensive hardpan at depth.
- Alluvial plain, sands, grits and clays, red earths
and extensive hardpan.
- PROTEROZOIC
PI Shale, sandstone, quartzite, basalt and
dolomitic limestone.
- ARCHAEO
Ag Granitic intrusives and gneiss, including
extensive areas of mottled zone and pallid
zone beneath breakaways.
- Avs Greenstone, including metavolcanic and meta-
sedimentary schists, jaspilite, quartzite.

0 5 10 15 Km