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UNITED NATIONS - INTERNATIONAL ATOMIC ENERGY AGENCY

HANDBOOK ON SURFICIAL URANIUM DEPOSITS

CHAPTER 3

World Distribution Relative to Climate and Physical Setting

by

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Contents

3.3 WORLD DISTRIBUTION RELATIVE TO CLIMATE AND PHYSICAL SETTING

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3.3.1 Introduction

This chapter discusses regional controls which affect the world distribution of surficial chemogenic uranium deposits (Fig.____, Table____). The most important of these are 1) climate, 2) geomorphology, including physiographic and climatic stability, and 3) provenance, i.e., the weathering terrain from which uranium and associated substances are derived. These features apply to large areas and determine uranium-deposit favorability or nonfavorability for regions as a whole. Their influence is both chemical and physical. Thus if the climate, geomorphology and provenance of a region is favorable for uraniferous calcrete deposits, for example, such occurrences are likely to be found in a wide range of valley, deltaic and lacustrine settings, provided that such settings exist. Much the same can be said for purely evaporative uranium occurrences and for given kinds of bog or organic-play deposits. However, the specific favorability criteria, i.e., the particular kinds of climate, and geomorphic development and source terrain likely to result in ore are different for each of the three major surficial uranium environments.

The three economically most important environments and some characteristics of each in physical and chemical terms are as follows:

1) The calcrete environment (including dolocrete and gypcrete) is characterized by groundwater transport and shallow subsurface co-precipitation of uranium, vanadium and potassium in association with authigenic carbonate (sulfate) in an oxidizing and chemically complex evaporative regime. The ore mineral in carnotite. Introduced carbonate cement ranges from sparce to dominant and reworking of both ore and gangue minerals may be extensive. Economically this environment may be the most productive of surficial chemogenic occurrences.

2) Simple evaporative environments are characteristic of open basins of accumulation or playas, less commonly springs. They are chemically diverse and yield a variety of hexavalent uranium minerals, often transient, along with other evaporite minerals. The mineralized beds are primary chemical sediments rather than introduced fillings and replacements as are calcretes. Under some circumstances the concentrated brines themselves are of economic interest and byproduct or coproduct production from these may be more important than from the purely surficial evaporite minerals.

3) Paludal environments; bogs, marshes, muskegs, swamps, organic-rich playas and the like. These are predominantly organically controlled environments. Uranium concentration involves incompletely understood mechanisms of transport, adsorption, chelation, cation exchange, uranium mineral precipitation and perhaps biological uptake. The chemical environment is most commonly but not necessarily reducing. As in the purely evaporative environment uranium concentrations are commonly "young", mobile and strongly deficient in gamma-ray producing daughter products. Deposits tend to be small but commonly occur in groups.

Of these three categories, the calcrete uranium environment is probably the most uniquely constrained in terms of regional climate, geomorphic setting, provenance (vanadium as well as uranium) and especially the need for long term stability of both climate and physiography. Purely evaporative deposits, though subject to some of the same kinds of constraints, can also reflect local circumstances and a wider range of climates, physiographic settings, and source terrains. The third category encompassing bogs, marshes and organic-rich playas can form under an even wider range of climates and settings (~~Culbart~~, *et al.*, herein) provided only that organic materials accumulate in abundance and are contacted by uranium-bearing waters.

For all of these reasons and also because of the great economic importance of the calcrete environment as well as its relative novelty and complexity the discussion in this chapter is focused on calcrete, dolocrete and gypcrete uranium deposits. Objective data are reviewed first followed by inferences and suggestions.

3.3.2 WORLD MAP OF KNOWN SURFICIAL CHEMOGENIC URANIUM DEPOSITS

Fig 3.3 1

Note to W. G. VI: The author would like to request that all contributors to the handbook provide locations of deposits of actual or potential economic significance anywhere in the world to the best of their ability. Indicate the country of occurrence and if possible augment the location with Latitude and Longitude.

3.3.3 Table 3.3.1

WORLD DISTRIBUTION OF KNOWN SURFICIAL CHEMOGENIC URANIUM DEPOSITS BY GEOMORPHIC SETTING AND SOME CHEMICAL CHARACTERISTICS

Note to W.G.VI: In addition to 3.3.2 above please also attempt to place your deposits within the table format provided (if the format is agreeable to W.G.VI). In the case of ambiguity, uncertainty or disagreement with the classification your further qualification, comment, or description will be very much appreciated.

3.3.1

TABLE 3.1 WORLD DISTRIBUTION OF SURFICIAL CHEMOGENIC URANIUM DEPOSITS [1]

A. CALCRETE, DOLOCRETE, GYPCRETE AND CLOSELY ASSOCIATED DEPOSITS [2]

PHYSIOGRAPHIC SETTING	CHEMISTRY AND NATURE OF THE AUTHIGENIC CEMENTING MATERIAL					
	Nonpedogenic [3]			Detrital Reconstituted Calcrete, etc.	Pedogenic [3]	<5% [4] Authigenic Cement
	Calcrete	Dolocrete	Gypcrete			
FLUVIATILE [5]						
Valley or Channel						
Flood Plain						
Deltaic						
Slope Wash						
Interdunal						
Other [6]						
LACUSTRINE/PLAYA/BASIN						
Basin Margin (other than deltaic)						
Basin Central						
Coastal Sabkha						
RESIDUAL/SOIL/REGOLITH						
OTHER [6] e.g., Spring fed (cienega) fault trace						

[1] Deposits of actual or potential economic significance

[2] Closely related includes deposits derived from or deposited along with calcrete dolocrete gypcrete uranium concentrations

[3] Pedogenic-Nonpedogenic: Use criteria outlined in text.

[4] Name host sediment or rock (i.e., sand, gravel, weathered bedrock).

[5] "Fluviatile" environments may include alluvial, colluvial, aeolian sediments and soils

[6] Other - Specify carefully if deposit cannot be fitted into classes given.

B. EVAPORITE ENVIRONMENTS (OTHER THAN CALCRETE, DOLOCRETE, GYPCRETE)

GEOMORPHIC SETTING	CHEMISTRY AND NATURE OF THE EVAPORITE & THE URANIUM				
	Mainly				Liquid Brine
	Carbonate	Sulfate	Chloride	Other	
FLUVIATILE					
(Specify) -if any					
LACUSTRINE/PLAYA/BASIN					
Basin Margin					
Basin Central					
Coastal Sabkha					
RESIDUAL/SOIL/REGOLITH					
(Specify)					
SPRING DEPOSITS					
Volcanic setting					
Nonvolcanic					
Other					

C. PALUDAL ENVIRONMENTS, PEAT BOG, MARSH, MUSKEG, SWAMP ORGANIC PLAYA, ORGANIC SPRING.

GEOMORPHIC SETTING	CHEMISTRY AND NATURE OF ORGANIC MATERIAL		
	Macroplants	Lesser Plants/ Microorganisms	Transported Humic Materials
	Alkaline-Saline	Alkaline	Fresh
FLUVIATILE			
Valley Fill			
Flood Plain			
Deltaic			
LACUSTRINE/PLAYA/BASIN			
Basin margin			
Basin central			
Lake bottom			
Coastal Sabkha			
RESIDUAL/SOIL/REGOLITH			
SPRING FED			

(Modified from Culbert and Leighton, 1981/2)

3.3.4 CLIMATE, GEOMORPHOLOGY AND SOURCE TERRAIN IN RELATION TO CALCRETE URANIUM MINERALIZATION: THE EXAMPLE OF WESTERN AUSTRALIA

3.3.4.1 Characteristics of Uranium Bearing Calcretes

The role of climate and other regional controls of calcrete uranium mineralization is tied to physical, chemical and genetic differences between common varieties of calcrete. Some definitions are necessary.

Kinds of calcrete. Calcrete, dolocrete and gypcrete consist of soils, alluvium, soft sediment or, in some circumstances, weathered bedrock which has undergone variable amounts of cementation and replacement by authigenic carbonate or sulfate. The point at which soil carbonate or calcified sand or gravel becomes calcrete is not clearly defined nor is it critical here since in the calcrete (gypcrete) setting, ore grade carnotite can occur in very weakly calcified (or gypsiferous) materials. Calcretes tend to evolve with time. In relatively early stages the carbonate occurs as powdery, nodular or honeycomb-like masses. With maturity laminar, plugged and hardpan calcretes develope, the most advanced of which may resemble bedded or massive limestone (Gile, 1966; Netterberg, 1969; Goudie, 1973). Calcite and dolomite are by far the most common cementing materials. Gypsum is subordinate to absent except under special conditions; on the margins of or downwind from salinas, for example, or, as on the Namib Desert, where marine mists provide sulfate. Calcretes may be eroded and the transported fragements reconstituted into detrital calcrete.

In calcrete uranium exploration, a critical distinction must be made between two major categories of calcrete (Figure 3.3.2):

1) Pedogenic calcrete, i.e., soil caliche, kunkar, croûte calcaire, nari or caprock, which is generated in the soil moisture zone by ordinary soil-forming processes and is not favorable for uranium mineralization and,

2) (Nonpedogenic) Groundwater calcrete (Netterbery, 1969; Carlisle, et al., 1978; Mann and Horwitz, 1979), i.e., "valley calcrete" or simply "calcrete" in earlier Australian terminology (Sofoulis, 1964; Sanders, 1973) which is generated mainly near the water table from moving groundwater and which, under favorable circumstances, may contain recoverable uranium.

Distinguishing Characteristics. Pedogenic calcrete, then, is simply a calcic soil horizon or, if indurated, a "petrocalcic" horizon. It is typically only a few cm to a meter or two thick, and laterally extensive. Other things being equal the thickness and maturity of a pedogenic calcrete is a function of the age and stability of the surface beneath which it forms. The calcrete in turn tends to reinforce the surface. Almost invariably pedogenic calcretes display some sort of "calcrete soil profile" consisting, for example, of calcified soil perhaps overlain by a completely cemented (plugged) or hardpan horizon and possibly by laminated or solution-brecciated calcrete or by more soil. Multiple or stacked pedogenic calcretes are quite common and there may be unreplaced soil or erosional surfaces between the separate calcrete layers. The Ca, Mg and CO_3^{2-} and trace elements are derived from adjacent soil or from the air and are merely redistributed vertically within the profile. Only if soils are unexpectedly rich in uranium or enriched from the air, from below, or by deep residual concentration are pedogenic calcretes likely to reach ore grade. Though small-scale examples are known, the favorability of pedogenic calcretes as uranium ore has been considered to be very low to negligible (Carlisle, et al., 1978).

Nonpedogenic groundwater 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 uranium from a large source area into a relatively compact calcrete body. Carbonate appears to precipitate not only in the capillary fringe but also slightly below the

the water table and probably in overlying vadose zones as well. Because water tables fluctuate and because flowing groundwater brings a continuing supply of constituents, such calcretes can be much thicker than a single pedogenic calcrete. In terranes of low relief, groundwaters move slowly over long distances and potentially are capable of 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 stable near-surface trunk drainages, or where they encounter bedrock constrictions, lower gradients, less permeable clays or, as on the edge of evaporative basins, dense hypersaline waters, there water tables tend to rise toward the surface, loss of CO_2 and H_2O is accelerated, and authigenic carbonate precipitates within the regolith. Carnotite may precipitate with it.

The nonpedogenic valley-channel calcretes in the uraniferous areas of Western Australia are irregularly lenticular masses extending along the axial portions of extremely low gradient near-surface drainages for tens to hundreds of km in length, several km in width and tens of m thick (Fig. 3.3.3). They are excellent and prolific aquifers. Delta-shaped masses of calcrete and marginal lacustrine calcretes occur where subsurface drainages enter evaporative basins. Some have formed essentially at the surface in swampy areas and lake margins. It at least one case groundwater calcrete appears to have formed within the main body of a playa itself. Groundwater calcretes on the Namib Desert have developed in steeply incised, gravel-filled valleys and occupy the greater part, if not the entire valley width. Cementation and permeability vary, greatly. In Western Australia and Southwestern United States domal calcrete structures, "mounds", "platforms", and "pinnacles" frequently develop around rising groundwater plumes. These may be primary features or replacements, perhaps dolomitic, of less mature calcrete. Subsequently these structures may be eroded and collapse into karstic features.

Provided that they have not been modified by later pedogenic processes, groundwater calcretes are diagonistically free of any pedogenic soil profile or vertical sequence of pedogenic calcrete horizons. Instead they tend simply to preserve the original sedimentary structures and textures of textures of the host materials or to develope new structures related to groundwater flow or to lateral and vertical growth of the calcrete. These might include mound and collapse structures, irregular inclusions of unreplaced host, subhorizontal solution channels and perhaps incrustations of non-carbonate materials. Groundwater calcretes that have developed within the phreatic zone or in relatively unweathered well-sorted sands or gravels tend to contain clean sparry carbonate as opposed to the clayey, impure and amorphous mixtures characteristic of pedogenic calcrete. But even in a clay-rich host, ground water calcretes do not contain a distinct horizon of clay accumulation (Bt horizon in soils terminology). Groundwater calcrete generated in swampy or lake margin environments may develop primary sedimentary - not pedogenic - layering, however, and may contain organic structures perhaps of algal, bacterial or macrobiotic origin. This latter variety is in essence a transition toward fresh-water limestone.

On a large scale groundwater calcretes may develop systematic changes in composition along their length reflecting lateral flow in an evaporative regime. In Western Australia there is a down-drainage sequence over several tens to hundreds of Km from silicified non-calcareous soils on the flanks of the valleys, to siliceous calcrete becoming increasingly magnesian in the main channels, then lake-margin gypsite and finally the salt pan itself. On the Namib Desert, where dolomite is apparently absent, the downdrainage transition from calcrete to gypcrete corresponds with the inland limit of marine mists.

Nevertheless, differentiating between groundwater and pedogenic calcretes at the local scale is not easy. Given hand specimens of the two varieties may appear physically and chemically identical. Moreover, upper surfaces of exposed groundwater calcretes are usually modified by pedogenic processes including solution-brecciation and recementation. Groundwater calcretes may be overlain by younger pedogenic calcretes or may rest on earlier ones. And locally with a very shallow water table, carbonate deposition from the capillary fringe or the phreatic zone may overlap pedogenic deposition in the soil moisture zone or as on alluvial fans pedogenesis may be combined with lateral transport and hybrid calcretes may result. However, as discussed next, there is a tendency, at least in some regions, for uraniferous groundwater calcretes to develop optimally under conditions which do not favor pedogenic calcretes and vice versa. The assertion is based on a present-day example.

3.3.4.2 The Unique Distribution of Uraniferous Calcrete in Western Australia

On geological evidence (Carlisle, et al., 1978) and by inference from isotopic studies (Lively, et al., 1979; Mann and Horwitz, 1979; Dickson and Fisher, 1980) the rich and well exposed uraniferous calcretes of Western Australia are less than 500,000, perhaps less than 25,000 years in age. Some are forming and some are being reconstituted today. The environment and the conditions of genesis are in essence directly observable.

With only a handful of exceptions, none of which have been shown to be economic, the reported uraniferous calcrete occurrences of Australia are in nonpedogenic valley deltaic and lacustrine calcretes and dolocretes in the most arid parts of Western Australia (Figures 3.3.4, 3.3.5) and in lesser numbers in the Northern Territory and South Australia. They are inland from the active coastal streams on the Indian Ocean, south of the monsoonal rain belt and entirely north of a curving boundary approximately along latitude 30°S.

Valley, deltaic, and lacustrine calcretes with at least traces of carnotite or anomalous radioactivity are extremely common in Western Australia, not just in the Yeelirrie drainage, but in all of the Archean Yilgarn Block north of latitude 30°S and as far north as the Gascoyne

Block and the Bangemall Basin. There are over sixty significant prospect areas in this region alone. A few others have been found in the Archean Arunta Block in the Northern Territory and still others in western South Australia.

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 3.3.4). In physiographic terms it is almost entirely within the Salt Lake Division (Figure 3.3.5), 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 3.3.6, 3.3.7). 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.

Yeelirrie, the first and largest 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 3.3.7). It is also near the center of the region of most persistent and extreme soil moisture deficiency (A_W on Figure 3.3.7). This location is thought to be significant in the light of changing Quaternary climates and the resultant expansions and contractions of the most arid central region.

Pedogenic calcretes - ordinary caliche or kunkar - occur extensively in the soils of Western Australia, south of latitude 30°S. None of these are known to contain uranium occurrences of economic interest.

3.3.4.3 Bedrock Geology and Source Terraine in relation to Calcrete Uranium Mineralization

Yeelirrie and the calcrete uranium prospects of greatest economic interest occur exclusively above archean rocks of the Yilgarn Block (Figure 3.3.4). This is in spite of the fact that the main region of valley calcretes 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 and Archean granites constituting roughly 50 percent of the Block are the most probable uranium source rocks.

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. In addition the infolded north-northwesterly trending belts of greenstone, metasediments including iron formation, amphibolites, gabbros, and felsic volcanic complexes may contribute calcium, magnesium, and vanadium to groundwaters.

It has been pointed out that, prior to erosion, the Archean-Proterozoic unconformity in Western Australia almost certainly extended over the greater part of the region of significant carnotite mineralization in valley calcrete and that, in view of the frequently observed physical and temporal association of pitchblende deposits with Proterozoic unconformities, there may have been some preconcentration of uranium along that surface. Though there have been verbal reports of uranium mineralization beneath Proterozoic outliers, the hypothesis is difficult to evaluate and to the writers knowledge there are no significant bedrock occurrences nor major concentrations of uranium within the calcrete uranium region.

3.3.4.4 Geomorphic Development in Relation to Calcrete Uranium Mineralization

The genesis of uraniferous groundwater 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.

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 ancient surface is perserved today only as remnants on broad divides, fragments of a rolling upland to which Jutson (1950) has given the name *Old Plateau*.

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 pervasively kaolinized *pallid zone* grading into weathered bedrock. Good exposures are commonly seen in escarpments or "breakaways" which mark the boundary between the relict Old Plateau and alluviated valleys of the New Plateau. Porosity and permeability are high, permitting rainwater to seep through the rock.

In many places a resistant silcrete covers the surface of the Old Plateau, in some closely associated with laterite, in others widely separated. It is widely thought to have formed under different, probably more arid conditions and somewhat later than the main period of laterization on the Old Plateau. In any event, silcretes are not known to contain significant uranium mineralization.

During the Tertiary, minor uplift affected the entire Precambrian shield and with rejuvenation, the ancient rivers of the Old Plateau cut through the lateritic duricrust into the soft pallid sone 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 began to change. Aridity may have begun as early as Mio-Pliocene, 7-10 m.y. ago but 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). 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. Nor has there been further rejuvenation. The landscape has been marked by unusual stability. The "New Plateau" thus formed 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 of the valleys.

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. Short, ephemeral rivulets on the valley flanks, 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. They are entirely within the uppermost portion of the valley fill - at Yeelirrie roughly the upper one-fifth - so they postdate considerably the time of onset of arid alluviation.

The proportion of calcrete to total catchment area represents an enormous concentration of Ca, Mg, and, in some places, of U, V and K. The calcrete-free drainage catchment above the ore zone at Yeelirrie is 3000 Km^2 which is 20 times the area occupied by calcrete and 1000 times the area underlain by ore.

Geomorphic history has also played a major role in the accumulation of uranium. Briot and Fuchs (citation needed) have drawn especial attention to the apparent preconcentration of uranium at the base of the deep lateritic weathering profile. They point out that a radiometric anomaly commonly found at the contact of kaolinized and slightly altered underlying granite records a pre-calcrete accumulation of uranium protected from dissolution by overlying laterite until Tertiary rejuvenation and erosion of the breakaways. Traces of carnotite have occasionally been found on granitic breakaway faces (Langford, 1974; Mann, personal communication, 1976), which suggests that under the arid climate of the region, with rare episodes of deep wetting during periods of high temperature and evaporation, uranium is mobilized and transported toward the evaporative surface. The precipitation of carnotite on that surface suggests also that adequate vanadium and potassium must be available under present conditions. It is interesting that soluble salts, notably NaCl are also found in breakaway profiles. 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 dust (Hutton and Leslie, 1958). 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?

Finally, and perhaps most important of all, the history of uraniferous calcrete development in Western Australia, and perhaps only slightly less so in other mineralized regions, has been one of profound tectonic and geomorphic stability.

3.3.4.5 Climate and Soil Moisture Regime in Relation to Calcrete Uranium Mineralization

Yilgarn granite source rocks are found and much the same geological and geomorphic history pertain to the area south of latitude 30°S. But here there are only pedogenic calcretes and no significant uranium mineralization.

Of the hypotheses that have been suggested to explain the contrasting distribution, the most likely rest either directly or indirectly on climate and its influence on the soil moisture regime. The pattern is clearly reflected in the Soil Map of Australia (Northcote et al., 1975). North of latitude 30°S and over an area almost precisely congruent with that of the valley calcretes, the dominant soils within the new plateau, exclusive of the calcretes themselves, are noncalcareous earthy loams with a red-brown siliceous hardpan (see Wiluna Hardpan below and Fig. 3.3.11 not to be confused with silcrete on the Old Plateau). None of these soils occurs in the semi-arid region south of latitude 30°S. Instead one finds great areas of alkaline and calcareous red earths and gray-brown calcareous earths, many with visible pedogenic calcrete.

An almost exactly correlative and equally striking difference is shown by the dominance of the Mulga tree (<u>Acacia aneura</u>) 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 with winter rainfal. Mulgas favor the more arid summer storm belt. These and other contrasts between climate and several features south and north of latitude 30°S are summarized in Table 3.3.2. Main climatic factors which influence soil moisture regimes and calcrete genesis are shown on Figures and .

The general nature of a soil moisture regime can be inferred from climadiagrams (Figs. 3.3.6 and 3.3.7) which are simply an arithmetic comparison of average monthly precipitation, potential evaporation (from standard evaporative pans) and temperature. Raw data from the Australian Bureau of Meteorology for 60 stations were used in preparing Figure . The ten climadiagrams shown are characteristic of the areas demarcated and quite comparable with patterns illustrated by soil scientists for xeric, aridic and ustic soil moisture regimes. The regimes inferred (Carlisle, <u>et al.</u>, 1978) from south to north are:

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

2) Inferred Aridic (A_k, A_w, A_n) - 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. Calcretes in general form predominantly in aridic regimes.

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

All of the major calcrete uranium occurrences are in region A_w.

The subdivisions A_k, A_w, and A_n are based upon additional criteria not shown by the climadiagrams alone. 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 (Figs. 3.3.8, 3.3.9, 3.3.10). The boundary of greatest interest separates the area of distinct summer-to-autumn episodic rain which characterized the valley calcrete region (Aridic Wiluna, A_w on Figure 3.3.7) from the region of indeterminate rain season (Aridic Kalgoorlie, A_k) where pedogenic calcretes form. It closely approximates latitude 30°S. It is, in fact, a consequence of the interplay of the main rain-bearing factors shown on Figure 3.3.8: A_w is the region of most extreme water deficiency (Fig. 3.3.9) and is directly in the belt of highly erratic tropical storms. Unlike the aridic Kalgoorlie region (A_k) it lacks year round precipitation and frontal rains which would cause the soil moisture zone to become saturated for long periods. The second criterion is derived from a comparison of ratios and arithmetic differences between annual evaporation and annual precipitation as shown on the caption of Figure 3.3.7. 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.

Coincidence of aridic region A_w with nearly all of the region of uraniferous nonpedogenic groundwater calcretes and siliceous Wiluna Hardpan is striking (Fig 3.3.11). The fact it falls short in the west and northeast is probably not so much due to lack of data there but rather to the fact that calcrete genesis was initiated under even more arid climates than that of today and that consequently the area of A_w would have been extended in these directions. However, the empirical correlation between soil moisture sub-regimes and the occurrence of nonuraniferous pedogenic and uraniferous groundwater calcretes does not in itself explain their distribution. The lack of pedogenic carbonate horizons in soils of the valley calcrete region and the ubiquity Wiluna Hardpan suggests that something more complicated than excessive rates of evaporation and CO_2 loss is involved in their genesis.

Wiluna Hardpan is an authigenic deposit, less conspicuous, but just as characteristic of the valley calcrete region as in the calcrete itself and essentially contemporaneous with it. It occurs as bodies of soil, colluvium, and alluvium up to 15 m thick, variably cemented and replaced by opaline or chalcedonic silica (Teakle, 1936, 1950; Litchfield and Mabbutt, 1962; Mabbutt et al., 1963; Brewer et al., 1972; Bettenay and Churchward, 1974; Northcote et al., 1975). It is found 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 but it tends not to occur on the poorly drained saline flats nor on strongly lateritic upper surfaces of the Old Plateau. Its silica is unquestionably derived from the lateritic profile through groundwater transport or indirectly through lateritic detritus and soil. The depth to hardpan on alluvial is typically less than 1 m in open areas but as much as 1.5 m in the areas of strong surface water recharge. It is "very previous when wet" (Sanders, 1972). Soils above the hardpan are porous earthy loams which are freely permeable and well drained. They are nonsaline, acidic, and low in organic matter and in base exchange capacity. In addition to the distribution shown on Figure 3.3.11, recent mapping near the Western Australia - South

Australia border has revealed hardpan in that area of nonpedogenic calcrete also (Firman, 1976). Except for small very arid 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.

Hypothesis: The writer suggests that hardpan, valley calcrete, and carnotite mineralization are related genetically in Western Australia. Moreover, 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 the particular climate, the associated soil moisture regime, evaporative concentration and loss of CO_2 from a flowing reservoir of sub-surface water.

North of latitude 30°S rain from the sporadic mid-summer and late-summer storms falls almost invariably on hot, dry surfaces. A large part of it evaporates directly or runs off initially as sheet flood. The bulk 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 CO_2. 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.

In essence, a relatively small fraction of the storm rain remains in the soil moisture zone where it is subject almost immediately to evapotranspiration. The soil does not remain wet for any long period, and there is very little opportunity for precipitation of pedogenic carbonate by 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.

The question is why this same arrangement does not prevail south of latitude 30°S 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 soils. 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 organic soil moisture zone but decreases toward the surface and between rains. As a consequence, calcium carbonate tends to precipitate directly in the soil moisture pH values increase toward a theoretical maximum value of 9.9 for a de-aerated solution in contact with calcite. This in turn enhances the solubility of silica. With time, evapotranspiration becomes increasingly important and salinities rise, but silica saturation is not necessarily reached. Groundwater recharge through the vadose zone, when it does occur in this soil moisture regime, it likely to produce waters which are saline and perhaps nonpotable, even on valley flanks (Table 3.3.2).

With strong desiccation and appropriate amounts of vanadium, potassium, and uranium in the soil or transported into it, carnotite may accumulate in certain parts of the carbonate horizon or in contact with clays as it does in the valley calcrete environment but without benefit of later concentration. It will be sparcely disseminated and noneconomic.

3.3.5 CALCRETE AND GYPCRETE URANIUM MINERALIZATION IN SOUTHERN AFRICA IN RELATION TO SOURCE TERRAIN, GEOMORPHOLOGY AND CLIMATE

Three calcrete-gypcrete uranium areas have been extensively explored in southern Africa (Fig 3.3.12): 1) the Namib Desert in Namibia - South West Africa, 2) a region centered on Upington in South Africa and 3) a small area near Beufort West. All have arid to very arid climates (aridic to hyperaridic soil moisture regimes) very comparable to Western Australia although on the Namib Desert this is complicated by marine mist.

3.3.5.1 Namib Calcrete, Gypcrete, Geomorphology and Source Terrain

On the Namib Desert carnotite-bearing groundwater calcrete and lesser gypcrete occur within paleochannels on the Mid-Tertiary African Surface from the Atlantic coast to the foot of the Great Escarpment 100 km inland. The calcretes, and probably the uranium mineralization as well, predate Quaternary gorge cutting. The orebody at Langer Heinrich, in fact, is exposed only because of headward erosion of the rejuvenated Gawib River. But this is atypical; most occurrences are not thus exposed and the mineralization itself has developed on extremely broad low-gradient surfaces that remained stable for large fractions of the Late Tertiary. A significant geomorphic difference from Western Australia is the Great Escarpment rising steeply to the Khomes Highland immediately east of the calcreted Namib Platform. The calcretes themselves differ from 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 unmineralized Pleistocene to Holocene pedogenic sheet calcrete and gypcrete. The groundwater calcrete does not develop abundant dehydration or shrinkage cracks as does the Australian calcrete, and for the most part it is not a good aquifer, though appreciably permeable. In the Langer Heinrich orebody carnotite occurs in a variety of gravelly, sandy and silty facies and is not uncommonly richest where calcification is least.

Gypcrete with the same kind of aggregate as the calcrete occurs directly above groundwater calcrete within the belt of almost ever-present fogs from the Atlantic Ocean. Thicknesses up to 25 meters have been drilled in paleochannels on the Tumas River where a potential orebody occurs beneath Holocene surficial gypcrete. The SO_4 is from marine mist. The uranium is probably derived from uraniferous calcrete updrainage and is reconcentrated as carnotite in a sparcely gypcreted sand facies adjacent to a paleo-water table (Carlisle, 1980). 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. Carnotite is found only very rarely in this superficial gypcrete or calcrete, a consequence mainly of capillary rise from subjacent mineralization.

In spite of the differences and much greater difficulty in delineating valley calcretes and gypcretes in Namibia, numerous examples support the conclusions that lateral transport of uranium in groundwater is essential to ore deposition and that bedrock barriers or constrictions which narrow the channel of subsurface flow, and thus force the water closer to the evaporative surface greatly 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. Within a given drainage, the ratio of catchment or source terrain to mineralized calcrete is of the same general order of magnitude as in Western Australia. Salt lakes are absent.

3.3.5.2 The Upington and Beaufort West Areas

The Upington calcrete-gypcrete region is entirely within the great central plateau in north Cape Province, and, although traces of carnotite are locally almost commonplace 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 non-pedogenic 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. More than thirty prospects are known, none as yet economic. The calcrete-bearing topography is flat to gently rolling. Thick groundwater or valley calcretes within deep river valley fills such as those on the Namib Desert or 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.

The great bulk of the bedrock throughout the region consists of Archaeozoic and Proterozoic metamorphic rocks in which intrinsic uranium contents of 12-25 ppm are common and some of 46 ppm are reported.

On the Great Karroo near Beaufort West, 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 Uranium 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 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. Reworking of very weakly mineralized pedogenic Tertiary calcrete in the Upington area has also produced concentrations, several of which have justified further investigation.

3.3.5.3 Climate in Relation to Calcrete-Gypcrete Uranium in Southern Africa

Do the climatic parameters separating uraniferous groundwater calcrete from non-uraniferous pedogenic calcrete in Western Australia apply in southern Africa? Is summer-only episodic rainfall and extreme aridity essential for calcrete uranium? If one compares the distribution of calcretes in southern Africa as recorded by Netterberg (1971) with present-day climates and inferred soil moisture regimes (Carlisle, 1980) Fig 3.3.12 two points become clear:

1. The overall distribution of calcretes in general, but predominantly pedogenic, coincides with present-day aridic and subaridic soil moisture regimes.
2. The greatest development of pedogenic calcretes, including great stretches of "Kalahari Limestone" is in the area with a present climate almost identical with region A_W, the valley calcrete region

of Western Australia.

But these latter are Tertiary to Pleistocene calcretes recording a wetter climate than that of today. With rare exceptions attributable only to especially favorable circumstances, pedogenic calcretes are not forming in that climatic region today. Instead throughout the Upington region nonpedogenic calcretes of Pleistocene(?) to Holocene age are found in shallow valleys eroded into the older calcrete. In some of these in constricted parts of the valleys, there are concentrations of carnotite. Although these nonpedogenic calcretes consist very largely of eroded and recemented fragments of older pedogenic calcrete, the climatic parameters for pedogenesis vs. nonpedogenesis would seem to apply.

The situation on the Namib Desert is considerably more complicated. Alkaline, sulfate-bearing morning fogs occur during three quarters of the year, extending at times 40 to 60 km inland, and at Gobabeb account for two-thirds of the total precipitation. Evaporation is greatly reduced. Gypsum is presently crystallizing on the moist surface. The eastern Namib Desert below the Great Escarpment is beyond the main influence of the fogs but receives more rain which probably accounts for the abundant Holocene pedogenic calcrete. Climates during the late Tertiary, when uraniferous groundwater calcretes were being formed were apparently arid to extremely arid but even then probably characterized by summer rains and dry winters (Korn and Martin, 1957). Gravels and sands mainly from the Escarpment and the Khomes Highland have overfilled valleys on the ancestral Namib Platform in places to well over 100 m thick. In spite of a favorable climate, calcrete would not form and still does not form on the Escarpment and the Highlands because of the relief and rejuvenation. The groundwaters migrating into alluviated African or post-African valleys on the gently sloping Namib Platform apparently still retain abundant carbonate and have progressively calcified almost the entire valley fill. Locally carnotite has been precipitated apparently in essentially the same way as in Western

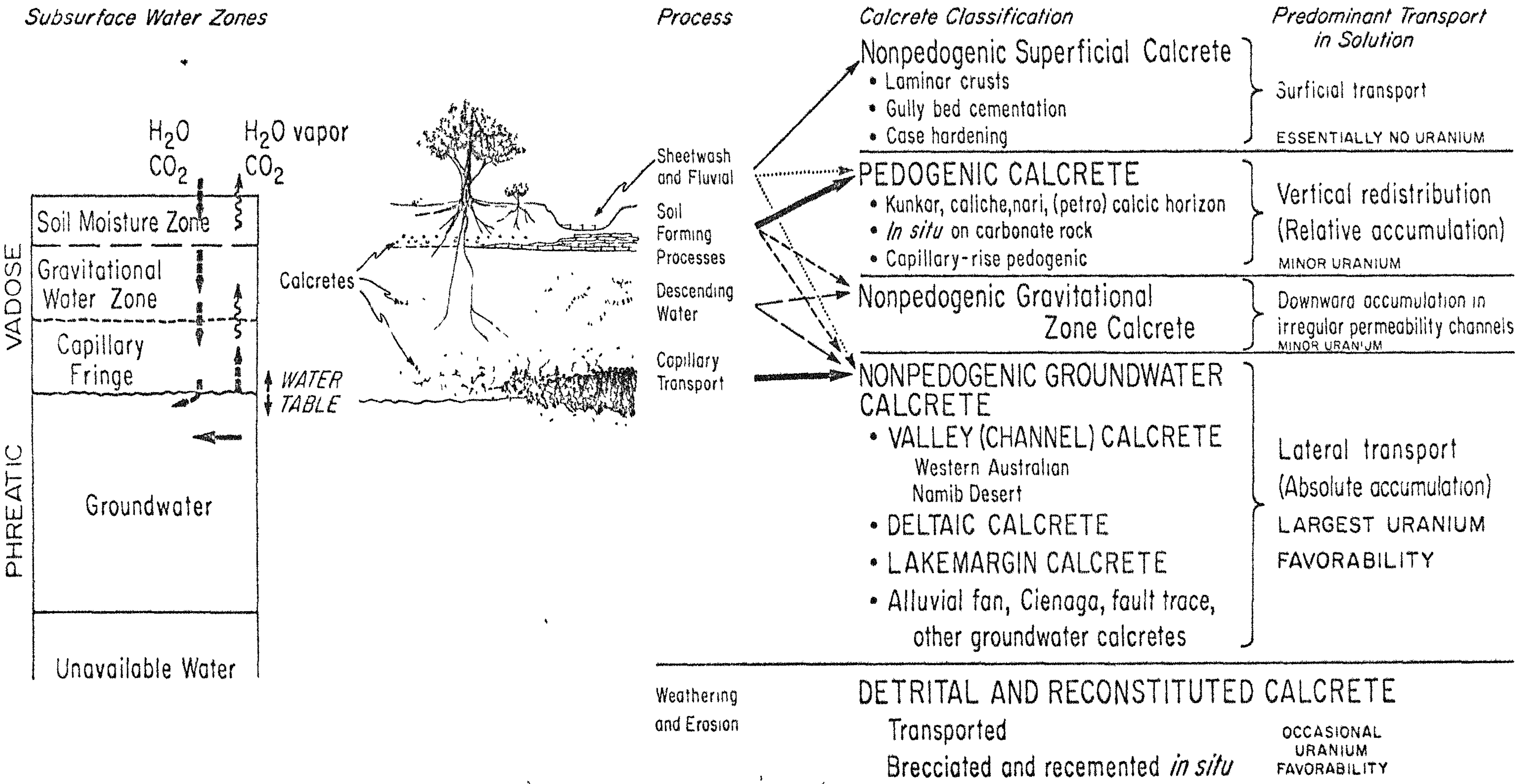
Australia. Presumably this process may have continued even as pedogenic calcrete may have been accumulating on the overlying desert surface through this is by no means clear at this time.

Oceanward, downdrainage, massive nonpedogenic gypcrete has developed in similar valley fill beneath Holocene laminar gypcrete crusts and commonly above groundwater calcrete. Carnotite reaching ore-grade occurs preferentially in permeable sands. Reworking and the evaporative succession characteristic of Western Australia are apparently operative on the Namib Desert but distorted by topography and marine mist.

Fig. 1

Figure 1

A Genetic Classification of Calcretes
and Their Uranium Favorability



Caption for Figure 3.3.2

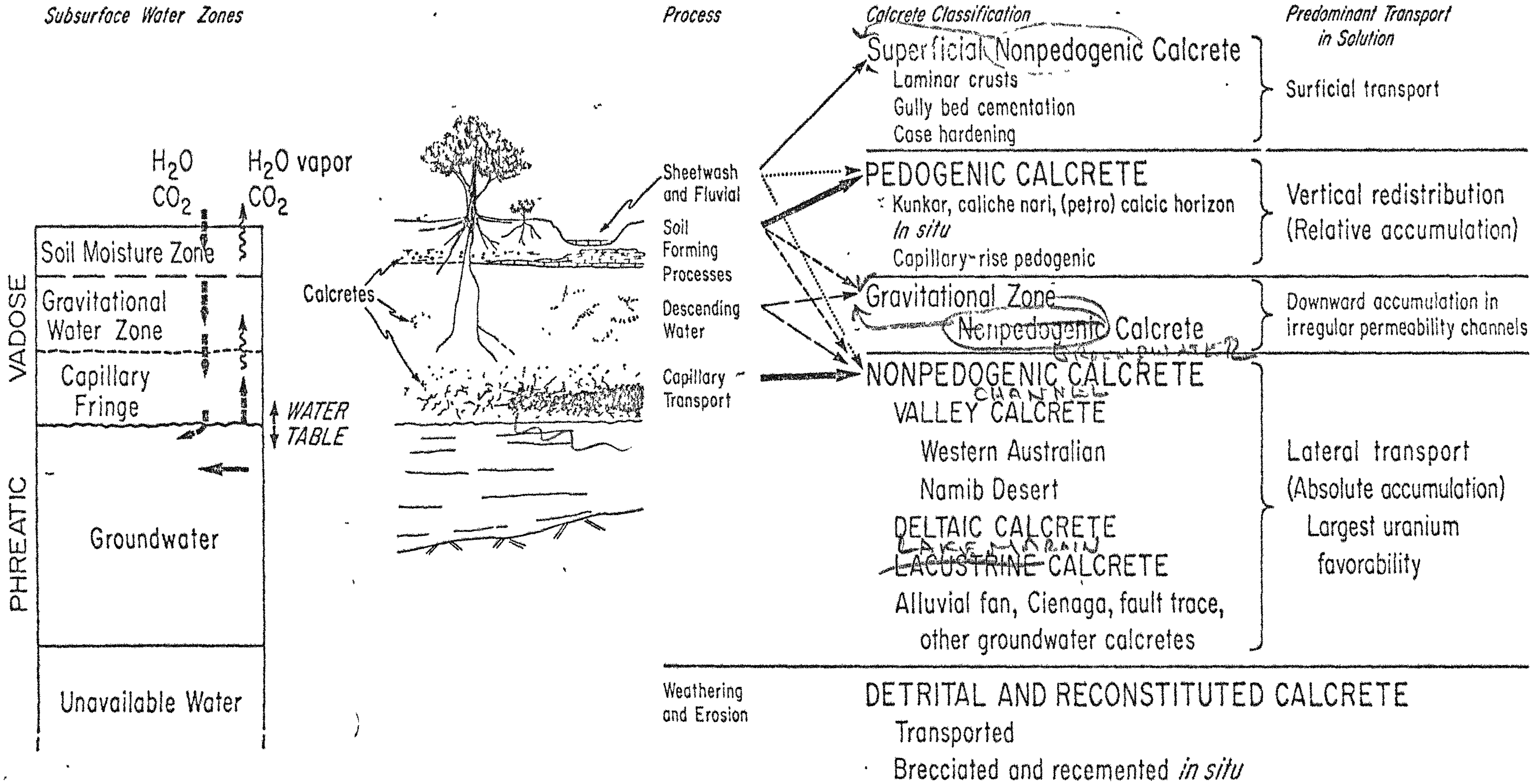
Genesis and Recognition of Calcrete Varieties

In Fig. 1 a genetic classification of calcretes is proposed based upon relationships to subsurface water zones, depositional process and geomorphic setting. Mechanisms are indicated diagrammatically and relative favorabilities for concentration of uranium are suggested. The diagram is not meant to imply that all the varieties of calcrete form conjointly or under identical soil moisture regimes; quite the contrary as discussed ~~below~~ in the text.

Figure 1: A Genetic Classification of Calcretes and their Uranium Favorability. A given calcrete may result from multiple processes as suggested by the arrows. Common-ion precipitation of calcite or dolomite, not shown in the diagram, is discussed in the text.

Figure ~~3.1~~ 3.3.2

A Genetic Classification of Calcretes and Their Uranium Favorability



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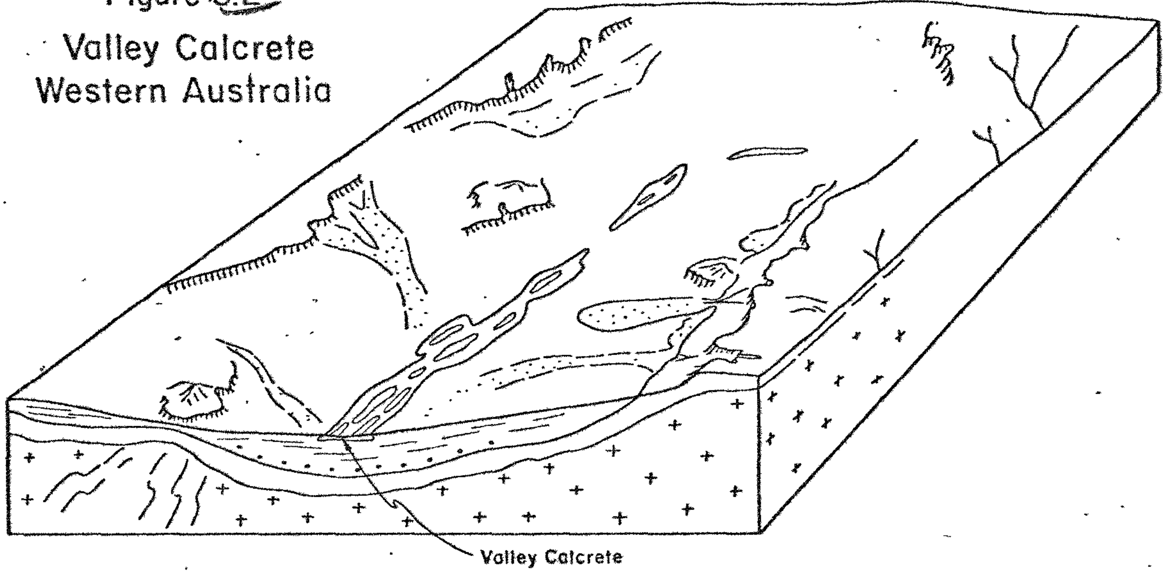
In Fig. 1 a genetic classification of calcretes is proposed based upon relationships to subsurface water zones, depositional process and geomorphic setting. Mechanisms are indicated diagrammatically and relative favorabilities for concentration of uranium are suggested. The diagram is not meant to imply that all the varieties of calcrete form conjointly or under identical soil moisture regimes; quite the contrary as discussed ~~below~~ in the text.

Figure ~~3.2~~ 3.3.3

a Valley Calcrete
Western Australia



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

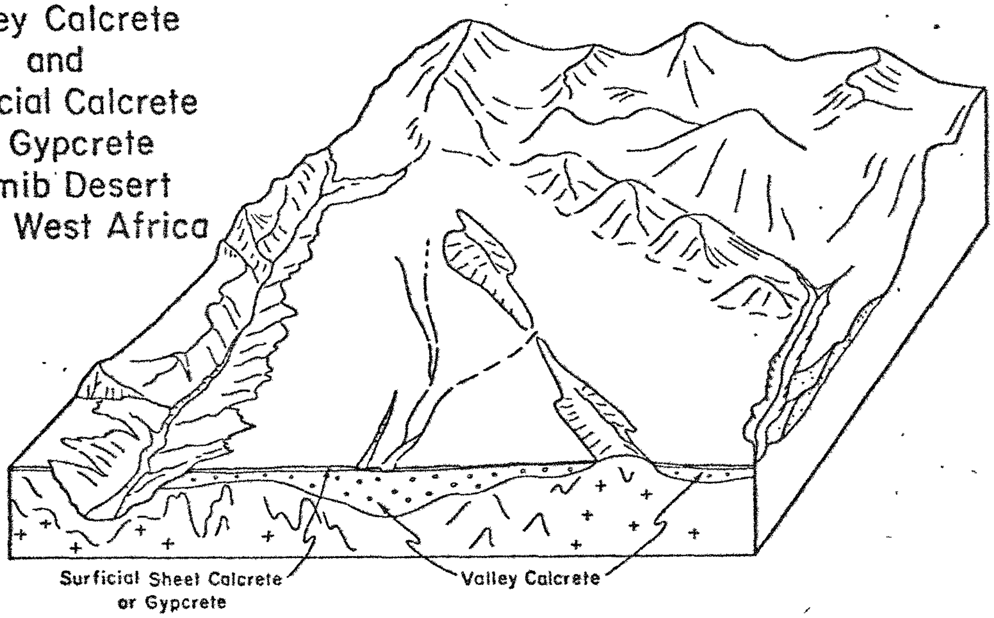
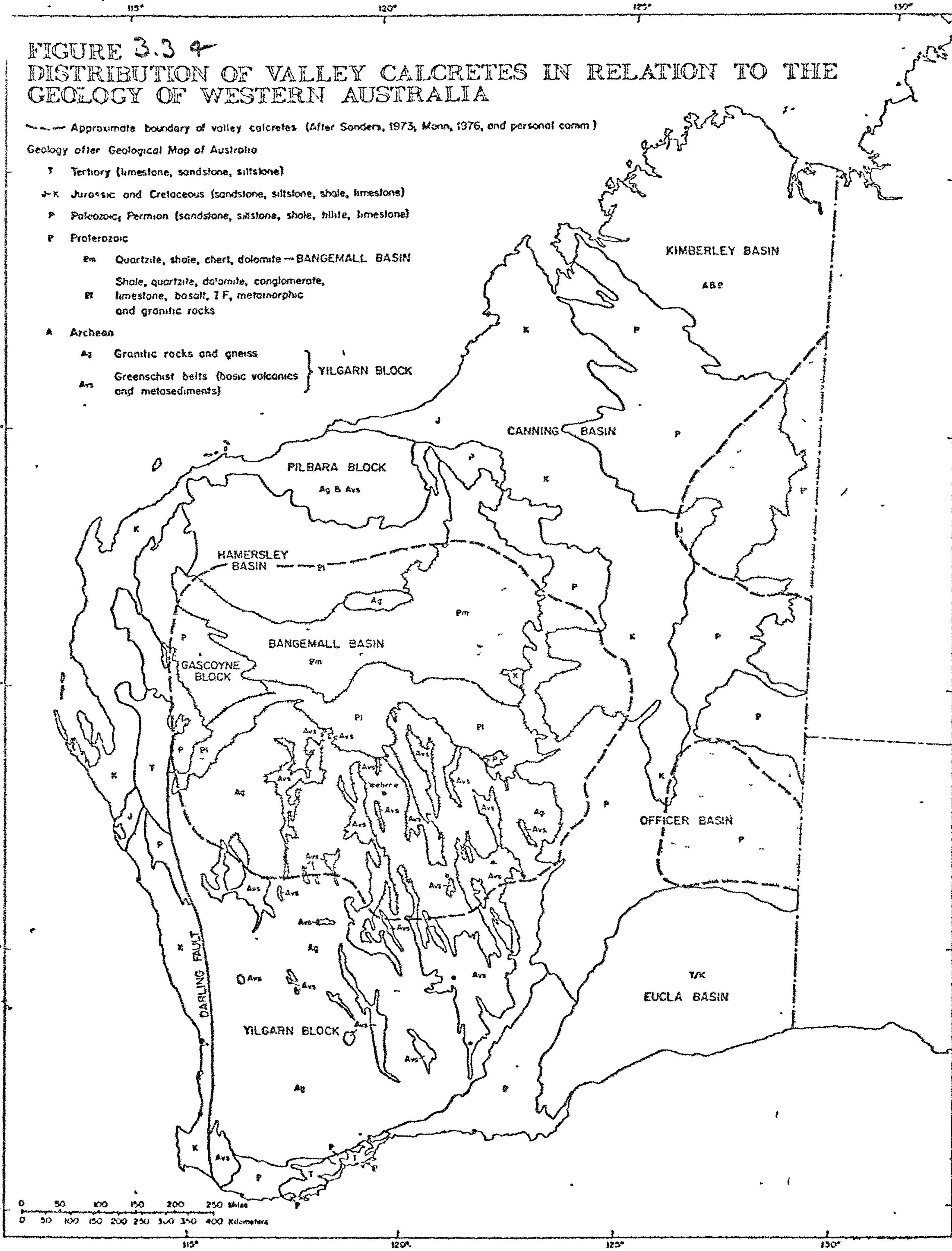


FIGURE 3.3 a
DISTRIBUTION OF VALLEY CALCRETES IN RELATION TO THE GEOLOGY OF WESTERN AUSTRALIA



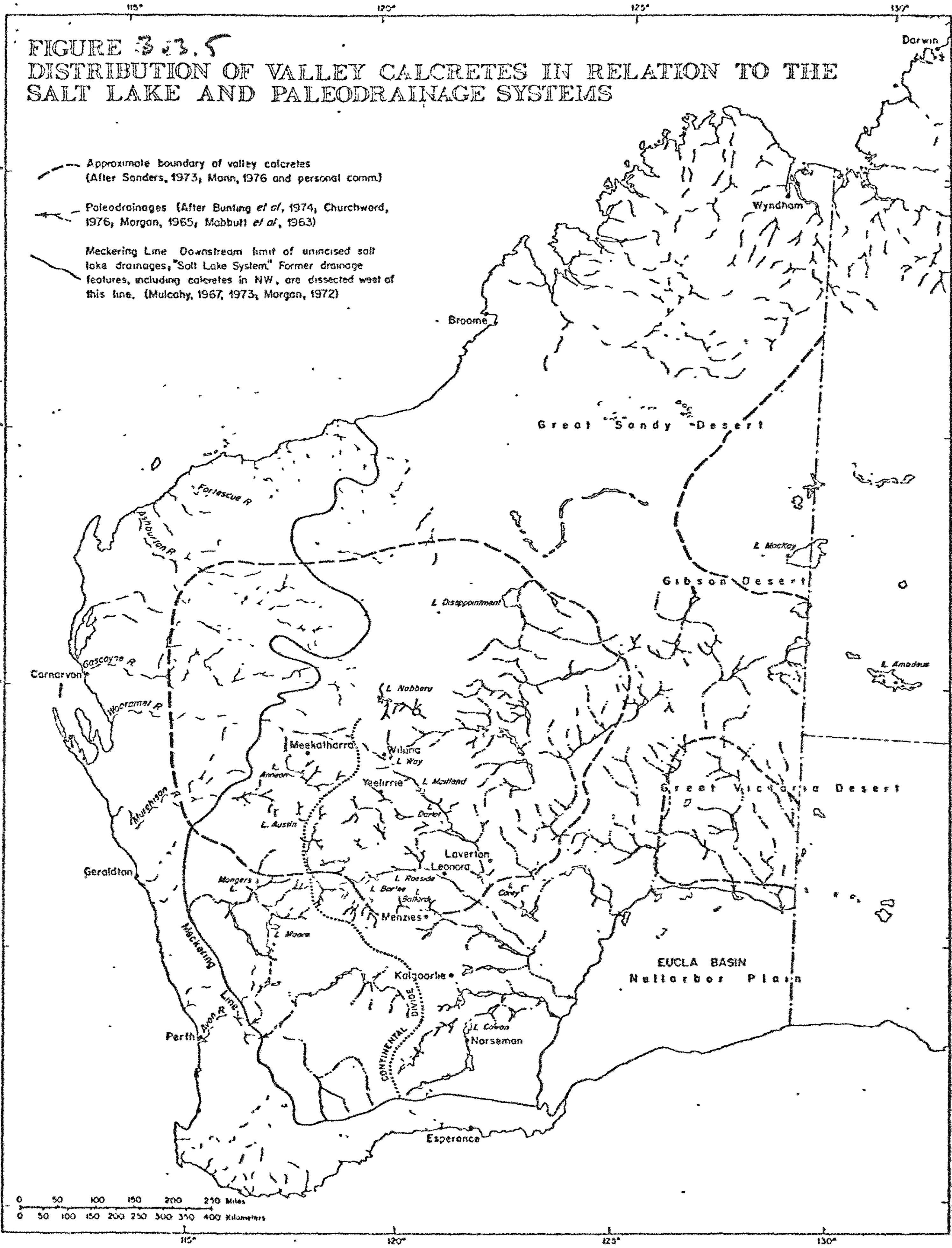


FIGURE 3.3.5
DISTRIBUTION OF VALLEY CALCRETES IN RELATION TO THE SALT LAKE AND PALEODRAINAGE SYSTEMS
Approximate boundary of valley calcretes (After Sanders, 1973; Mann, 1976 and personal comm.)
Paleodrainages (After Bunting et al, 1974; Churchward, 1976; Morgan, 1965; Mabbutt et al, 1963)
Meckering Line Downstream limit of unincised salt lake drainages; "Salt Lake System." Former drainage features, including calcretes in NW, are dissected west of this line. (Mulcahy, 1967, 1973; Morgan, 1972)
Darwin
Wyndham
Broome
Great Sandy Desert
Fortescue R
Ashburton R
L. MacKay
Gibson Desert
L. Disappointment
L. Amadeus
Carnarvon
Gascoyne R
Wooramel R
L. Nabberu
Meekatharra
Wiluna
L. Way
Yeelirrie
L. Maitland
Great Victoria Desert
Murchison R
L. Austin
Laverton
Leonora
Geraldton
Mongers L.
L. Raeside
L. Barlee
Menzies
L. Moore
EUCLA BASIN
Nullarbor Plain
Kalgoorlie
Meckering Line
Avon R
Perth
L. Cowan
Norseman
CONTINENTAL DIVIDE
Esperance
0 50 100 150 200 250 Miles
0 50 100 150 200 250 300 350 400 Kilometers
115°
120°
125°
130°
15°
20°
25°
30°
35°

Fig 3.3.6

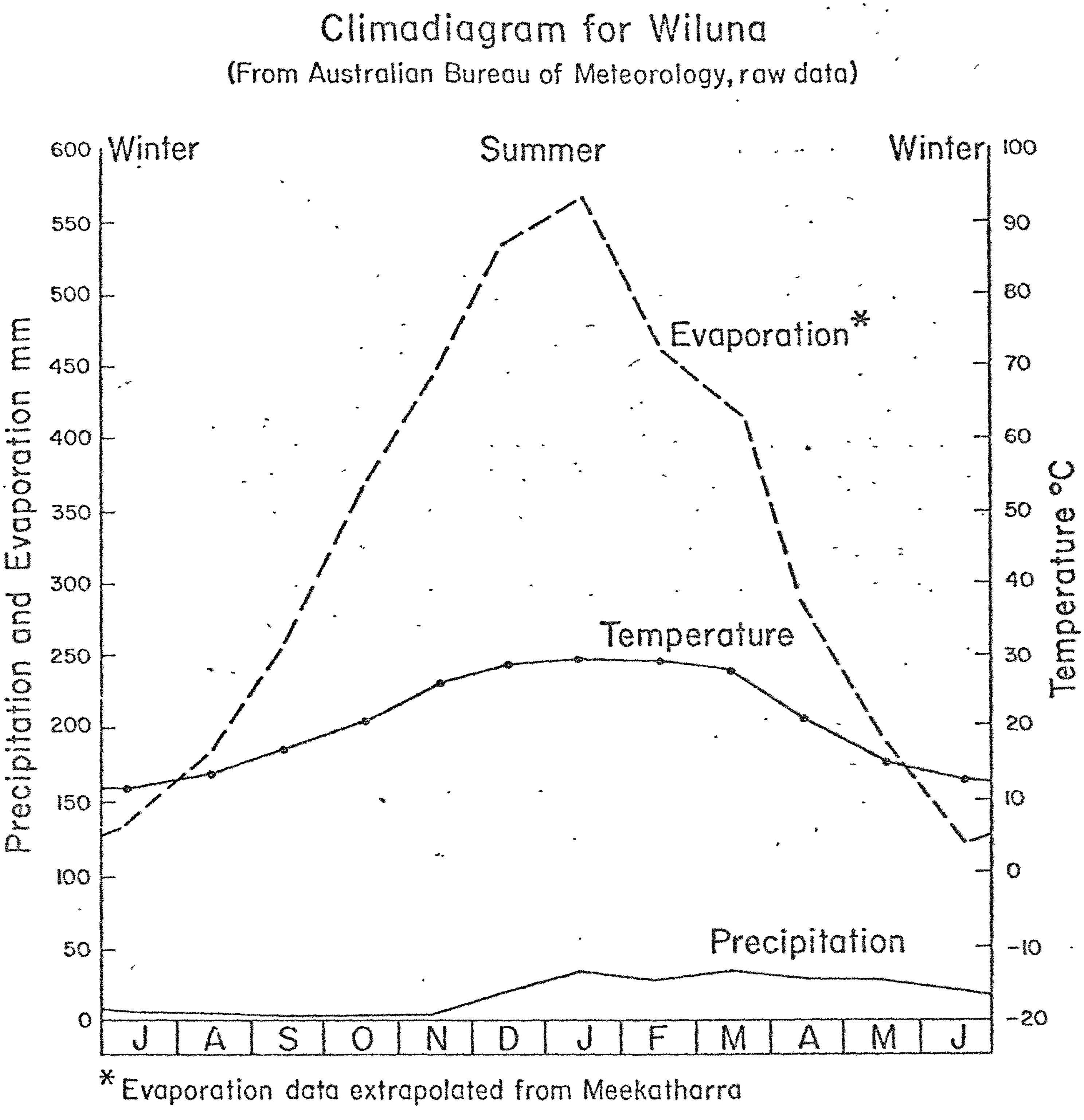


Fig. 3.3.6 (~~4-16~~) Mean monthly values for pan evaporation, temperature, and precipitation are plotted. Climadiagrams such as this were used for determination of seasonal rainfall dominance.

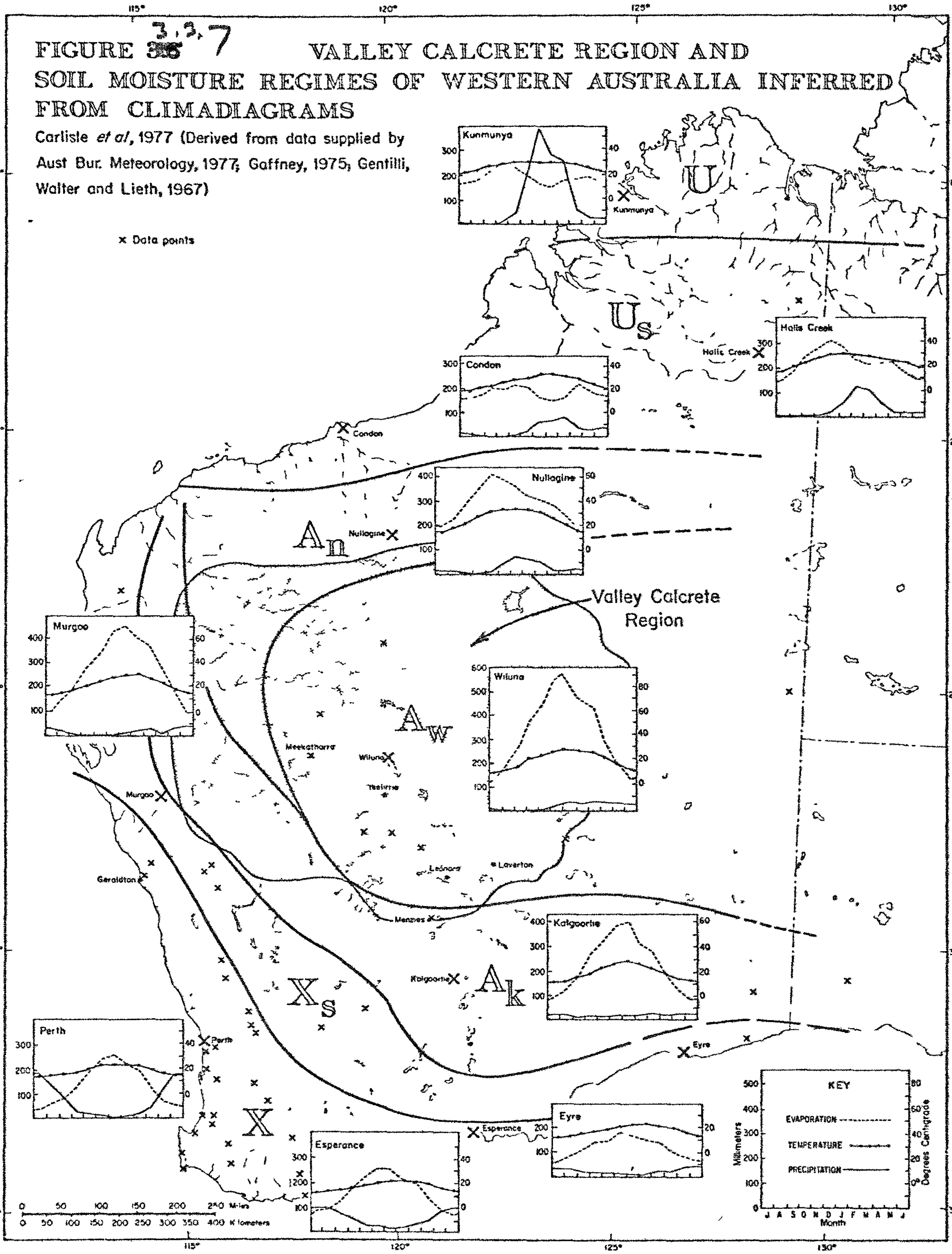


FIGURE 3.3.7 VALLEY CALCRETE REGION AND SOIL MOISTURE REGIMES OF WESTERN AUSTRALIA INFERRED FROM CLIMADIAGRAMS

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~~ 3.3.7

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.

$$E_a/P_a = 9\text{–}10$$
$$E_w/P_w = 3.5\ (10)$$
$$E_a - P_a < 3250 \text{ mm}$$

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

$$E_a/P_a = 12\text{–}20$$
$$E_w/P_w = 10\text{–}12$$
$$E_a - P_a > 3000 \text{ mm}$$

A_K — Aridic Kalgoorlie type. Indefinite rain season.

$$E_a/P_a = 6\text{–}16$$
$$E_w/P_w = 10 \text{ or less}$$
$$E_a - P_a < 3000 \text{ mm}$$

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

X — Xeric proper

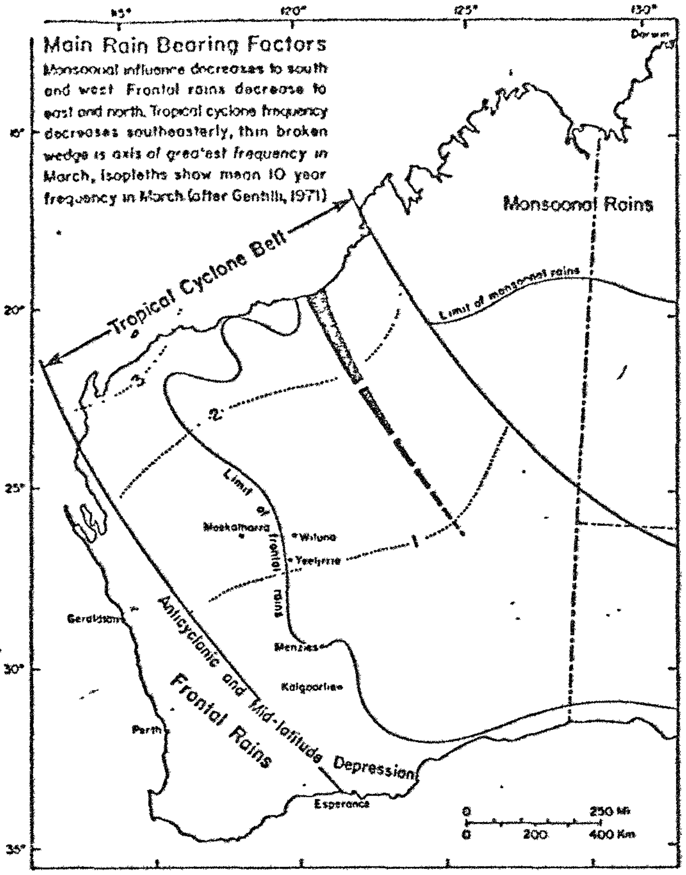
$$P > E \text{ in all three winter months}$$

X_s — Subxeric.

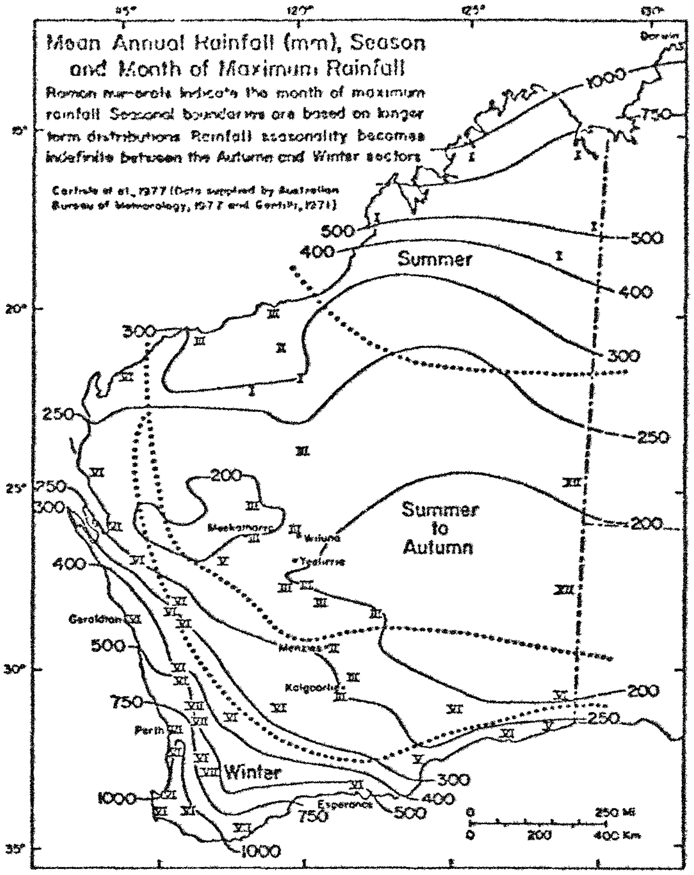
$$P > E^{0.75} \text{ in all three winter months}$$

(a = annual; w = wet month)

Figure ~~417~~ Western Australia, Main Climatic Factors

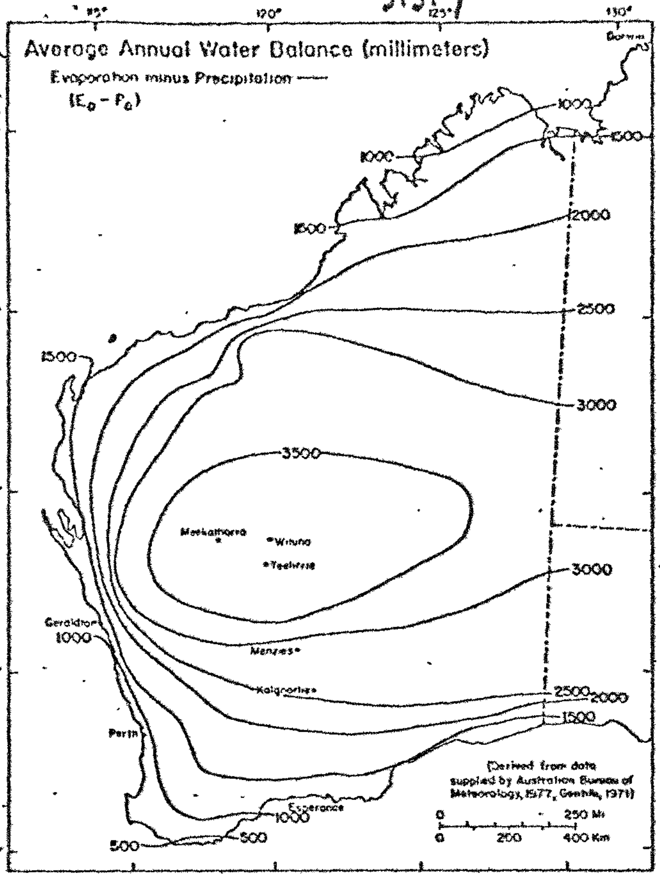


a) These factors explain the low and extremely variable rainfall of the interior. Frontal rains tend to be long duration and low intensity, but are rare and extremely weak in the valley calcrete region. Monsoonal rains occur as localized high intensity, short duration falls. Tropical cyclones bring extremely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

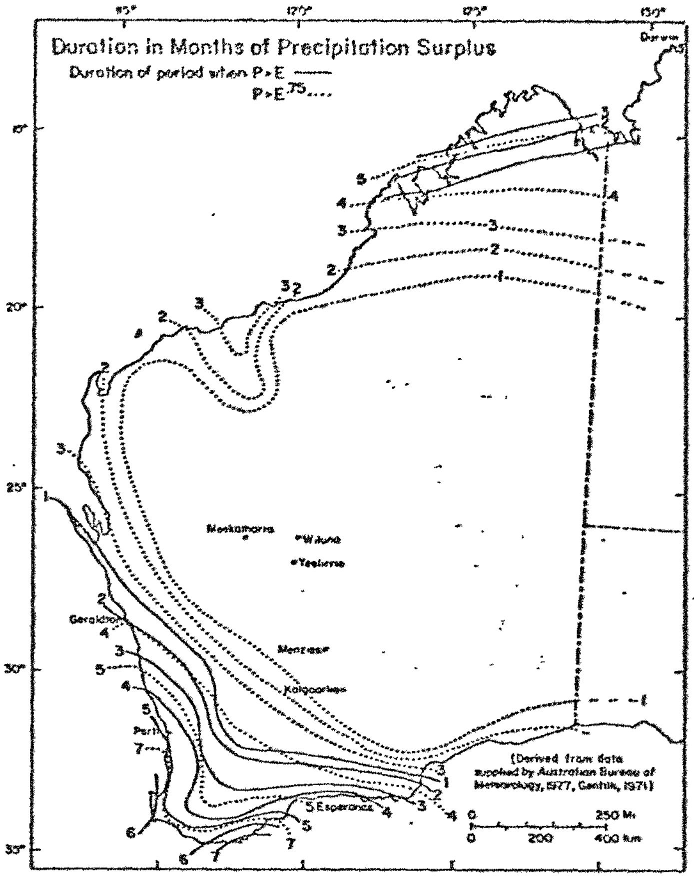


b) Seasonal maxima represent the center of rainfall peaks of 3 months or greater on climadiagrams. The month of maximum rainfall has highest mean rainfall irrespective of position within the year.

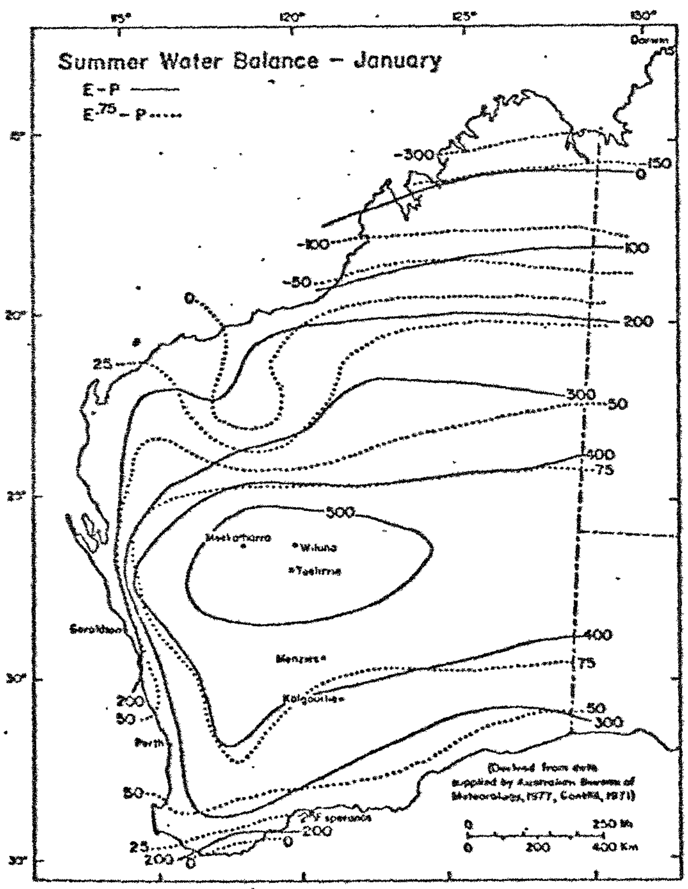
Figure ~~4.6~~ 3.3.9 Western Australia, Water Balance

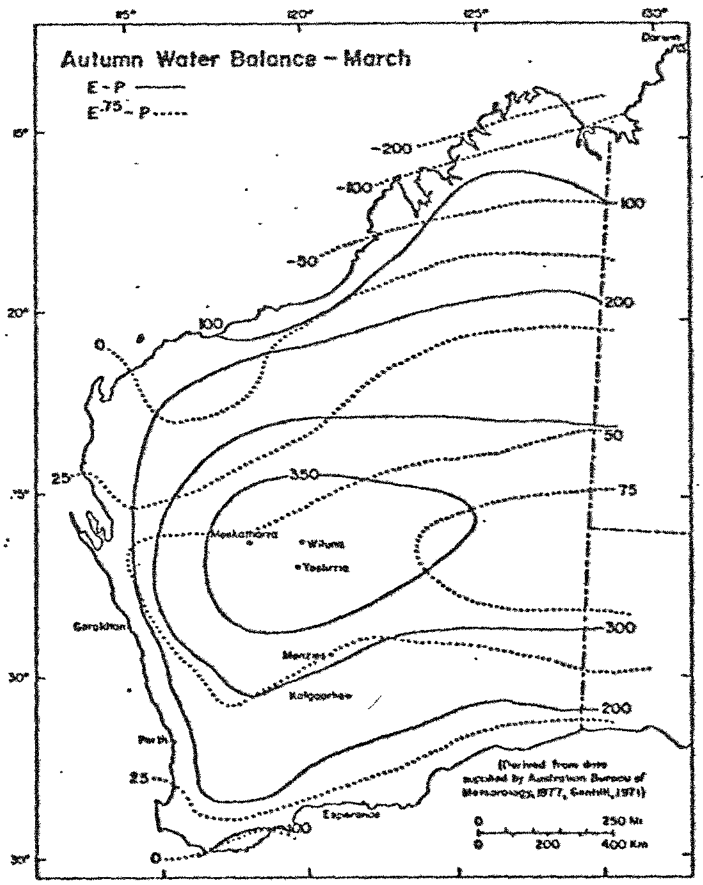


a) The average annual water balance defined as the arithmetic difference between evaporation and precipitation ($E_a - P_a$) suggests the annual net flux of water through the soil moisture zone.



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.



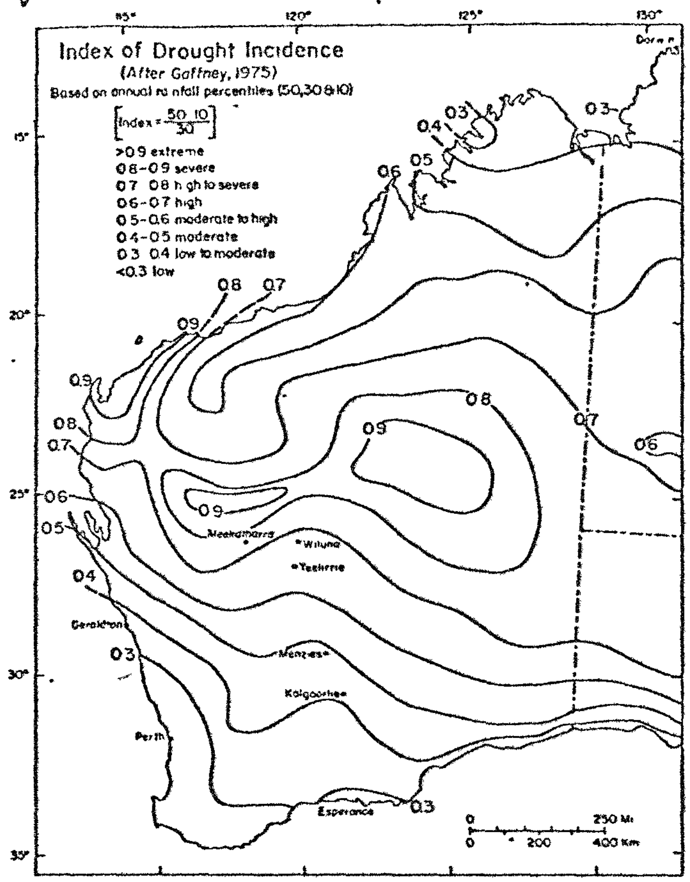


c) & d) Mean pan evaporation minus mean precipitation (E-P) suggests a water balance deficit much greater than that computed using $E^{0.75}$ as a model for soil evaporation. The nonparallelism of the contours is the expression of the fact that the exponential function $E^{0.75}$ reduces higher values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

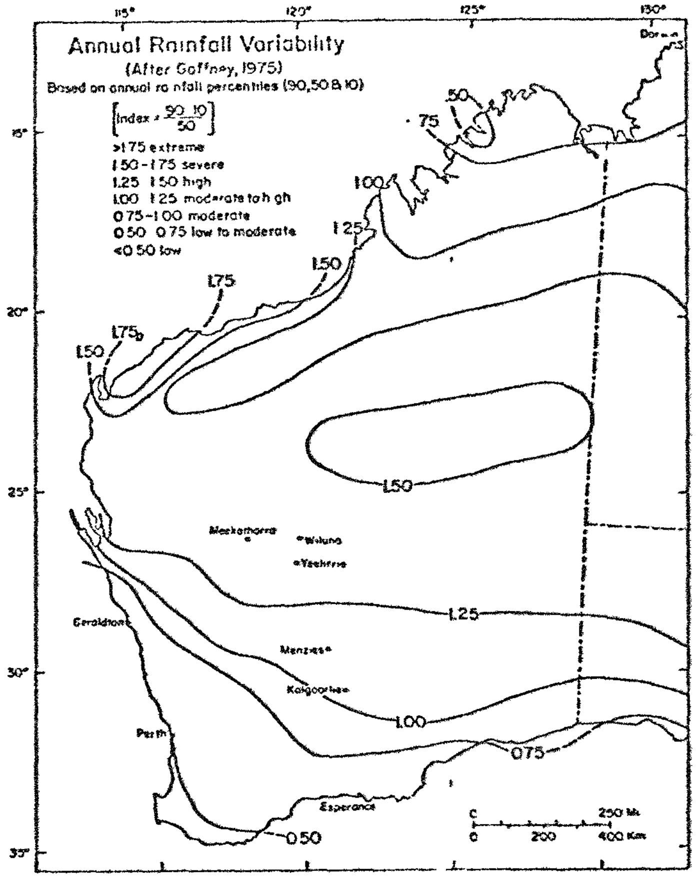
c) Summer Water Balance/January
An area of net surplus under both models exists in the monsoonal northeast, while the interior experiences extreme deficit due to extreme evaporation rates (see Figure 4.16).

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.

V. Fig 3.3.10.



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. Gaffrey (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 [illegible] tends to emphasise variability of low rainfall areas. Additional [illegible] of variability developed by the writer such as the ratio of [illegible] range of mean monthly rainfall in the three maximum rainfall months to the [illegible] mean, the ratio of the maximum recorded 24-hour fall to [illegible] annual total, and the probability of a dry month during the three [illegible] months, reinforce the variability shown here. Data required to generate detailed distributions of these factors were not available [illegible] the writer

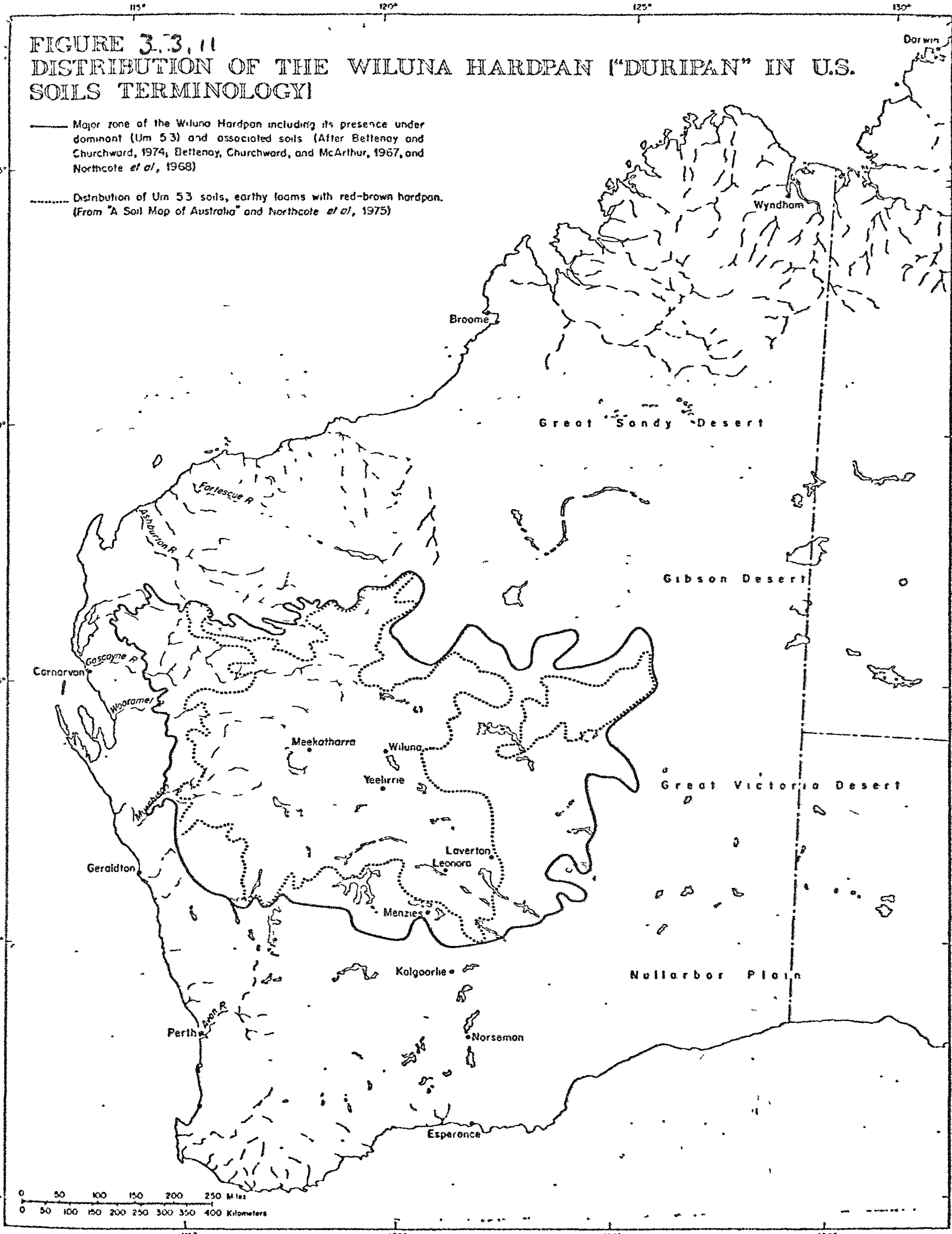


FIGURE 3.3.11
DISTRIBUTION OF THE WILUNA HARDPAN ("DURIPAN" IN U.S. SOILS TERMINOLOGY)

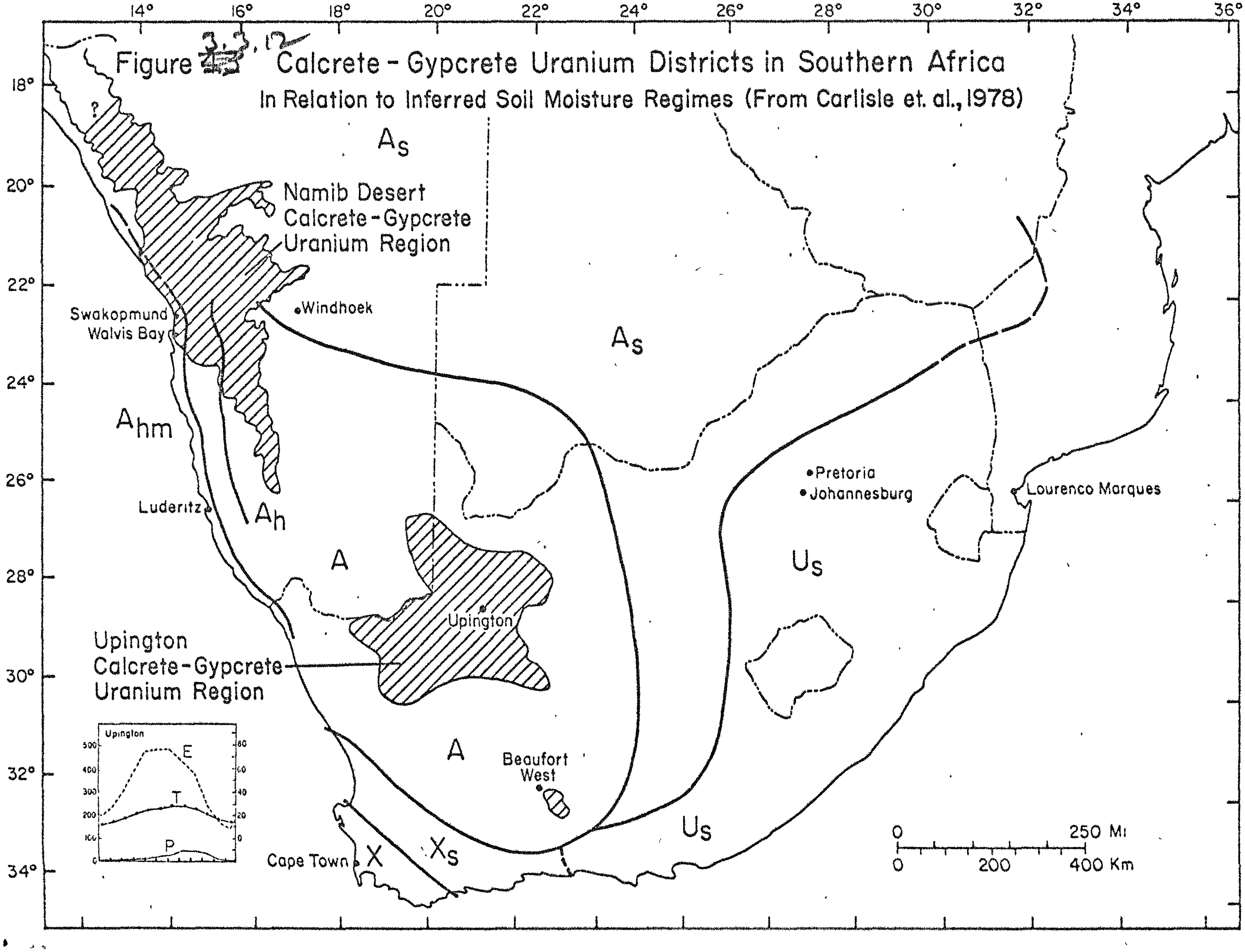


Figure 3.3.12 Calcrete - Gypcrete Uranium Districts in Southern Africa In Relation to Inferred Soil Moisture Regimes (From Carlisle et. al., 1978)

Table ~~4-3~~

Some Contrasts between Uraniferous and Nonuraniferous Regions on the Yilgarn Block

	Generally south of the Menzies Line	Generally north of the Menzies Line
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	Strongly aridic and distinctive ("Wiluna type," Figure 4.4; 4.16, and text).
	Moderate to low drought incidence.	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 (*Acacia aneura*) 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.

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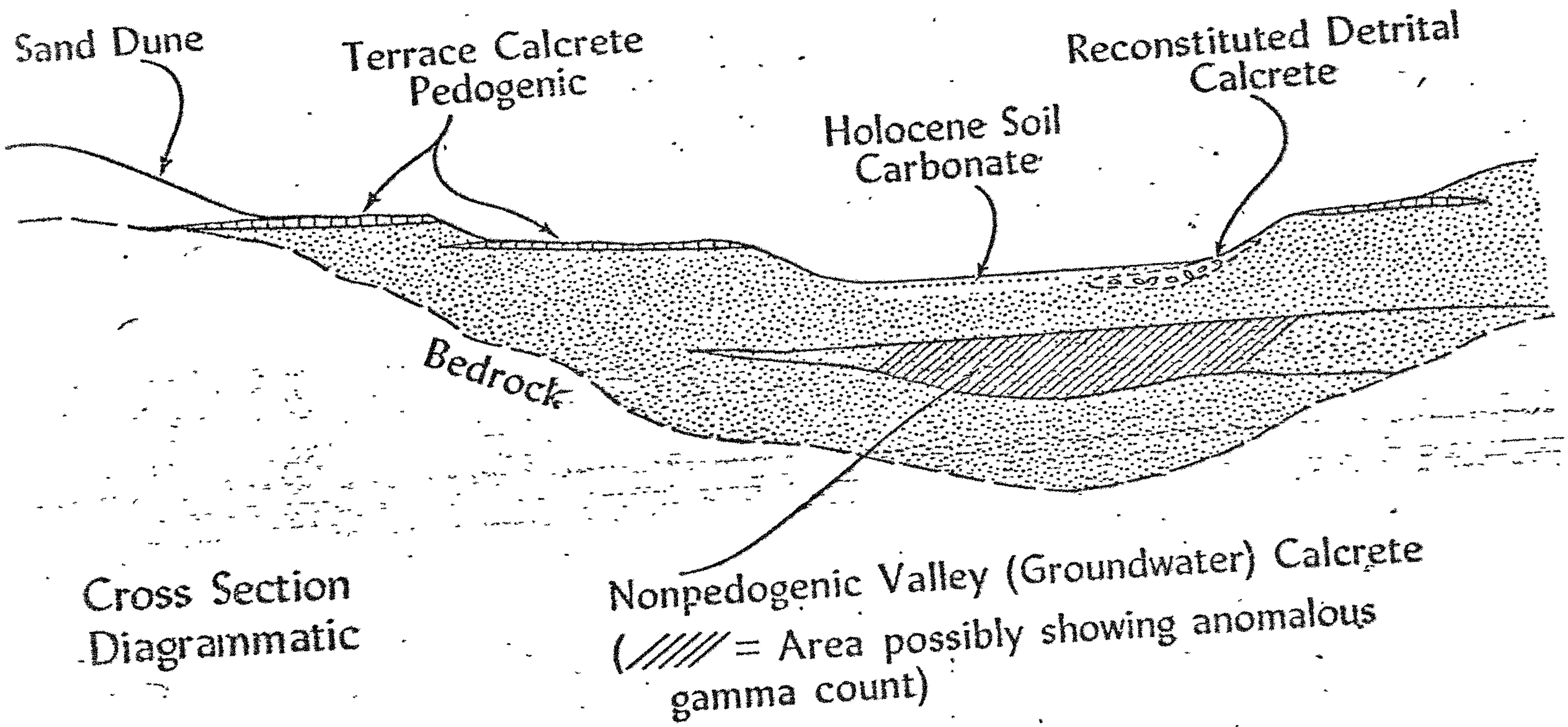

Cross Section Diagrammatic