Possible Variations on the Calcrete-Gypcrete Uranium Model

by

Donald Carlisle

January 1, 1980

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

DISCLAIMER

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1.0 SUMMARY

Genetic models and favorability criteria for calcrete and gypcrete uranium deposits based upon Yeelirrie and other occurrences in Western Australia and upon Langer Heinrich and others in Namibia-South West Africa are summarized in the first part of this report.

Viable analogues of these world-class deposits have not yet been found in United States even though several of the favorable conditions--strongly evaporative climates, closed or constricted basins, suitable source rocks and near-surface waters enriched in U, V and K--do occur in the southwest. A principal deterrent to economic concentration has been tectonic instability. But even in the most favorable areas it is not clear that climates have ever been sufficiently similar to that of the valley-calcrete region of Western Australia. Extensive, thick valley (nonpedogenic) calcretes such as those which host the carnotite in Australia and in Namibia have not been documented here. Nevertheless, submarginal occurrences of carnotite have been found in southwestern United States in small bodies of nonpedogenic and mixed pedogenic-nonpedogenic calcrete.

The question raised in this follow-on study, therefore, is whether there are components or portions of the calcrete-gypcrete uranium models which might fit the geological setting in United States and give rise to calcrete-related occurrences.

Much of the study is based upon occurrences of carnotite-bearing calcrete and calcrete-gypcrete in the Republic of South Africa which were not generally known nor investigated during preparation of the earlier report. Several of these are described briefly. Some reference is also made to new occurrences and to new data on previously described occurrences on the Namib Desert.

Possible variations on the Western Australian and Namibia-South West Africa models which are considered here are:

1. Capillary rise of U in solution.
2. Addition of new uraniferous sediment over a calcrete.
3. Lateral access of U into a pedogenic calcrete.
4. Reworking of U from a weakly mineralized pedogenic calcrete or gypcrete: a) into a new or a reconstituted calcrete or
   b) into an unrelated environment for fixation of U.

The last of these in which pedogenic calcrete serves as a temporary sink or protore for U is potentially the most interesting. Category 4a) is represented by several of the occurrences in South Africa. Category 4b) opens up a wide range of possibilities in which primary fixation of U in the oxidizing environment of a calcrete or gypcrete is succeeded by secondary and perhaps stable fixation in a classical reducing environment.

2.0 INTRODUCTION AND ACKNOWLEDGMENTS

Genetic models and favorability criteria for uranium deposits in calcrete, dolocrete and gypcrete have been presented in an earlier report prepared for the United States Department of Energy as a part of the National Uranium Resource Evaluation (NURE) program (Carlisle et al., 1978, GJBX-29-(78)). That report was based largely on a study of the Yeelirrie, Langer Heinrich and neighboring deposits in Western Australia and Namibia/South West Africa. Additional work, including examination of less well-known prospects in South Africa, has suggested some possible variations on the models and the criteria, some of which may justify further consideration of calcrete or calcrete-like possibilities in the United States.

The studies in southern Africa were completed between July 27 and August 23, 1978. They involved carnotite-bearing calcretes and gypcretes in the northwest Cape Province (Upington region), the Great Karoo and the Namib Desert and nonmineralized calcretes and gypcretes over larger areas of South Africa and Namibia/South West Africa. In addition to a search for possible variations on the earlier calcrete-gypcrete U models in areas not previously studied, one purpose of the studies was to discover if U minerals other than carnotite were important in these ores. None was found.

The writer benefitted greatly from preliminary discussions held in Pretoria with F. Netterberg of the National Institute for Transport and Road Research (CSIR); P. D. Toens, Director Geology, B. Hambleton-Jones, B. Corner and M. Levine of the Atomic Energy Board staff; P. J. Smit and D. J. Richards of the Geological Survey and in Johannesburg with several industry representatives. For permission to examine or to re-examine calcrete and gypcrete uranium occurrences on the Namib Desert of Namibia/South West Africa and for a great deal of additional help, he is greatly indebted to General Mining and Finance Corporation Limited with the operating interest in Langer Heinrich; to Anglo American Corporation of South Africa Limited with the operating interest in the Tubas Grant and on Welwitschia Flat; to Omitaramines; and to Falconbridge of South West Africa (Pty) Ltd. For permission to examine calcrete-gypcrete uranium occurrences and for both logistical support and data in the Upington area of the northwest Cape Province and in the Great Karoo near Beaufort West, the writer is especially indebted to Newmont South Africa Limited; General Mining and Finance Corporation Limited; Phelps Dodge of

Africa Limited and Union Corporation Limited. These organizations have kindly given permission to release relevant data in this report.

Numerous individuals connected with industry were extremely hospitable and provided generous help with the study throughout the Republic of South Africa and in Namibia/South West Africa. This is most gratefully acknowledged. A part of the travel expense was provided for by the Academic Senate Research Committee of the University of California Los Angeles in connection with a calcrete symposium at the Tenth International Congress on Sedimentology in Jerusalem. The remaining costs were defrayed under Subcontract No. 76-022-E between BFEC and the Regents of the University of California.

3.0 REVIEW OF THE CALCRETE/GYPCRETE URANIUM MODELS AND FAVORABILITY CRITERIA

3.1 LIST OF CONCLUSIONS AND CRITERIA

The main conclusions of the earlier report by Carlisle et al. (1978) are as follows:

A. ORE-BEARING CALCRETES ARE NONPEDOGENIC

Ore-bearing calcretes, dolocretes and gypcretes are derived by lateral transport of Ca, Mg and U, V, K in meteoric groundwaters rather than by typical soil-forming processes (caliche). They are deposited:

1. In axial portions of large stable subsurface drainages or other areas of groundwater convergence in regions of very low relief, i.e., valley, deltaic, lacustrine calcretes.
2. In regions with uniquely arid climates.
3. Mainly in the capillary fringe above slowly moving groundwaters.

B. SOURCE AREAS FROM WHICH THE Ca, Mg, U, V AND K ARE DERIVED ARE:

1. Very large, deeply weathered, typically granitic.
2. Variably anomalous in uranium content.
3. Do not necessarily contain uranium ores.

C. URANIUM TRANSPORT IS IN NEAR-SURFACE GOUUNDWATER:

1. The waters are anomalous in U and V.
2. Concentrations of U, V, K are increased downdrainage by evaporation.
3. U is transported in the form of uranyl carbonate complex ions.

D. CARNOTITE IS THE ONLY ORE MINERAL AND IS PRECIPITATED BY:

1. Destabilization of uranyl carbonate complexes by lowered $a_{CO_3^{2-}}$ resulting from:
   a) evaporative precipitation of Ca/Mg carbonate.
   b) common-ion precipitation of Ca/Mg.

(Both a) and b) result in an intimate association of carnotite with carbonate.)

2. Evaporative concentration of U, V and/or K.
3. Oxidation of V(IV) to V(V) in upwelling groundwater.

E. ORE CONTROLS INCLUDE THE FOLLOWING:

1. Catchment areas should be free of pedogenic carbonate or other factors which fix uranium prior to concentration in areas of groundwater convergence.
2. Concentrations of carnotite develop preferentially in calcrete where subsurface flow is constricted and/or where the uraniferous groundwaters are forced toward the evaporative surface.
3. Reducing environments are neither required nor operative.
4. Subsequent reconcentration of initially syngenetic carnotite may be essential to produce ore grades.
5. Ore-grade mineralization may develop both within the main calcrete and immediately below it.

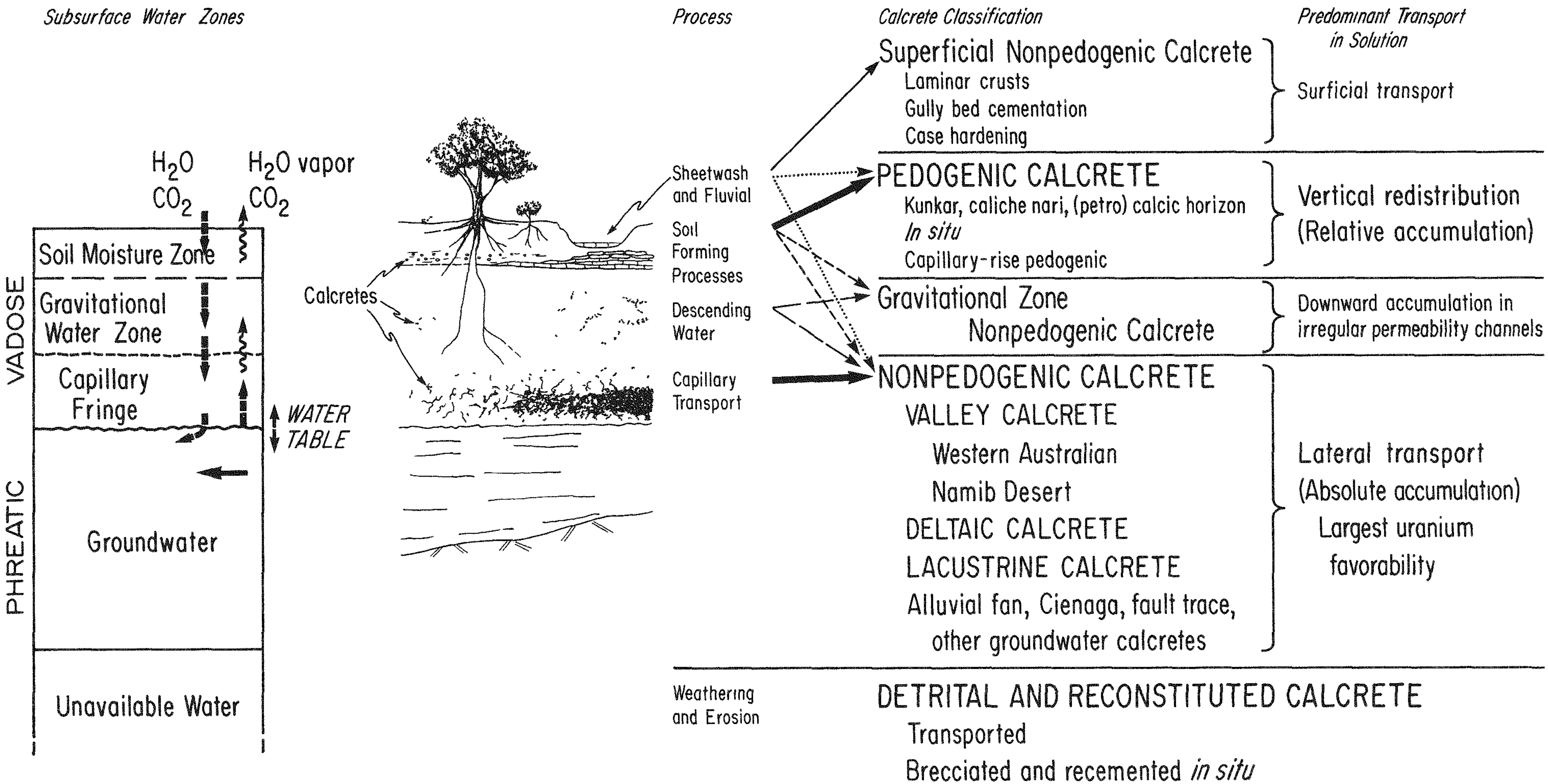
F. PRESERVATION OF MINERALIZATION REQUIRES:

1. Tectonic and climatic stability.
2. Protection of carnotite from continued dissolution.

It can be seen that climate is a factor under all six headings. Each of these conclusions and criteria is enlarged upon briefly and in the same order in the next section.

Figure 3.1

A Genetic Classification of Calcretes and Their Uranium Favorability



3.2 ANNOTATIONS AND DIAGRAMS ILLUSTRATING THE CONCLUSIONS AND CRITERIA

3.2.1 Nonpedogenic Calcrete

(Figs. 3.1, 3.2, 3.3, 3.4, 3.5, 3.6, 3.7)

The genetic distinction between pedogenic and nonpedogenic calcretes is illustrated in Fig. 3.1. In essence pedogenic calcretes (i.e., ordinary caliches) result from predominantly vertical redistribution of Ca, Mg, CO_3^{2-} and trace elements within the soil moisture zone or from the air. They are extensive, thin horizons within the soil and mainly illuvial. Only if the soils are unexpectedly rich in U or enriched from the air, from below, or by deep residual concentration are pedogenic calcretes likely to reach ore grade on any large scale. Though small-scale examples are known, the favorability of pedogenic calcretes as U ore has been considered to be very low to negligible (Carlisle et al., 1978).

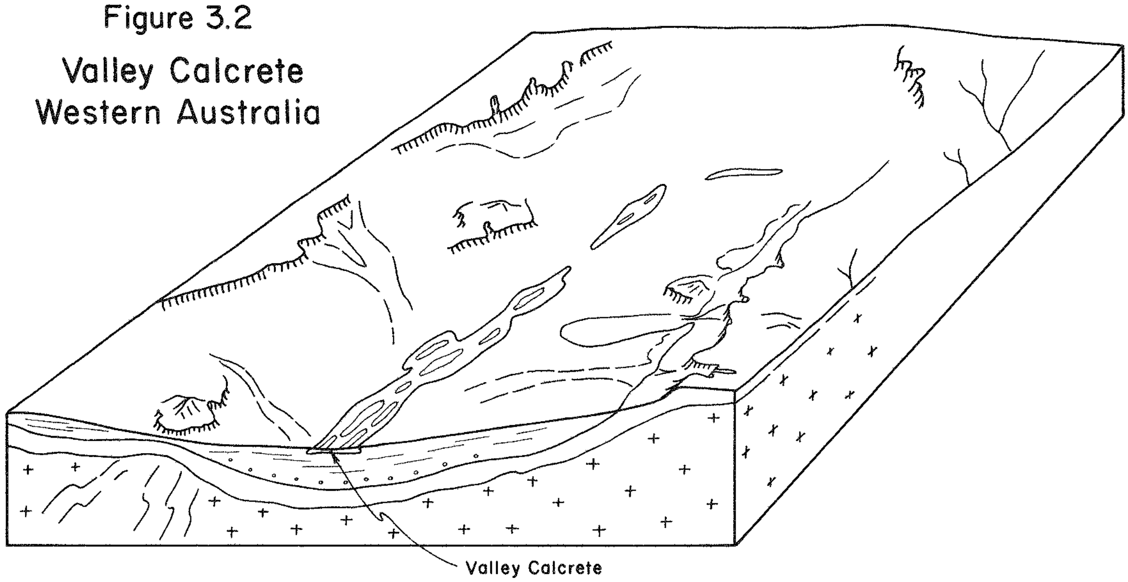
Nonpedogenic calcretes, on the other hand, result from lateral transport of soluble ions toward favorable sites of deposition, making it possible for ores to develop by concentration of U from a large source area into a relatively compact calcrete body.

Deposition. The largest, most continuous and thickest nonpedogenic calcretes are those which develop within the capillary fringe or overlapping vadose subzones above a shallow groundwater table (Fig. 3.1). In terranes of low relief (Figs. 3.2a, b) groundwaters move slowly over long distances. leaching and transporting vast amounts of U, V and K as well as Ca and Mg. In arid regions, concentrations are increased downdrainage by evaporation except for dissolved CO_2. As groundwaters converge, typically along the axes of stable paleodrainages, water tables approach the surface, loss of CO_2 and H_2O is accelerated and authigenic carbonate precipitates within the regolith (Figs. 3.2, 3.3, 3.4, 3.5, 3.7). The nonpedogenic valley, deltaic and lacustrine calcretes of Western Australia and the valley calcretes of the Namib Desert, up to tens of km in length, several km in width and tens of m thick, are type examples.

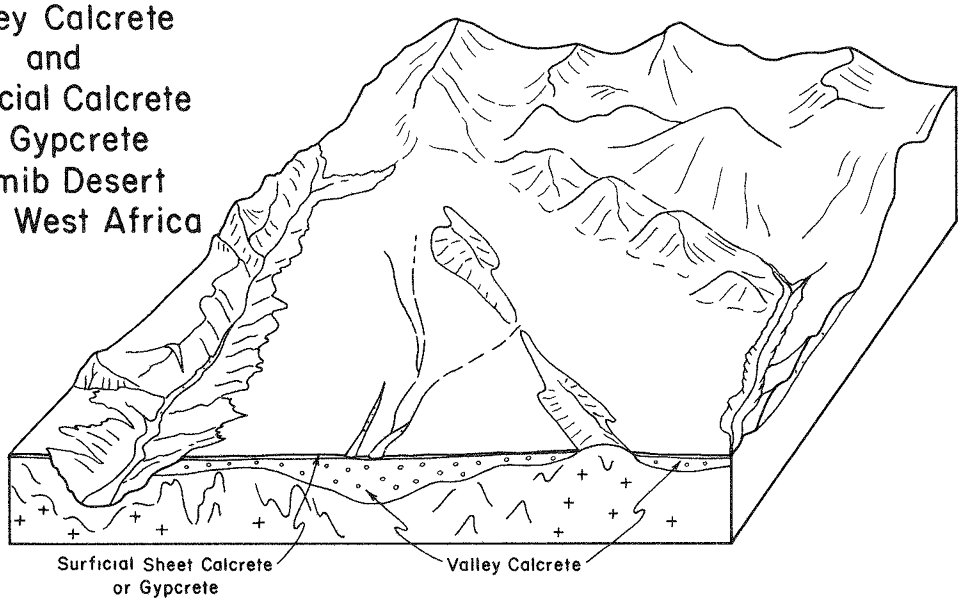
Climate. Nonpedogenic calcretes are developed under a much more arid climate than are pedogenic calcretes. This is particularly clear in Western Australia, where valley, deltaic and lacustrine calcretes are forming today in a very specific climatic (and soil moisture) regime (Fig. 3.6 and Table 3.1).

Figure 3.2

a Valley Calcrete
Western Australia



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



They apparently formed similarly throughout the same areas, though more abundantly, some 0.5 m.y. ago. The climate is characterized by excessive potential evaporation and, most importantly, by highly variable rainfall from episodic storms which occur predominantly while soil surface temperatures and evaporation rates are very high. In contrast the nonuraniferous pedogenic calcretes (i.e., soil horizon caliche) are forming only to the south of the valley calcrete region in subarid to submediterranean climates.

3.2.2 Source Area (Fig. 3.2)

The necessity for a large, deeply weathered U source terrane is clear enough. For Yeelirrie, Langer Heinrich and neighboring deposits these are predominantly granitic including, on the Namib, anatectic granites, pegmatites and metamorphic rocks. The Yeelirrie catchment is some 3000 km^2. Known U contents of unweathered granitic rocks range from 2-3 ppm to 25 and 50 ppm on the Yilgarn Block of Western Australia. Much higher concentrations are found very locally on the Namib, but there is no clear evidence that the nearby Rössing or Rössing-like occurrences are necessary sources for known calcrete/gypcrete uranium deposits.

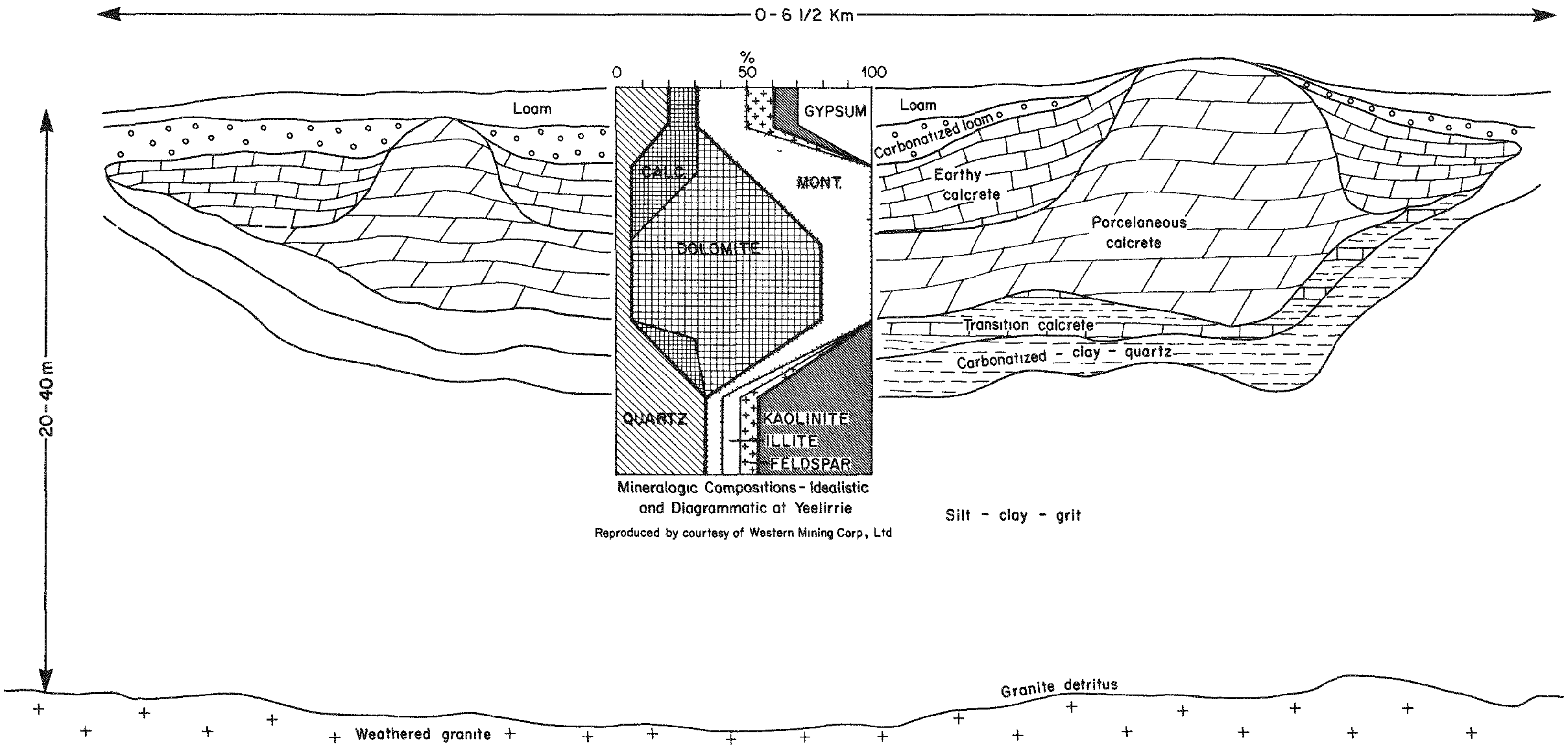
3.2.3 Uranium Transport (Figs. 3.4, 3.5)

Groundwaters contain from 15-70 ppb U and 3-12 ppb V in one catchment area above mineralized valley calcrete in Western Australia (Mann and Deutscher, 1979; cf. Dall'aglio et al., 1974). Close to and within the mineralized calcrete, concentrations rise to 100-400 ppb U, 15-50 ppb V. Still further downdrainage carnotite is apparently precipitating from these same waters in recent deltaic calcrete (Fig. 3.4b) adjacent to a salt lake. Other ions, except carbonate species, also increase disproportionately from headwaters to salt lakes. Though mainly due to evaporation, the increases in some parts of the system probably result in part from dissolution of existing uraniferous calcrete. Groundwaters in contact with calcrete uranium ore on the Namib contain as much as 1000 ppb U.

Since the waters are carbonated, oxidizing and, for most of the system, neutral to alkaline, U is undoubtedly in solution as uranyl carbonate complex ions. Neutral to acid waters occur in the upper parts of some lateritic catchments, and there U hydroxyl, sulfate, phosphate or other complexes may be important.

Figure 3.3

Diagrammatic Cross Section of Valley Calcrete, Western Australia



Mineralogic Compositions - Idealistic and Diagrammatic at Yeelirrie

Reproduced by courtesy of Western Mining Corp., Ltd

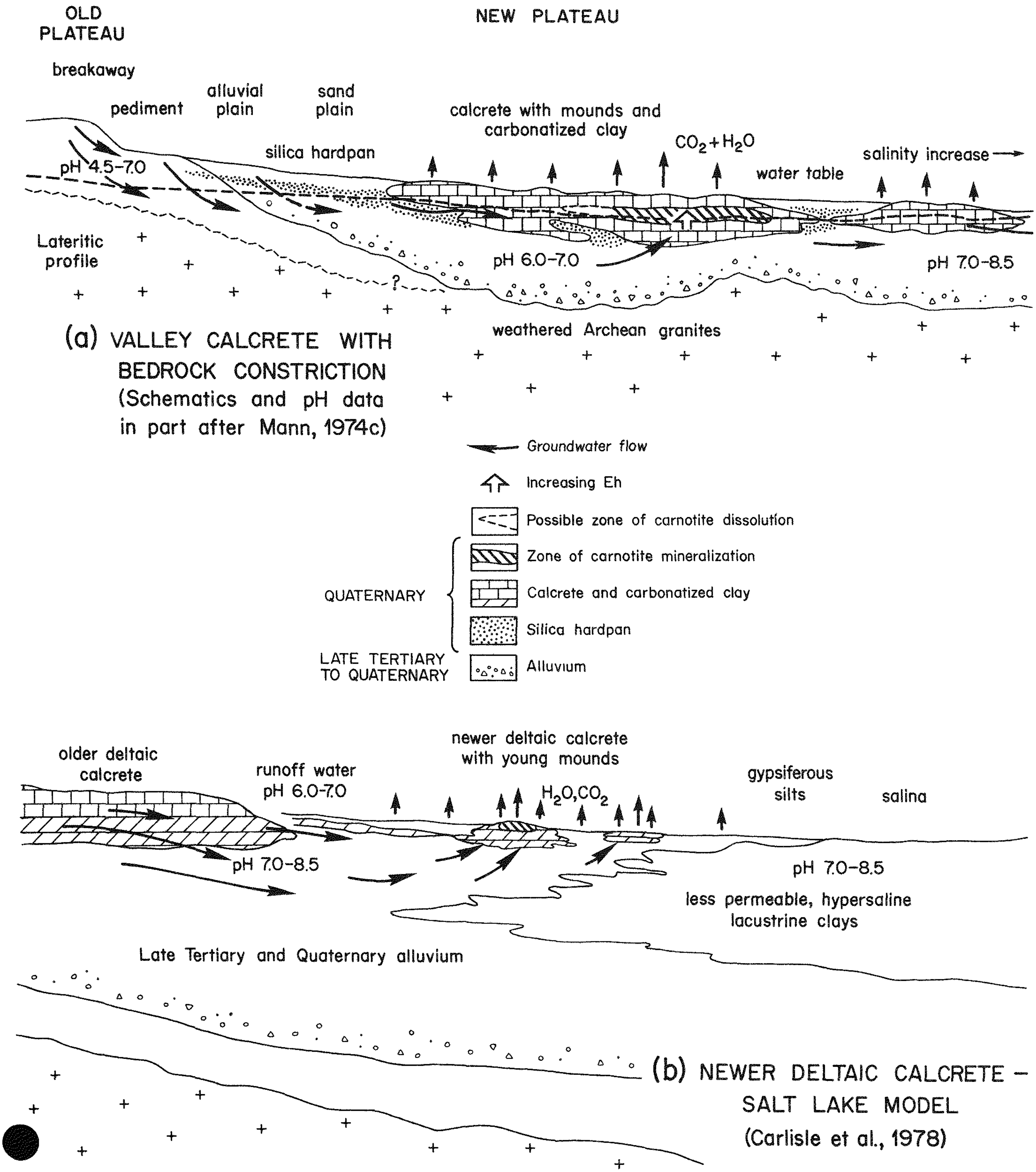
Table 3.1

Some Contrasts between Uraniferous and Nonuraniferous Calcrete Regions in Western Australia

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

Figure 3.4

Schematic Models for Nonpedogenic, Uranium-bearing Calcrete, Western Australia



(a) VALLEY CALCRETE WITH BEDROCK CONSTRICTION (Schematics and pH data in part after Mann, 1974c)

(b) NEWER DELTAIC CALCRETE – SALT LAKE MODEL (Carlisle et al., 1978)

3.2.4 Carnotite Precipitation

(Figs. 3.4, 3.5)

The model represented in Fig. 3.4 illustrates the increasingly alkaline pH of infiltrative waters. Note that pedogenic soil carbonate is absent from the catchment areas updrainage from valley calcrete in Western Australia. Authigenic silica is almost ubiquitous. Less data are available for the Tertiary calcretes of the Namib (Fig. 3.5), but an analogous system is inferred

As the water approaches the valley axis carbon dioxide begins to escape, the pH gradually rises, and $CaCO_3$ or $(Ca,Mg)CO_3$ begins to precipitate.

Increased CO_2 loss and then evaporation takes place at the valley axis and all the way down the valley but especially where bedrock constrictions or shallower gradients inhibit the flow of groundwater and bring it closer to the surface.

As shown by Mann and Deutscher (1979) and Dall'aglio et al. (1974), concentrations of U, V, K, and Ca and Mg (salinity in general) are all increased by evaporation, but CO_2 is not.

In areas of strong evaporation followed by desiccation, the increasing Ca- and Mg-ion concentration permits calcium or magnesium carbonate to precipitate with ever-diminishing concentrations of CO_3^{2-} ion, and, as a consequence, uranyl carbonate complex ions begin to destabilize.

$$UO_2(CO_3) \cdot 2H_2O^{2-} = UO_2^{2+} + 2CO_3^{2-} + 2H_2O$$

$$UO_2(CO_3)_3^{4-} = UO_2^{2+} + 3CO_3^{2-}$$

Also, in areas of extreme evaporation, brines enriched in Ca, Mg, SO_4 and Cl ions accumulate, and where uraniferous carbonated groundwaters flow into these, $CaCO_3$ or $(Ca,Mg)CO_3$ precipitate by common-ion effect. Carbonate ion is consumed by this process and this, too, destabilizes uranyl carbonate complex ions.

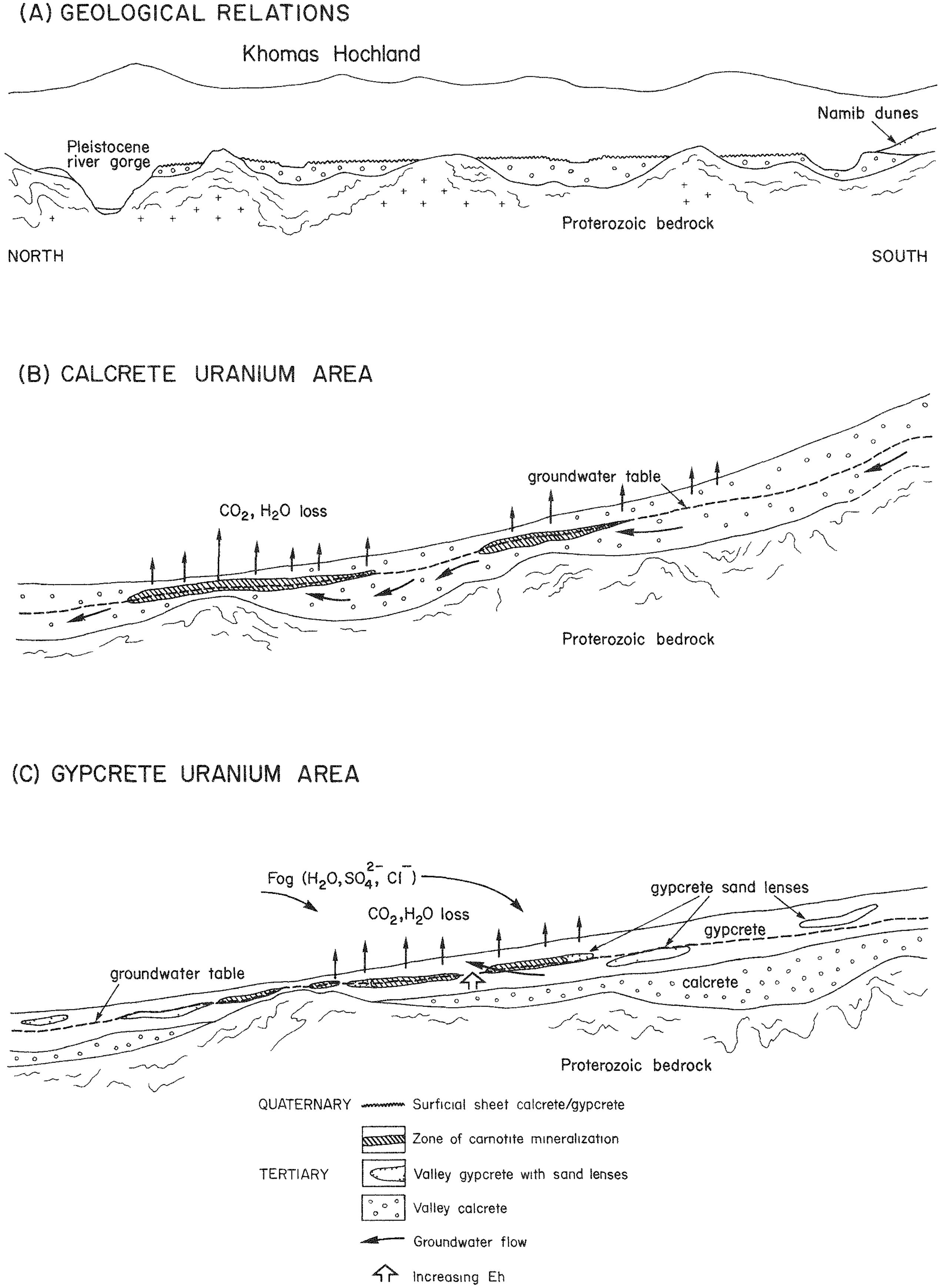
In areas of upwelling water the more soluble four-valent vanadium may be oxidized to five-valent vanadium, making it available for precipitation of carnotite (Mann and Deutscher, 1979).

In various ways, then, the concentrations of uranyl ion UO_2^+, K and V(V) are increased to the point of carnotite precipitation

$$2UO_2^{2+} + 2H_2VO_4^- + 2K^+ + 3H_2O = K_2(UO_2)_2V_2O_8 \cdot 3H_2O + 4H^+$$

Figure 3.5

Schematic Models – Namib Desert



and in almost every case the carnotite is precipitated in association with the carbonate. Conversely, precipitation of carbonate whether pedogenic or nonpedogenic almost invariably entails precipitation of carnotite. In the pedogenic situation, however, the carnotite is widely dispersed and noneconomic.

In addition, adsorption of U on clays or precipitation of carnotite through change of pH toward a neutral value or through addition of V from some independent source are possibilities but have not yet been substantiated as prominent mechanisms.

3.2.5 Ore Controls

1. Lack of soil carbonate. Calcrete orebodies can develop only if the U remains in solution and is not precipitated diffusely throughout the catchment area before reaching a valley calcrete host. Since carnotite does precipitate in association with carbonate, the occurrence of extensive soil-horizon (pedogenic) calcrete throughout the catchment area is a bad omen for calcrete U orebodies (unless, as on the Namib, the pedogenic calcrete is entirely post-ore). This is very likely the situation south of the valley calcrete region of Western Australia where isolated occurrences of carnotite in pedogenic calcrete are known but no calcrete ores are found. The uraniferous valley calcrete region of Western Australia is free of pedogenic calcrete.

2. Constrictions. In numerous examples in Western Australia and Namibia/South West Africa including Yeelirrie and Langer Heinrich, carnotite is most abundant where mineralizing waters have been forced toward the surface by narrowing or shallowing of the subsurface channel, by meeting less permeable clays or dense hypersaline waters, or wherever CO_2 loss, evaporation and possibly also oxidation of V have been facilitated. As on the Namib Desert, paleodrainages may have courses appreciably different from present-day drainages.

3. No reduction. The calcrete system is oxidizing throughout and U is continuously in the hexavalent state.

4. Reconcentration. In Recent calcrete/dolocrete mounds at lake edge in Western Australia carnotite is apparently contemporaneous with

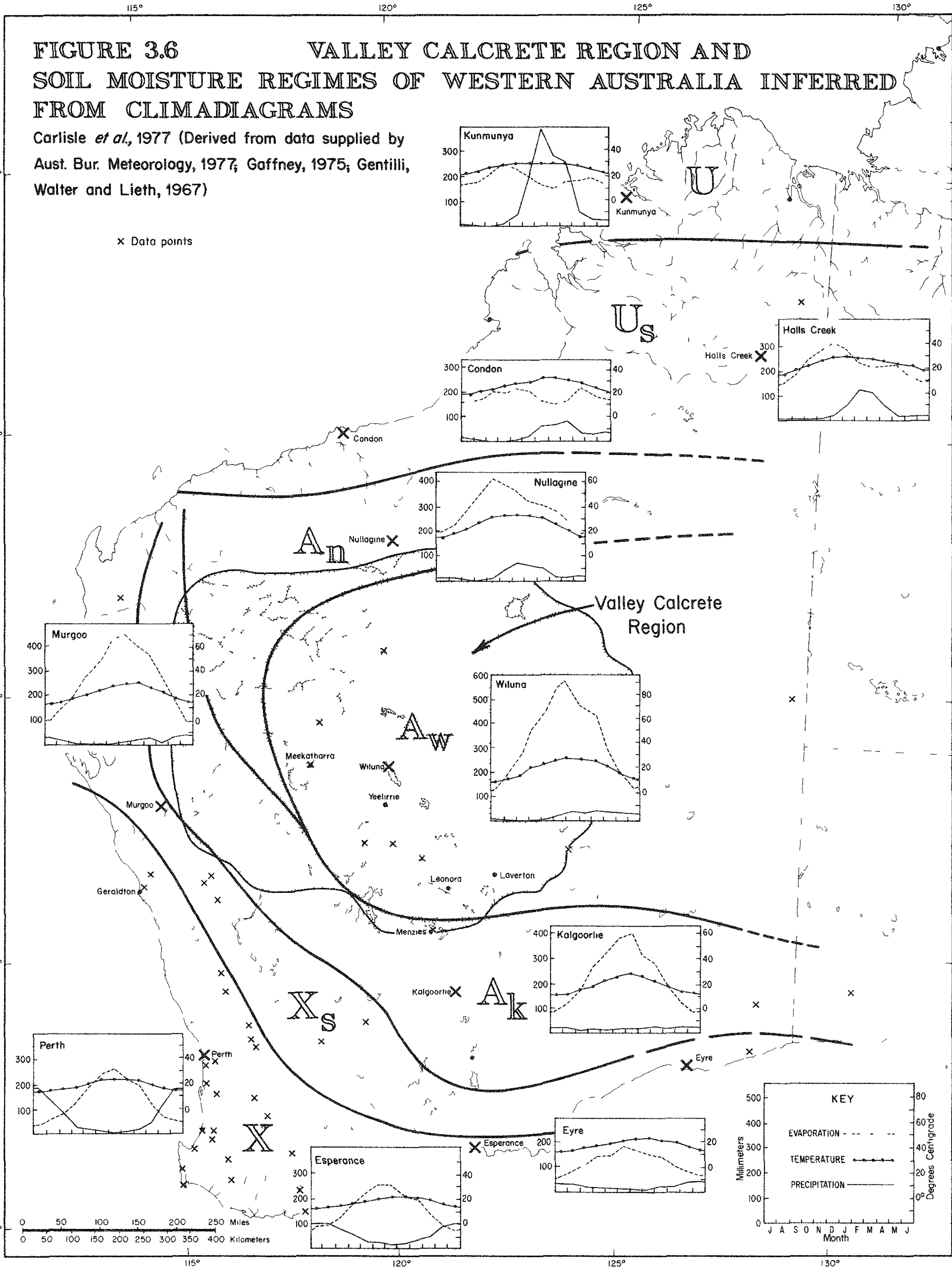


FIGURE 3.6 VALLEY CALCRETE REGION AND SOIL MOISTURE REGIMES OF WESTERN AUSTRALIA INFERRED FROM CLIMADIAGRAMS

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

Explanation for Figure 3.6

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.

$E < P$ in wet months

U_s Subustic.

$E^{0.75} < P$ 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.

$E_a/P_a = 9\text{-}10$

$E_w/P_w = 3.5\ (10)$

$E_a - P_a < 3250$ mm

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

$E_a/P_a = 12\text{-}20$

$E_w/P_w = 10\text{-}12$

$E_a - P_a > 3000$ mm

A_K Aridic Kalgoorlie type. Indefinite rain season.

$E_a/P_a = 6\text{-}16$

$E_w/P_w = 10$ or less

$E_a - P_a < 3000$ mm

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

X Xeric proper

$P > E$ in all three winter months

X_s Subxeric.

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

(a = annual; w = wet month)

carbonate (Fig. 3.4a, b) and locally reaches ore grade. In general, however, such syngenetic carnotite is less than ore grade and may require reworking and reconcentration to make ore. This appears to have happened at Yeelirrie, for example, where visible carnotite occurs as epigenetic fillings on dehydration cracks and solution cavities, coated with chalcedonic silica. At Langer Heinrich, also, much of the richer ore occurs in secondary replacement and filled-solution nodules, tubules or pipes which transect the primary mineralized calcrete. Vadose gravitational and laterally moving waters subjected to evaporation are responsible.

Carnotite mineralization in gypcrete on the Namib Desert has probably been reworked in large part from calcrete occurrences updrainage.

5. Carnotite within and below calcrete. In Western Australia, carnotite reaches ore grade both within the main calcrete and equally, if not more so, in carbonated clay immediately below (Fig. 3.3). On the Namib, carnotite can occur in weathered bedrock for a meter or more immediately below mineralized calcrete or once-present calcrete but is spotty.

3.2.6 Preservation of Mineralization

Carnotite in the oxidizing, carbonate-rich environment of calcrete is very subject to leaching by meteoric waters and eventual destruction of the ore. The valley calcretes of westerly Western Australia, for example, which have been incised by rejuvenated streams flowing into the Indian Ocean and thus exposed to percolating waters, appear to retain only traces of carnotite. On the other hand, excessive alluviation during the time that calcrete and carnotite are precipitating, dilutes or precludes recognizable mineralization. These are serious problems both in tectonically active regions and in regions where climates have become more humid since mineralization. The known major calcrete and gypcrete uranium occurrences are in tectonically stable arid areas.

In addition, at Yeelirrie, visible carnotite has been protected from dissolution by a later film of microcrystalline quartz. At Langer Heinrich, although deep stream rejuvenation has caused the erosion of some mineralized calcrete in addition to overlying nonmineralized calcrete, it has also resulted in such drying out of the remaining deposit that adequate amounts of carnotite remain. We have no examples and do not know the fate of carnotite in a mineralized nonpedogenic calcrete which has been deeply buried.

Figure 3.7 Nonpedogenic Calcrete, Namib Desert

3.3 ASSESSMENT

The conclusions and criteria reviewed above for calcrete/gypcrete uranium mineralization provide some encouragement for exploration in North America, but they also imply some serious obstacles to the formation and preservation of economic deposits. On the positive side, large source areas, both granitic and nongranitic, are available in regions of relatively low relief which have climates possibly suitable for nonpedogenic calcretes or have had them in the past. In some of these regions groundwaters with anomalous U concentrations are known. In a few places, carnotite has been found in calcrete; both pedogenic and nonpedogenic and modest radioactive anomalies have been found in many more. On the other hand, well-developed large nonpedogenic valley calcretes of the sort found in Western Australia or Namibia/South West Africa have not yet been documented in southwestern United States. Nonpedogenic or partly nonpedogenic alluvial fan calcretes are abundant, and other varieties along fault traces, cienegas and some lake margins are known, but the great bulk of calcretes in United States are pedogenic (caliche). This may reflect the prevalence of a winter rain component and resultant fairly long-term wetting of the soil moisture zone even in the desert areas of the southwest. Equally significant is the tectonic instability and consequent continuing alluviation and/or stream rejuvenation, erosion and leaching in so many of the favorable areas. The possible occurrence of valley-like calcretes has been suggested on the High Plains and elsewhere in western Texas and Oklahoma, and at least one uranium occurrence has been reported, but these have not been studied by the writer. What then are the possiblities that more substantial occurrences may have been developed by processes related to, but not identical with, those which apparently operated in Western Australia and on the Namib Desert?

4.0 VARIATIONS ON THE MODEL

4.1 SOME POSSIBILITIES SUMMARIZED

The U concentration within a caliche profile commonly increases from top to bottom. Simple downward reworking in solution by meteoric water is the plausible explanation, especially when Th is shown to be minimal or absent. In one small occurrence on the Western Mojave Desert, for example, cU increases progressively from 4.6 ppm at the surface, to 13 ppm in upper laminar calcrete 1 ft. down, to 293 ppm in basal calcrete 4 ft. further down, then decreases to 17.8 ppm in subjacent weathered granitic detritus. In another occurrence values of 43 and 35 ppm cU are found in calcrete from 1 and 3 ft. depth, respectively, in an otherwise barren soil. In still others the U in carbonate nodules is up to 10 times the concentrations in adjacent soil regardless of depth. Th is either negligible or undetected. Carnotite was not observed by the writer in any of these American pedogenic occurrences but is known to occur in pedogenic calcrete in the Lake Moore area of southwestern Australia (Eric Cameron, personal communication, 1978) and in southern Africa (below).

Presumably, the probability of finding a significant concentration of carnotite in pedogenic calcrete or gypcrete should be greatest on ancient stable weathering surfaces of very low relief in an arid climate. Given even a small content of U in the underlying rock, increasing amounts should be fixed in the lower parts of the calcrete as weathering and soil formation degrade the surface. However, a mature pedogenic calcrete with a dense impermeable hardpan, and perhaps overlying laminar layers, tends to protect and stabilize a topographic surface, and this in turn can be expected to cause the supposed illuvial or quasi-residual concentration of U to come to a halt. Significant deposits of U seem unlikely through pedogenesis, therefore, unless one of the following comes in to play:

1. Capillary rise of U in solution.
2. Addition of new uraniferous alluvial or aeolian material on top, i.e., aggradation of the surface.
3. Lateral access of U creating in effect a hybrid pedogenic-nonpedogenic calcrete or gypcrete.

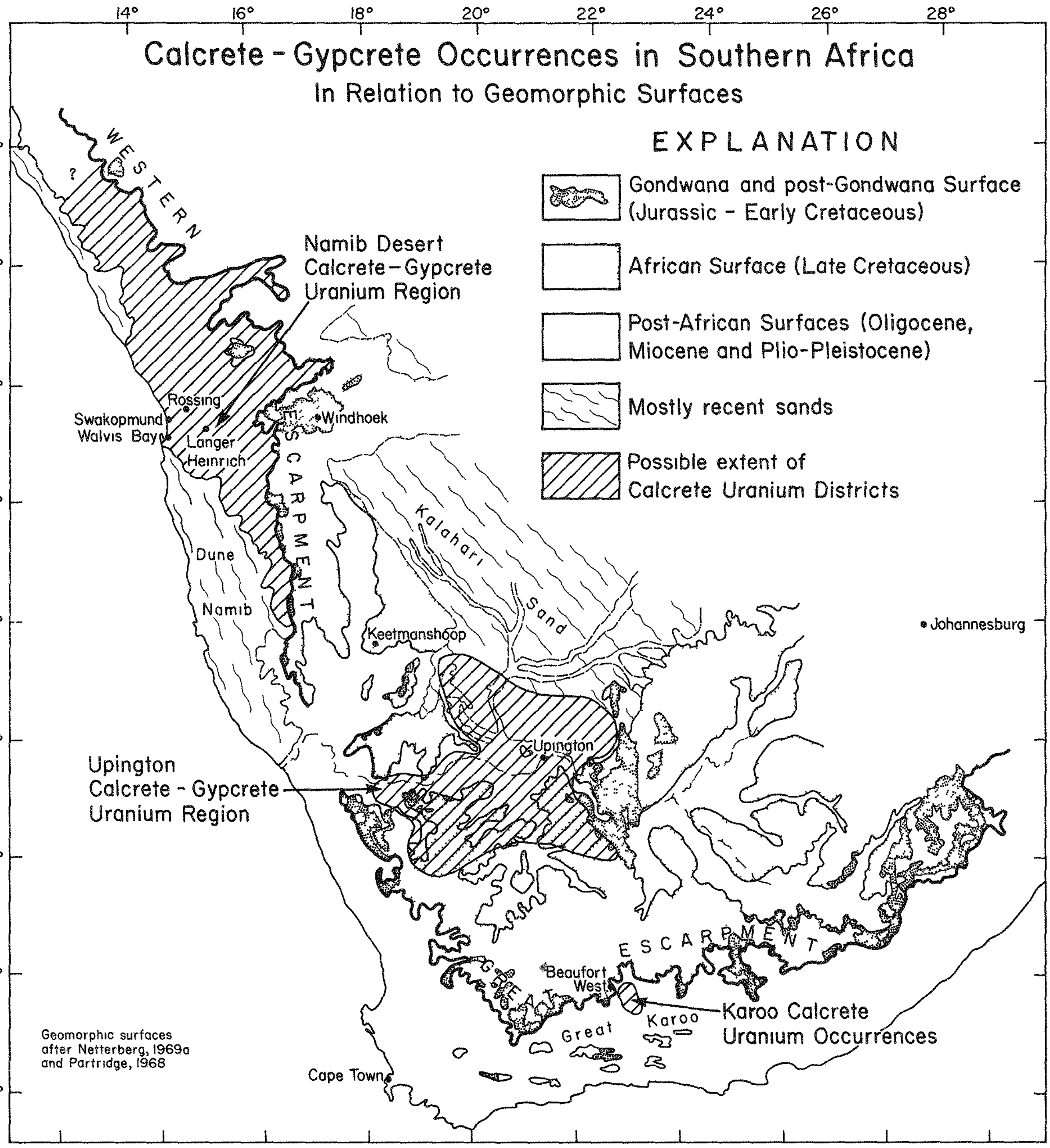
4. Reworking of weakly mineralized pedogenic calcrete or gypcrete accompanied by lateral transport and reconcentration of the U in:

a) a new or redeposited calcrete or gypcrete or

b) an unrelated environment for fixation of U.

Some light can be thrown on these possibilities by an examination of certain submarginal and incompletely evaluated occurrences including some in the Republic of South Africa not previously described. Possibilities 1, 2, 3, 4a) and 4b) are examined in sections 4.4, 4.5, 4.6 and 4.7, respectively, after a brief review of some pertinent aspects of the surficial geology of southern Africa (4.2) and of U in pedogenic calcrete (4.3).

Figure 4.1



Calcrete - Gypcrete Occurrences in Southern Africa
In Relation to Geomorphic Surfaces
EXPLANATION
Gondwana and post-Gondwana Surface (Jurassic - Early Cretaceous)
African Surface (Late Cretaceous)
Post-African Surfaces (Oligocene, Miocene and Plio-Pleistocene)
Mostly recent sands
Possible extent of Calcrete Uranium Districts
14° 16° 18° 20° 22° 24° 26° 28°
18° 20° 22° 24° 26° 28° 30° 32° 34°
WESTERN
ESCARPMENT
Namib Desert Calcrete-Gypcrete Uranium Region
Rossing
Swakopmund
Walvis Bay
Langer Heinrich
Windhoek
Kalahari Sand
Dune
Namib
Keetmanshoop
Johannesburg
Upington
Upington Calcrete - Gypcrete Uranium Region
GREAT ESCARPMENT
Beaufort West
Karoo Calcrete Uranium Occurrences
Great Karoo
Cape Town
Geomorphic surfaces after Netterberg, 1969a and Partridge, 1968

4.2 BACKGROUND FOR SOME SOUTHERN AFRICAN EXAMPLES

4.2.1 The Ancient Surfaces

Over large areas of southern and central Africa a succession of long-lived stable planation surfaces has developed from the Late Paleozoic onward. King (1967) has tabulated a cyclic succession involving eight erosional episodes listed here and illustrated in part on Figure 4.1. Calcretes have not yet been documented, to the writer's knowledge, on any of the first four surfaces, but both pedogenic and nonpedogenic calcretes are developed abundantly on or within sediments connected with episodes 5, 6 and 7, below, and also following the last period of incision.

1. Pre-Karroo landscape (Late Paleozoic). Glaciated in the south beneath Dwyka tillite. Folded and faulted.
2. Intra-Karroo landscape (Triassic). Commonly buried by Stormberg Series.
3. Gondwana landscape (Jurassic - Early Cretaceous). Post-Karroo, pre-continental rifting. A smooth surface, subsequently warped but widely preserved and exposed.
4. Post-Gondwana dissection (Early Cretaceous). Usually in the vicinity of upwarps.
5. African Planation (Late Cretaceous - Middle Tertiary). The most perfectly planed surface of Africa; with inselbergs and subsequently dissected. Correlative sediments in the Kalahari have extensive and commonly multiple calcrete horizons.
6. Broad valley-floor pediplanation (Miocene) within the African Surface. Sands and subsequent calcretes on the Kalahari.
7. Second valley planation (Pliocene).
8. Deep gorge cutting near coasts (Quaternary) following alluviation of African and post-African surfaces.

In all of the following discussion, we are concerned with the African Surface and with post-African events including the incision and reworking of calcretes.

4.2.2 Pedogenic and Nonpedogenic Calcretes in Relation to Present and Past Climates

If one compares the distribution of calcretes in southern Africa as recorded by Netterberg with present-day climates and inferred soil moisture

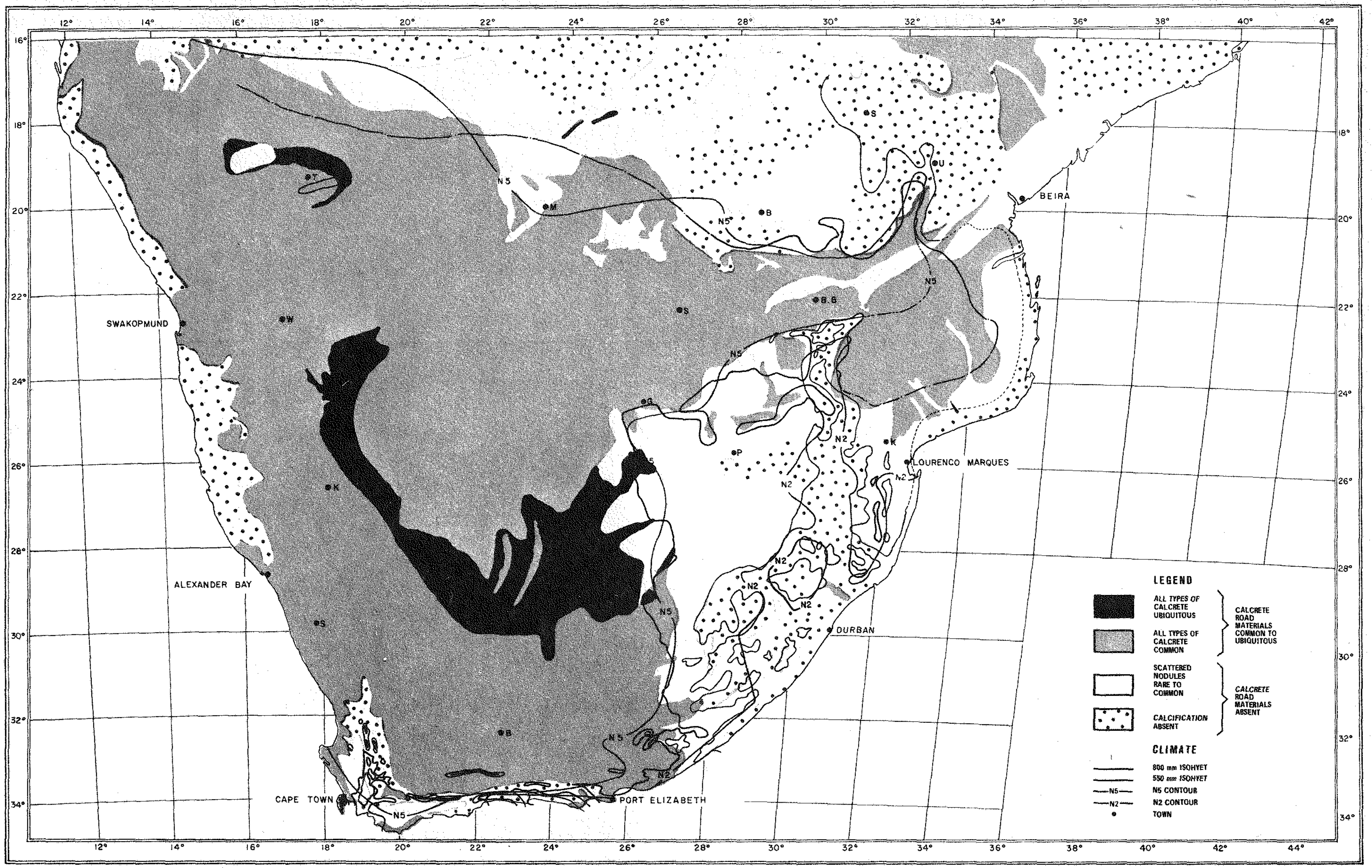


Figure 4.2. Distribution of calcretes in Southern Africa in relation to climate. From Netterberg, 1971. Reproduced by courtesy of the author and CSIR.

regimes (Figures 4.2 and 4.3), two points become clear:

1. The overall distribution of calcretes, predominantly pedogenic, coincides with present-day aridic and subaridic soil moisture regimes.

2. The most intensive development of these calcretes is mainly within the present-day extremely aridic soil moisture regime (A on Fig. 4.3). Yet this soil moisture regime is almost identical with that of the Wiluna-Yeelirrie region in Western Australia where nonpedogenic valley calcretes rather than pedogenic calcretes are forming today.

In other words, if the conclusion drawn from the Western Australian occurrences is valid regarding climates most favorable for pedogenic and nonpedogenic calcretes, then the region of most extensive pedogenic calcrete in southern Africa is mainly within an area where pedogenic calcretes should not be forming today! The writer's observations indicate that this is indeed the case; with very rare exceptions which can be attributed to especially favorable circumstances, pedogenic calcretes are not seen to be forming today in the region labeled A on Figure 4.3. The very extensive pedogenic calcretes in this region are, in fact, fossil calcretes which cap one or more Tertiary or later surfaces.

Netterberg (1969c) also has concluded from paleontological and isotopic evidence that calcretes in southern Africa are predominantly Pliocene and Pleistocene, though a few are pre-Pliocene and a very few are Recent. Moreover, these fossil calcretes record a wetter climate than that of today. Zinderen Bakker and Butzer (1973) have deduced from palynologic, geomorphologic and pedologic studies that precipitation during the Upper Würm Pleniglacial (29-25,000 B.P. to 17-16,000 B.P.) was double that of today, and that in general glacial periods were appreciably wetter and cooler than interglacials. Lancaster (1979) has similarly documented a humid period at 17-15,000 B.P. in the Kalahari using ^{14}C dates on lacustrine stromatolites.

4.2.3 Uraniferous Calcretes in Relation to Geomorphic Surfaces

Next one can compare the distribution of ancient geomorphic surfaces and of uraniferous calcretes and gypcretes on Figure 4.1. Here again the distinction between pedogenic and nonpedogenic calcretes is a central issue. Three uranium-bearing areas are identified: 1) the Namib Desert, 2) the

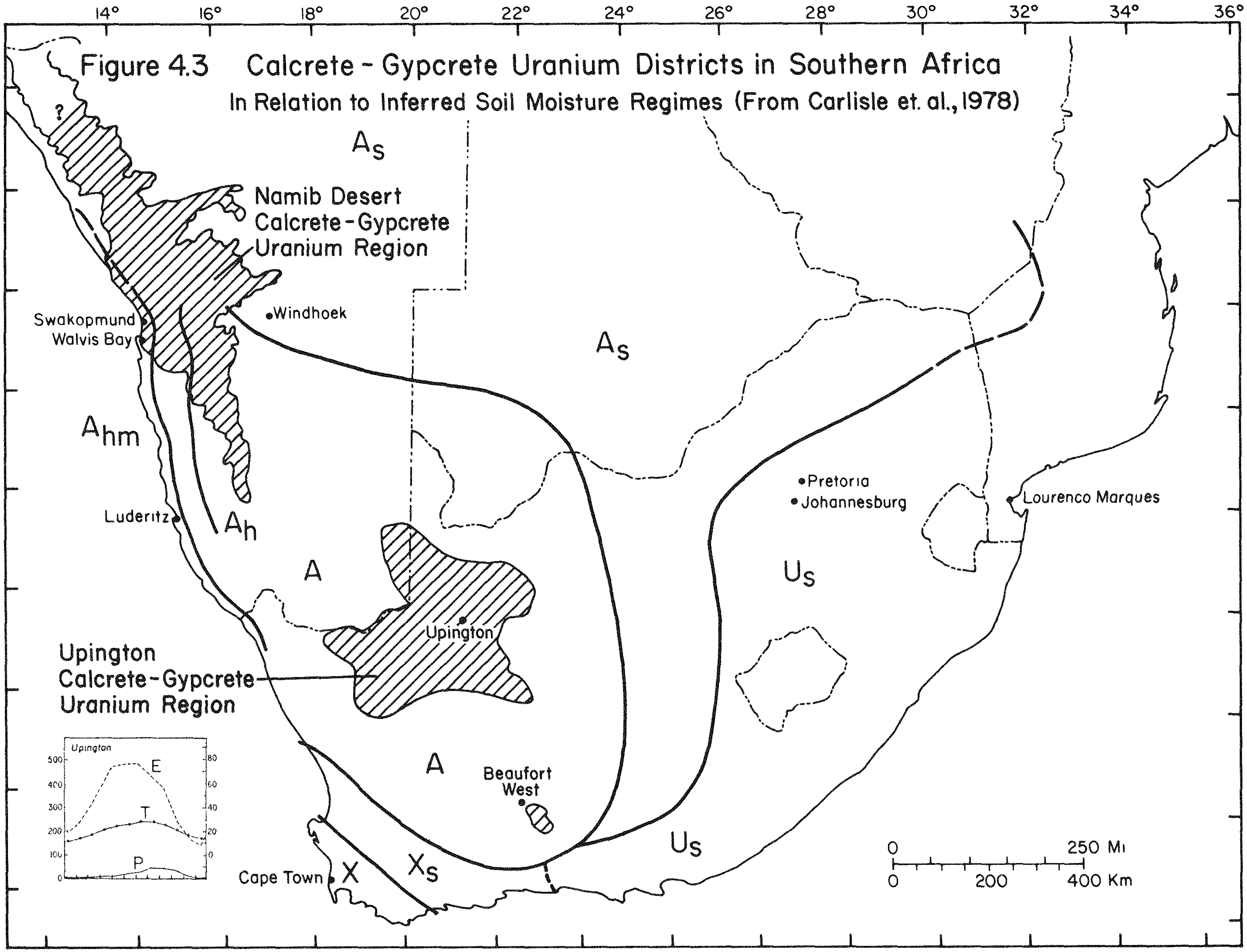


Figure 4.3 Calcrete-Gypcrete Uranium Districts in Southern Africa
In Relation to Inferred Soil Moisture Regimes (From Carlisle et. al., 1978)

Explanation for Figure 4.3

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 Gobabeb)

$E_w/P_w > 11$

$E_a - P_a > 3000$ (3559 at Gobabeb)

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.

$E_a/P_a = 5\text{-}10$

$E_w/P_w = 2\text{-}4$

$E_a - P_a = 2000\text{-}3000$

Subustic Regime:

U_s Subustic. Broad midsummer precipitation peak. Orographic rain on the eastern escarpment and storms on eastern plateau.

$E_a/P_a = 2\text{-}4$

$E_w/P_w = 1\text{-}2$

$E_a - P_a < 2000$

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)

Upington Region (or North West Cape) and 3) a portion of the Great Karroo.

1. On the Namib Desert (Carlisle et al., 1978) uraniferous calcretes are nonpedogenic valley calcretes formed within alluvium deposited in part on the Mid-Tertiary African Surface but predominantly in valleys within the African Surface corresponding probably with King's episodes 6 (Miocene) and perhaps 7 (Pliocene) listed above. The ore-bearing calcretes, and probably the U mineralization as well, predate Quaternary gorge cutting. Overlying nonuraniferous pedogenic calcretes and surficial gypcretes on the alluviated surface of the Namib Platform, i.e., on the nonincised surface between gorges (Fig. 3.5A) are Pleistocene to Holocene.

2. The Upington calcrete-gypcrete region is entirely within area A on Figure 4.3, and, although traces of carnotite are locally common in the pedogenic pre-Holocene calcretes which dominate the landscape, the U prospects are in a variety of calcrete not previously described as a uranium host. This is reconstituted nonpedogenic calcrete formed by erosion and locally by gentle undercutting of the great sheets of nodular and hardpan pedogenic calcrete followed by redeposition downgradient. The process is both mechanical and chemical as evidenced by the reworked compound nodules, at times in graded beds, and by calcite overgrowth, calcite and gypsum cement and by redeposited carnotite.

Thick groundwater or valley calcretes within deep river valley fills such as those on the Namib Desert or those described by Netterberg (1969b) on the Vaal and other rivers to the east have not been demonstrated. One can find occasional examples of Holocene pedogenic calcrete, formed for example on weathered bedrock by illuviation of carbonate through a shallow soil or, rarely, in a thicker soil where greater local abundance of carbonate or rainfall facilitates carbonate authigenesis under a climate otherwise too arid for abundant pedogenic calcrete. These are exceptional and of no importance for U mineralization.

3. On the Great Karroo near Beaufort West (Fig. 4.1) pedogenic calcrete and perhaps some hybrid pedogenic-nonpedogenic calcrete have formed on what the writer takes to be one or more post-African surfaces. Known uraniferous occurrences are limited, weakly mineralized

and confined to a small area within the region of Karroo sandstone U deposits. Sandstone mineralization is the most plausible source for the calcrete uranium, and indeed some patches of mineralized calcrete overlie mineralized, reportedly ore-grade sandstone.

In summary, all three uraniferous areas shown on Figure 4.1 contain calcretes of probably Late Tertiary age and from traces to abundant carnotite, probably also Late Tertiary in age. Reworking of the uranium within nonpedogenic Tertiary calcrete on the Namib Desert, especially at Langer Heinrich, has resulted in some enrichment of the ore (Carlisle et al., 1978). Reworking of very weakly mineralized pedogenic Tertiary calcrete in the Upington area has also produced concentrations, some of which have justified further investigation and are mentioned in Section 4.7 below.

4.3 ILLUVIAL CONCENTRATION OF URANIUM IN UNREWORKED PEDOGENIC CALCRETE IN SOUTHERN AFRICA

Reflecting the geomorphic stability and prevalence of uranium-anomalous bedrock, one can find examples of illuvial U concentration, including visible carnotite, in pedogenic calcretes in all three areas shown on Figure 4.1. None is economic.

On the Namib Desert, for example, carnotite was observed in chalky calcrete at the base of pedogenic mesa-forming hardpan calcrete about 1 m thick on a surface undergoing erosion. Spectrometry on the chalky layer indicated 65 ppm eU, 0 ppm eTh. Some downslope transport and minor secondary U mineralization was observed. Downward transport of U into weathered bedrock beneath mineralized calcrete as described in the earlier report is also common. Such carnotite in bedrock is commonly associated with supergene vein calcite.

In parts of the Upington calcrete-gypcrete uranium region, sparse carnotite in the lower parts of mature pedogenic calcrete is almost commonplace. During exploration for base metals, according to one explorationist, carnotite is found essentially "wherever you drill through calcrete" in some areas. The writer has observed some spectacular though noneconomic examples. In addition, a very slight increase in U content with depth--in one case up to 6 ppm eU--can be observed in some of the rare pedogenic calcretes forming today in shallow soil above gneissic bedrock.

The great bulk of the bedrock throughout the Upington uranium-bearing calcrete-gypcrete region consists of Archaeozoic and Proterozoic metamorphic rocks in which intrinsic uranium contents of 12-25 ppm are common and some of 46 ppm (Moon, 1976) and 150 ppm (Schutte, 1976) are known.

On the Great Karroo near Beaufort West thin films of carnotite on fractures in the lower part of pedogenic calcrete profiles are common. One road quarry shows a uniform increase in eU by field spectrometer from 2 ppm at the surface to 22 ppm at 1½ m. Thorium is less than 10 ppm eTh throughout.

4.4 CAPILLARY RISE OF U INTO A PEDOGENIC CALCRETE OR GYPCRETE

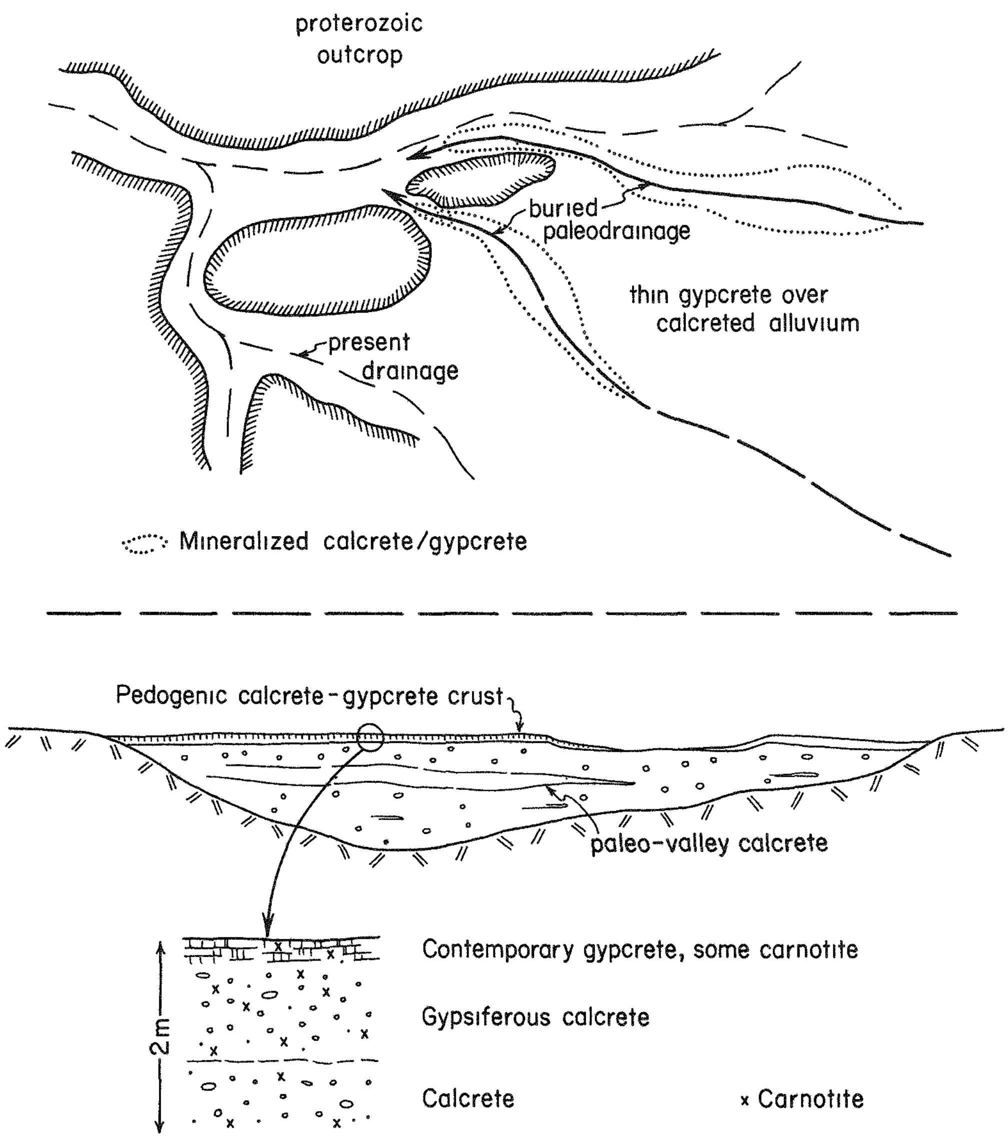
Hambleton-Jones (1976; personal communication, 1976) has presented a rationale for upward diffusion of U through vertical distances of tens of meters followed by capillary rise under the influence of "soil suction" as a mechanism for U mineralization of calcrete on the Namib Desert. He envisages a groundwater system in which more or less cyclic changes in rainfall cause pronounced variations in the depth to the water table and concomitantly in the abundance of oxygenated and carbonated water able to leach U from bedrock. The result is a cyclic transport of U from bedrock into surficial calcrete with each rise in the water table. During high stands of the groundwater, both P_{H_2O} and P_{CO_2} in the now-uraniferous water decrease upward as a consequence of "soil suction," i.e., by upward capillary transport and diffusion through the capillary fringe and the soil moisture zone. Decrease in P_{CO_2} will cause calcite to precipitate not far below the surface. By analogy, he then postulates, precipitation of carnotite will follow the same pattern due to destabilization of uranyl carbonate complexes in the presence of V and K. Some of the difficulties inherent in this last step have been discussed (Carlisle et al., 1978). Contrary to the emphasis given to vertical transport by Hambleton-Jones, the writer believes that the evidence is compelling on the Namib and in Western Australia for lateral transport of ions in solution over tens of km and for mineralization in areas where constrictions to lateral groundwater flow cause a partial ponding and a shallower water table (Figs. 3.4, 3.5).

Nevertheless, transport of U into pedogenic calcretes and/or gypcretes by capillary rise above a permanent, perched or temporary water table from immediately underlying or very shallow uraniferous sources does occur. As shown in the following, this is at times useful in exploration, and very locally it contributes to the grade of potential ore.

Capillary-rise U mineralization in surficial gypcrete on the Namib Desert above mineralized nonpedogenic calcrete and gypcrete was mentioned in the earlier report (Carlisle et al., 1978, p. 158) but only in passing. Figure 4.4 illustrates a rather interesting case. An underlying nonpedogenic (valley or channel) calcrete containing carnotite in concentrations which reach ore grade occurs in paleochannels unrelated to present-day ephemeral streams in an

Figure 4.4

A Carnotite Occurrence in the Calcrete-Gypcrete Transition Zone — Namib Desert



area of bedrock constriction. The channel calcrete is comparable in texture, composition and general appearance with that at Langer Heinrich and in places more than 19 m thick. Both drilling and resistivity survey have been used to outline the paleochannels. Above the channel calcrete and over the entire present surface, except for exposed bedrock and active stream channels, is a layer of purely surficial pedogenic calcrete-gypcrete a meter or so thick. Where this surficial calcrete-gypcrete rests on well-mineralized channel calcrete it commonly contains significant amounts of carnotite as secondary open-space fillings. Gypsum-rich portions tend to be most enriched. In one exploration pit this puffy, surficial gypcrete reaches a grade of 0.62% cU_3O_8. Field spectrometry indicates eU of only some 300 ppm, suggesting recent emplacement of the carnotite.

Additional examples of the potential use of capillary rise U in pedogenic calcrete as an exploration tool are suggested in the Karroo calcrete area near Beaufort West. Several carnotite-calcrete prospects have been investigated since 1975. None is economic. Some, however, are in small patches of calcrete, perhaps erosional remnants, which directly overlie mineralized Karroo (Lower Beaufort Series) sandstone, and on at least one of these the grades in the sandstone have been substantial enough, reportedly $\sim$0.05% U_3O_8, to justify continuing exploration through 1978.

4.5 ADDITION OF NEW URANIFEROUS SEDIMENT ABOVE A PEDOGENIC CALCRETE

Though the possibility is sometimes raised during discussions, no documented examples of U mineralization due to deposition of uraniferous material on top of an existing calcrete are known to the writer. It has been suggested that in situations where a vertical succession of closely spaced calcrete horizons has developed U might be fixed temporarily in each calcrete, then reworked and perhaps concentrated in one or more of the lower horizons. Carnotite occurs in the lower part of a succession of three calcretes on an aggrading surface at Hidden Valley, Nevada (see next below). but the primary accession of U in this case is thought by the writer to have been by lateral transport.

One might speculate about possible aeolian reworking in a desert environment. Evaporative and efflorescent U minerals, such as schroekingerite deposited as films on playa lake surfaces, may be readily picked up by the wind; perhaps as readily, for example, as the salts blown from dry lakes in Australia, which apparently account for much of the halides in breakaway scarps marginal to the Old Plateau. This is an unlikely source for ore but possibly a complicating factor in geochemical exploration.

More attractive in this category of possibilities would be the superimposition of a uraniferous tuff directly over calcrete. Whether the chemical contrast between overlying tuff, which might yield U upon devitrification and leaching by rain water, and the underlying already formed calcrete would result in mineralization of the calcrete or of the underlying soil is not clear.

4.6 LATERAL ACCESSION OF U TO A HYBRID PEDOGENIC-NONPEDOGENIC CALCRETE OR GYPCRETE

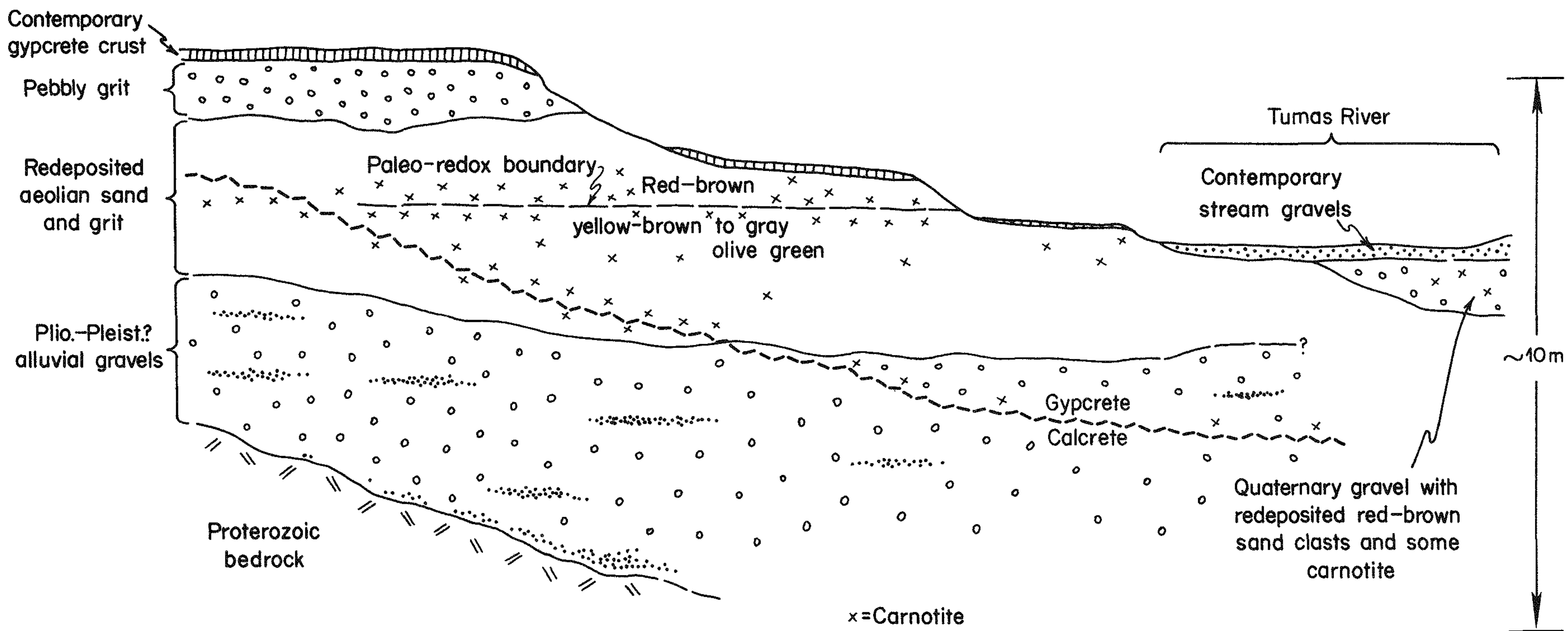
Perhaps the most familiar examples of mixed pedogenic-nonpedogenic calcretes in which both vertical and lateral transport of materials are important are those on the steeper portions of alluvial fans. Carnotite-bearing calcretes, 5 m or more thick, in the Jean-Sloan area of southern Nevada are of this type (Carlisle *et al.*, 1978). Surficial gradients range from 1.7% to 3.0%. Although primary sedimentary layering within the fanglomerate is reflected by variations in the degree of calcretization, all of the exposed calcrete has reached stage 4 maturity of Gile *et al.* (1966), and neither an argillic (B_t) soil horizon or other evidence of a continuous soil profile is preserved within it. The cementing calcite, dolomite and lesser gypsum appear to have been deposited throughout the vadose zone from a combination of surficial, soil, gravitational and laterally flowing groundwaters. Visible carnotite occurs sparingly as thin films on fractures, as coatings on pebbles, and as specks in the cement at various depths in the calcrete. It is commonly at the contact between carbonate and gypsum. Carnotite is only seen in artificial exposures. Natural exposures of weathered calcrete fail to show either the mineral or anomalous radioactivity. This and the slightly greater abundance of carnotite in areas of jointing indicates reworking of earlier precipitates. Th is absent. The source of the U appears to be the uraniferous Erie Tuff, variably exposed updrainage from the fanglomerate showings.

At Hidden Valley, another site in this same district but on a gentle slope, lateral transport in solution over and/or through a predominantly pedogenic calcrete appears to be responsible for weak carnotite mineralization. Up to three calcrete layers are closely superposed, each one showing a well-developed pedogenic profile, including a massive plugged horizon overlain by variably developed laminar caliche and some rockhouse structure at the surface. Illuvial transport of solubles including uranium is indicated by the occurrence of carnotite, 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 valley, and the localization of visible calcrete there indicates appreciable lateral

Figure 4.5

Carnotite in Gypcrete, Calcrete and Alluvium on a part of the Tubas Grant, Namib Desert

Diagrammatic Section, Vertical Greatly Exaggerated



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. Moderately anomalous (3-5 ppm cU) biotite trachyte 2-3 km updrainage is the probable source rock.

On the Namib Desert the deeper carnotite-bearing gypcrete which constitutes the deposits of greatest interest on the Tumas River (Figs. 4.5, 3.5c and Carlisle et al., 1978)--not to be confused with the surficial crusts described under "Capillary Rise" (Fig. 4.4) above--is downdrainage from both mineralized calcrete and U-anomalous bedrock. It also grades downward into calcrete. The host sediments for the gypcrete consist of: 1) valley-filling gravels of the same age, source and setting as those of the valley calcretes higher on the Namib Platform including those at Langer Heinrich and 2) lenses and sheets of sand and grit with aeolian rounding, pitting, sorting and some ventifacts but without sedimentary structures suggesting redeposition of dune sand as debris flows, according to the Anglo American Corporation field staff. The sulfate component of the gypcrete is undoubtedly from marine fogs, primarily illuvial and in that sense "pedogenic." The Ca, U, V, and K, however, can only have been derived laterally from bedrock and/or calcrete, higher on the platform and in the Khomas Highlands to the east.[1] Carnotite mineralization (Fig. 4.5) is predominantly in the slightly to moderately gypcreted (10-35% gypsum) sand and is significantly more abundant as follows:

1. adjacent to (within ∿ 1 m of) an apparent paleo-redox boundary, interpreted as a paleo-water table, with yellow-brown to gray olive-green sand below and red-brown sand above. This boundary and the associated mineralization observed in 30 or so pits and river-bank exposures is nearly level and is

---

[1]Lack of a recognizable soil profile or persistant stratification of any sort clearly related to pedogenesis in this deeper gypcrete weakens its classification as "hybrid-pedogenic." Nevertheless, the example does illustrate the concept emphasized in this section with concentrations reaching ore grade. In addition, it provides an opportunity to update the previous report on this deposit (Carlisle et al., 1978, p. 156-164), especially in regard to systematic excavations accessible in August 1978 which appear to have 1) confirmed the concept of a paleo-redox boundary related to a fossil water table and 2) provided striking evidence for reworking of carnotite into younger stream gravels.

truncated by the recent Tumas River incision.

2. broadly adjacent to the underlying transition from gypcrete to calcrete.

In addition, minor amounts of carnotite occur very locally in small concentrations (estimated 0.3% U_3O_8) as open space fillings in noncalcreted, nongypcreted fluviatile gravels within the Recent Tumas River incision which transects the mineralized paleo-redox boundary. The gravels contain reworked cobbles of the red-brown gypcreted sand. This is clearly a younger generation of carnotite.

The following mechanisms contributing to carnotite precipitation in Namib gypcrete are suggested.

1) Near-surface carbonate-rich, alkaline uraniferous groundwaters having come to near equilibrium with calcite in calcrete higher on the platform, pH ∿ 7.0-8.5, move downgradient into the gypcrete with near-neutral pore water. This alone tends to diminish carnotite solubility because lowered pH reduces the ratio CO_3^{2-}/HCO_3^- which in turn lessens the stability of uranyl carbonate complex ions.

2) An additional effect might be expected from the common-ion precipitation of $CaCO_3$ and accompanying decrease in $a_{CO_3^{2-}}$ consequent to mingling of calcium carbonate-saturated waters with gypsum-saturated waters. This may account for preferential precipitation near the gypcrete calcrete transition in Fig. 4.5.

3) Excessive evaporation on the Namib Platform undoubtedly increases the concentration of U, V and K.

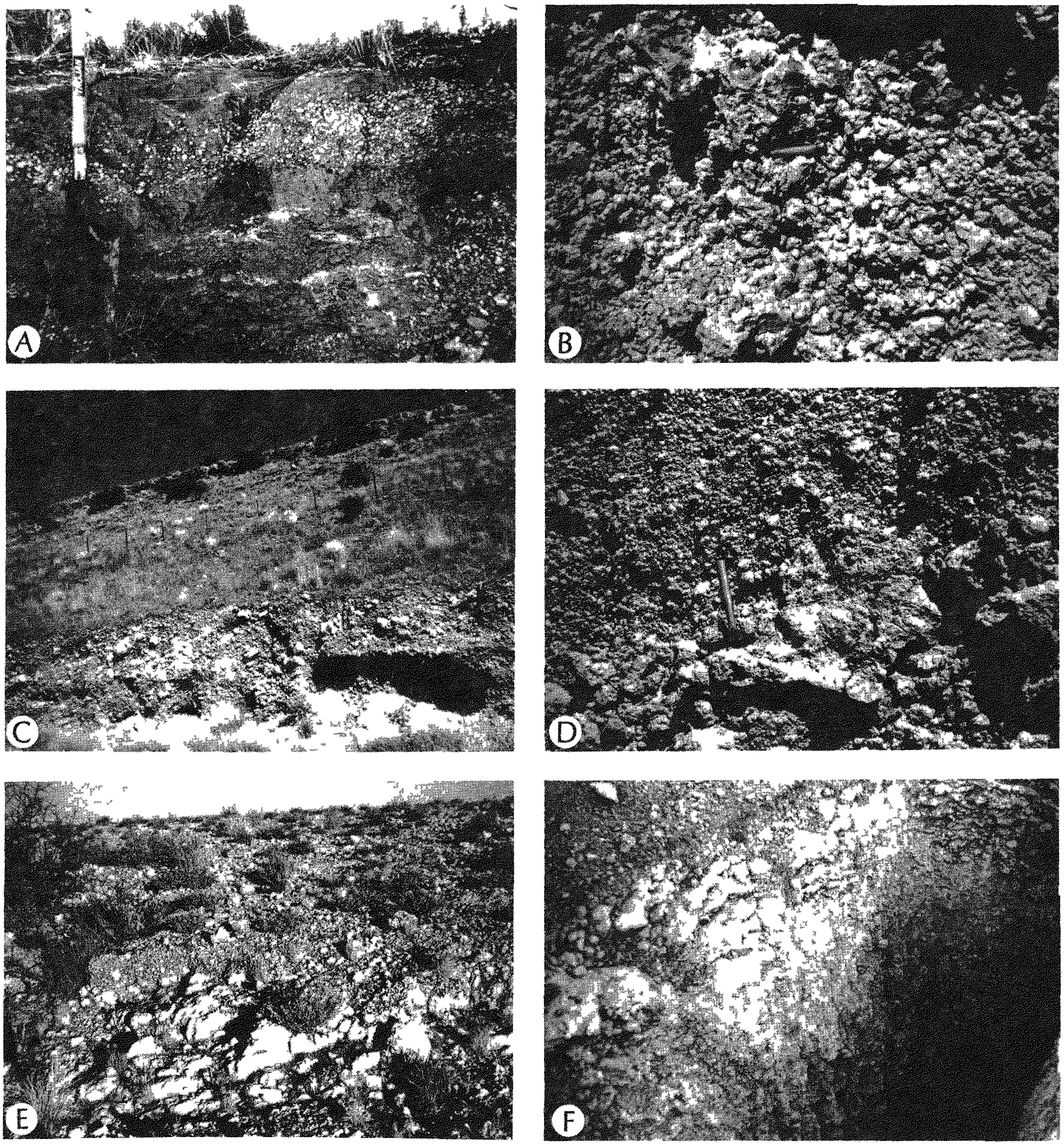
4) Finally, to the degree that the incoming carbonated groundwaters are depleted in oxygen and rise toward the surface near groundwater constrictions on the lower Namib platform, some oxidation of soluble V(IV) to V(V) will further facilitate carnotite precipitation.

This last mechanism, emphasized by Mann and Deutscher (1979) for Western Australian calcretes, could readily account for the apparent concentration of carnotite near the paleo-redox boundary shown on Fig. 4.5.

In North America, because of the several qualifications listed earlier (Section 3.3), lateral migration of U into a pedogenic or mixed pedogenic-nonpedogenic calcrete or gypcrete may be a more expectable mechanism for ore-grade concentrations of U than is the pure calcrete model. Lacustrine calcretes or lake-bordering pedogenic calcretes and gypcretes downdrainage from potential U sources in United States would warrant further investigation.

Figure 4.6

Primary and Reconstructed Calcretes



a) Primary nodules in situ, pedogenic calcrete Western Australia

b) Primary nodules in situ, Kalahari pedogenic calcrete

c) Primary (skyline) and transported (foreground) Kalahari calcrete

d) Reconstituted nodular Kalahari calcrete

e) Transported nodular calcrete, Upington region

f) Reconstituted calcrete, Upington region

4.7 REWORKING OF WEAKLY MINERALIZED PEDOGENIC CALCRETE OR GYPCRETE ACCOMPANIED BY LATERAL TRANSPORT AND RECONCENTRATION OF URANIUM

4.7.1 Reconstituted Detrital Calcrete

Disruption, transport and reconstitution of Pleistocene and older pedogenic calcrete is commonplace over wide areas of the Upington calcrete-gypcrete region and of area A on Figure 4.3 (4.2.3 above). Mechanical transport of calcrete nodules is particularly obvious on talus slopes below mesas capped by Kalahari calcrete (Fig. 4.6c) and in some contemporary stream gravels. It is only slightly less obvious on gentle valley flanks. The nodules are typically hard, very mature calcrete, abraded and commonly compound as though derived from a surficial layer of "rockhouse" (brecciated-recemented) calcrete. Frequently, as in the road quarry at Kleinbegin (Fig. 4.13) or the railroad cut at Dyasons Klip, the nodules show graded bedding, imbrication or flattened orientation in the horizontal plane. None of these features is characteristic of primary nodules <u>in situ</u> (Fig. 4.6a,b). Exotic cobbles may be present. Recementation results in overgrowth, dripstone textures on lower surfaces, and bridging between and coalescing of the nodules, at first with earthy calcrete but ultimately producing a new hardpan calcrete. Gypsum cement is very common in this region, especially, it seems, in places where the recementation occurs in or around an evaporative pan.

Reconstituted detrital calcrete was recognized by Treasure (1976a) who referred to it as "conglomeratic" in the vicinity of McTaggarts Kamp. It can be observed at most of the occurrences shown on Figure 4.7, usually in small valleys gently eroded in the African or post-African surface and usually with pedogenic hardpan calcrete on the older surface not far away (Figures 4.9, 4.10, 4.13).

4.7.2 Reconcentration of Carnotite in Reconstituted Calcrete or Gypcrete

Reconstitution of calcrete makes possible either the dispersion or the reconcentration of contained U. We have seen, for example, that groundwaters in contact with or downdrainage from carnotite in calcrete are commonly enriched in U and V. In Western Australia, the newer calcrete

Figure 4.7

Some Calcrete-Gypcrete Uranium Prospects in the Upington Region, South Africa

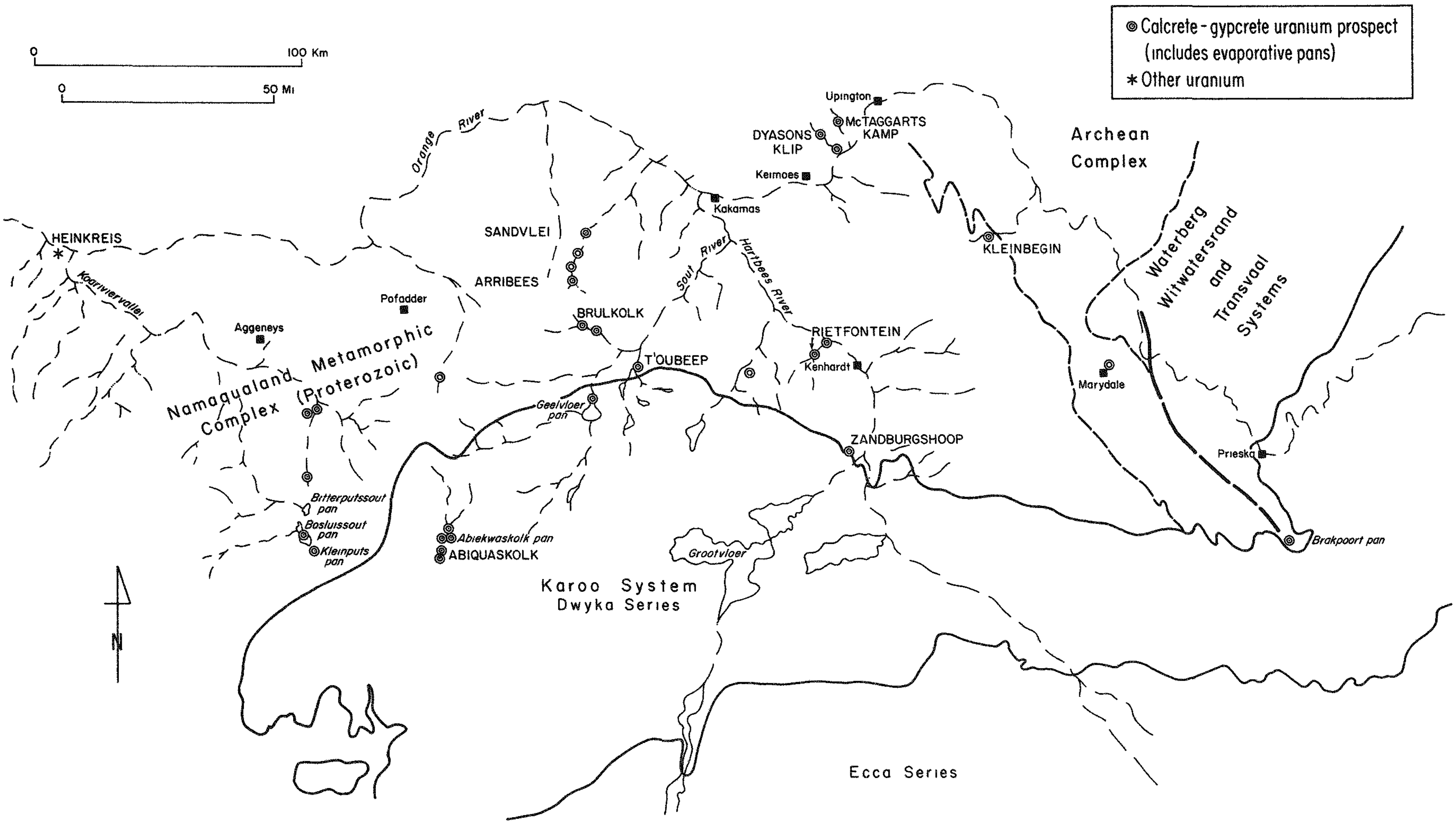
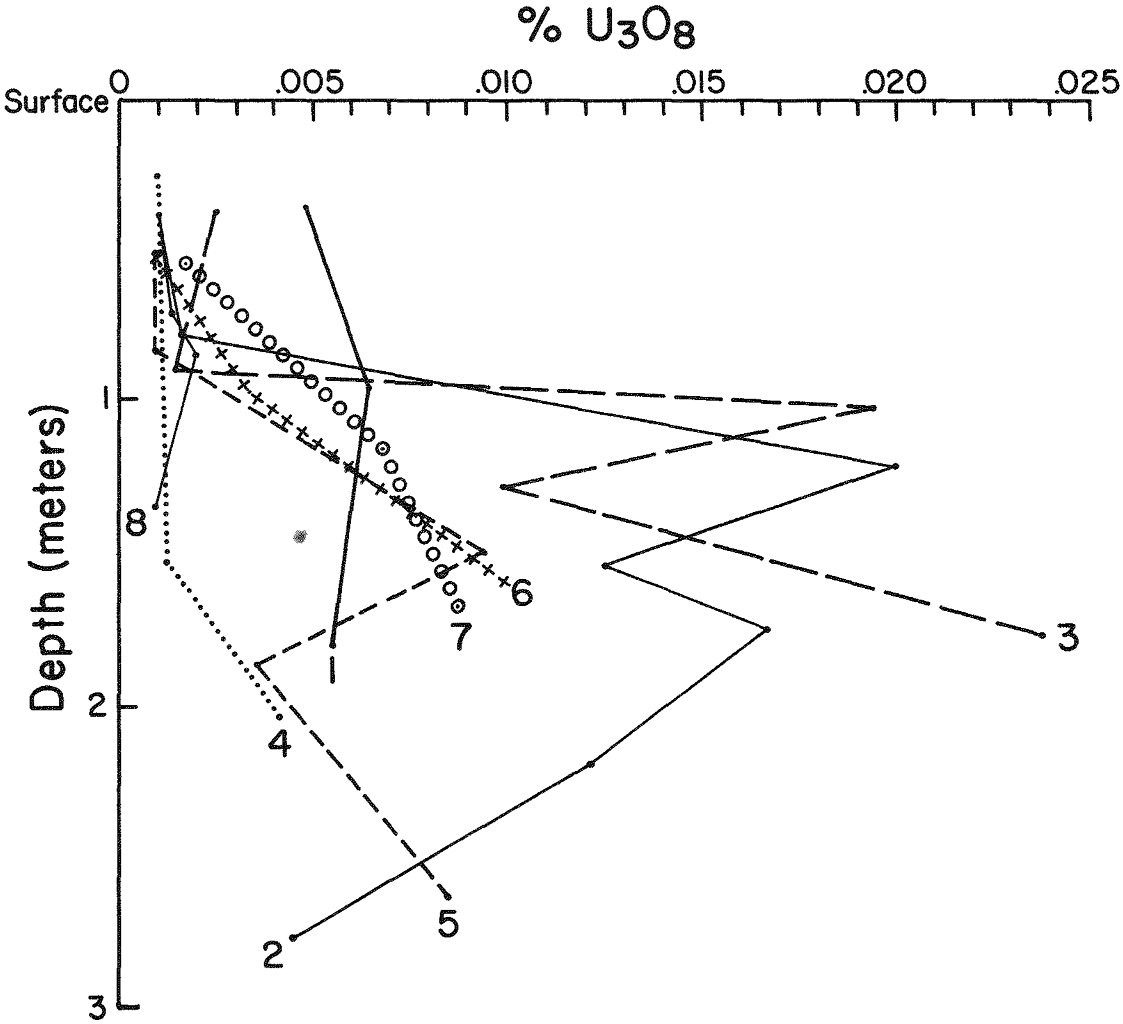


Figure 4.8



DISTRIBUTION OF URANIUM WITH DEPTH IN A THIN, PARTLY RECONSTITUTED PEDOGENIC CALCRETE.

The distribution suggests that illuvial transport of uranium to bedrock or to lower zones in the calcrete is particularly effective in the uppermost 2 m. Bedrock is at approximately 0.5 m below the lowest analysis indicated in each pit. The only uranium mineral observed is carnotite.

Data from eight exploration pits to bedrock on a single prospect near Upington, South Africa. Sample interval varies. Courtesy General Mining and Finance Corporation, Ltd.

deltas with "young" dolocrete mounds and contemporaneous carnotite fringing some lakes (3.2.3 above, Fig. 3.4 and Carlisle et al., 1978) are perhaps largely derived by dissolution and reprecipitation of older uraniferous valley calcrete. Even within a single calcrete body, as inferred for Yeelirrie and Langer Heinrich, solution and redeposition may enhance the grade in favored locations (3.2.5 above).

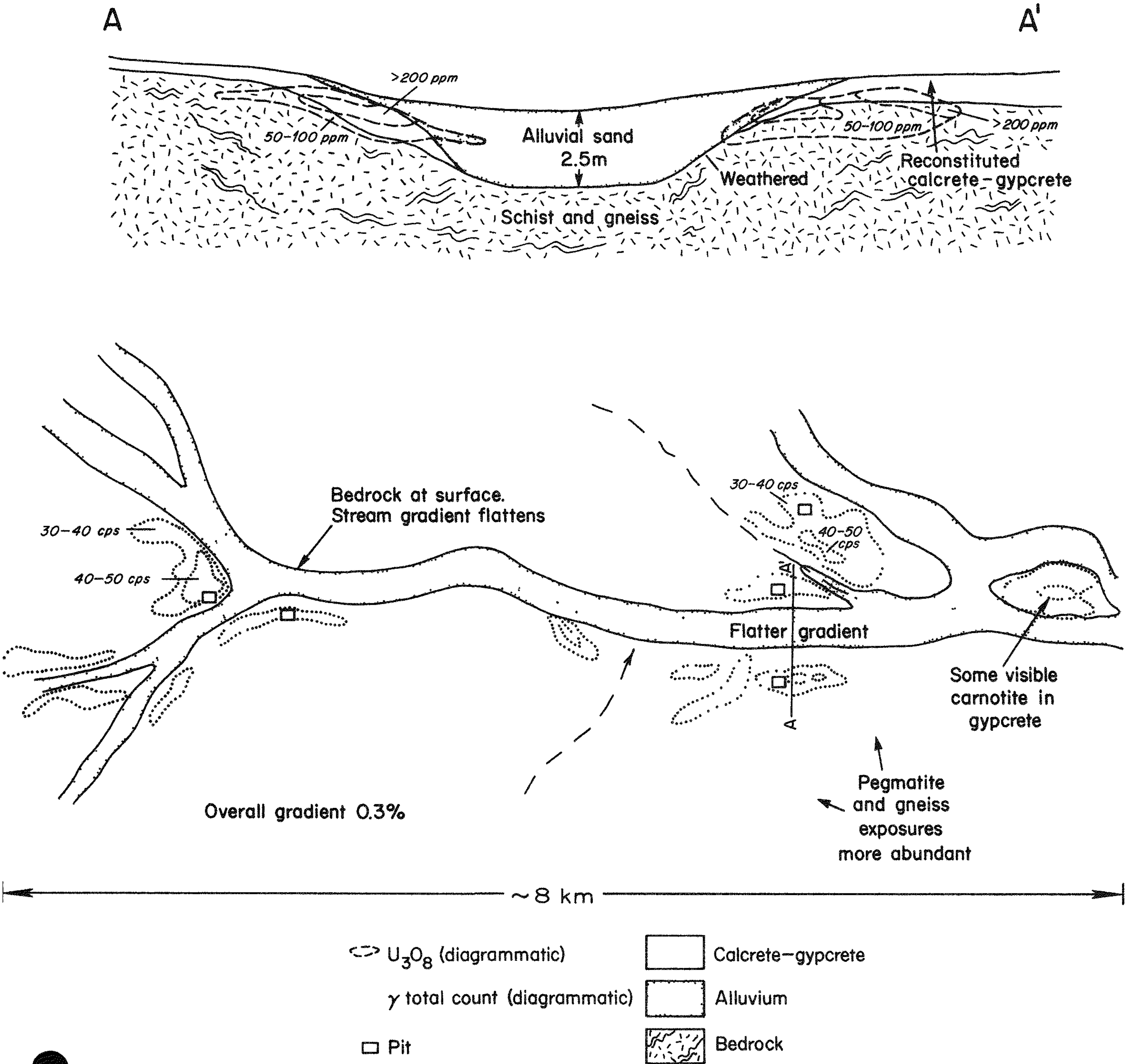
Most, if not all, of the calcrete-gypcrete U prospects along valleys in the Upington Region (Fig. 4.7) and some of those in evaporative pans are thought by the writer to involve reconcentration of U once contained in pedogenic calcrete.

4.7.2.1 Reconstituted Calcrete with Carnotite in Post-African Rejuvenated Valleys

The prospect illustrated in Figures 4.6e,f and 4.8 extends for several hundred meters along the gentle flank of an ephemeral rejuvenated stream which is incised a few meters at most into the African (or post-African) Surface. This older surface is a pediplane irregularly covered by hardpan pedogenic calcrete. Precambrian augen gneiss and occasional pegmatite veins are exposed where calcrete has been eroded and at the bottom of prospect pits 1 1/2 - 3 m deep. Reconstituted calcrete is thickest near the stream. Its upper 20 - 30 cm consists of reworked and recemented nodular hardpan and laminar calcrete containing little if any U. The next 2 m contain both reworked compound nodules, variably recemented, and hard gritty calcrete undergoing further rebrecciation. Scattered pebbles of quartz included in the calcrete are similar in size to the nodules. The distribution of U with depth in this and other reconstituted calcretes typically shows the same pattern of illuvial concentration as it does in simple pedogenic calcretes. Visible carnotite in the calcrete matrix and as coatings on calcrete nodules and quartz pebbles reaches a maximum about half way through this section but continues down into weathered bedrock in some pits. Chemical and radiometric equivalent U show a parallel distribution. In this same prospect area specks and small concentrations of carnotite can also be found in noncalcified contemporary stream alluvium, testifying to its mobility under the existing climate. This and the fact that the U content of the reconstituted calcrete, though subeconomic, is appreciably greater than that of the older pedogenic calcrete are the main evidences for carnotite reconcentration.

Figure 4.9

Carnotite in Calcrete-Gypcrete, Alluvium, and Weathered Bedrock in the Upington Region, South Africa



Evidence for lateral transport and reconcentration of carnotite is much clearer in the prospect illustrated in Fig. 4.9, which is 100 km or so from the last. This too is along an ephemeral rejuvenated drainage gently incised into the nearly flat African (or post-African) Surface. Scattered outcrops of Proterozoic schist, gneiss and pegmatite whose U-anomalous character was noted above (4.3) belong to the Namaqualand Metamorphic Complex. Patches of pedogenic calcrete occur on the older surface but much of the calcrete or calcrete-gypcrete along the drainages including the mineralized portions is reconstituted. Natural exposures, pits and drill data bring out two points:

1) mineralization is in part, if not entirely, Recent; carnotite concentrations occur not only in calcrete-gypcrete but also in continguous weathered bedrock and Holocene stream alluvium, including windblown--so-called Kalahari--sand and
2) as shown on Figure 4.9, U concentrations are localized in areas of flattened gradient and of groundwater convergence or ephemeral stream junction. In other words, bedrock constriction and partial ponding of groundwater is the primary control here, as it is for the Western Australian and Namibian calcrete model. Uranium had to have been transported laterally.

As exposed in the prospect pits, the upper 1/2 - 1 m of the host calcrete is composed of transported mature calcrete nodules within an earthy to sandy carbonate cement. This part is characteristically barren, although carnotite can be found infrequently in larger compound nodules. The next 1 - 2 m tends to be dominated by sandy to pebbly gypcrete with some carbonate cement throughout and in one occurrence with amoeboid calcrete nodules which are probably not reworked but are forming in situ. Angular reworked gypsum fragments are common in some pits. Generally this middle portion of the section is noticeably enriched in U, particularly in the gypsum-rich sandy portions where visible carnotite coats fracture surfaces and pebbles. In the lower 1/2 - 1 m of the pits angular fragments of weathered bedrock increase in abundance while carbonate cement and U decrease. None of the calcrete has reached a maturity beyond stage 2 or 3 of Gile et al. (1966) except for very local pedogenic modifications showing hardpan, rockhouse and laminar horizons on exposed surfaces. In one of these places carnotite has been transported downward into weathered bedrock and is quite noticeable.

These same characteristics, i.e., 1) host rocks composed of reconstituted calcrete with variable amounts of gypsum, 2) Quaternary or Recent mineralization and 3) reconcentration of carnotite in areas of groundwater convergence and/or partial ponding, typify most of the prospects in the central part of Figure 4.7. Consequently, one can predict the occurrence of many showings on the basis of dendritic paleodrainage patterns and the trends of resistant rocks in the foliated metamorphics as seen on air photographs. In no case known to the writer is the reconstituted host calcrete-gypcrete more than 4 m thick, and commonly it is only one-half that. Nor does the reported grade exceed a few hundred ppm over mineable thicknesses or areas of a few hundred meters on a side. Richards (1975), Moon (1976), Schutte (1976) and Treasure (1976a,b) describe several such occurrences on the basis of air radiometric and/or follow-up ground surveys. On the T'Oubeep prospect, for example, values of 236, 118, 202 and 197 ppm U_3O_8 over an average thickness of 40 cm of calcrete are reported from four pits less than 1 m deep, and on the Zanburgshoop prospect south of Kenhardt values of 71, 81, 257 and 414 ppm U_3O_8 are reported over thicknesses of 90, 90, 60 and 70 cm in separate pits within the middle part of a shallow calcrete (Moon, 1976). The mineralized calcrete is along minor streams and laterally impersistent. Favorable areas are located near stream junctions in the same manner as Figure 4.9. Similar relationships are shown at Arribees (Treasure, 1976a). Carnotite is the only identified U mineral.

4.7.2.2 Uranium in and Adjacent to Evaporative Pans

In addition to the calcrete-gypcrete carnotite occurrences, anomalous amounts of U in several evaporative pans in the Upington Region (Fig. 4.7) are described in the reports just cited. Chemical U contents of 2-55 ppm but mainly in the range 20 - 30 ppm are reported. No U mineral is identified. For several of these pans, U-Th anomalies in nearby bedrock have been suggested as U sources, the U having been selectively leached and transported to the pans (Richards, 1975; Moon, 1976; Schutte, 1976). Reworking of U from weakly mineralized pedogenic calcrete is a likely alternative or co-existing source in the present writer's view.

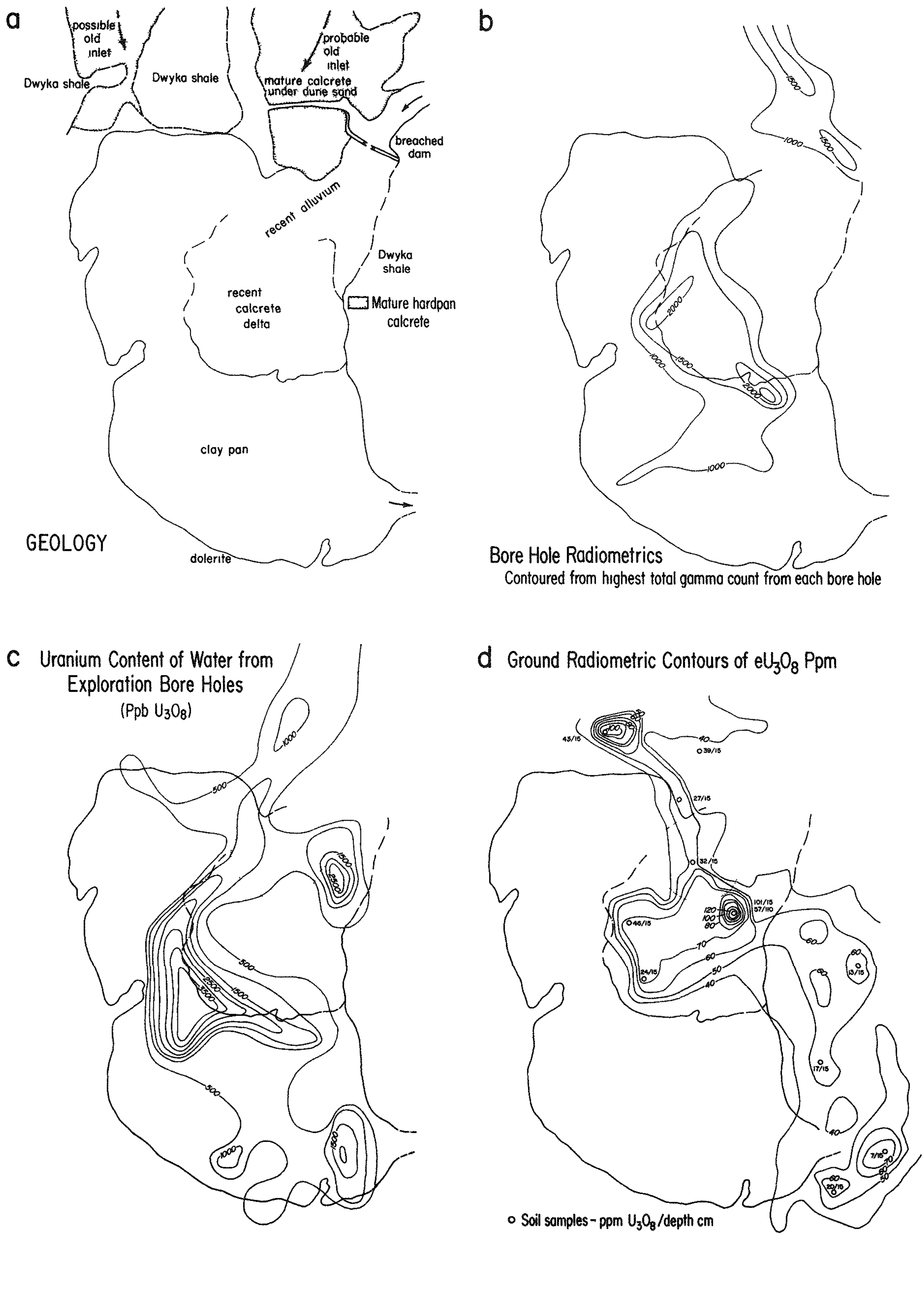
At Geelvloer Pan the U concentration is not so much a feature of the pan surface but occurs as carnotite on gypsum-coated calcrete nodules and within soft friable gypcrete and calcrete-gypcrete on the northwest edge or outlet of the pan. This appears to be another classic example of carnotite mineralization

Figure 410

Uranium Mineralization in Relation to a Recent Calcrete Delta

Abiquaskolk, Upington Region, South Africa

Maps a, b, c after field staff, Phelps Dodge of Africa, Ltd. Map d after E. P. J. Schutte, 1976



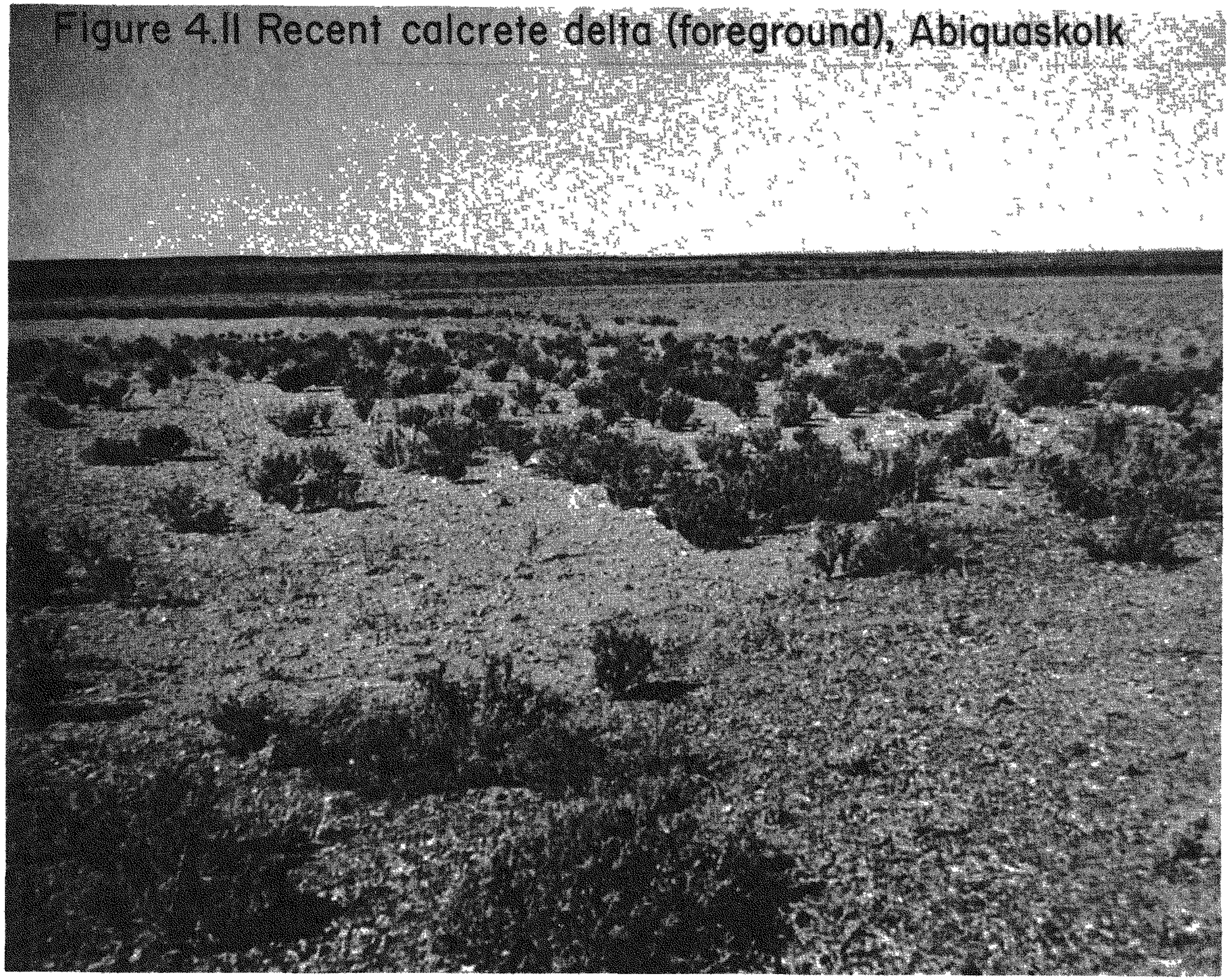


Figure 4.II Recent calcrete delta (foreground), Abiquaskolk

at a drainage constriction but in this case with sufficient evaporative free water above the constriction to have resulted in abundant sulfate. Visible carnotite is said to be noticeably associated with gypsiferous facies.

4.7.2.3 Mineralized Calcrete Delta at Abiquaskalk

A most interesting variation occurs at Abiekwaskolk pan (Abiquaskalk, Figs. 4.7, 4.10), shown to the writer by J. Hobbs of the field staff of Phelps Dodge of Africa. The prospect is within the outcrop belt of Dwyka shale (lower Karoo System) and dolerite. Namaqualand Metamorphic Complex rocks are exposed only a few km away beneath the partly exhumed pre-Karoo glacial landsurface. African and post-African surfaces dominate the landscape. Mature calcrete, very likely a deltaic variety in the Western Australian sense (3.2 above; Fig. 3.3b) or a hybrid deltaic-pedogenic variety has developed within older alluvium leading into the northerly end of the pan. An east-westerly ditch excavated through this calcrete (Fig. 4.10a, adjacent to breached dam) exposes carnotite in the calcrete and subjacent weathered bedrock. Borehole data (Fig. 4.10b) may reflect similar mineralization. In addition the Dwyka shale contains anomalous amounts of U locally (Fig. 4.10d).

The richer concentration of U, however, though again subeconomic, occurs within and adjacent to a very recent thin delta of calcrete covering one-quarter of the pan surface (Fig. 4.11). It is not clear how much of this recent delta is due to mechanical and how much to chemical reworking of calcrete. A proximal tongue of pebbly and sandy alluvium, for example, is related to breaching of the farmers' dam on the present-day northeasterly inlet. On the other hand, calcrete nodules on the main delta surface are less mature (hard) than the older calcrete and not typically compound, suggesting growth _in situ_. Borehole radiometrics and water analyses reported by Schutte (1976) all correlate with the recent calcrete delta. The distribution of borehole water values suggests groundwater circulation 1) beneath the old northerly deltaic calcrete (shown only in part in Fig. 4.10c), 2) beneath the current northeasterly inlet and 3) upward toward the evaporative surface of the pan at the distal edge of the Recent delta. If this is a correct interpretation, the groundwater pattern fits the Australian model shown in Fig. 3.4b. Increments of U may have been continually added from weathering of Karoo rocks, but it seems likely that a large fraction, if not

Figure 4.12

Kleinbegin General Setting

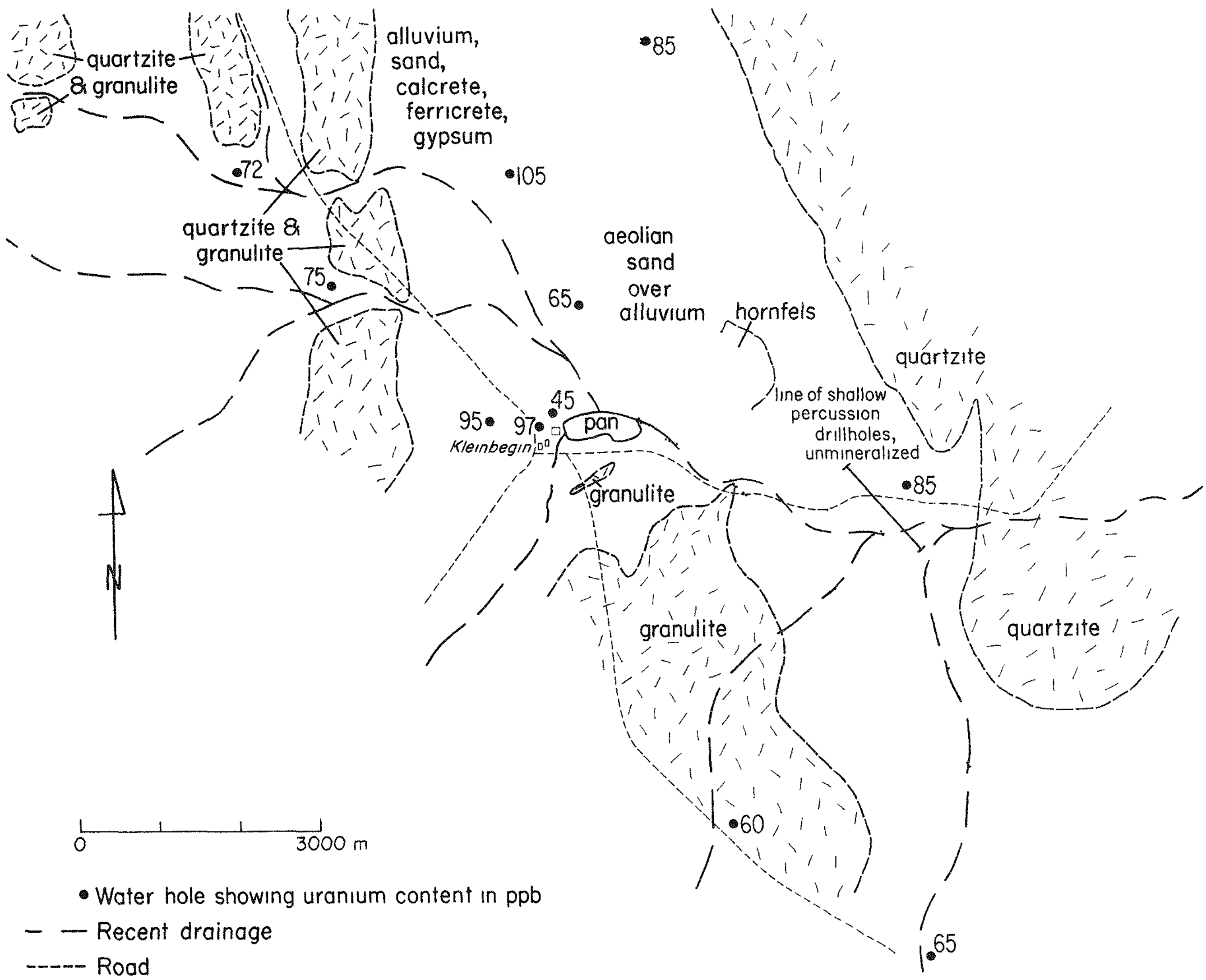
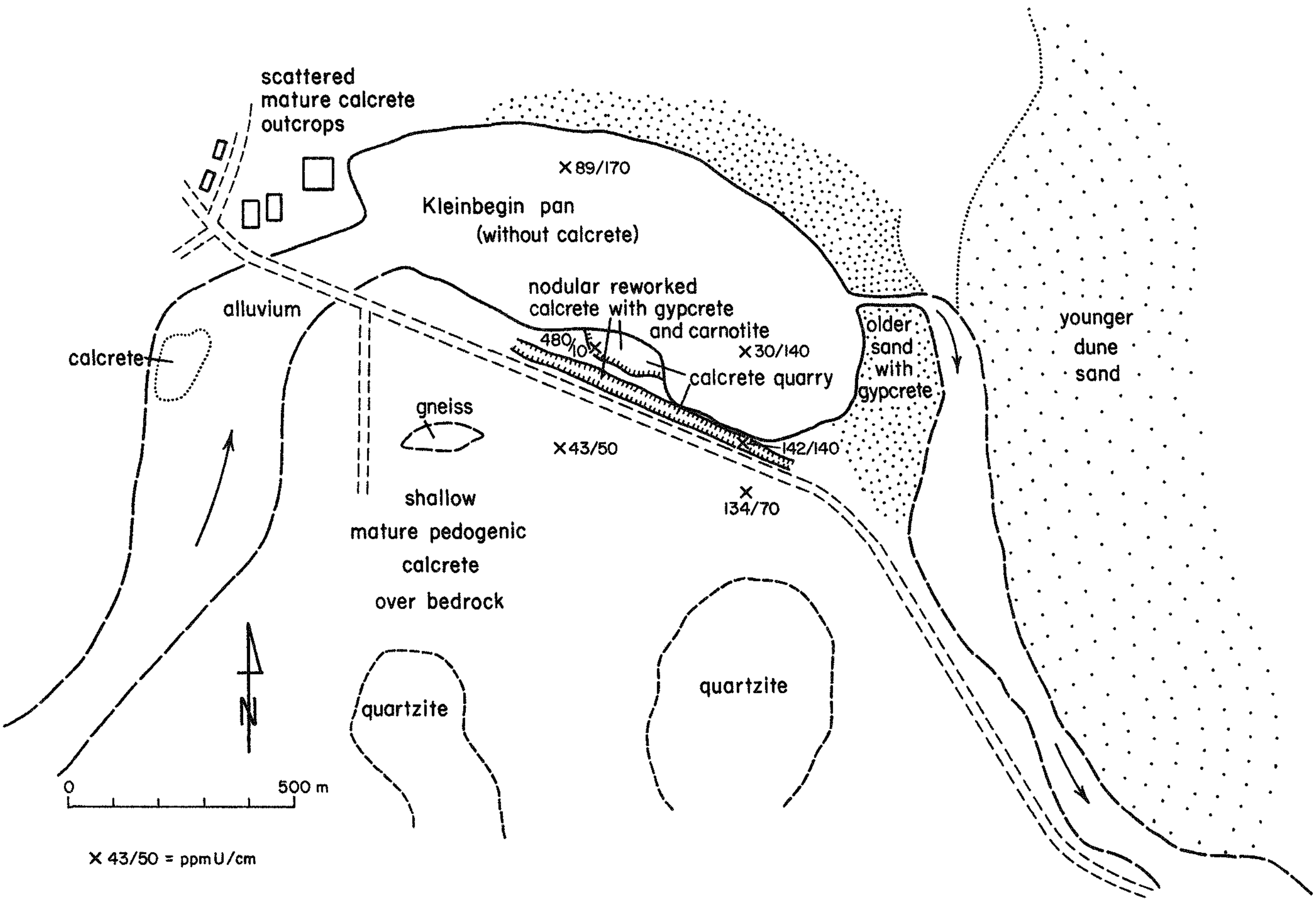


Figure 4.13

Kleinbegin Prospect



the major part, of the U in the pan has been reworked from older pedogenic calcrete (not shown) on the African or post-African surface into the older calcrete delta, or directly or indirectly into the Recent calcrete delta and into the pan itself via the sub-delta circulation.

4.7.2.4 Kleinbegin

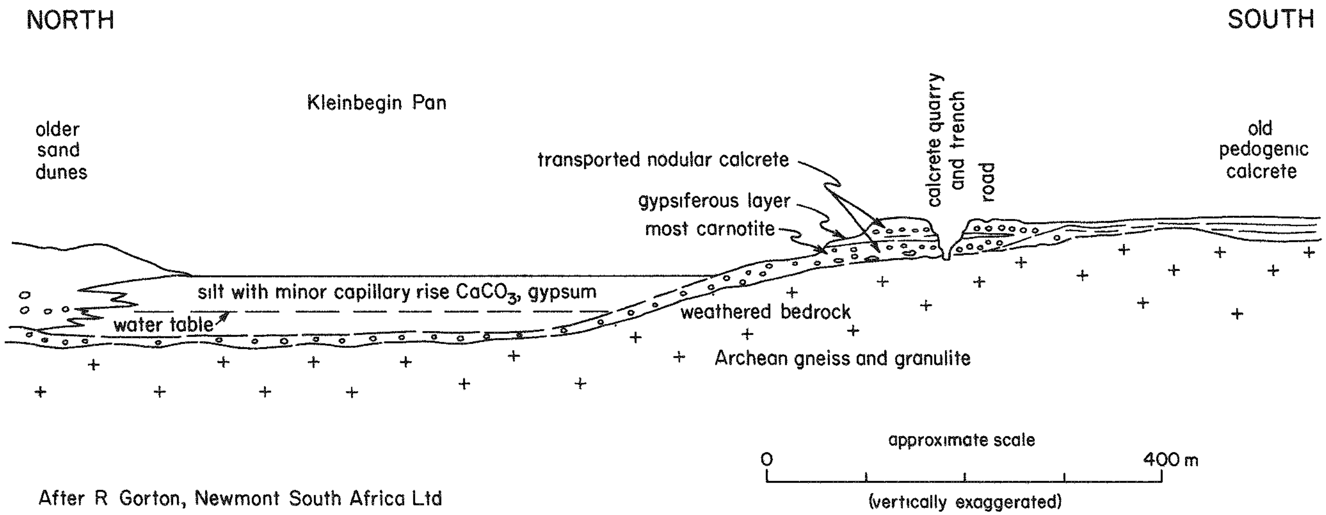
The prospect at Farm Kleinbegin appears to have been the first calcrete-uranium find in the Upington Region. The discovery of mineralization was made by Newmont South Africa Limited in 1976, not on the property itself but by car radiometric traverse over bridge fill 20 km to the east! Calcrete is a prime source of road metal in southern Africa. In this case the source was the shallow calcrete quarry beside the pan at Kleinbegin (Fig. 4.13). Later on, in retrospect, a weak anomaly on an airborne radiometric survey made in 1967 prior to excavation of the quarry was correlated with the occurrence. Figures 4.12, 4.13, 4.14 and 4.15 are from data made available to the writer by Newmont South Africa Limited.

The prospect area is on the African and post-African surfaces near the transition from Proterozoic to Archean basement. Pedogenic hardpan calcrete is preserved in patches. Surficial water is ephemeral; groundwater flow is constricted from place to place by belts of quartzite, gneiss and granulite cropping out in belts perpendicular to the drainage. Present-day groundwaters are anomalous in U (Fig. 4.12) but the major and most obvious groundwater constrictions do not seem to have produced significant U concentrations. A line of shallow percussion holes through calcrete near the prominant quartzite barrier 3 km east of the prospect, for example, was barren (Fig. 4.12). The existing pan at Kleinbegin reflects a less obvious bedrock configuration and, secondarily, the distribution of dune sand which, near the pan outlet, has been partly cemented by gypsum (Fig. 4.13). The pan is at the northern tip of a bend in the stream, and the carnotite occurrence is entirely on the inner side of the bend, i.e., on the south side of the pan.

The host for the carnotite mineralization consists of transported and reconstituted bedded calcrete with varying proportions of earthy calcrete cement and gypsum (Fig. 4.15). Detrital calcrete nodules are mature (hard), typically compound and commonly appear in graded beds or with a preferred

Figure 4.14

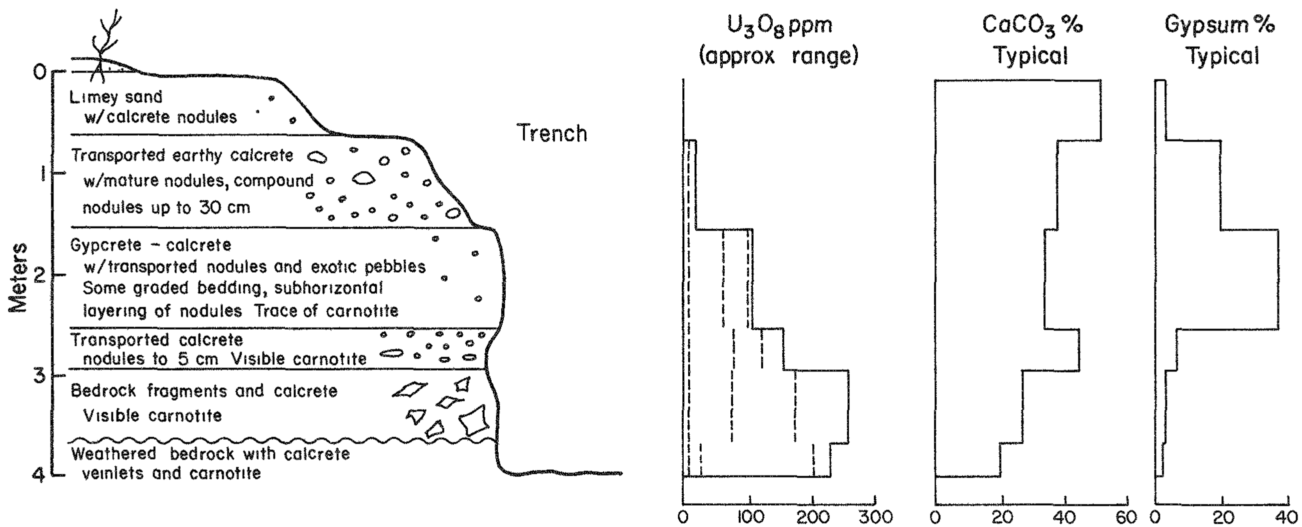
Diagrammatic Cross Section - Kleinbegin



After R Gorton, Newmont South Africa Ltd

Figure 4.15

Carnotite-Bearing Transported Calcrete-Gypcrete, Kleinbegin



Generalized from data supplied by R Gorton, Newmont South Africa Ltd subhorizontal orientation of their longer axes. Otherwise the sorting is poor. Exotic cobbles of bedrock participate in the bedding. Some dripstone carbonate has accumulated on the lower surfaces of nodules and cobbles. The proportion of gypsum cement changes fairly abruptly from bed to bed in the calcrete reaching almost 40% in a middle bed exposed in the northerly half of the quarry. Gypsum and carbonate contents vary inversely. These features, as well as the overall geometry, indicate that the nodules accumulated in a fluvial environment modified by periods of evaporative precipitation along the margins of a lake (pan) and probably a slight migration of the lake northward.

Carnotite occurs as coatings on pebbles with or without gypsum cement and as films and specks in the carbonate or gypsum. A consistent increase in U content (Fig. 4.15) and in radiometric response in lower beds of the calcrete-gypcrete probably reflects illuvial transport during or after calcrete reconstitution rather than any systematic relationship to the proportions of gypsum or carbonate or of transported calcrete or bedrock fragments. One's impression in the field, therefore, that there is an antipathetic relationship between gypsum and the precipitation of carnotite is almost certainly incorrect. Instead, deposition of gypsum was caused and initial precipitation of carnotite was most likely abetted by evaporative concentration, especially along the margin of the pan. In fact, U continues to be transported into the pan by groundwater and concentrated evaporatively with carbonate and gypsum today; prospect pits 2 1/2 - 3 m deep near the center of the pan encounter silt with capillary-rise carbonate, gypsum and other salts above the water table. containing 20 - 50 ppm U_3O_8 (R. K. Gorton, personal communication, 1979). On the other hand, carnotite does not now occur where gypsum is the sole cement as, for example, in the older sand dunes at the easterly end of the pan. The ultimate source of the U is Proterozoic bedrock but once again the widespread occurrence of weak mineralization in older pedogenic calcrete, the anomalous U content of groundwaters draining pedogenic calcrete and particularly the many-fold enrichment of U in reconstituted as compared to pedogenic calcrete strongly support the hypothesis that pedogenic calcrete has served as an intermediate sink or protore for U. Concentrations of U in the prospect pits reach a maximum of slightly less than 300 ppm eU_3O_8 over 0.7 m. Probably less than 1 million tons of mineralized calcrete is presently known in the occurrence illustrated.

4.7.3 Reconcentration of Uranium in a Non-calcrete Environment

From the examples just cited it may be concluded that pedogenic calcrete is capable of acting as a temporary sink for U subsequently reconcentrated in the oxidizing environment of reconstituted calcrete. Under suitable conditions, therefore, might pedogenic calcrete become a protore for reduced uranium occurrences? A great many possibilities come to mind.

A recent discovery in the northwest Cape Province may provide an example. Uranium mineralization has been found at Heinkreis Vally near the junction of the ancient Koa River Valley with the Orange River (Fig. 4.7). This is from 100-400 km down-drainage from the uraniferous occurrences of calcrete-gypcrete and the evaporative pans just described. The writer was unable to visit the prospect but is informed that it is not a calcrete or gypcrete occurrence but rather is associated with dark organic-rich sediments. Conceivably this represents U derived in part at least from eroding calcrete and evaporative pans in the Upington region.

Another example might be the modest concentrations of U in organic-rich diatomaceous muds offshore from mineralized calcrete and gypcrete near Walvis Bay on the Namib Coast (Meyer, 1973). This is the area which yields abundant H_2S from decaying organic matter, at times issuing explosively from the ocean. Neither the chemical character nor the site or mechanism of U fixation are established. However U contents averaging <10ppm to >40ppm correlate reasonably well with both organic carbon and phosphorous content. Underlying clays and sands are not mineralized. As to the probable source of U, the immediate association on land of U-anomalous groundwaters--reported as high as 1000ppb--with calcrete/gypcrete ore, the observed redistribution of carnotite along streams in calcrete areas during rainstorms, the illuvial migration of carnotite into weathered bedrock below calcrete and the mineralization of Holocene alluvium on the Tumas River described earlier all attest to the availability of U from calcrete/gypcrete in drainages leading into Walvis Bay and vicinity. Weathering bedrock, including Rössing and related occurrences also yield U directly to groundwaters though perhaps not in such high concentrations. This offshore occurrence at Walvis Bay results from a favorable coincidence of an especially proliferative marine environment and widespread uraniferous calcrete/gypcrete undergoing erosion.

A slightly different role for calcrete as a precursor or enabler of reduced U concentration was suggested several years ago by Weeks and Eargle (1963) in connection with deposits beneath the Catahoula Tuff in Texas. Extensive caliche was developed over both Jackson Group and Catahoula tuff-bearing sediments in a climate somewhat drier than today. In some places this pedogenic calcrete is still fairly continuous and in others there are only remnant patches or veinlets of carbonate in the subsoil. Alkaline carbonate-bearing groundwaters generated during formation of the calcrete would have favored dissolution of U from the tuff and the evaporative climate would have favored its enrichment. Some U would have been fixed in the calcrete as carnotite. More importantly, however would be the role of alkaline carbonated waters--derived in part from eroding calcrete--as a means of carrying uranium carbonate complex ions down dip to a reducing environment where uraninite would precipitate.

Over the past several years both new discoveries and growing scientific evidence support the importance of surficial and near-surface environments for the mobilization, transportation and deposition of U. Initial fixation of U in the primary or trend deposits of the Grants Mineral District, for example, is now widely held to have occurred only very slightly after deposition of the fluvial host sands and at depths of as little as a few feet or tens of feet. And, of course, many of the deeper-seated vein-like or Proterozoic deposits of Athabasca and the Northern Territories, Australia are at least spacially related to a "paleosurface" (e.g. 1974). Uraniferous calcretes can be expected to have developed in the geological past but to the writer's knowledge no deeply buried uraniferous paleocalcretes have been found. It is likely that any U once present would have been remobilized. Calcreted paleoregolith, therefore, would appear to warrant consideration as a potential U protore.

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