THE GEOMETRY OF SOME BEAUFORT GROUP SANDSTONES AND ITS RELATIONSHIP TO URANIUM MINERALISATION.

by

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Thesis submitted for the degree of Master of Science

in the Faculty of Science,

University of Cape Town.

1981

FRONTISPIECE - Extensive flat bedded sandstone of the Teekloof Formation with the Nuweveld Escarpment in the background. A goz is seen at the right.

ABSTRACT

From field evidence gained whilst working on the Pristerognathus/ Diictodon Assemblage Zone west of Beaufort West it is found that three discrete sandstone types called:-

A) straight channel sandstones,

B) low sinuosity channel sandstones and

C) transitional sandstones

can be identified, in what has previously been considered as high sinuosity channel facies association sediments.

Palaeocurrent analysis has demonstrated that the transitional sandstones were high sinuosity and were the larger fluvial systems; the straight channel and low sinuosity channel sandstones were generally much smaller and had as their names imply a much lower sinuosity.

The palaeo-variability of current vectors in these systems, in the study area, is such that a standard deviation of greater than $\pm 40^{o}$ is considered diagnostic of the transitional sandstones. Moreover in the study area only this type of sandstone is of importance in uranium exploration.

From the palaeocurrent data and the reduction-oxidation states of the sandstone types it is proposed that the transitional sandstones represent semi-perennial fluvial systems flowing across

an arid intracratonic basin, whilst the straight and low sinuosity channel sands are intrabasinal tributaries of the transitional sandstones.

From this study of the sandstone geometry has evolved a new model of uranium mineralisation. It is proposed that the mineralisation is syngenetic and generated by reduction of uranyl carbonates on carbonaceous material. The carbonaceous material must however be lying closely below or within a weak REDOX front, since it is vital to transport complexes in an oxidising environment, and yet such an environment will not allow reduced uranium to be preserved for any length of time, as the carbonaceous material on which it reduced will eventually oxidize. Such a REDOX front, it is proposed, is created by the coalescence of two discrete sands. The upper sand is an oxidising active channel. The lower sand has been buried for some time and is weakly reducing due to anaerobic breakdown of its carbonaceous material by bacteria. Fluids in the two sands mix at the point of coalescence and uranium in transport in the upper sand is transported to and fixed at the REDOX front by carbonaceous material in the lower sand.

Borehole data suggests that the correlation between coalescence of two discrete sandstones (the lower being a transitional sandstone) and mineralisation is very good.

It is believed that the three sandstone types, whilst representing major fluvial systems and their tributaries, were undergoing water loss along their length such that distal portions of even the major (transitional) sandstones were likely ephemeral. Evidence for this is found in the arid climate, lack of in-channel vegetation, dominance of flat-bedded sandstones and clear evidence for bedload transport.

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1 INTRODUCTION

1.1 GENERAL

Over the last decade a large amount of information has been generated about Beaufort Group sediments due to the realisation that these sediments were likely targets for uranium mineralisation.

The beginning of the current spate of exploration for uranium, was in the late 1960's when the Union Carbide Corporation started systematic car-borne radiometric traverses. These resulted in the finding of uranium mineralisation on the farm Grootfontein 180 in 1970, and subsequently many more anomalies on other farms were located (Kübler, 1977).

Union Carbide's technical staff had in the 1960's recognised that Beaufort Group sediments had many similarities to sandstone-type uranium deposits in the United States of America. The factors that they had considered were, the fluvial nature of the sediments; that the sandstones were calcareous, arkosic, contained carbonaceous fragments, were intercalated between mud and siltstones, and were of late Palaeozoic to Mesozoic age (Kübler, 1977). They did not apparently consider it significant that the average grain-size of Beaufort Group sandstones was much finer than that commonly associated with the American sandstone uranium deposits.

Subsequent to this initial work by Union Carbide a large number of other companies moved into the Karoo. Kübler (1977) states that "by 1976 about nine different companies had become actively involved in uranium exploration...." At present (January 1981) a similar number are still actively engaged in uranium prospecting in the Karoo.

This dissertation is a product of the research done into uranium mineralisation in Beaufort Group sediments by the author, whilst working for Johannesburg Consolidated Investment Co. Ltd., and is the result of some fifteen months field work.

1.2 AIMS

The aim of the research conducted was three-fold:

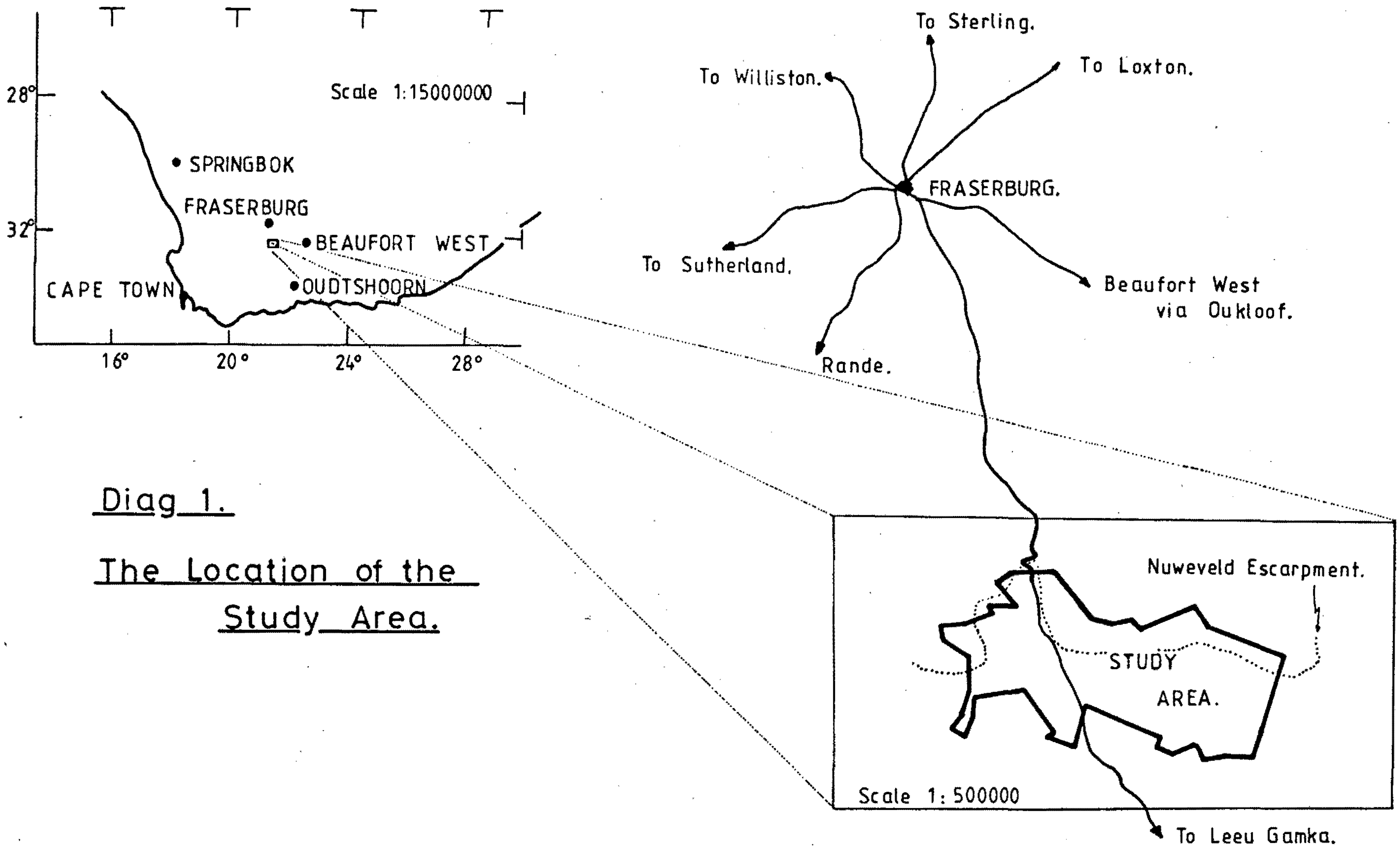
A) to establish the three dimensional geometry of the sandstones, and to attempt to classify them,

B) to examine the controls on uranium mineralisation and if possible to attempt to explain the development of mineralised pods and

C) to determine the environment of deposition.

1.3 GEOGRAPHICAL SETTING AND LOCATION

The study area lies some 45 kms. S.S.E. of Fraserburg, in the Cape Province, Republic of South Africa (see Diagram 1). It lies therefore in the Karoo.



Diag 1.

The Location of the Study Area.

Topography in the study area is marked, the dominant topographic feature being the Nuweveld Mountains, which form the Great Escarpment in this area. They lie in the northern portion of the area, striking east-west, and separate two relatively flat plains. The northern of these plains lies at an elevation of about 1 370 m. and the southern, the Great Karoo at between 610 m and 730 m. Dolerite-capped mountains in the area attain elevations of up to 1 900 m. and are topography-supporting. The escarpment provides numerous exposures on its steep slopes and many of these were utilised.

Rainfall occurs mainly as showers (December to March) and supports only small stunted Karoo bush and succulents. Drainage in the area is ephemeral and only one river, the Teekloof, crosses the study area.

Access is generally good, using tertiary provincial and farm roads, although in some areas especially along the escarpment, inaccessible areas were encountered.

1.4 GEOLOGICAL SETTING

1.4.1 The Karoo Supergroup - an Overview

The regional stratigraphy is given in Table 1 (after Johnson et al., 1976; Venter, 1969; Truswell 1977; Kübler, 1977; Keyser and Smith, 1978; Kitching, 1977;

Table 1.

The Stratigraphy of the South-Western Karoo.

Super Group	Group	Subgroup	Formation	Biostratigraphy. Existing (Kitching 1977)	Biostratigraphy. Proposed (Keyser + Smith 1978)	Thickness	Age
Karoo	Drakensberg					1370	Jurassic
			Clarens			60 - 90	190 My
			Elliot			500	
			Molteno			610	Triassic
	Beaufort	Tarkastad	Burgersdorp	Cynognathus	Kannemeyeria	610	
			Katberg	Lystrosaurus	Lystrosaurus	300	225 My
		Adelaide	Teekloof	Daptocephalus	Dicynodon lacerticeps	2740	
				Cistecephalus	Aulacephalodon baini		
					Tropidostoma microtrema		
					Pristerognathus/Dictodon		
			Abrahamskraal	Tapinocephalus	Dinocephalian		
	Ecca		Waterford			1500 - 3000	Permian
			Fort Brown				
			Ripon				
			Collingham				
			Whitehill				
			Prince Albert				280 My
			Dwyka			600 - 650	
Cape						1900	

Compiled from Johnson and Keyser (1979), Kübler (1977), Venter (1969), Truswell (1977), Johnson et al (1976), Kitching (1977), and Keyser and Smith (1978).

and Johnson and Keyser, 1979).

The basal unit of the Karoo Supergroup is the Dwyka Formation. It is characterised by the presence of glacial material such as tillite, varved shales and fluvioglacial gravels and conglomerates. The tillite is a dark grey to blue-grey coloured rock containing clasts, set in an argillaceous matrix. (Truswell, 1977; Kübler, 1977). The clasts are subangular, often striated and include granite, gneiss, quartzite, hornstone, limestone, jasper, banded ironstone, diabase and amygdaloidal andesite (Johnson and Keyser, 1979).

Above the Dwyka Formation lies the Ecca Group. The contact with the Dwyka Formation is usually relatively sharp although a thin transition zone (less than 6m) may be present (Johnson and Keyser, 1979). The Ecca Formations are generally muddy, i.e. muddy sandstones and mud and siltstones, which are drab grey or green coloured and display clear evidence of a sub-aqueous formation (Johnson et al., 1976; Ryan, 1967; Truswell, 1977; Kuenen, 1963; and Turner, 1978).

In broad terms the Ecca Group "can be divided into a lower part, deposited under conditions of rapid subsidence mainly be turbidity currents (not necessarily marine); a middle part which records a transition from a deep water open shelf facies to a landward and progressively shallower prodelta facies (where conditions were probably inhospitable to life); and an upper part forming up to three progradational (coarsening-upward) delta front sequences" (Turner, 1978).

The uppermost Formation is the Waterford which is a thick succession of massive sandstones with interbedded, generally ripple-marked shales, overlain by a thin but laterally persistent shale. The Ecca and Beaufort Groups are conformable and it is very likely that they represent net progradation, with the Ecca basin withdrawing northwards prior to progradation of Beaufort sediments in the same general direction. Thus argillaceous sediments assigned to the Ecca Group in the northern part of the basin, may be time equivalent to the Beaufort Group in the north (Turner, 1978).

The Beaufort Group sediments are a sequence of thin (generally less than 5m) laterally continuous, subparallel, fine to very fine grained sandstones, intercalated with mud and siltstones deposited in an Upper Permian fluviatile system (Truswell, 1977; Turner, 1978). They have a maximum thickness in the southern Cape of between 3 000 m and 3 600 m (Winter and Venter. 1970; Du Toit, 1954), and cover approximately 25 000 km^2

being deposited in an intracratonic basin (Southern Karoo Basin) on the original Gondwana surface (Turner, 1978).

The Molteno Formation overlies the Beaufort Group and according to Turner (1975) consists of a maximum of seven cycles. The lowest cycle, the Bamboesberg member, is conformable with the uppermost Beaufort (but is distinguished on lithological grounds). The overlying members are however unconformable and successively truncate the Bamboesberg member and underlying units of the Beaufort. The Molteno Formation is composed of coarse grained sandstones, grey and blue coloured shales and occasional coal seams (Truswell, 1977).

The Elliot Formation is a succession of red or purple argillaceous rocks containing yellowish lenticular sandstones (Truswell, 1977).

The Clarens Formation appears to have accumulated as a wind blown deposit in desert conditions (Beukes, 1970). The Formation is composed of a white or cream coloured very fine to fine grained sandstone with occasional lenticular shales and a few fluvial channels, towards the top (Truswell, 1977).

1.4.2 The Beaufort Group.

The Beaufort Group is divided into two Subgroups, the lower Adelaide Subgroup and an upper Tarkastad Subgroup. The Tarkastad Subgroup does not appear in the Western Karoo Basin and it will therefore not be considered further.

The Adelaide Subgroup is divided into two Formations, a lower Abrahamskraal and an upper Teekloof (Keyser and Smith, 1978).

The Abrahamskraal Formation as suggested earlier has a diachronous lower contact with the Ecca. The upper contact with the Teekloof Formation is based on numerous changes in lithology and is not markedly diachronous. The Formation has a total thickness of some 1 800 m (Rossouw and De Villiers, 1952).

The sediments of the Abrahamskraal Formation consist of a monotonous sequence of alternating siltstones and mudstones with numerous fine grained interbedded sandstones. The argillaceous sediments are blue-grey, occasionally purple or red mudstone, intercalated with greenish-grey ripple laminated siltstones. Interbedded with these sediments are numerous lenticular sandstone bodies varying in thickness from 0,5 to 15 m. (Keyser and

Smith, 1978).

The sandstones are generally lenticular, plano-convex or planar. Individual lateral outcrops of the major sandstones are usually of the order of 1 - 2 kms, and they display cyclic sedimentation structures. The basal erosion surface is of low profile and often blanketed by varying thicknesses of clay pebble conglomerate. (Keyser and Smith, 1978). The sandstones are fine to very fine-grained. Their colour is highly variable, depending on the amount of leaching, the valency and quantity of iron, the concentration of carbonaceous material and their syngenetic development.

Calcareous nodules are found in the argillaceous units, as small discrete bodies of roughly ovoid cross-section. Such nodules may form discrete horizons and they occur throughout the Abrahamskraal Formation.

Numerous discrete lenses of highly silicified chert are also present. These chert bands are normally associated with argillaceous sediments and display cross-bedding, convolute bedding and ripple structures. Individual outcrops are up to 1m thick and several metres in length and can be correlated over several kilometres (Rossouw and De Villiers, 1952).

The volumetric ratio of arenaceous to argillaceous sediments varies considerably on a local scale (and this will be considered again later) but it is generally between 1:2 and 1:3 with sandstone always (?) subordinate to mudrock (Keyser and Smith, 1978).

The Teekloof Formation lies above the Abrahamskraal Formation. Its top is never seen in the Western Karoo Basin. Its total thickness is of the order of 1 000 m., and it is muddier than the Abrahamskraal Formation. Typical arenaceous to argillaceous ratios are 1:4 or 1 : 6. The mudstones are generally redder than in the Abrahamskraal Formation and diagesis and metamorphism (to be discussed) is not as advanced. Nodular carbonates are abundant - some showing septarian development; and chert lenses, of creamy white chert are found.

The sandstones of the Teekloof Formation are fine to very fine grained buff or greenish grey, weathering to a reddish colour. They are plano-convex or biconvex with a greater depth of scour than those of the Abrahamskraal Formation. The major sandstone bodies taper rapidly away from their thickest development as intercalations of mudrock become more common (Keyser and Smith, 1978). This tapering is much more marked in the Teekloof sands than in the Abrahamskraal sands. The irregular multiple scour profile of the basal surface of the former is in contrast to the smoother, shallower scours of the latter (Keyser and Smith, 1978).

Unfortunately there is some confusion in the literature as to where the formations, i.e., the Abrahamskraal and Teekloof, contact. Keyser and Smith (1978) state that "The Pristerognathus/Diictodon assemblage zone straddles the contact between the Abrahamskraal and Teekloof Formations" and that "chert bands do not occur in the Teekloof Formation". Further, their diagram Fig.2.1. clearly shows the base of the Poortjie sandstone to lie towards the base of the Pristerognathus/Diictodon assemblage zone. This would indicate that the study area - which lies in the Poortjie sandstone horizon and has chert bands - would lie at the top of the Abrahamskraal Formation.

Johnson and Keyser (1979) state that the contact which they used whilst producing the explanation to Sheet 3222 on the 1:250000 series of Beaufort West "has been arbitrarily located at the base of the Poortjie Sandstone". Keyser and Smith (1978) Fig. 2.1., clearly indicates that such a definition places the study area in the Teekloof Formation.

It is thus not feasible to assign the study area to a specific Formation, although it can be said to be within the Pristerognathus/Diictodon assemblage zone, and the Poortjie Sandstone horizon.

1.5 METAMORPHIC AND TECTONIC SETTING

Post formational changes vary. In some sandstones little change beyond some silica overgrowth has occured. In others considerable amounts of authigenic chlorite are found. Still others have extensive calcite and silica cementation, suggestive of locomorphic diagenesis (Dapples, 1967). Only poorly developed authigenic micas were noted, indicating a maximum of phyllomorphic diagenesis. However in hand specimen, zeolites are found causing distinctive red mineral aggregates and mottling, and Turner (1978) suggests laumontite facies. Stapleton (1978), examining the degree of alteration of vegetable material to amorphous carbon, called the study area 'metamorphic facies' and suggested a lowest boundary temperature of 280^{o}C. Rowsell and De Swardt (1976) concluded that these sediments were in a state of anchimetamorphism, and had suffered strong burial compaction and high temperature (less than 270^{o}C,) burial depth being an estimated 6 000 m.

Tectonically the area has remained extremely stable. Within the study area Karoo dolerites are rare and where encountered occur as sills and dykes, less than 0,2 m thick which had little or no appreciable affect on the host sediments. No major faults were encountered.

Folding is extremely open, limbs dipping at less than 5^{o} to the south and north. An overall dip of 1 - 2^{o} to the north as suggested by Wilke (1962) is likely. Most of the study area displayed dips of 1 - 2^{o} in a northerly direction.

Jointing is well developed particularly in the sandstones, where two almost perpendicular sets are common. Jointing sets run north to south and east to west and probably relate both to folding and unloading.

No evidence was found to suggest that primary mineralisation occurred with some relationship to jointing. There is however clear evidence of epigene migration of primary mineralisation along joints as a late stage process and Kübler (1977) found numerous secondary minerals along joints and fissures.

1.6 PREVIOUS WORKERS

Some of the earliest work done in the Karoo was that carried out by Schwartz (1896) who examined amongst other things the pseudo-coals of Brandewyns Ghat. In 1902 Rogers and Schwartz did further work in the area. Rogers (1910) wrote a comprehensive report on the geology of the Beaufort West, Fraserburg, Victoria West, Sutherland and Laingsburg areas, in which he gave thin section descriptions noting that the orthoclase in the sections was more altered than the plagioclase. Broom in 1911 envisaged a large inland basin which became silted up by aggrading flood plains.

Rossouw and De Villiers (1952) mapped an area south of latitude 32° 30'S. They recognised that the Ecca Group contact came nearer the surface towards the north (i.e. that the Ecca - Beaufort contact was diachronous).

Wilke (1962) whilst working on his thesis for the University of Stellenbosch examined the ground water hydrology around Fraserburg and determined that the sandstones constituted 10 - 15% of the stratigraphic section.

Keyser (1966) found rosette-shaped inclusions ~~in Beaufort Group beds~~ composed of calcite, quartz and barite in Beaufort Group Beds and suggested these were 'desert roses', indicating an arid climate. Further evidence for a hot climate was given by Hotton (1967) and Kitching (1977).

Ryan (1967), working dominantly on the Ecca, recognised three facies in the lowermost Beaufort Group sediments, a northern, western and southern facies. This study is located within the southern facies described by Ryan (1967) as relating to a northerly trending dispersion pattern, with blue, green, grey, purple and maroon mudstones, fine-to-medium grained sandstones, and occasional lenses of chert and limestone.

Theron (1973) doing a palaeocurrent study of the entire Beaufort Group, demonstrated a southerly source for all Beaufort units (with the exception of the north-eastern outcrop area). He found a major entry point in the South-east (East London area), and a second entry point in the south west (which is probably responsible for the sediments of the study area). He postulated a provenance area consisting of granites, granulites and gneisses lying south of and close to the present continental margin.

Johnson (1966) and Keyser (1970) were the first authors to recognise the lenticular sandstone bodies of the Beaufort Group as portions of fluvial channels.

Much time has been spent conducting research into uranium mineralisation in Beaufort Group sediments. Von Backström (1974) concluded that all the then known uranium occurences were in the Adelaide Subgroup but suggested that the uranium was not restricted to this unit. He found syngenetic uraninite and coffinite associated with wash-outs and erosion channels. Moon (1974) whilst working for the South African Geological Survey suggested that the sediments that he examined were probably deposited on the lower part of a flat flood plain, or on palaeontological grounds a marginal marine shelf. He considered that the most likely mode of formation of the uranium mineralisation was the reduction of uranium (transported as carbonate complexes) on carbonaceous debris.

Henderson (1974) and Roberts (1974) working on Beaufort Group sediments as part of their B.Sc. Hons. course, in the Beaufort West District suggested a fluvial environment.

Turner (1975) proposed that the environment of deposition was comparable to that generated by modern meandering streams. However he also recognised some coarsening upward rather than fining upward, and he suggested that the overall picture was more consistent with deposition on the lowermost reaches of a flood plain, in close proximity to a delta which he suggested lay to the east. He concluded that the uranium displayed an affinity for channel and crevasse splay sandstones and he suggested that the uranium may have been derived by leaching of the volcanic material found within the sediments.

Volcanic material in Beaufort Group sediments was first reported simultaneously by Martini (1974) and Elliot and Watts (1974) the latter reporting the presence of replaced volcanic shards. Later reports include those of Ho-Tun (1979) and Stuart-Williams (1979) who took photomicrographs of volcanic shards in lithic fragments from Beaufort Group material.

Horowitz (1976) conducted a palynological survey in the Beaufort West District and concluded that the sediments were laid in a wide shallow delta at the northern or north western shore of an oceanic basin in late Permian times. He suggested a transport direction from the north since he found a greater proportion of marine microfossils to the south, and stated that rivers flowing from the north carried uranium mineralisation which precipitated on contact with the saline environment giving rise to the mineralisation. Such a viewpoint contradicts the work of Ryan (1976) Theron (1973), Moon (1974) and Turner (1975).

Stapleton (1978) examined the relationship between uranium occurences and organic metamorphism in the Western part of the Karoo basin and concluded that there was strong evidence that the uranium was of secondary origin, and that the origin was somehow controlled by the degree of thermal alteration, but failed to explain how.

Kübler (1977) completed his M.Sc. at Witwatersrand University and in a very succinct work based on field experience gained between 1974 and 1977 whilst working for Union Carbide produced the first major work on uranium to come out of the Beaufort Group. He covered all aspects from depositional facies, through thin section descriptions, to a discussion on uranium provenance and included isopach maps, drilling data and a brief discussion on sandstone geometry.

Stear (1978) working on the farm Putfontein, some 33 kms SSW of Beaufort West found sedimentary structures "which resemble some of those currently formed on modern tidal flats and other low energy shorelines. Diagnostic environmental criteria imply that sedimentation of the sandstone unit took place in a fluvial environment during ephemeral flooding along the lower reaches of an arid flat."

Beeson (1978) examined the geochemistry of surficial uranium mineralisation in the south west Karoo basin and suggested that their geochemistry was consistent with previously observed element migrations in tropical probably semi-arid climates, with only the most mobile elements (Ca, Mg, and Zn) being removed.

Turner (1978) found a systematic upward decrease in the sandstone to mudstone ratio and suggested that this could relate to a decreasing sediment supply with an associated decrease in stream gradient. The facies associations developed probably represent the proximal, intermediate and distal components of an extensive fluvial depositional system which built out from a distant source to the south and west. He further considered that uranium mineralisation was confined to high sinuosity channel sandstones, that permeability barriers and carbonaceous debris were major controls, and that uranium transported as uranyl complexes derived by leaching of volcanic detritus.

The Reptilian fossils of the Beaufort Group have also generated considerable interest. Works include those of Bain (1845), Wyley (1859), Jones (1867), Rogers (1905), Watson (1914), Du Toit (1918), Broom (1905, 1907), Von Huene (1925), Case (1926), Boostra (1969), Kitching (1970, 1977), Stapleton (1974), Smith (1978) and Keyser and Smith (1978). Keyser and Smith's (1978) vertebrate biozonation is generally accepted for the western Karoo basin.

1.7 SUMMARY OF CURRENT CONCEPTS

Turner (1978), Smith (1978) and Keyser and Smith (1978) are all in general agreement in their interpretation of the palaeoenvironment of the Adelaide Subgroup in the western Karoo basin. A summary of Turner's (1978) interpretation will therefore be used.

Turner (1978) proposed that the Adelaide Subgroup called by him the Tapinocephalus, Cistecephalus and Daptocephalus zones after Kitching (1973), be divided into three sedimentary facies associations, (see Table 1).

These were:

A) a Low Sinuosity channel facies association,

B) a High sinuosity channel facies association and

C) a Floodbasin facies association

The Low sinuosity channel facies association is only found at the base of the Abrahamskraal (see Turner 1978, Fig 2 p.833 the base of the Tapinocephalus zone) and can therefore be excluded from this summary as it does not occur in the study area.

The high sinuosity channel facies association is characterised by lenticular sands with scoured bases, which grade upward and laterally intertongue with mudstone. Individual cross-beds are up to 1,5m thick and are generally confined to the lower and middle parts of sandstones. Palaeocurrents are bimodal and directed north and east. In plan the sandstones reproduce all the features of modern arcuate point bar ridges (see Kübler, 1977; frontispiece). Such a facies association is therefore interpreted as being created by high sinuosity, fluvial systems.

Meander belts were narrow, suggesting their early abandonment possibly in favour of gradient advantages offered by interfluve basins (Ferm and Cavaroc, 1968). As point bars accreted laterally, their deposits became overlain by overbank fines deposited mainly from suspension. Repeated inundation of the overbank environment occurred as suggested by sandstone and siltstone intercalations, mudcracks, pedogenesis and the presence of calcareous nodules

(Reeves, 1970.)

The Floodplain facies association is characterised by red massive mudstone with occasional sandstones. Dessication cracks occur along the bases of sandstones and siltstones, calcareous concretions are common, and 'desert roses' (Keyser 1966) may be present. This facies association is interpreted as being dominantly overbank fines with occasional channel deposits. Evidence of exposure abounds in modern overbank deposits especially in semi-arid environments and the presence of mudcracks and 'desert roses' would suggest that the Beaufort Group formed in a semi-arid to arid environment. Plant cover was probably sparse and restricted to channel margins, and since vegetation capable of colonising and stabilising interfluves had not evolved, run-off and sediment yield were exceptionally high (Schumm 1968) promoting thick sequences of flood sediments, (Turner, 1978).

2 LITHOFACIES USED IN MAPPING

2.1 INTRODUCTION

In order to facilitate mapping (in both plan and section), a number of lithofacies were used. Several alternative nomenclatures are available, such as those of Kübler (1977), Greenshields (1978), Miall (1977), Turner (1977) and Allen (1970). The nomenclature suggested by Allen (1970) was decided on, for its simplicity and easy usage in the field. As far as possible no genetic implication is assumed by the author whilst using this nomenclature.

Allen's (1970) six lithofacies are

- A - Conglomerate facies,
- B_1 - Cross-bedded sandstone facies,
- B_2 - Flat-bedded sandstone facies
- B_3 - Cross-laminated sandstone facies,
- C - Alternating facies, and
- D - Siltstone/Mudstone facies

Allen (1970) defines these facies as being "quite distinct from one another, but within themselves show different degrees of variation as regards overall texture, total thickness and number of constituent sedimentation units."

Greenshields (1978) considered certain homogeneous sandstones which showed no evidence of bedding as a separate lithofacies. Kübler (1977) quoting Reineck and Singh (1973) states "this was not regarded as a separate facies since most homogeneous looking sediments show internal laminations if special techniques are applied". The author agrees with this viewpoint. The exact process or processes of homogenisation of the sediment are not known but biological activity is a possibility, in a few instances rapid dewatering is a likely contender, and physical turbation (e.g. wetting and drying) may also have occurred.

2.2 LITHOFACIES A - CONGLOMERATE FACIES

This lithofacies consists of red and green siltstone and mudstone clasts, calcareous concretions (derived from adjacent argillaceous units) and rare bone fragments, in a fine to very fine grained matrix (medium sized grains have not been identified). An example is shown in Photograph 1. Both clast- and matrix-supported textures are present. The mudstone and siltstone clasts are probably locally derived and transported only short distances (Smith,1974) and it seems likely that the carbonate concretions were similarly derived from adjacent soil horizons. Exotic rock fragments were identified in thin section and these are discussed briefly in Chapter 3.

PLATE I

Photograph

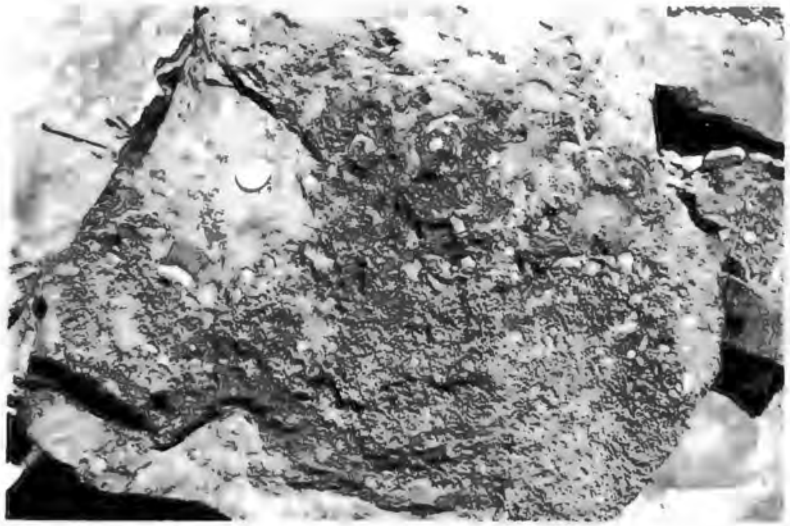
1 Lithofacies A - Carbonate concretions (derived from adjacent pedocals) show as pale clasts. The mudstones have generally weathered out leaving the sandstone matrix standing out. A bone fragment is present to the bottom left of the coin.

2 Lithofacies B_1 - A large trough cross-bed (Allen's 1963, pi type). Note that the foresets can be seen to curve initially to the left and then the right going away from the photographer. View on Sandstone 10 looking west.

3 Lithofacies B_2 - This is the dominant sand lithofacies.

4 Lithofacies B_2 - Primary current lineation and parting lineation, both of which characterise the B_2 lithofacies can be seen in this photograph.

PLATE I.



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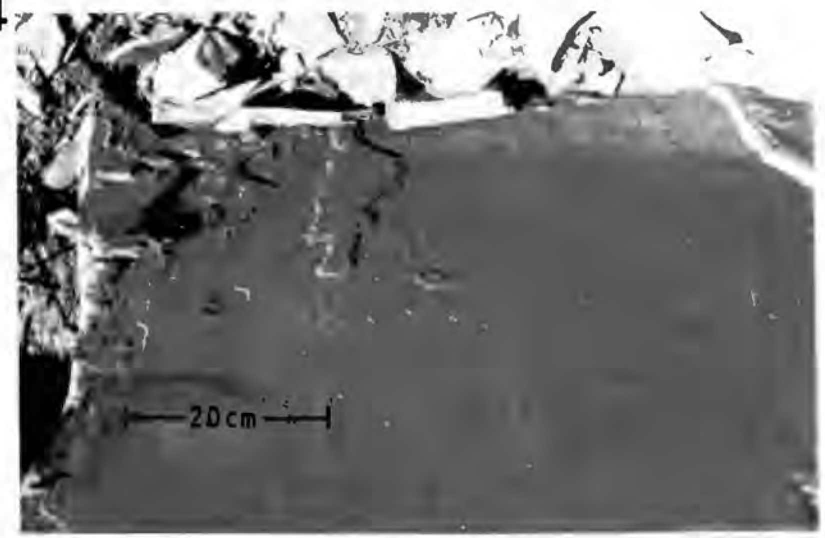


Generally the facies is less than 25cm thick. It has a dark brown colour on weathered surfaces probably due to a high carbonate content in the matrix. A sharp erosional basal contact is almost always present, but may be indistinct, particularly if the underlying lithofacies is sandy. Basal erosional topography is seldom more than 30 cm.,and some small clast filled sumps are found. The conglomerate may erosively overlie any of the six lithofacies. Structures are poorly preserved, but trough cross-bedding (Allen's,1963; pi type) and horizontal bedding are found. Upward fining of the grain-size is common and imbrication has been observed.

2.3 LITHOFACIES B_1 - CROSS BEDDED SANDSTONE FACIES

This lithofacies is fine-to- very fine-grained cross-bedded sandstone in solitary or grouped sets made up of units seldom thinner than 10 cm and rarely thicker than 80 cm. The sets are dominantly trough cross-bedded (Allen's, 1963; pi type) and more rarely tabular (Allen's, 1963; omikron type). Sorting is generally better than in lithofacies A, although some clasts may still be found along bedding surfaces. Foresets dip at 15^{o} - 25^{o}, and suggest a dominant unimodal flow direction. The thicker sets tend to lie in the better developed sandstones. For an example see Photograph 2.

2.4 LITHOFACIES B_2 - FLAT BEDDED SANDSTONE FACIES

Without a doubt this is the dominant sand lithofacies present in the measured sections. It is characterised by horizontal to low angle laminations (almost always less than 10^0) with a thickness less than 0,2 cm (this can vary from thinly laminated i.e. less than 0,3 cm, to thin bedded, i.e.1 - 3 cm thick; after Ingram, 1954), which may have a lateral persistence of several metres. See Photograph 3. A parting-plane lineation (McBride and Yeakel, 1963; termed a parting lineation by Potter and Pettijohn, 1977; primary current lineation by Allen, 1963; and a streaming lineation by Conybeare and Crook, 1968)and parting step lineation (McBride and Yeakel, 1963) tend to be well developed. See Photograph 4. Internal erosion surfaces (planar, irregular and trough-like) are frequent (particularly planar), cross-cutting the laminae. The azimuth and inclination of the laminations frequently change slightly at the erosion surfaces and intraformational conglomerates are occasionally developed. Sandstones are fine to very fine-grained.

2.5 LITHOFACIES B_3 - CROSS LAMINATED SANDSTONE FACIES

This lithofacies is found commonly as thin beds (frequently less than 10 cm. thick) of very fine grained sandstone. It is commonly found either high in the sandstone bodies or towards their margins.

Small scale cross-laminations of nu or more kappa and lambda types (Allen, 1963) are present, being seen as sinuous, linguoid, straight, interference and climbing ripples. See Photograph 5.

2.6 LITHOFACIES C - ALTERNATING BEDS FACIES

This lithofacies is difficult to define unequivocally in the field and was only definitely recognised in a few sections. Allen's (1970) equivalent facies shows an alternation between arenaceous and argillaceous units on a scale varying from some centimetres to a few decimetres. The argillaceous units are chiefly medium to coarse grained siltstones, sometimes showing cross-bedding. Bioturbation is present, being found as mottling and worm (?) tracks, (termed Planolites by Kübler, 1977; see also Frey and Howard, 1970). The arenaceous units are fine-to very fine-grained sandstones, frequently fining upward, which normally have a sharp lower contact suggesting a time break, or erosion.

The apparent rarity of this lithofacies in the mapped area suggests a fairly marked deviance from the interpretations made by Allen (1970), and the reader is again cautioned against making any subconcious genetic interpretation of these lithofacies. An interpretation will be attempted in Chapter 10.

PLATE II

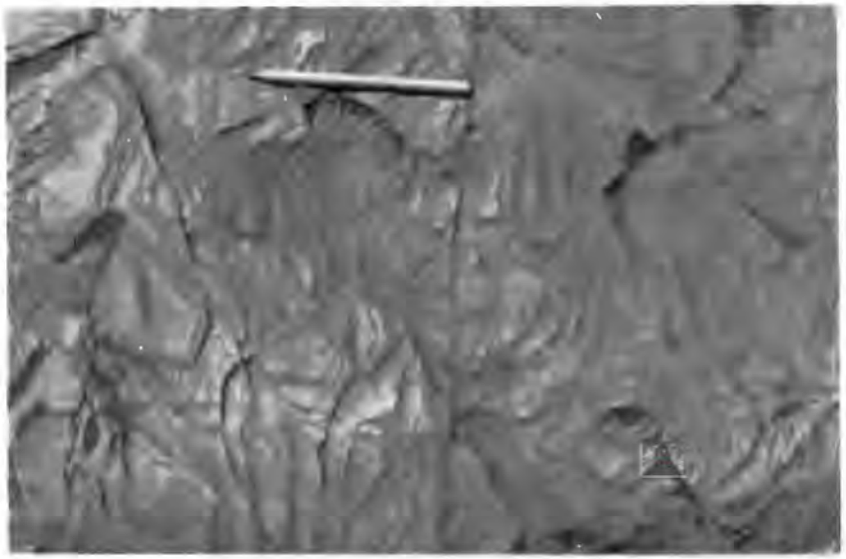
Photograph

5 Lithofacies B_3 - Rib and furrow structure (as seen in this photograph) typifies this lithofacies. The ripples were migrating approximately parallel to the pen from right to left.

6 Lithofacies D - A road-cutting in mud and siltstones gives a good example of the type of alternation seen in this lithofacies.

7 A Linguoid bar - foresets can be seen to dip away from the photographer in the photographs middle left, whilst a dip to the right is visible in the middle-right. Note that this direction of curvature in relation to the foreset dip is opposite to that seen in Photograph 2.

PLATE II.


5


6


7

2.7 LITHOFACIES D - SILTSTONE/MUDSTONE FACIES

This is the dominant lithofacies, making up some two-thirds to three-quarters of the vertical succession. It is comprised of a series of silt and mudstones which vary in colour from drab grey through green to maroon. Within these are a number of laterally persistent palaeosols (persistence over more than 100 m is rare) present as carbonate nodule horizons (pedocals). These nodules are the 'cornstones' described by Allen (1970) which are the dominant clast found in lithofacies A. A typical section is shown in Photograph 6.

3 SANDSTONE PETROLOGY

3.1. GENERAL

When mapped in the field, two broad sandstone divisions can be recognised, based on colour. These two divisions are a) the grey, grey-green and green sandstones which are considered to carry iron in the reduced state (Fe^{++}), and b) the brown, reddish-brown and purplish sandstones which are oxidised and carry iron in the ferrous state (Fe^{+++}). Since the sandstones are in most cases closed systems, being surrounded by essentially impermeable mudstones, it is felt by the author that in many cases the colour of the sandstone is representative of the oxidation - reduction potential (Eh) during diagenesis. In fact it is likely that the colour of the matrix in most sandstones is a direct result of the presence or absence of reductants in the sandstone from its formation. Field evidence suggests that these two major sandstone divisions may represent perennial fluvial systems and ephemeral fluvial systems respectively, in an arid environment.

During mapping, grain size was estimated using an AMSTAT visual comparator, which is a plastic sheet with printed grains, covering every ½ ϕ (phi) subdivision for sand size grains. It was found by comparison with grains measured using a calibrated microscope to give an accurancy of slightly less than ½ ϕ such that nearly all sandstones would have been correctly classified.

Grain angularity was only determined in thin section, by comparison with a visual chart (after Powers, 1953).

3.2 MODAL ANALYSIS

The sandstones are composed mainly of quartz, feldspars, rock-fragments and detrital matrix. Locally carbonate cement may be a significant constituent. Before discussing the analysis in more detail however, a number of points need to be clarified.

The most important of these is that any modal analysis generated will not be representative of the primary detrital composition. This is because in many thin sections considerable quartz overgrowth has taken place, largely at the expense of argillaceous rock fragments and matrix, with many quartz grains showing primary rounded margins, on which overgrowth has generated a higher angularity. In some slides this overgrowth has increased the quartz percentage by as much as 5 - 10% at the expense of the other modes.

In many slides the feldspars are extensively replaced by chert (see Kübler, 1977) and this silicification makes identification of some feldspars impossible. It is felt by the author that some cherty rock fragments may have been derived from silicification of orthoclase feldspars, and this can make the accurate partitioning of chert a problem.

A further problem is encountered in distinguishing between mud matrix, and locally derived sand size grains of mudstone. In some instances the original rounded grain margins are visible, but in others compaction has destroyed the primary grain shape and distinguishing them from the matrix becomes impossible. Interestingly Kübler (1977) in summarising his own modal data and that from Moon (1974) and Hotton (1967) ignores the presence of any rock fragments and presumably includes sand size mudstone grains with matrix (see Table 2). If this is the case his matrix mode appears to be less than that of Moon (1974), Hotton (1967) and also of this study.

Silicification of the feldspars has already been mentioned. In addition it should be mentioned that feldspar alteration is in some cases very well advanced and calcitisation, sericitisation and kaolinisation are also in evidence. In some instances feldspar alteration is so extreme that only ghost-like outlines remain of the original detrital grain. It is thus feasible that some altered feldspars have been counted as matrix.

Lastly it should be noted that this author has followed Hotton (1967) in that he has included carbonate and chlorite as matrix, largely because they are either representative of matrix replacement or alteration. The data are presented in Table 2, and in general there is good agreement between the findings of this and previous studies.

Table 2.

Modal Analysis of Beaufort Group Sandstones.

<table>
<tr><th></th><th>This Study.</th><th colspan="2">Kübler(1977).</th><th colspan="2">Moon(1974).</th><th>Hotton (1967).</th></tr>
<tr><td>Quartz</td><td>36</td><td colspan="2">39</td><td colspan="2">31</td><td>28 - 45</td></tr>
<tr><td>Chert</td><td>Not Applicable</td><td colspan="2">2</td><td colspan="2">5</td><td>7 - 10</td></tr>
<tr><td>Orthoclase</td><td rowspan="2">25</td><td>30</td><td rowspan="2">33</td><td>13</td><td rowspan="2">15</td><td rowspan="2">11 - 19</td></tr>
<tr><td>Plagioclase</td><td>3</td><td>2</td></tr>
<tr><td>Matrix</td><td rowspan="3">21,5</td><td rowspan="2" colspan="2">24</td><td>24</td><td rowspan="2">50</td><td rowspan="3">25 - 40</td></tr>
<tr><td>Chlorite, Mica</td><td>26</td></tr>
<tr><td>Carbonate</td><td colspan="2">2</td><td colspan="2">–</td></tr>
<tr><td>Rock Fragments</td><td>15,5</td><td colspan="2">–</td><td colspan="2">–</td><td>–</td></tr>
<tr><td>Others</td><td>2</td><td colspan="2">–</td><td colspan="2">–</td><td>–</td></tr>
</table>

3.3 THIN SECTION DESCRIPTION OF THE MAIN COMPONENTS

3.3.1 Quartz

From the modal analysis it can been seen that quartz constitutes about 36% of the sandstones by volume, occurring as fine to very fine detrital grains. The grains were originally (?) sub-angular to rounded, but quartz overgrowths have rendered the grains in general more angular, and have displaced matrix (original grain margins being frequently identified by lines of included sericite (?)). Extended straight and sutured contacts are a further development of quartz overgrowth. On a few quartz grains the reverse has occurred and it appears that the original grain boundary has been lost to solution - this is probably the pressure point solution described by Kübler (1977).

Three types of quartz were identified:-

A) few inclusions - straight extinction,

B) numerous inclusions such as rutile hairs and unidentified spherulites - straight extinction, and

C) which has a strong undulose extinction.

Chert was an abundant constituent and was considered as either a rock fragment or as quartzified feldspar.

3.3.2 Feldspar

As noted earlier the feldspars are heavily altered and their exact modal percent is unsure, some being so quartzified as to be counted as rock fragments, whilst others are so sericitised that they may have been included as matrix.

No attempt was made to determine the ratios of the feldspars but microcline, orthoclase, plagioclase (one grain determined as An_{55} - labradorite) and sanidine were identified. In some of the altered plagioclase, polysynthetic twinning was still visible. The mean composition of the plagioclase was found by Kübler (1977) to be andesine- labradorite (Union Carbide Research Report, 1972) and by Moon (1974) to be albite-oligoclase.

Silicification and sericitisation have already been mentioned as have calcitisation and kaolinisation and these four processes appear to have acted syngenetically and diagenetically to alter the feldspars present, in some cases to the point where they are no longer recognisable. However in a few instances very clearly defined angular K-feldspar grains are found and these are believed to be authigenic, possibly forming when the pile reached peak temperature and pressure, during or shortly after dolerite intrusion.

Feldspar grains have a similar size to the detrital quartz grains, but may be better rounded.

3.3.3 Rock fragments

Essentially two types of rock fragment are found -

a) sand-sized mud and silt grains and,

b) true rock fragments (rare).

Type a) fragments comprise about 98 - 99% of those rock fragments recognised. They are rounded to sub-rounded grains of almost idential size to the quartz and feldspar grains and were probably in hydrodynamic equivalence with them. They are almost certainly derived from reworked upstream river banks, and due to this are soft enough to deform under load.

Type b) grains are less than 2% of all rock fragments, and both igneous and metamorphic (IRF and MRF) types have been recognised. Only one igneous rock fragment has been identified by the author in the study area (see Stuart-Williams, 1979). This particular specimen was tuffaceous and contained good volcaniclastics, one of which had a classic 'sickle' shape. The American Association of Petroleum Geologists (Memoir 28), considers such volcanic rock fragments as 'excellent indicators of a volcanic source terrain'. Martini (1974) and Elliot and Watts (1974) have also reported volcaniclastics.

Metamorphic rock fragments are almost as rare and only four have been positively identified. All four were typified by good parallelism of muscovite grains such as would be found in a sericitic schist. The metamorphic grade would probably be fairly low, and the rock is almost certainly a meta-argillite.

3.3.4 Matrix

Volumetrically the matrix is about 21,5% of the rock (excluding rock fragments). It consists of silt-sized grains of quartz and abundant clay minerals and chlorite.

Calcite is frequently present, particularly in lithofacies A, but is normally replacing detrital matrix. Sericite is sometimes found but is probably secondary after altered feldspars. Haematite may be present as either small discrete grains or as a universal brown discolouration of the matrix.

The mention of haematite and chlorite brings the discussion back to the question of sandstone colour, because it is the matrix which is dominantly responsible for the colour. Earlier it was suggested that the colour of the matrix is dependant on the oxidation/reduction state of iron and therefore was dependant on the formation of haematite or chlorite (see Dapples, 1967; p 100 - 101). It was also suggested that the reductants in the sandstones were introduced during sandstone formation. If this is the case, then since the dominant reductant is organic carbon. It could be proposed that the two sandstone subdivisions based on colour may represent two different fluvial styles, only one of which was generating carbon in the form of vegetable material. This idea will be followed in later Chapters.

3.3.5 Accessory Minerals

The following minerals, which make up about 2% of the sandstones, were identified; biotite (which is frequently deformed, presumably during compaction, and may occasionally have frayed ends - some phyllomorphic mica is also present (see Dapples, 1967)); garnet, apatite, sphene, hornblende, epidote, magnetite, ilmenite, zircon, tourmaline, muscovite and in some thin sections, carbon.

3.4 GRAIN SIZE ANALYSIS

Kübler (1977) conducted a fairly detailed grain-size analysis, on ripple-, trough-, and horizontal-bedded sandstones, in which he found his samples to be moderately sorted, fine-, to very fine-grained sandstones. In view of the amount of overgrowth and difficulty in recognition of the detrital grain shape found in the author's own thin sections no such attempt could be made, with any degree of accuracy.

Grain analysis was however conducted on a small number of slides to ensure that the grain-sizes allocated in the field using the AMSTAT comparator were correct. A mean grain size of 0,192 mm (lying at about 2,3 ϕ) was found for 100 grain counts on each of 4 slides, which placed them in the fine sand size. The very fine grained sands were not measured.

3.5 CLASSIFICATION OF THE SANDSTONES

The sediments examined in thin section have been classified following the scheme suggested by Folk, Andrews and Lewis (1970). Since grain-size distribution and mineralogical composition are independent variables in most sediments, separate classifications are necessary to describe them. The following format is therefore suggested -

(sorting term)(size term):- (cement) (prominent nondetrital)
(detrital composition).

Using this format typical sandstones are-

Muddy fine sandstone : Felsarenites

Muddy very fine sandstone : chloritic lithic felsarenites

or Muddy very fine sandstone : Feldspathic Litharenites

whilst the conglomerates are -

Fine sandstone pebble conglomerates, calcite cemented lithic felsarenites.

4 SECTION GEOLOGY

4.1. INTRODUCTION

The lithofacies used during mapping were discussed in Chapter 2, and the mineralogy, petrology and petrography were considered in Chapter 3. They will not be considered further and the lithofacies A, B_1, B_2, B_3, C and D will be used with no explanation, if and when needed.

Twenty three sections were measured at approximately one kilometre intervals along the Nuweveld Escarpment starting at the Leeu Gamka to Fraserburg tar road and going eastward. The position of the sections is shown in Diagram 3. Each section was designed to cover as much of the Poortjie horizon as possible, and the section lengths were only limited by the topography and lack of sandstones, (i.e. entry into the overlying mudstone units).

Sections were measured using a Jacob staff and level. Rock samples were collected on most sandstones, on some mudstones and wherever for any reason the outcrop had an unusual appearance. Both ends of the sections were beaconed, so that if desired they could be relocated. The sections were then photo-identified onto a 1:18 000 series of black and white aerial photographs. These locations were then transferred onto the 1:50000 series government aerial photographs and thence to the 1:50000 series topographical maps, which were used as the base plan for Diagram 3.

From the 1:18000 black and white photographs it was possible to photo-interpret the sandstones between the section lines. The tops and bases of the sandstones as shown in Diagram 2., are thus interpreted.

When compiling Diagram 2 it was assumed that sandstone 10 (an arbitrary number) was horizontal and the elevations of all the other sections were corrected to give a horizontal sandstone 10. This helped to correct for the effects of dip generated by the presence of bluffs and canyons along the escarpment.

Sandstone numbering is, as stated, arbitrary. No adequate stratigraphy has been evolved for mapping limited areas in the Beaufort Group, largely due to the limited lateral continuity of sandstones and of other lithologies which could be used as marker horizons. Thus Kübler (1977) described an A_1, A_2, A_3, and C sand, and Eddington and Harrison (1979) talk of the "Ryst Kuil Sand". In this study area the major sandstone was numbered 10 and subsequent sandstones decrease downward and increase up the succession.

4.2 AIMS OF THE SECTION MEASURING

As stated in the introduction part , the overall aim of this project was 'to determine the geometry of the sandstones and to define the sandstones if more than one type of geometry was found'. Clearly by measuring the sandstones at regular intervals some of the elements of this geometry can be examined. The following elements are examined:-

A) The sequence of the lithofacies and the contact types between them; this will provide data for Markovian type analysis and give some environmental indications.

B) The mudstone and siltstone : sandstone ratio which may provide data on the presence of fluvial and interfluvial zones as well as on the relationship between uranium mineralisation and the sandstone content of the host unit.

C) The continuity of the sandstones.

4.3 MARKOVIAN ANALYSIS

A Markov process is defined as a natural 'process which has a random element, but also exhibits an effect in which previous events influence, but do not rigidly control subsequent events' (Harbough and Bonham-Carter, 1970; p.98). It would therefore be hoped that a good general impression of the character of any fining upward cyclothems present could be gained using the pooled data from the 23 sections measured.

That such cyclothems exist has been clearly demonstrated by Kübler (1977), Cole (1979) and Stuart-Williams (1979). The purpose of this exercise is thus to demonstrate only that such cyclothems are present, to show that there is a strong Markovian element present and to determine the commonest lithofacies sequences.

A total of 1024 transisitions between the lithofacies (as discussed in Chapter 2) is considered. Repetitions of the same lithofacies, i.e. B_2 to B_2 are not considered even though they were recorded in the field. This is because variations between lithofacies C and D are not always easily recognised due to their poor outcrop and this would result in a weighting of the sandstone lithofacies.

One further problem encountered in doing such an analysis is created by the presence of massive sandstones - which are present in the sections but not afforded lithofacies status. Kübler (1977) for purposes of Markov analysis constructed a separate lithofacies for the structureless sandstones. The same approach is considered here and therefore a seventh lithofacies 'M' will be noted in Tables 3 - 6 and Diagram 4.

The presence of a first order Markov chain will be demonstrated using the transistion count matrix (Table 3) and a statistic which follows the"chi squared" distribution. The formula used is presented in Till (1974; p.75) and is:-

Table 3.

Upward Transition Count Matrix.

	A	B_1	B_2	B_3	M	C	D
A		21	36	9	18	1	-
B_1	13		23	39	12	2	15
B_2	18	20		69	57	5	31
B_3	7	20	22		21	8	141
M	12	14	58	29		10	27
C	-	-	2	1	1		24
D	36	28	60	63	49	2	
(S_j)	86	103	201	210	158	28	238
						t =	1024

Table 4.

Upward Transition Probability Matrix (P_{ij}).

	A	B_1	B_2	B_3	M	C	D
A		0,247	0,423	0,106	0,212	0,012	-
B_1	0,125		0,221	0,375	0,115	0,019	0,145
B_2	0,090	0,100		0,345	0,285	0,025	0,155
B_3	0,033	0,091	0,100		0,096	0,036	0,645
M	0,080	0,093	0,387	0,193		0,067	0,180
C	-	-	0,071	0,036	0,036		0,857
D	0,151	0,118	0,252	0,265	0,206	0,008	

$$- 2 \log_e \lambda = \sum_{i=1}^{m} \sum_{j=1}^{m} n_{ij} \log_e p_{ij}/p_j$$

at $(m-1)^2$ degrees of freedom, where

m = number of rows or columns in the transition count matrix,

n_{ij} = frequency in cell ij of the transition count matrix,

p_{ij} = the probability in cell ij, shown in the probability matrix (Table 4),

p_j = marginal probability in the jth column calculated from column tally divided by total tally (Table 4).

Using tables 3 and 4; m, n_{ij}, p_{ij} and p_j can be found and the statistic calculated. It is found that:-

$$- 2 \log_e \lambda = 743{,}78$$

An H_0 hypothesis is erected that suggests that the successive events, i.e. lithofacies are independent. If H_0 is rejected then H_a the alternative hypothesis is that they are not independent and form a Markov chain. The chi-squared value for $(m - 1)^2$ degrees of freedom at the 0,5% level is

$$\chi^2_{(0{,}005;\ 36\,d.f)} \simeq 60.$$

In this instance the value for $-2 \log_e \lambda$ obtained is much higher than the chi-squared value and H_0 must be rejected. The results would suggest that there is much less than 0,5% chance that the sequence of lithofacies observed are due to random processes and therefore H_a must be accepted, i.e. that there is a strong Markov property present.

Having demonstrated that a Markov property is present it should be possible to examine the most probable lithofacies sequences developed. This can be done by comparing the probabilities actually found (Table 4) with those that should be found if the processes were random.

An independent trials probability matrix (Table 5 is constructed, based on a formula published by Miall (1973) and used by Cole (1979). It is

$$r_{ij} = S_j/t$$

where

r_{ij} = the independent trails probability

t = total number of transitions,

S_j = the sum of the transition counts of the jth column.

More recently Miall (1977a) has used a slightly different formula, where

$$r_{ij} = S_j/(t-S_i)$$

and this gives a slightly different matrix.

Table 5.

Independent Trials Probability Matrix, (r_{ij}).

	A	B_1	B_2	B_3	M	C	D
A	0,084	0,100	0,196	0,205	0,154	0,027	0,235
B_1	0,084	0,100	0,196	0,205	0,154	0,027	0,235
B_2	0,084	0,100	0,196	0,205	0,154	0,027	0,235
B_3	0,084	0,100	0,196	0,205	0,154	0,027	0,235
M	0,084	0,100	0,196	0,205	0,154	0,027	0,235
C	0,084	0,100	0,196	0,205	0,154	0,027	0,235
D	0,084	0,100	0,196	0,205	0,154	0,027	0,235

Table 6.

Residual Transition Probabilities, (d_{ij}).

	A	B_1	B_2	B_3	M	C	D
A	-0,084	0,147	0,227	-0,099	0,058	-0,015	-0,235
B_1	0,041	-0,100	0,025	0,170	-0,039	-0,008	-0,090
B_2	0,006	-0,000	-0,196	0,140	0,131	-0,002	-0,080
B_3	-0,051	-0,009	-0,096	-0,205	-0,058	0,009	0,410
M	-0,004	-0,007	0,191	-0,012	-0,154	0,040	-0,055
C	-0,084	-0,100	-0,125	-0,169	-0,118	-0,027	0,622
D	0,067	0,018	0,056	0,060	0,052	-0,019	-0,235

Since it appears that a non random process is acting, by finding the residual values between the probability matrix and the independent trials matrix (Tables 4 and 5) it should be possible to see the transitions with the greatest deviation from that expected simply by subtracting one from the other. In Table 6 this has been done, and therefore

$$d_{ij} = P_{ij} - r_{ij}$$

where

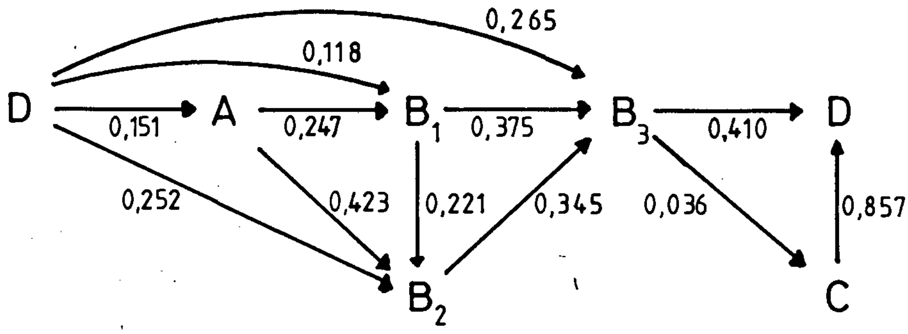
d_{ij} = the residual probability of cell ij. Those cells with the darker margins in Table 6, have positive residuals and represent those transitions with a higher than random probability of occurrence.

Assuming the presence of a cyclothem sequence based on D (the finest-grained lithofacies) then the sequence with the highest probability is DB_3D with a probability (p) = 0,455. As can be seen in Diagram 4, this figure agrees well with Allen (1970).

Diagram 4 is a tree diagram showing all those transitions shown as significant in Table 6. Note that the seventh state 'M' has been left out of the diagram since it was never given lithofacies status. This must be allowed for when comparing Diagram 4 and Table 6. Also note that only forward transitions are shown, thus for example $B_2 \rightarrow A$ is not shown as this is a backward transition (note Allen, 1970; p.305, Fig. 4).

Diag 4.

A Tree Diagram Showing Upward Facies Transition Probabilities



NOTE : Significant transitions are taken from the table of RESIDUAL TRANSITION PROBABILITIES. The numbers (e.g. 0,151) are the observed PROBABILITIES (Table 3) of transition between the states.

Some Typical Transitions.

	Mean p	(From ALLEN , 1970)
D A B_1 B_2 B_3 C D	0,371	–
D B_3 D	0,455	0,465
D B_3 C D	0,386	–
D B_2 B_3 D	0,336	0,403
D B_2 B_3 C D	0,372	–
D B_1 B_3 D	0,322	0,331
D B_1 B_2 B_3 D	0,289	0,450
D A B_1 B_3 D	0,295	–
D A B_2 B_3 D	0,332	–
D A B_2 B_3 C D	0,362	–
D B_1 B_2 B_3 C D	0,328	0,433
D B_1 B_3 C D	0,362	0,339

Using only forward transitions a number of common sequences have been examined and their probabilities worked out. These are tabulated in the second half of Diagram 4. It is apparent that with the exception of the DB_3D transition the other transitions all have similar probabilities suggesting considerable variability in the sandstone lithofacies. Having said this it is worth considering the comments made by Turner (1978, p.838) who states that "although Kübler (1977) considered the coarser member to be most variable it appears that the upper more argillaceous member shows the greater variability"; Turner (1978) suggests this is due to several overbank sub-environments. In view of the lack of good argillaceous outcrops this point must remain in contention.

The modal depositional cycles are probably DAB_1B_3CD with p = 0,333 and DAB_2B_3CD with p = 0,362. This is in line with Kübler (1977) who found a sequence DB_1B_3CD with p = 0,253 and DB_2B_3CD with p = 0,254 respectively (he did not use the conglomerate lithofacies,A) Further the $B_3 \rightarrow C$ transition is not that common (its p = 0,036) and this lack of lithofacies C will be considered again, as it may be environmentally diagnostic.

4.4 MUDSTONE + SILTSTONE : SANDSTONE RATIOS ; AN INDICATOR OF FLUVIAL AND INTERFLUVIAL ZONES?

In the Markov analysis just completed no account was taken of the thickness of the individual lithofacies, and it is not the intention to do so now. It is however possible that information can be gained from the ratio of the sandstone lithofacies (A, B_1, B_2, B_3) to the mudstone and siltstone lithofacies (C and D).

When mapping started little cognisance was taken of this ratio, since it had been assumed to remain fairly constant along the approximately 20 km of escarpment measured - even though it was recognised that local increases in the sandstone : mudstone ratio could be associated with uranium mineralisation (Kübler 1977). However as mapping proceeded it became apparent that the middle sections 13 - 17 (see diagram 2), were considerably more sandy than sections towards the margins of the mapped area. Further the individual sandstones in this central zone were not only more abundant than towards the margin but clearly tended to be more continuous, thicker, and greener - suggesting more extended reduction. Sands at the eastern and western margins were redder, muddier and thinner and tended to be more B_3 - rippled than equivalent sands in the central zone. The general impression gained whilst mapping was therefore one of a more fluvial central zone with interfluvial areas to the east and west.

It was suggested that if this were true, it could be demonstrated by examining the mudstone to sandstone ratio and the sandstone continuity. Such a hypothesis assumes that the fluvial system must remain static through time otherwise fluvial and interfluvial zones could not be 'stacked' one on top of the other.

Table 7 and Diagram 5 give the mudstone : sandstone ratios for the measured sections. It is apparent that sections 13 - 17 are much sandier than any of the other sections. In fact section 17 (174,5m long) has more sand than mudstone. If a moving mean of three adjacent sections is used (Diagram 5) then there is some evidence to suggest that a fluvial sandy zone may be present, in the central portion of the study area.

If the central zone (sections 13 - 17) is a more fluvial environment then it may be possible that the sandstones have a greater continuity than those in the interfluvial zones which would be more distal (in a lateral sense). This is considered in the next few paragraphs .

4.5 SANDSTONE CONTINUITY

It has been suggested that the central zone of the portion of escarpment measured may contain sandstones with a greater continuity (i.e. a greater lateral persistence) . To examine

Diag. 5 – Illustrating how the Mudstone and Siltstone : Sandstone Ratio may Define Fluvial and Interfluvial Zones.

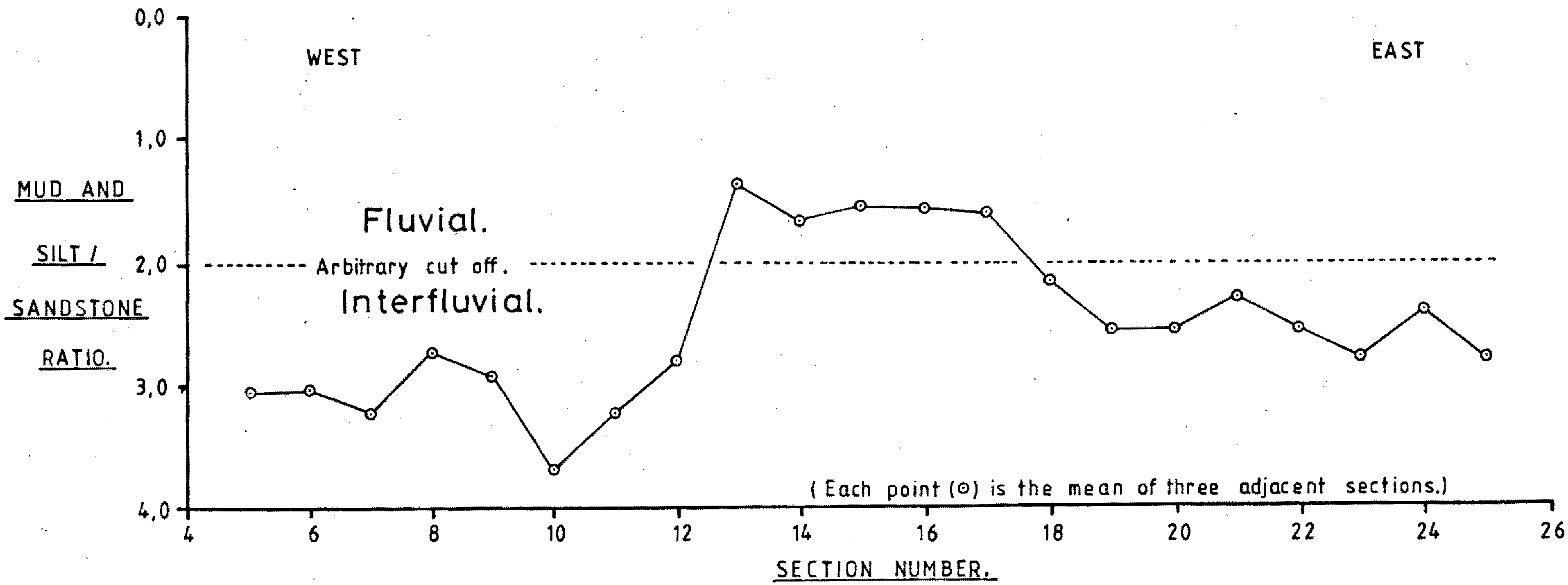


Table 7.

Sandstone / Mud + Silt Ratio

Section No:	Mud + Silt. (m)	Sandstone (m)	RATIO
4	62,0	25	1 : 2,48
5	110,5	43,5	1 : 2,54
6	89,5	21,5	1 : 4,16
7	76,5	31,5	1 : 2,43
8	77	25	1 : 3,08
9	118,5	44,5	1 : 2,66
10	127,5	42,5	1 : 3,00
11	113	21	1 : 5,38
12	70,5	54,5	1 : 1,29
13	124,5	72	1 : 1,73
14	100	90	1 : 1,11
15	137	63	1 : 2,17
16	126,5	80,5	1 : 1,57
17	86,5	88	1 : 0,98
18	142	61	1 : 2,33
19	131	40	1 : 3,27
20	102,5	47,5	1 : 2,16
21	89	38	1 : 2,34
22	100	41	1 : 2,44
23	108,5	36,5	1 : 2,97
24	129	42	1 : 3,07
25	76	58	1 : 1,31
26	133	32	1 : 4,15

Table 8.

Sandstone Continuity

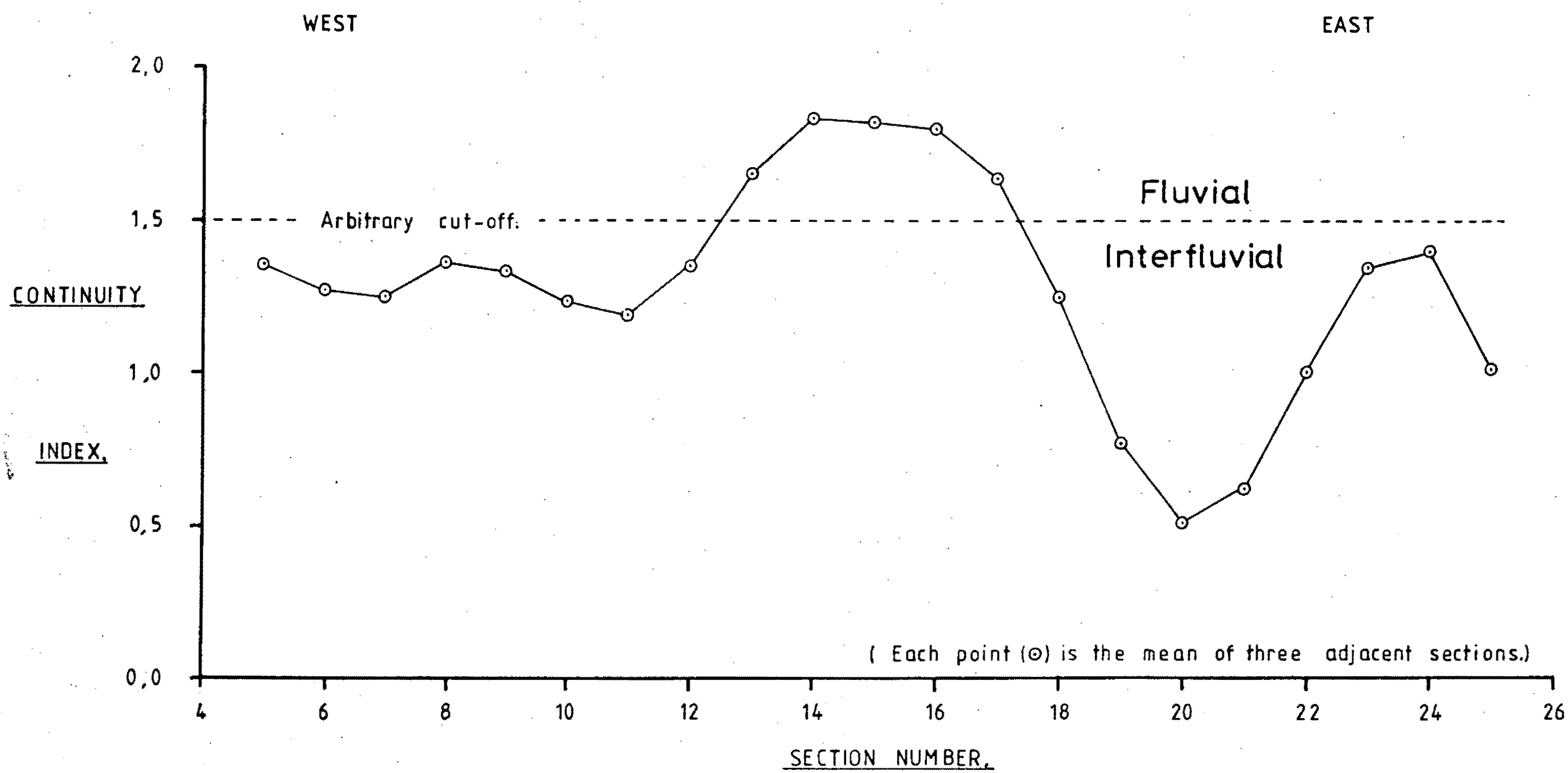
Section No.	No. of Contacts	No. of Sandstones	INDEX
4	4	2,5	1,6
5	8	6	1,33
6	8	7	1,14
7	8	6	1,33
8	9	7	1,29
9	8	5,5	1,45
10	5	4	1,25
11	3	3	1,00
12	6	4,5	1,33
13	13	7,5	1,73
14	16	8,5	1,88
15	15	8	1,87
16	12	7	1,71
17	11	6	1,83
18	9	6,5	1,38
19	3	5,5	0,55
20	2	5	0,40
21	3	5	0,60
22	7	8	0,87
23	8	5	1,60
24	8	5	1,60
25	8	8	1,00
26	1	1,5	0,66

this possibility a sandstone continuity index was evolved (see Appendix 11.2). Essentially on any one section if the sandstones are reaching adjacent sections the index approaches 2, if none of the sandstones reach adjacent sections the index is 0. The sandstone continuities are given in Table 8, and Diagram 6 plots these values as the moving mean of three adjacent values. The highest continuities are found on sections 13 - 17 lending credence to the earlier suggestion that these sandstones may lie in a more fluvial zone with interfluvial areas to the east and west.

This could suggest that there was some stability in the fluvial system through time and that rather than switching regularly the systems remained more static than previously realised. Such a suggestion is at variance with Turner (1978) who stated that "meander belts were narrow suggesting their early abandonment possibly in favour of gradient advantages offered by interfluvial basins," (author's emphasis).

A small size for the individual systems is evidenced by limited lateral sandstone continuity (as suggested by Turner, 1978) and also by the recognition of fluvial and interfluvial zones in the vertical succession. This question of the size of the fluvial systems will be raised again in Chapter 10.

Diag. 6 – Illustrating the use of a Continuity Index to help Define Fluvial and Interfluvial Zones.



Lastly it should be realised that the continuity index calculated is based on the interpretation of the aerial photographs. In most cases this means that small sandstones (such as those which could be generated by crevasse splays) are not considered. The continuities calculated can therefore be considered to equate with meander belts, but not with thinner sands, such as crevasse splays which _may_ have much greater lateral persistence.

5 PALAEOCURRENT ANALYSIS

5.1 INTRODUCTION

The value of palaeocurrent analysis lies in the determination of the direction of sediment transport for those sands under investigation. From the explorationist's viewpoint it can therefore provide information on the general direction of provenance of the sediments and the direction of elongation of the sandstone units (and thus of uranium orebodies - should these be present). Further it can provide information about the type of fluvial system which deposited the sandstone body e.g. sinuosity, and in conjunction with petrology and mineralogy, features such as tributary sand bodies can be recognised.

It is likely that a considerable amount of palaeocurrent analysis has been completed throughout the Beaufort as an off-shoot of uranium exploration; unfortunately little of this has been made available and much useful information is thus lost.

Theron (1973) published a generalised palaeocurrent map for the entire Beaufort, in which he gave a general north-east transport direction for the current study area.

Kübler (1977) examined an area some 15 kilometres north-east of the present study area and did a palaeocurrent analysis of his sandstones A, A_2 and A_3. He found respective means of 028°, 012°, and 013°.

Stuart-Williams (1979) examined sandstone 10 (at that stage called '0') and using 630 readings from all bedforms measured (see the discussion on bedform rank and order, later in this chapter), found a mean of 023°.

In this current study a number of sands covering a stratigraphic interval of some 100 - 200 m have been examined and will be discussed over the next few pages.

5.2 DATA GATHERING

The sands examined are tabulated in Table 9. Ideally on each sand examined, palaeocurrent measurements were taken every 10 m x 10m using a prismatic compass. In practice however, being so close to the Nuweveld Escarpment, no good plan outcrop of the sandstones was present and measurements were taken every 10 m along the sandstone scarp (but still in plan).

It was found that bedform preservation was not uniform. Frequently bedforms are absent for several hundred metres followed by a plethora. Certain elevated portions of sand on the top of sandstone bodies (considered allied to Gozes - see discussion in Chapter 10, and Photographs 23 and 24) are also structureless. This lack of structure is felt to be due to physical turbation caused by alternate wetting and drying in a sub-aerial environment and possibly to a lack of primary structure. Allowing for these problems, the grid was adhered to where possible.

A wide range of bedforms was used, the most common being the parting lineation (Potter and Pettijohn (1977, p.179 - 180), Yeakel (1959)); the primary current lineation (Allen, 1964) shown in Photograph 4; rib and furrow - shown in Photograph 5 (the micro cross laminations of Hamblin, (1961)); and trough cross bedding - Photograph 2 (pi type after Allen, 1963). Omikron cross-stratification (Allen, 1963) such as is normally associated with linguoid and transverse bars (Allen, 1968) was also used - see Photograph 7.

For each bedform used, the bedform type was recorded, the azimuth was noted and size estimated. Since most bedforms were seen in plan and not in section, size was taken as the bedform width, normal to palaeoflow (a criterion which excludes primary current lineation and parting lineations). This allows the use of a weighting factor (as discussed by Miall, 1974) should one be required.

Orientations for trough cross-beds and rib-and-furrow structures were taken as the trough axis, following Dott (1973). Primary current lineations and parting lineations were oriented using other directional bedforms.

In addition to bedform type, size and azimuth, two other features were recorded:- grid position, and the author's own genetic interpretation of the bedform. The genetic interpretation was considered important in that only too frequently, such information is lost in statistical data treatment. Thus large features such as transverse bars with classic planar tabular foresets were noted as transverse bars - a genetic nomenclature. Such nomenclature is of importance when determining the palaeo-environment and will be considered again in Chapter 10.

After collection, all azimuths, which were recorded as magnetic bearings, were corrected to true bearings and these were used in subsequent calculations. No dip corrections were made, all dips being less than 5^{o} (Potter and Pettijohn, 1977, p.371 and 394).

5.3. DATA TREATMENT

All data were processed in the field using an HP-33E calculator. Three programmes were devised and these are included in the Appendix (see Appendix 11.1.1., 11.1.2 and 11.1.3). In essence the three programmes will:-

A) convert magnetic compass readings to bearings based on true north (Appendix 11.1.1.)

B) find a resultant vector ($\bar{X}_V$) in degrees for (n) azimuths (Appendix 11.1.2), and

C) will count (n) azimuths to give a resultant vector ($\bar{X}_V$), the magnitude of this resultant vector in terms of a fraction (R) and as a percentage (L), the consistency ratio (R/n) and the standard deviation of the (n) azimuths i.e. (σ).

Both programmes b) and c) operate using Currays (1956) circular summation method - see Appendix 11.1.2. for a discussion. Programme b) terminates with a true bearing, whereas programme c) gives the bearing in terms of Sin θ and Cos θ and requires further data handling.

Due to the large number of sandstones examined it was decided not to construct rose diagrams for all the sandstones, but only for those used as specific examples. All the results are however tabulated in Table 9, and as can be seen a mean palaeo-vector of 032^{o} was found, which agrees reasonably well with Kübler (1977) and Theron (1973)

It should be pointed out that in Table 9 there are numerous sands not considered in Diagram 2 because many of these lie between section lines. Further not all the sandstones shown in Diagram 2 are tabulated in Table 9. In all, 24 sandstones are tabulated in Table 9.

5.4 RESULTS

One feature of Table 9 that is immediately obvious is the variability of the palaeoflow directions ($\bar{X}_v$) in different sandstones. This variability ranges from westerly (e.g. sandstones 16, 11 and 13*), through north to easterly (e.g. sandstones 10 and 17). No mean vector has a southerly palaeoflow direction and clearly therefore the provenance area lay to the south or south-west of the study area: this agrees with the mean palaeoflow of 032^o.

The consistency ratio (R/n) can be considered as the fraction or percentage of vectors that flow in the direction of the mean palaeoflow. If this ratio is examined (see Table 9, (R/n) and (L)), it is found that some sandstones have very high consistencies, suggesting that all the bedforms migrated almost parallel to each other, whilst others have low consistency ratios. Thus sandstone 13* has a consistency ratio of 0,9839 (i.e. L = 98,39%) for 45 readings, whilst sandstone 10 has a consistency ratio of 0,4837

Table 9.

Sandstone Palaeocurrent Data.

(The Sandstones are Arranged Stratigraphically.)

SANDSTONE NUMBER	N (No. of readings)	R (Vector Magnitude)	R/N (Consistency ratio)	L (Resultant vector in percent)	σ° (Standard deviation)	θ° (Azimuth of resultant vector)
17b	14	8,16	0,583	58,30	52,33	342
17a	66	59,87	0,907	90,71	24,70	101
17	54	51,64	0,956	95,64	16,93	86
16b	28	19,67	0,702	70,24	44,20	44
16	264	157,80	0,598	59,77	51,39	314
15	201	178,61	0,889	88,86	27,05	34
14b	41	28,01	0,683	68,33	45,60	350
14a	22	12,44	0,566	56,56	53,41	328
14	104	93,71	0,901	90,11	25,49	349
13*	45	44,28	0,984	98,39	10,26	258
13b	17	12,21	0,718	71,80	43,03	112
13	97	90,34	0,931	93,12	21,25	68
13c	19	15,52	0,817	81,68	34,68	93
13a	32	29,79	0,931	93,08	21,32	2
12	156	140,69	0,902	90,19	25,38	85
11c	209	185,12	0,886	88,57	27,39	74
11b	58	39,40	0,679	67,93	45,88	55
11x	43	39,64	0,922	92,18	22,67	73
11z	18	17,81	0,989	98,94	8,32	223
11a	23	21,11	0,918	91,79	23,21	79
11w	16	15,24	0,952	95,25	17,66	350
11	44	38,81	0,882	88,21	27,82	314
11y	20	13,28	0,664	66,39	46,97	6
10	1701	822,84	0,484	48,37	58,22	16
TOTAL 'N' =	3292				Mean Azimuth =	32

Dark borders around the sandstone number denote a TRANSITIONAL SANDSTONE.

(i.e. L = 48,37%). This shows that some sandstones have larger variations in palaeoflow direction for the measured bedforms, than others. This variability in palaeoflow direction is also reflected by the standard deviation (σ). Sandstone 13* thus has $\sigma = 10,26^{0}$ whilst sandstone 10 has $\sigma = 58,22^{0}$. This would suggest that the standard deviation (σ), the consistency ratio (R/n) and the resultant vector in percent (L) must relate to the sandstone sinuosity since they are reflecting the primary bedform variability. This concept will be discussed in the next section.

5.5 SANDSTONE SINUOSITY

Sinuosity is defined as the ratio of channel length to meander axis or valley length - see Diagram 7.1 (Brice, 1964; page 25) where channel length is normally taken as thalweg length. In modern rivers the sinuosity index (P) can be readily determined (Leopold and Wolman, 1957) as seen in Diagram 7.1. However in palaeo-fluvial systems the thalweg cannot in most cases be identified and a more sophisticated approach must be used.

Langbein and Leopold (1966, p.H5) provide an empirical equation relating the angular change of the channel to sinuosity. Miall (1976) rewrites their equation in degrees, not radians and finds that the sinuosity (P) is:-

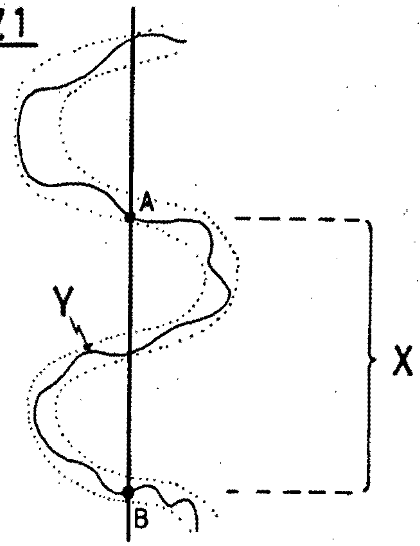
$$P = 1 / 1 - (\theta / 252)^{2}$$

Where θ is the maximum angular range of the mean azimuth (i.e.

Diag. 7.

Methods of Determining Sinuosity.

Diag. 7.1



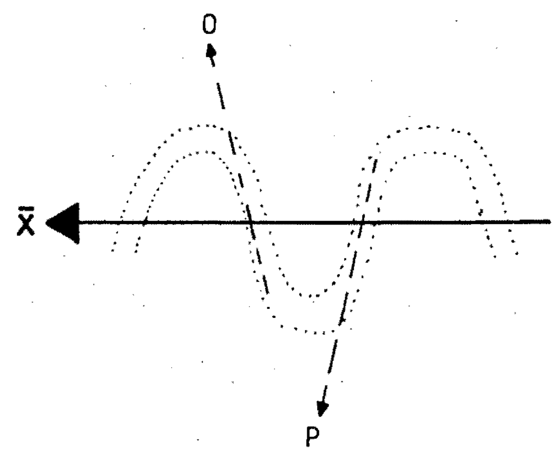
SINUOSITY INDEX (P) = $\frac{Y}{X}$

Diag. 7.2

SINUOSITY INDEX (P) = $\frac{1}{[1-(\theta/252)^2]}$

Where θ is the maximum range of the mean azimuth of the channel (i.e. O to P).

(after Miall, 1976)



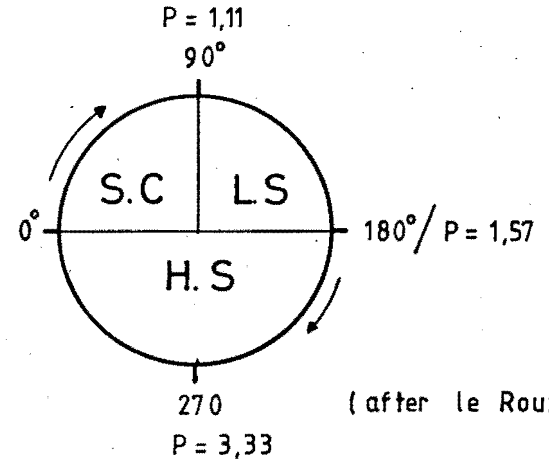
Diag. 7.3

For further detail see the text.

S.C - Straight channel.

L.S - Low sinuosity channel.

H.S - High sinuosity channel.



(after le Roux, 1979)

the channel); this is shown in Diagram 7.2. Since θ is the mean angular range of the channel azimuth, this again means that the geologist wishing to determine the sinuosity of a sandstone requires to define the channel. He is thus needing to determine a rank 3 variability (after Miall, 1974) whilst working with rank 5 and 6 bedforms. Miall (1976) in an analysis of some vertical profiles from Banks Island, Arctic Canada, determined the maximum angular range of channel movements by calculating moving means from vertical profiles, assuming that the variability encountered in the vertical sections was caused by larger scale trends than those which generate 'in channel' variability, such as meander migration. The idea was that the use of a large enough moving average would remove set-to-set (i.e. in-channel) variability. Such an approach is not feasible in the Beaufort for two reasons. Firstly Miall (1976) was working in only partly consolidated Cretaceous sediments, and was therefore easily able to determine the azimuth of individual sets, and secondly he had a large number of set-to-set changes. The approach used by Miall (1976) to determine sinuosity is not thus applicable to Beaufort Group sediments.

Le Roux (1979) proposed a measure of channel sinuosity based on the angular variability of the channel (see Diagram 7.3.) He suggested that an angular variability of less than 90^{o} be called a straight channel, one between 90^{o} and 180^{o} be called low sinuosity, and a variability greater than 180^{o}, high sinuosity. However, as he states, "because of local variations in the main stream caused by, for example, eddies or channel bars, palaeocurrent directions constituting less than a certain percentage of the total should be eliminated in order to bring out the meaningful, main flow directions". Le Roux (1979) then suggests that the palaeocurrent direction measured be divided into 10^{o} segments and that the segment with the most readings be taken as 100%. Other segments, are then expressed as a percentage of this value; all segments which have 10% or less of the 100% segment should be dropped.

Le Roux's (1979) suggestion is useable, although it will be shown that a 10% cut-off is incorrect. Further, there is no evidence that the channels classified using Le Roux's (1979) scheme are classified correctly when compared to modern fluvial systems. In fact this whole discussion suggests just how difficult it is to determine sinuosity when no primary channel can be observed, and the geologist only has access to minor bedforms.

Certain sands were easily classified: thus the Palmietfontein sand (see Diagram 8) is clearly a straight channel, with the total variability of 131 readings being only 094^{o}, even allowing for upstream channel bifurcation. On the other hand sandstone 10 has a total variability of greater than 360^{o} and a standard deviation of $\pm 58,22^{o}$ (compared with $\sigma = \pm 20,63$ for the Palmietfontein sand), suggesting a high sinuosity.

PLATE III

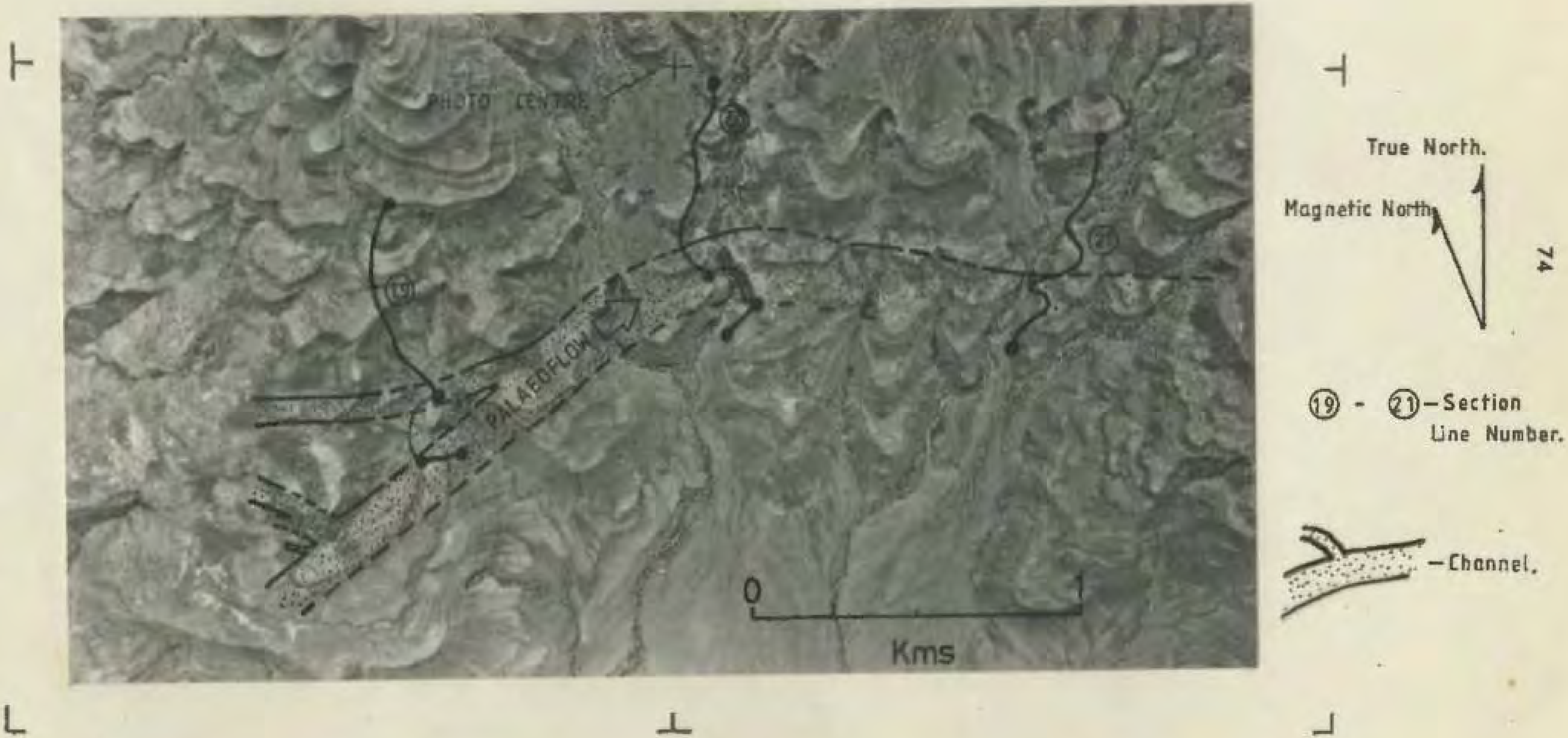
Photograph

8 An aerial view of the Palmietfontein straight channel. Note the upstream bifurcation, and the clearly defined channel banks.
The photograph scale is approximately 1:18000

Diagram and Photograph 8.

Straight Channels on the farm PALMIETFONTEIN.

Based on aerial photograph 7417 - see text for details



So far high and low sinuosity have not been defined as a sinuosity ratio. Miall (1976) considers meandering rivers (high sinuosity?) to have a sinuosity of greater than 1,3 and braided rivers (low sinuosity?) are thus less than 1.3. He then suggests that straight channels have P = <1,5, which means that between P = 1,3 and 1,5 straight and meandering channels would be indistinguishable using the formula in Diagram 7.2. Leopold et al (1964) and Leopold and Wolman (1957) suggested that meandering rivers had a P = >1,5 whilst braided were P = <1,5. This suggests then that even if the sinuosity can be determined for a channel sandstone, the sinuosity is not necessarily diagnostic of the fluvial regime. For this reason an alternative approach to sinuosity is suggested.

5.6 AN ALTERNATIVE APPROACH TO SINUOSITY

From the previous discussion it can be seen that the determination of sinuosity by relating it to the variability of the primary channel azimuth is fraught with problems. Ideally then the classic concepts should be borne in mind, but an alternative method of deriving the sinuosity should be sought, which could be used in examining Beaufort Group sandstones.

Intuitively it is recognised that the higher the sinuosity of a channel system, the greater will be the bedform variability, regardless of preservation potential and bedform hierarchy. This would suggest that bedform variability as used by Le Roux (1979) is suggestive of sinuosity. At the same time the use of a 10% cut-off is totally arbitrary. What is required should be a natural cut-off, and the standard deviation (σ) is proposed.

Clearly the relationship of the standard deviation to channel sinuosity will not be direct, and it is not the intention here to decide on the relationship between the sinuosity and the standard deviation. What is however intended is to demonstrate how, using the standard deviation, Beaufort Group sandstones can be classified into two discrete types.

In Table 9, the standard deviation for all bedforms on each sand is given. It can be seen that with the exception of sandstone 13c, all the sandstones have a standard deviation either greater than $\pm 40^{0}$ or less than $\pm 30^{0}$. Sands with a standard deviation greater than 40^{0} are shown with dark borders in Table 9, and are considered high sinuosity and termed 'Transitional' sands. Those with a standard deviation of less than 40^{0} are considered to have a low sinuosity. It is apparent, and this will become clearer, that the two sand types represent clearly different fluvial regimes.

Let it again be stressed however that the use of a standard deviation of $\pm 40^{0}$ to separate sandstones is not a criterion suggested for general use. It works well in the study area but could only be used elsewhere after careful consideration. Ideally many modern systems should be examined and empirical limits set on the range of standard deviations used for different types of fluvial systems.

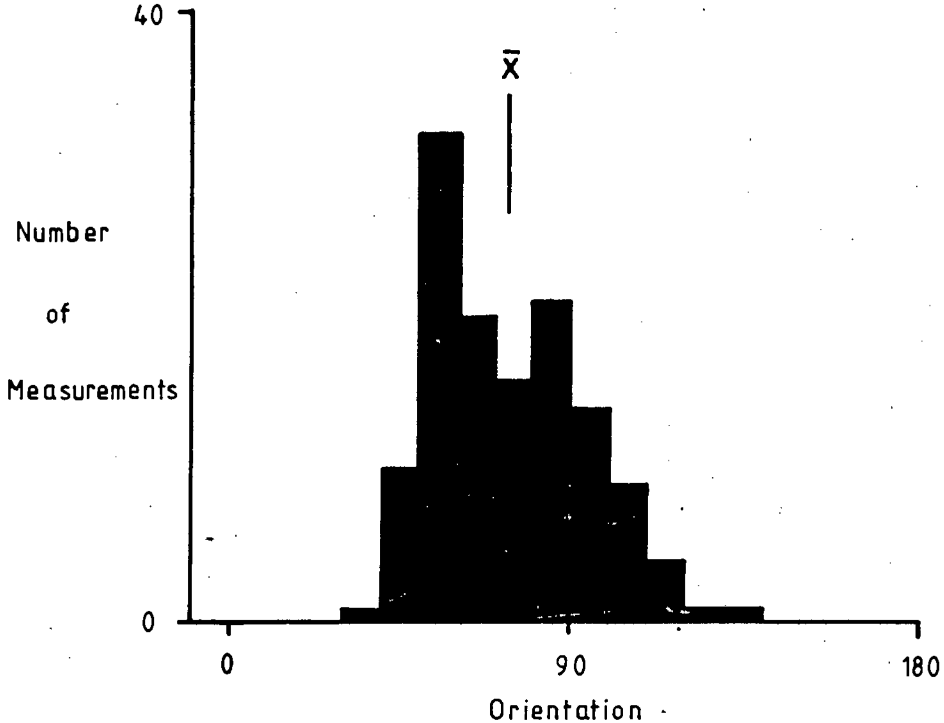
Accepting the limitations imposed in the last paragraph the palaeocurrent patterns of three different sandstones (the Palmietfontein sand, Sandstone 15 and Sandstone 10) will be examined. These are considered to represent a straight channel, a typical low sinuosity channel sandstone and a transitional sandstone respectively.

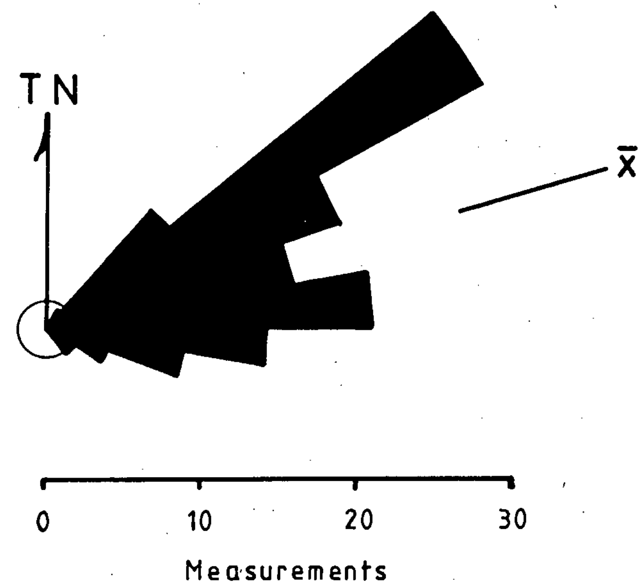
The Palmietfontein sandstone is shown in Diagram 8 and Photograph 8, and its associated palaeocurrent data in Diagram 9. Total variability of the bedforms in this straight channel system is 094^{o} and this can be seen to be little more than the variability of the channels. The bedforms within the channel were thus migrating essentially parallel to the banks of the system. Applying Le Roux's (1979) criteria, such a channel system is classified as straight. If formula 7.1. is used (see Diagram 7.1), the sinuosity of the main channel is found to be 1,07. If formula 7.2 (see Diagram 7.2) is used then a sinuosity of 1,03 is found. Note that because the channel is seen in plan, formulae 7.1 and 7.2 can be used in this case.

Sandstone 15 (see Table 9, and Diagram 10) is classified by both Le Roux (1979) and this author as a low sinuosity sandstone, since

Diag. 9 – Straight.

Distribution Frequency and a Rose Diagram of all Bedforms Measured on the PALMIETFONTEIN Sandstone.





NUMBER OF MEASUREMENTS = 131

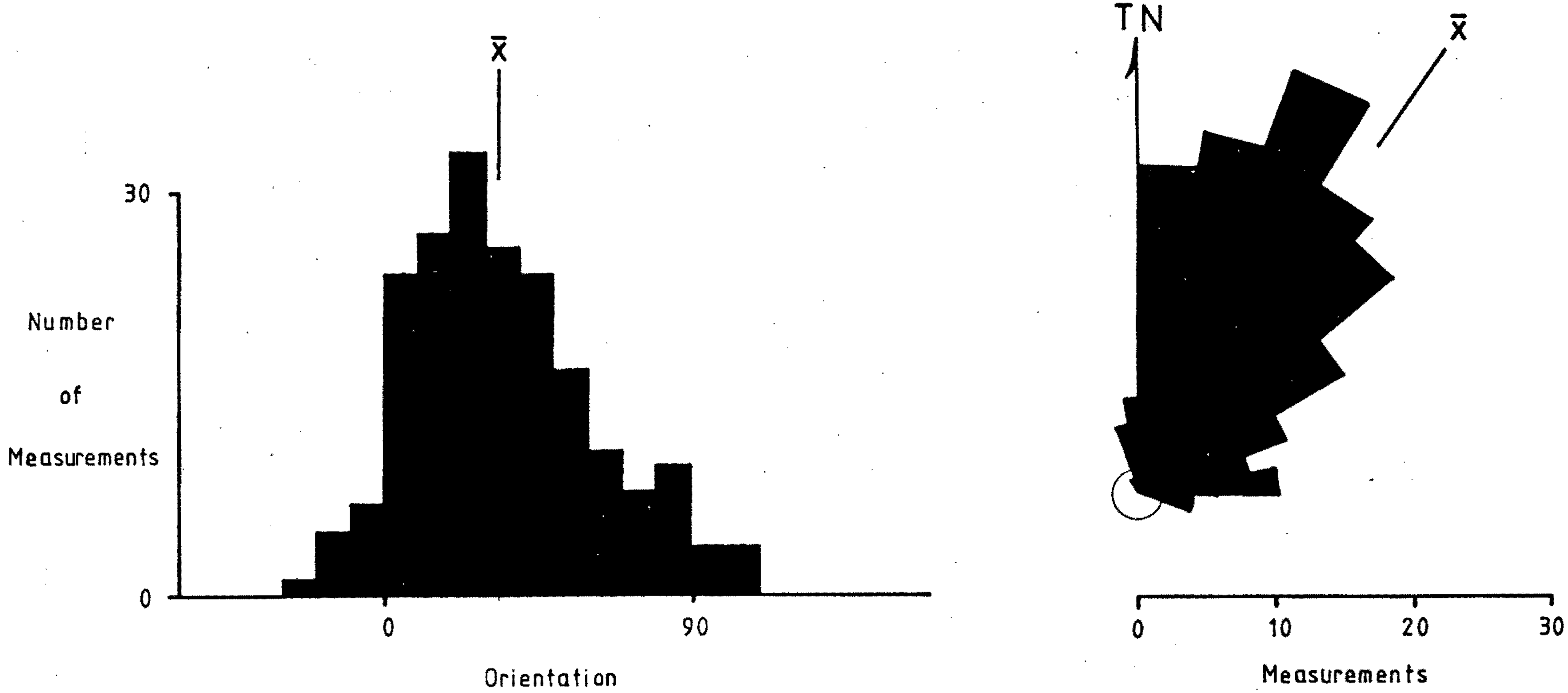
CONSISTENCY RATIO = 0,93

RANGE = 094°

STANDARD DEVIATION = 20,63°

Diag. 10 – Low Sinuosity.

Distribution Frequency and a Rose Diagram of all Bedforms Measured on SANDSTONE 15.



NUMBER OF MEASUREMENTS = 201

CONSISTENCY RATIO = 0,88

RANGE = 134°

STANDARD DEVIATION = 27,05°

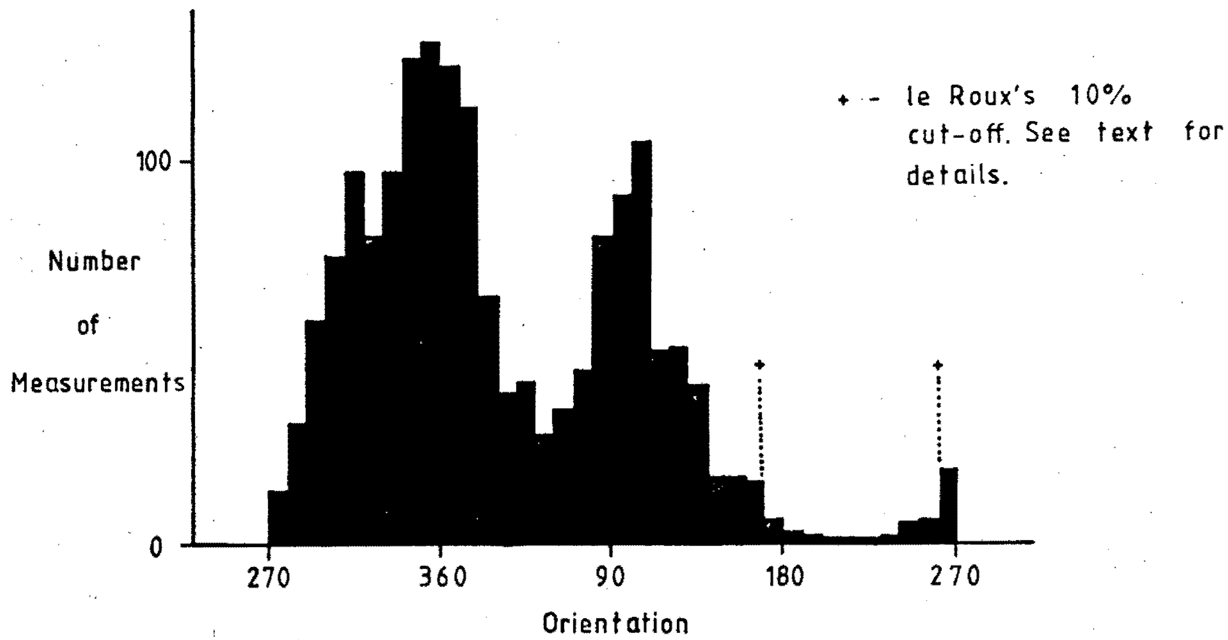
it has an angular range at the 10% cut-off of between 90^{o} - 180^{o} and a standard deviation of less than 40^{o}. The low sinuosity sandstones and the straight channel sandstones are considered to be gradational and are the numerically dominant sandstone types in the Poortjie package examined. In Table 9 these two sandstone types are shown with light borders. Sandstone 15 has a total variability of 134^{o} and there may be some tendency for the data to be less peaked, suggesting a greater primary bedform variability than seen in the Palmietfontein sandstone. (Diagram 8 and 9). There is no bimodality present in these two sand types.

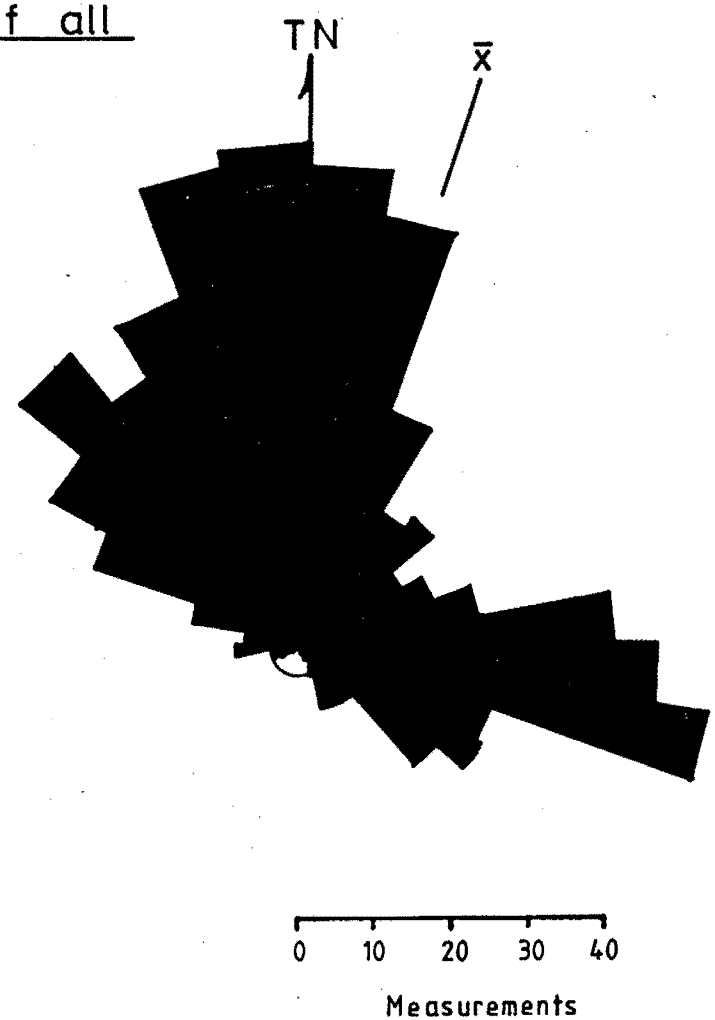
Diagram 11 shows the palaeocurrent data for Sandstone 10. Immediately two major differences are noted between this, a transitional sand (see Table 9), and the previous two sands discussed. These are a) a marked bimodality and b) a very wide variability in palaeoflow (here it is at least 360^{o}) direction. Such a marked deviation in character from the previous sandstone types suggests a radical difference in fluvial style and ~~thse~~ these sands are considered to be of a 'transitional' high sinuosity type.

It is interesting to note that if Le Roux's (1979) 10% cut-off is applied (see Diagram 11) a channel variability of 270^{o} is found. Such a variability cannot be used in formula 7.2 (Diagram 7.2), which was based on empirical observation (Langbein and Leopold, 1966). Thus his classification may be correct but his 10% cut-off is not in this instance applicable.

Diag. 11.– Transitional.

Distribution Frequency and a Rose Diagram of all Bedforms Measured on SANDSTONE 10.





NUMBER OF MEASUREMENTS = 1701

CONSISTENCY RATIO = 0,48

RANGE = > 360°

STANDARD DEVIATION = 58,2°

Having suggested that Sandstone 10 is high sinuosity it would be hoped that some evidence of meandering could be found on the ground. Such was in fact the case (see Diagram 12) and this will be discussed in Chapter 6.3..

5.7 WHAT IS THE MEAN PALAEOFLOW DIRECTION OF SANDSTONE 10?

The mean palaeoflow direction ($\bar{X}_v$) for Sandstone 10 (see Table 9) is 023^o. This is however an arithmetic mean derived from 1701 readings taken in the field. It assumes that the bedforms measured are a representative sample of the entire population and that they are evenly distributed. Is this however, correct? Diagram 11, clearly demonstrates that the distribution is bimodal, but that one mode is dominant. Further, in Diagram 12 (see Chapter 6.3) it can be seen that the meanders mapped all migrated eastward, such that only western meander loops are preserved. We may not therefore be obtaining a representative distribution of the total bedform population since preservation of the bedforms may be biased in favour of western meander loops.

It is thus tentatively suggested that in a sandstone with a clear bimodality generated by meandering, a different approach be used and the arithmetic mean ignored. It is alternatively proposed that the lowest point of the saddle between the two modes be used, since theoretical considerations would suggest that it is nearer to the true palaeo-mean. Such a suggestion would give $\bar{X} \simeq 50^o$. The reciprocal value of 230^o lies in the zone of minimum readings, particularly when allowance is made for biasing of the western lobe.

5.8 INTRABASINAL TRIBUTARIES?

Evidence was given in section 1.7 to suggest that the environment was semi-arid to arid. Moreover Turner (1978) indicated that the Beaufort was deposited in an intracratonic basin. Is it not therefore probable that since the study area is several hundred kilometres from the provenance area (Theron, 1973), both ephemeral intrabasinal drainages and more perennial rivers fed from the provenance area will be present?

The major sandstones (which are almost exclusively the so-called transitional sands) would appear to be fairly perennial in that they do support some vegetation, which ephemeral systems in the Permian may not have done. Further, their meandering nature may suggest some degree of stability of flow. They are also thicker, have the largest lateral development, tend to be strongly reduced, and are fairly strongly and deeply scoured. It could then be suggested that the transitional sands represent the larger fluvial systems, with relatively steady flow regimes, which are perennial and fed from the provenance area.

On the other hand, the low sinuosity systems are generally strongly oxidised, and show little evidence for vegetation having developed on them. They tend to be B_2 lithofacies - dominant and have fairly flat scoured bases, suggesting a tendency to sheet flow. These sands could well be intrabasinal tributaries in an arid environment which only flowed seasonally or more probably after heavy localised rainfall in the basin.

The palaeocurrent evidence for such a suggestion is not conclusive. However there does seem to be a suggestion that the low sinuosity and straight channel sands have a greater range of azimuths than the transitional sands, particularly if sandstone 13b (a very thin, small sand of limited extent) is ignored. Then the transitional sands range from 314^{o} - 44^{o} , some 90^{o}; whereas the low sinuosity and straight channel sands range from 258^{o} - 101^{o}, some 203^{o}.

Ignoring the presence of sheet type sands (i.e. crevasse splays, etc.), the belief that two separate types of sand (transitional and low sinuosity) representing different fluvial styles are present, does answer a number of queries. Thus the oxidised nature of the smaller sandstones and reduced nature of the larger is explained. Further such a model partially explains the presence of most major uranium anomalies in the major sands - since these sands have the vital carbon reductants. This will be considered in greater detail in Chapters 8 and 9.

6 PLAN GEOLOGY

6.1 INTRODUCTION

Sinuosity has been discussed and it has been demonstrated that channels within the portion of the Beaufort Group examined, vary from those with very low standard deviations - such as that which generated the Palmietfontein sand (Diagram 8 and Photograph 8) to those with very high standard deviations - such as sandstone 10 (Diagram 11 and 12, and Table 9.)

6.2 STRAIGHT AND LOW SINUOSITY CHANNELS

Sandstones falling within this category (i.e. considered as being generated by straight and low sinuosity channels) are defined as having standard deviations of less than $\pm 40^{o}$ (see Chapter 5.6). A typical straight channel sandstone has already been mentioned (Chapter 5.6) and is illustrated in Diagram 8 and Photograph 8. This is by no means the only straight channel in the study area, but is used for demonstration purposes since it has the best plan exposure.

In Diagram 8 and Photograph 8, it can be seen that the total variability of the system is very low (094^{o}) and that upstream bifurcation is pronounced. Banks are well exposed and easily mapped and it is clear that the sand is incised fairly strongly into the underlying mudstone. The detailed geometry will be discussed in Chapter 7.2.

Sandstones 11c, 13 and 15 also have clear evidence of incision although their standard deviations are marginally higher and they are considered low sinuosity rather than straight channel sands (see Chapter 5.6). Their banks are equally well defined. Clear evidence of bed-load transport is common, with well developed trough cross-bed swarms and B_2 lithofacies suggesting ephemerality and braiding, although this will be discussed in detail in Chapter 7.2.

6.3 TRANSITIONAL SANDSTONES

These sandstones as stated have a standard deviation of greater than $\pm 40^{\circ}$. A number of features can be recognised in these sandstones, and Sandstone 10, being the biggest examined, will be used as an example.

Initially, interest in Sandstone 10 was generated as the result of the finding of a major radiometric anomaly, located by airborne radiometrics. Mapping was commenced over the anomalous zone, but was not very successful due to a lack of interpretation of the sandstone's internal geometry. It was however recognised even at this stage that Sandstone 10 thinned and terminated to the west, thickened to the east and had distinct convex based zones of thickening. Subsequent mapping of the sandstone showed that both the eastern and western margins of Sandstone 10 thinned and became very B_2 - dominant, suggesting sheet sandstones.

This was borne out by the examination of the marginal palaeocurrents, which although fairly variable, showed more consistency than sandstones in the thicker central zone of sandstone 10 (see 'A' and 'B' in Diagram 12). These marginal sheet sandstones could be analagous to crevasse splays, but the term has deliberately not been used, since to date only rare levees through which a crevasse could form, have been identified.

A number of radiometric anomalies were eventually located on Sandstone 10, but surprisingly, abundant carbon was only located at two places - at the original radiometric anomaly at the western side of Sandstone 10, and towards the eastern margin. This carbon distribution is considered extremely important (see Chapter 9.2) and is believed to be controlled by the fluvial style of the river. Carbon is believed to be dominantly allocthonous (due to the abundance of carbon macerals, evidence of rounding on larger vegetation and lack of evidence for autocthonous vegetation) and its position in the sandstone body is believed to be controlled by two processes, oxidation and reworking. Thus carbon in the sheet sandstone (i.e. extreme east and west sides of the sandstone body) was oxidised out, whilst carbon in the thicker zones of the sandstone was reworked out by the meandering demonstrated in Diagram 12, and moved both downstream and towards the sand margins. It appears that in Sandstone 10 there is strong symmetry of carbon distribution present, with essentially carbon-free margins and central zone, and two symmetrical zones of carbon-rich sand between them.

This symmetry is also reflected by black sands (sands with a high concentration of opaque heavies). These black sands were found to lie fractionally closer to the sandstone margins than the carbon-rich zones. Their formation is unclear, but it is likely that they are controlled in a similar manner to the carbon in the system, being reworked by meandering in the central portion and accumulated during flood periods.

That the central zone of Sandstone 10 is meandering is shown in Diagram 12, and was discussed in Chapter 5.6. This meandering was initially identified by plotting palaeocurrent readings onto a base plan. Later, with practice, it became possible to identify meander-channels without the laborious plotting used initially. Using this technique, five meander loops were identified numbered 1 to 5 - see Diagram 12 (in the map folder at the back). Each meander loop is erosive into its predecessor, thus meander loop 1 is eroded by 2, etc. It appears that the loops represent a dominantly northward and eastward migration of the channel, which is logical since the palaeoflow is about north north-east (NNE).

This meandering suggests a high sinuosity stream as defined by Allen (1965, p.96). At the same time many of the connotations attached to present day meandering systems are not applicable to Beaufort Group fluvial systems and the use of the term meandering suggests <u>only</u> a high primary channel sinuosity.

Channel X (Diagram 12) is a strongly erosive convex-based channel, filled with very fine-grained sand and silt/mud, which flowed dominantly eastward, and is clearly erosive into Sandstone 10 meander loops 1 and 2, but is in turn eroded by 3. It is some 200 - 300 m wide and is seen as an intrabasinal tributary channel.

That it has to some extent been backfilled with fine-grained sand from Sandstone 10 is evidenced by a clear bimodality of 180^{0} (up and down channel) which has produced 'herringbone cross-beds', and by a fining of grain size away from Sandstone 10. Its formation appears to have involved an initial major erosive event with flow from west to east. Subsequent flow was of a much lower energy and involved both west-to-east and east-to-west flow.

Channel X should be an ideal location for luxurious vegetation, being low in a major sandstone body and containing a high percentage of fines. That it is not, and displays only very week bioturbation in grey to maroon silts, implies that vegetation was limited throughout the system, as suggested earlier. This will be discussed further in Chapter 10.

Meander loops 1 and 2 are interesting in that they can be mapped clearly on the ground, yet the point bar surfaces show no vegetation and little or no evidence of levee or ridge and swale development.

In fact point bar surfaces are very flat and B_2 - lithofacies dominates, suggesting that at certain flow regimes flow was straight over the point bar surface (see the palaeoflows inside meander loop 1 and between loops 2 and 3). This point will be considered further in Chapter 7.

7 SANDSTONE GEOMETRY

7.1 INTRODUCTION

In Chapter 5.6 it was demonstrated that, using a standard deviation of $\pm 40^{\circ}$ as a critical value, it was possible to split the sandstones examined in Table 9, into two discrete types, i.e. high sinuosity sands, called transitional sandstones, and low sinuosity and straight channel sands. It was further suggested in Chapter 5.6 that these two different types could represent perennial fluvial systems and ephemeral tributaries respectively. It is the intention of this chapter to examine this concept further and to look at the internal geometry of these sands such that in Chapter 10 it will be possible to try and interpret the depositional environment.

7.2 LOW SINUOSITY AND STRAIGHT CHANNEL SANDSTONES

The classic straight sandstone has already been examined briefly (see Diagram 8), but needs to be considered in more detail. Photograph 8 and Diagram 8 show the Palmietfontein sandstone, the overlay giving the scale and the channel banks. As can be seen the channel has a strike length of approximately 3 kms. The smaller tributary sandstones have well defined banks and a maximum sand thickness of about 1 m. They comprise very muddy maroon sands with extensive development of B_3 - (rib and furrow) rippling. Bioturbation is rare. They have a weak basal scour and are very shallowly convex-based. The banks rise at about 20°

and as can be seen on Photographs 9 and 10, no sand overtops the banks. B_2 lithofacies is present but is subordinate to B_3.

The main channel sandstone has a width of 300 - 400 m and a maximum sand thickness of 10 metres. The sand is multi-storied and no single event was responsible for more than a few metres of sand. The banks, like those of the tributary sandstones, have a very shallow inward dip, of generally much less than 20^{o} and frequently less than 5^{o} (see Photographs 9 and 10). As it rises up the bank, the sandstone thins but never overtops the bank - in fact at no location in this straight channel system was sand seen overtopping the bank, a point which could suggest that the channel was fairly deeply incised.

As the sand thins going up the bank it changes from being dominated by the B_2 lithofacies, to a dominant B_3 lithofacies. Rib and furrow structures predominate with occasional sinuous ripples; they tend to run at a tangent across the bank due to variable water depth along the ripple length.

The underlying mudstone, particularly at the banks, is reduced over several centimetres to a pale green colour; this was originally assumed to be due to organics, but the lack of bioturbation in most places suggests that this reduction is diagenetic.

Within the main channel, longitudinal bars (Miall, 1977) are well developed (see Photograph 11) in the direction of palaeoflow. No

PLATE IV

Photograph

9 The northern bank of the Palmietfontein channel sandstone. Note how the sandstone clearly thins from right to left as it gently 'climbs' the channel bank.

10 This is the same sandstone as in Photograph 9, but only the very uppermost portion of the bank. The sand disappears to the left of the photograph.

11 A longitudinal bar on the Palmietfontein straight channel sandstone. The bar is being viewed slightly oblique to palaeoflow which is from the upper right to lower left of the photograph.

12 The southern bank of Sandstone 11c. The true bank is below the standing figure and not the sand seen thinning further to the right.

PLATE IV.

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side bars were noted; multi-storied stacking is evidenced by parallel accretion surfaces along the channel margin, indicating that no meandering thalweg was present and that vertical accretion was occurring within the convex channel confines. This, combined with strong basal scour and an almost total lack of the B_1 litho-facies, could suggest a fairly well incised ephemeral channel which had a high flow velocity, associated with a limited volume of water and sand in transport. This interpretation is reached because although the channel is fairly large, each flood event appears to have brought in only a small volume of sand.

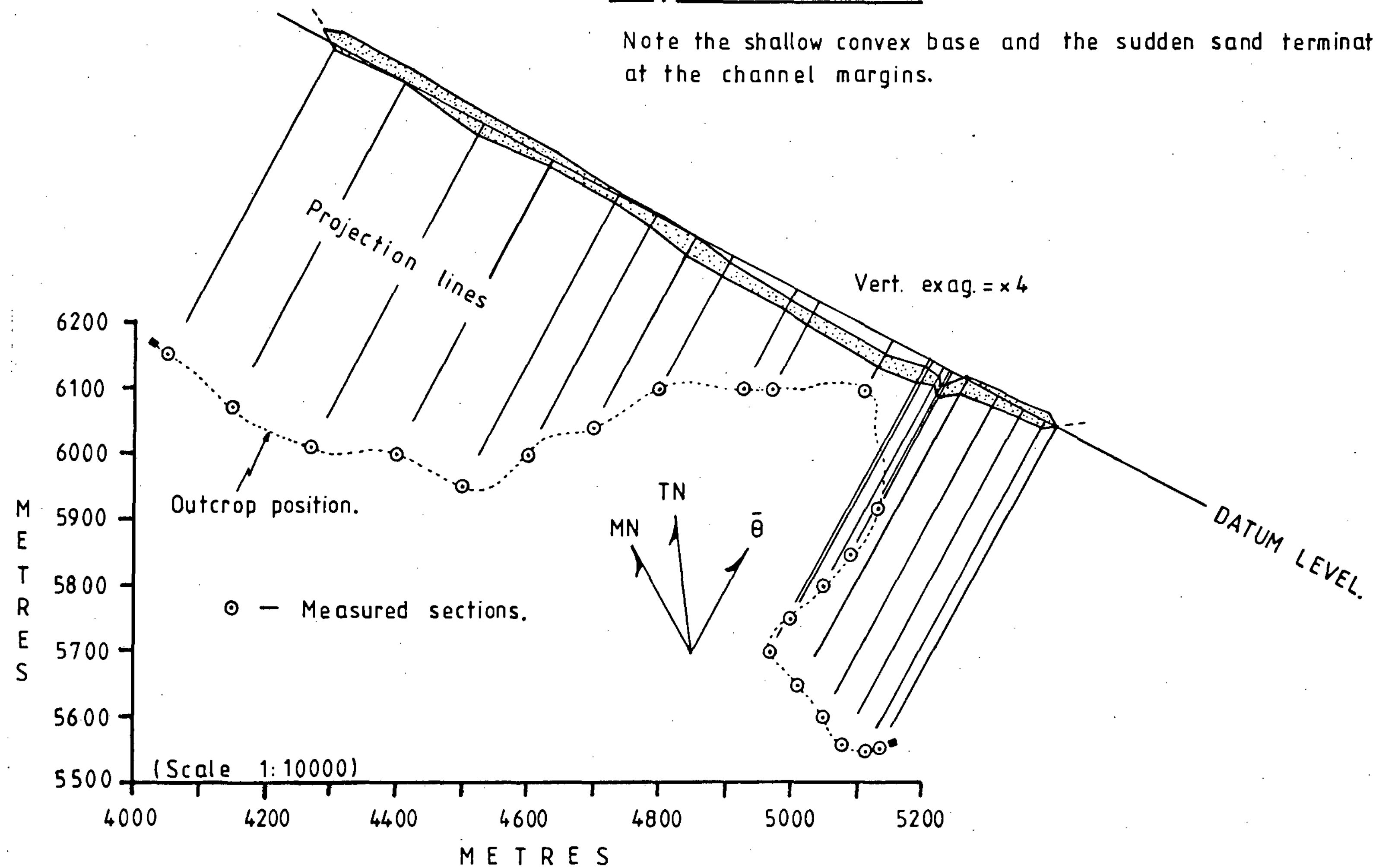
The low sinuosity sandstones display many of the features seen in the Palmietfontein straight channel. Thus the southern bank of sandstone 11c (see Photograph 12) has a very similar dip to that of the Palmietfontein sandstone.(see Photographs 9 and 10). It also displays tangential B_3 ripples and has a few centimetres of reduced mudstone on its footwall. On the bank of sandstone 11c very weak bioturbation is present, largely of the Planolites type (Kübler, 1977; Frey and Howard, 1970). The eastern bank of sandstone 15 and the western bank of sandstone 12 are identical and this bank geometry appears typical of all the sandstones - including the transitional sandstones, a point which will be discussed later.

The sandstone bases are approximately convex, as demonstrated in Diagram 13, and this appears universal. Allowing for the X4 vertical

Diag. 13.

Sandstone 15 in Plan and Profile. (Dip corrected).

Note the shallow convex base and the sudden sand termination at the channel margins.



exaggeration used, it can be seen that the convexity is very shallow. This shallow convexity of the channel base combined with a marked dip of the channel banks has led some writers to describe these sands as flat based. No sand examined in the study area is truly flat based.

Sand thickness is fairly uniform within the channel confines of sandstone 15 (see Diagram 13), and with the exception of a small topographic high, which relates to differential scouring of the basal mudstone, the general symmetry of the system is high.

Sandstones 11c, 15 and 12, and the Palmietfontein sandstone clearly are incised and have removed much more material than they have deposited. The incised and muddy-oxidised nature of these sandstones lends credence to the belief expressed in sub-chapter 5.8. that the sands are intrabasinal tributaries which are ephemeral and only flowed after unusual precipitation in the basin. They are dominantly erosive and have little bedload since they are draining very fine-grained flood-plain deposits.

In the Palmietfontein sandstone (Diagram 8 and photograph 8), clear upstream bifurcation was noted. In sandstone 11c and 12 there is some evidence of downstream bifurcation. In outcrop on sandstone 12 the mudstone base rises and almost bifurcates the sandstone. Palaeocurrent data suggests a marked change in palaeoflow around this high. Unfortunately confirmation of a bifurcation downstream cannot be demonstrated owing to poor outcrop. Equally, at one outcrop on sandstone 11c there is a single sandstone and yet on a further outcrop, down palaeoflow there appear to be two discrete sandstones. It appears then that both downstream and upstream bifurcation of these systems is possible. Downstream bifurcation is believed to be due to differential erosion in the channels, leaving mudstone islands around which the sandstones developed.

Bedforms developed in the low sinuosity and straight channel sandstones are those that would normally be associated with bedload-dominant fluvial systems. Longitudinal bars (Miall, 1977) are well developed, an example from the Palmietfontein sand having been given already (see Photograph 11). In some cases as the mudstone is weathered away the primary morphology is retained, with down current elongation being preserved. Horizontally bedded sandstones (B_2 lithofacies) are very common, with primary current lineation (Allen, 1963) and parting lineation (Potter and Pettijohn, 1977) being particularly prevalent. The B_3 lithofacies is subordinately represented by rib and furrow structures (Stokes, 1953; and Photograph 5) and occasional washed ripples. Trough cross-beds are relatively uncommon (see Photograph 2). When present they are dominantly pi-type (after Allen, 1963) and occur in deeper portions of the sandstone body. This dominance of the B_2 lithofacies and subordinate position of the B_1 and B_3 lithofacies may suggest that flow was typically shallow and of upper flow regime (Simons et al, 1965).

Planar tabular cross-bedding is observed on rare occasions (for example in Photograph 7); the foresets are curved and this feature is interpreted as the front of a linguoid bar (Miall, 1977), on sandstone 13. Cross-bedding can be seen to curve through well over 100^{0}, and secondary ripples on the northern and southern limbs indicate an eastward palaeoflow, showing that water flowed around both limbs.

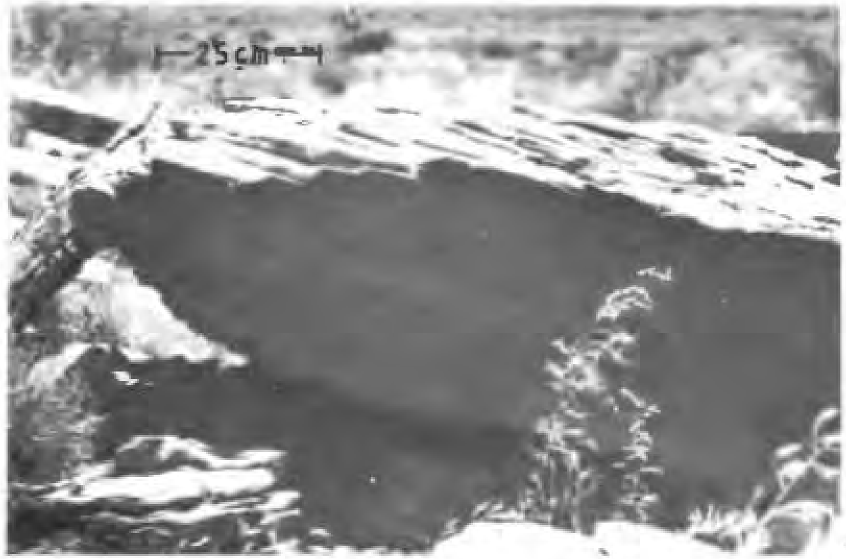
Penecontemporaneous deformation was noted on bar fronts and associated with trough cross-bedding, indicating extremely rapid deposition (Allen and Banks, 1972; and Photograph 13 on sandstone 10). This type of deformation is found on all sandstones in the Beaufort Group and is particularly well developed in the transitional sandstones. Further evidence for rapid stream flow, particularly in the low sinuosity and straight channel sandstones is provided by the formation of flute casts, found on sandstones 10, 12 and 15 (see Photograph 14) and by drag striae (see Photograph 15).

Side bars generated by low sinuosity meandering and which are analogous to point bars have been noted. Photograph 16 on sandstone 12, attempts to show them. Although not well developed there is also

PLATE V

Photograph	
13	Penecontemporaneous deformation in a trough cross-bed foreset, believed due to rapid sedimentation. Photograph taken on Sandstone 10.
14	Flute casts developed on a sandstone sole due to rapid water flow. The current would have been from left to right during their formation.
15	Drag striae and crystal casts (?) found on the sole of Sandstone 10.
16	Side-bars (?) - palaeoflow is from just below the middle right to just above the middle left of this photograph taken on sandstone 12. The ridges which run obliquely across the photograph are therefore parallel to palaeoflow in a low sinuosity system, and being adjacent to the channel bank, they are interpreted as side-bars.

PLATE V.



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some evidence of ridge and swale development, and accretion surfaces are easily identified. This suggests that the recognition of accretion surfaces does not necessarily imply high sinuousity (Miall, 1977, p.16).

To summarise, it appears that the sandstones of the low sinuousity and straight channel association were probably generated mainly by shallow, broad, almost flat-based streams that seldom produced the B_1 and B_3, but rather the B_2 lithofacies. Flow was ephemeral and the sandstones were often probably totally oxidising, with no water in the system. Floral and faunal turbation is minimal, upper sandstone contacts generally being sharp.

7.3 TRANSITIONAL SANDSTONES

In sub-chapter 5.6 the transitional sandstones were defined as having a standard deviation greater than $\pm 40^0$, and it was also proposed (sub-chapter 5.8) that they could represent perennial streams flowing from the provenance area towards the Ecca depo-centre in the north. In Chapter 3 the oxidation states of the various sandstone types were considered and an examination of those results inferred that the transitional sandstones were dominantly reduced, whilst the straight and low sinuosity channel sandstones were mainly oxidised. What was not emphasised about the transitional sandstones was that they are the major uranium host sandstones - no significant uranium find being made in the study area, in any other sandstone type. The internal geometry of these sandstones is therefore very significant to the uranium geologist.

Photograph 17 is of the eastern bank of sandstone 10, and when compared with Photographs 9, 10 and 12, illustrates the similarity of bank geometry. Shallowly dipping banks are typical of the mapped sandstones of the study area and cut-banks as normally associated with meandering streams are not observed.

The B_1 lithofacies is better developed in these sandstones than in the low sinuosity and straight channel sandstones. Trough cross-beds are common (pi type after Allen, 1963; see Photographs 2 and 18), and planar-tabular cross-beds, although less frequent, are also present.

However as before the B_2 lithofacies is best developed. In some areas it occurs continuously over several hundred square metres with little or no change in palaeoflow over the whole area. Gentle curvature of the palaeoflow may be inferred from primary current lineations. Photograph 19 and the frontispiece show the extensive areas that can be characteristic of the B_2 lithofacies.

Lithofacies B_3 is very apparent, occurring frequently at the top of sandstones, but is subordinate in most areas to lithofacies B_2 and B_1. In most examples noted it has a sharp contact with overlying muds and silts.

Channel meandering has been demonstrated in earlier chapters and Diagram 12. This meandering has resulted in the development of a few poorly developed ridges and swales (scroll-bars) - see

PLATE VI

Photograph

17 The eastern bank of transitional sandstone 10 can be seen below the person standing in the centre middle-ground . The channel bank dips away from the observer. Note that at least 1 metre of sand is present where the man is standing, but that the sandstone is absent below the photographer. No cut-bank is present and B_3 lithofacies dominates.

18 A major trough cross-bed (Allen's, 1963, pi type) on sandstone 10.

19 Lithofacies B_2 can be extremely well developed as seen in this photograph, where it is present for several hundred square metres. This photograph was taken on sandstone 10, looking north.

20 Ridges and a swale seen on sandstone 10 looking north-west towards the escarpment. The photographer is standing on one ridge and the two seated people are on the adjacent ridge, with a swale in-between. Palaeoflow was right to left in this portion of the palaeo-meander loop.

PLATE VI.

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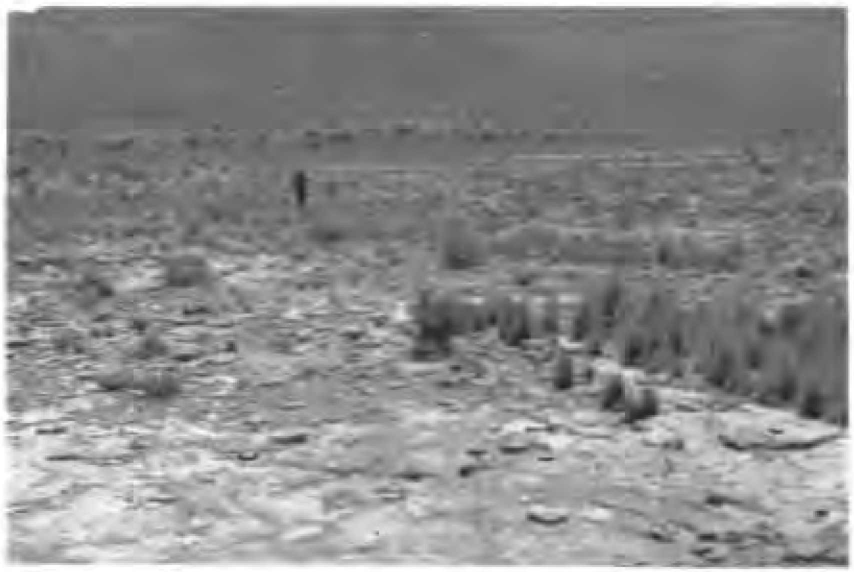

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Photograph 20; and epsilon cross-beds (after Allen, 1963; alternatively called accretion surfaces) - see Photograph 21. It should be emphasised that ridge and swale structures are rare, only one 'set' being noted in the study area (which has evidently been largely obliterated by a later flood event) whilst accretion surfaces are common. Thus in Diagram 12, between channels 1 and 2, where a point bar surface would be expected, no evidence of palaeocurrent curvature is noted. This lack of palaeocurrent curvature and the dominance of the B_2 lithofacies may suggest that during flood, sheet-flow crossed the point bar surface.

The basal topography of the transitional sandstones is more complex than that of the low sinuosity and straight channel sandstones. Towards the margins, where the sandstone appears to be formed mainly by sheet flow the base is fairly flat, with only small scour hollows. However in the central zone, where meandering has occurred the base becomes much more irregular. Thus meander channel 2 (see Diagram 12) which runs northward, has scoured much deeper than the sandstones on either side of it. This suggests that the channel is the result of avulsion and switching rather than migration, since had the channel migrated no marked channel deepening of the mudstone should be apparent. The eastern bank of channel 2 when mapped in detail plunges at about the same angle as the bank margin of 11c, i.e. about 10^{o}, to the west. The western bank similarly dips eastward. In the upper portions of the channel, channel 2 has eroded earlier sands rather than the underlying mudstone and a scalloped erosion surface is present, with a weak intraformational mudstone lag differentiating

PLATE VII

Photograph

21 An epsilon cross-bed(after Allen, 1963; alternatively called an accretion surface), outcrops from the photographs left horizon and strikes across the picture curving towards the photographer at the pictures right hand-side. The accretion surfaces found, have very low angles (less than 2^{0}), and on horizontal surfaces are extremely hard to see.

22 Fossil rootlets in a very oxidised, muddy, bioturbated sandstone. Bifurcation of the rootlets is well developed.

23 A goz (?) - this is believed to be the fossil equivalent of photograph 24. The photograph is taken on sandstone 10 looking east along the Nuweveld Escarpment.

24 A goz photographed on a modern alluvial fan. Wind blown sediment is trapped by vegetation and forms irregular structureless sand piles (after Boothroyd and Nummedal, 1978).

PLATE VII.

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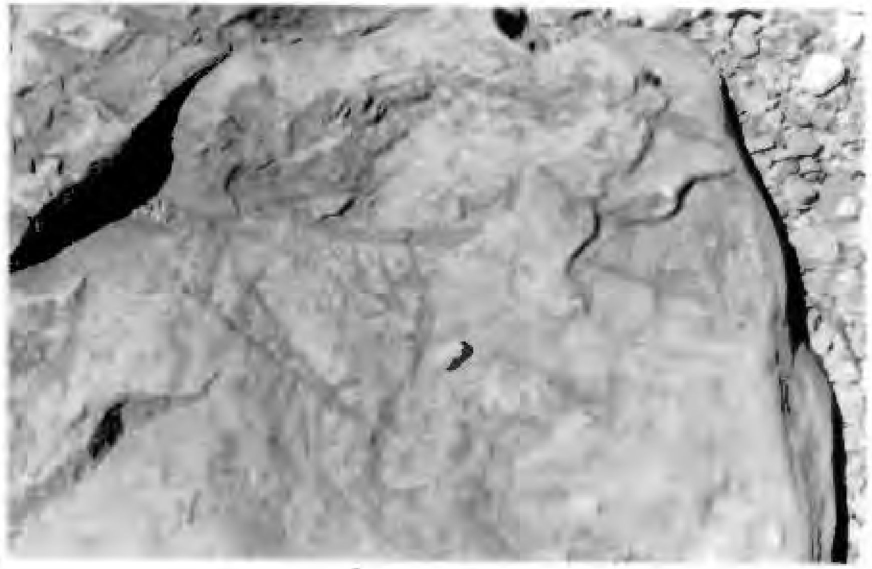

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the two sandstones. Interestingly, the earlier sand was clearly fairly competent, possibly due to its high mud content, and can be seen to have remained cohesive well beyond its natural rest angle.

The formation of meander channel 2 was probably associated with a flood event, since, as suggested, it appears not to have developed by migration but by avulsion and switching. Its depth of scour (being deeper than the surrounding sands) would support this conclusion. Subsequent to the formation of meander channel 2, the channel has been concentrically sand filled (even if somewhat asymmetrically) with a sandstone which is essentially identical to the rest of sandstone 10, with one major exception - that it contains abundant vegetable material (now present as carbon). This carbon is mineralised and the mineralisation process will be considered in Chapters 8 and 9.

In an earlier paragraph it was noted that a lack of palaeocurrent curvature and a dominance of the B_2 lithofacies on point bar surfaces could suggest that sheet flow, during flood, crossed the point bar surface. Another factor in support of floods sweeping the point bar surface is felt to be the lack of lithofacies C, which although present is very subordinate.

At first the author felt that this lack of lithofacies C (genetically equated to levee units) was due to a failure to recognise it.

Typically, levees have a triangular cross-section with maximum elevation near the stream channel, dipping into the flood plain. This geometry is generated during flood, because the coarsest sediment is deposited near the channel. In meandering systems the levee is commonly vegetated and this vegetation helps 'trap' sediment during flood. Further, typically sandy and muddy horizons alternate, with the sandy horizons being some tens of centimetres thick and the muds some centimetres thick. Oscillation ripples, mud-cracks, raindrop impressions and bioturbation may be present (Allen, 1965); and Reineck and Singh,(1975).

However, using the above criteria, a levee unit WAS identified within the study area, showing sand and mud alternations and a typical triangular geometry in association with oscillation ripples and bioturbation (weak as usual).

The fact that many of the transitional sands do not display lithofacies C could be due to one of two things: either the lithofacies was not developed as a primary sedimentary structure - as Allen (1965) suggests is the case with the Yukon River in Alaska; or, it was developed, but was not preserved.

This apparent lack of lithofacies C is at variance with work done by other authors. Keyser (1978) in his abstract states "Levee deposits comprise a 1 to 3 metre succession of rapidly alternating siltstones and mudstones. Cyclicity of sedimentation is evidenced by the numerous scour surfaces covered by siltstones grading into mudstones. Mud-cracks and raindrop impressions preserved as sole markings on siltstones record periods of sub-aerial exposure. Horizons of root impressions and continuous sheets of calcareous nodular material indicate pedogenesis within the levee deposits". Equally Kübler (1977) states that "in very well exposed cross-sections of the lower part of the Beaufort Group interbedded siltstones and mudstones were commonly encountered. These were interpreted as having been deposited on natural levees".

It appears unusual that both Kübler (1977) and Keyser (1978) indicate that mud and siltstone levee units are found, as sand would be expected in proximal levee units, since as Reineck and Singh (1975) state "the composition of upper point bar sediments is rather similar to the composition of the levees". Further it is the author's opinion that the proximal levee units are comprised of dominantly saltated grains (since transported up the levee during flood), and not suspension load as would be the case suggested by Keyser (1978) and Kübler (1977).

In view of the fact that levee units as described by Allen (1965), Visher (1972) and Reineck and Singh (1975) are present, which do contain sand, it is the author's opinion that the criteria applied by Kübler (1977) and Keyser (1972) are no more indicative of a levee deposit than of a flood plain deposit. Further it is the author's belief that a careful re-appraisal of levees as described in past literature may well prove that levees are much rarer in the Beaufort Group than suggested by the literature. Such a suggestion may be supported by Turner (1978, p.837, Fig.4) who presents eight sections from the high sinuosity channel facies association, only one of which could be possibly interpreted as containing lithofacies C. Having said this, the author must also state that the study area is small and may not be representative of the Beaufort Group as a whole.

The apparent lack of levee development must to some extent be a reflection of the amount of vegetation. To the author's knowledge no 'seat-earths,(i.e. horizons which supported abundant vegetation) are present within the study area. Infrequent evidence of bifurcating rootlets is found (see Photograph 22), but there is no evidence for extensive development of vegetation. It seems likely that vegetation was small and fairly sparse, a finding which is in general agreement with Turner (1978). This however raises the question of how there can be limited vegetation in a warm climate with perennial water flow? This problem will be considered further in Chapter 10.

One other sedimentary structure that appears characteristic of the transitional sandstones deserves mention - gozes. Gozes were first described by Bagnold (1954) and are described as undulatory sand surfaces where growing plants act as a sediment trap and produce mounds of wind blown sand, where the vegetation inhibits dune formation. They are therefore a feature of arid environments.

Photograph 24 (from Boothroyd and Nummedal, 1978) is a modern example from an alluvial fan, whilst Photograph 23, shows what the author interprets as a fossil equivalent. A further example can be seen in the right foreground of the Frontispiece. Evidence for their Aeolian origin is provided by rare B_3 lithofacies ripples which have very low amplitudes relative to their wavelengths (Tanner, 1967).

8 URANIUM - ITS SOURCE, MODE OF TRANSPORT AND CONCENTRATION

8.1 SOURCE OF THE URANIUM

Qidwai and Jensen (1979) suggest that there are three possible sources of uranium for sandstone type deposits namely:-

A) Magmatic hydrothermal sources

B) Leaching of exposed pre-sediment granites and/or

C) Leaching of tuffaceous volcanic rocks.

There seems little reason to invoke magmatic hydrothermal activity for sandstone-type uranium deposits when there is no evidence for such activity, particularly when it is apparent that tuffaceous material is present, and that the feldspars in the sandstones are themselves anomalously high in uranium. Further magmatic hydrothermal fluids would lose their identity on encountering meteoric water with the result that they would become indistinguishable from meteoric fluids (Qidwai and Jensen, 1979).

The in situ weathering and leaching of granitic rocks may by deep oxidation ~~solubilise~~ dissolve much of the loosely-bound uranium from the granites,which will then be free to migrate and enter the aquifer system (Kübler, 1977). The petrology strongly suggests that some granite was present in the provenance area and this could have contributed some of the uranium found. The third potential source for uranium is tuffaceous sediments. Grutt (1975) found that tuffaceous sediments in the stratigraphic section above the host rocks were a feature of all the major sandstone-uranium districts of the United States that he considered in his review. Certainly the presence of tuffaceous sediment at Matjieskloof cannot be denied (Stuart-Williams, 1979). However nowhere is it present in beds of more than some 20 cm thick in the study area and even allowing for some solution of silica, it can never have been volumetrically very significant. At best it is likely therefore to have been only a minor source of uranium.

There is however a fourth source not directly considered by Qidwai and Jensen (1979) and that is the pile of sediment itself. Much of the material entering the basin was clearly only partially leached (as suggested by the degree of preservation of many of the feldspars) and it is highly probable that much of the uranium present in groundwater in the basin could have come from intra-basinal leaching possibly associated with palaeosols (McPherson and Germs, 1979). Such a proposal was made by Gruner (1956) for the Colorado Plateau and in this instance he calculated that a potential 800 million tons of uranium would have been liberated from the sediment pile within the basin.

It would therefore appear that uranium could have been derived from three sources: deep leaching of granites and associated rocks in the provenance area, leaching of these self-same rocks in the depositional basin possibly at or near soil horizons and from tuffaceous material. The high feldspar content of the sandstones and the presence of volcaniclastics suggests that at least two discrete sources may have been present in the Beaufort Group.

8.2 TRANSPORT OF URANIUM IN THE SEDIMENTARY ENVIRONMENT

Uranium is geochemically very mobile in oxygenated ground water in the hexavalent state (Hostetler and Garrels, 1962), and stable as the major ore minerals uraninite and coffinite under reducing conditions in the tetravalent state. More recent data have shown however that U(IV) is less stable relative to U(VI) than previously assumed and that a third species U(V) ignored by geochemists, has an appreciable field of stability in reduced waters, below pH 7 (Langmuir, 1978).

Transport of uranium as uranyl carbonate complexes in mildly reducing conditions with a neutral to alkaline pH in the presence of abundant carbon dioxide has long been recognised (Hostetler and Garrels, 1962). In view of the abundance of carbonates in the Beaufort Group and the almost universal association of carbonates with mineralised zones, transport of uranium in the Beaufort Group as uranyl carbonate complexes is assumed dominant and will be discussed further.

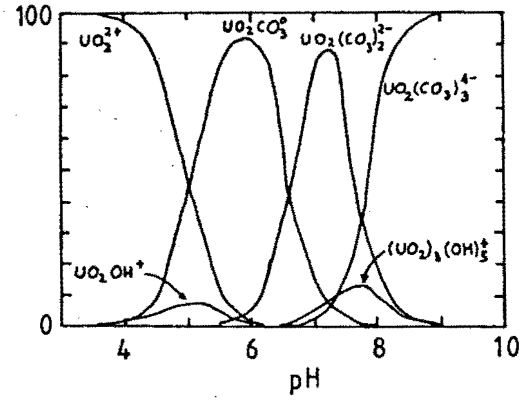
Diagram 14.1 (from Langmuir, 1978) shows the distribution of uranyl-hydroxy and carbonate complexes vs pH. In the kind of environment envisioned for the Beaufort Group it is likely that the di-and tri-carbonate complexes would dominate. In ground water at P_{co2} 10^{-2} atm. and $25^{o}C$ the uranyl complexes are the major transporting species down to about pH 5(see Diagram 14.1.) At higher temperatures the uranyl carbonate complexes are minor species at all pH values and thus only low temperature carbonate transport is being considered.

That carbonate complexing greatly increases the mobility of uranium can be seen in Diagram 14.2 (from Langmuir, 1978). Here a rise in P_{co2} from the atmospheric value of 10^{-3} atm. to 10^{-2} atm. increases the solubility of $UO_2(c)$ by more than 1000 times for Eh values above - 0,05V.

Diagram 14.3 (from Langmuir, 1972) shows the stability field for uraninite, and the solution boundary for the uranyl carbonate species. From Diagrams 14.1 - 14.3 it can be seen that solution and transport in the sedimentary environment as uranyl complexes is of primary importance. It can also be seen that only small changes in Eh and pH are needed to change a transporting solution

Carbonate Transport.

Diag.14,1



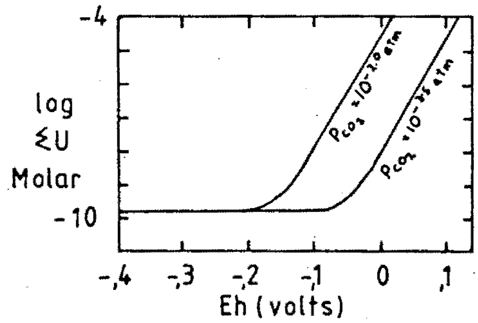
Mole percent dissolved U (VI) species

(After LANGMUIR, 1978)

Distribution of uranyl-hydroxy and carbonate complexes vs pH for $P_{CO_2} = 10^{-2}$ atm and $\Sigma U = 10^{-8}$ M at 25°C.

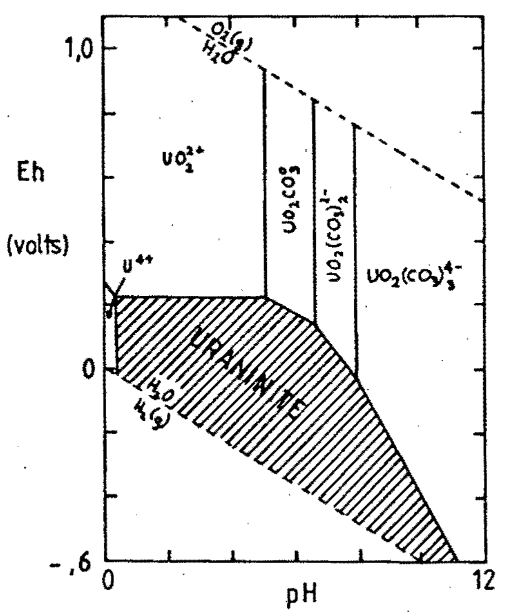
Diag.14,2

(After LANGMUIR, 1978)



The solubility of uranium, UO_2 (c), at pH = 8 and 25°C as a function of Eh and P_{CO_2}.

Diag 14.3



Eh - pH diagram in the $U-O_2-CO_2-H_2O$ system at 25°C for $P_{CO_2} = 10^{-2}$ atm. Uraninite, UO_2(c), solution boundaries are drawn at 10^{-6} M dissolved uranium species.

(After LANGMUIR, 1978)

into a precipitating solution. The question of reduction will be considered in the next sub-chapter.

8.3 THE REDUCTION AND FIXATION OF URANIUM

Gabelman (1971) suggests that five main processes of uranium fixation are found:-

A) by reduction,

B) by adsorption,

C) by ion exchange,

D) by ionic substitution and,

E) by the formation of insoluble ionic complexes.

Of these five processes, A) is almost certainly the most common, and the two most abundant reductants are typically carbonaceous material and pyrite.

Reduction of uranyl complexes by pyrite can occur if solutions are migrating through permeable, pyritic sandstones. Such a process typically generates roll-front bodies (to be discussed in section 9.1) which commonly are sinuous in plan, 'C' shaped in section and discordant to bedding. A strong Eh gradient is generated across the front (Adler, 1974; Stanton, 1972). No such ore geometry has been observed at Matjieskloof nor to the author's knowledge elsewhere in the Karoo, and a roll front model appears unlikely to have controlled mineralisation at Matjieskloof.

Carbonaceous material has long been recognised as an important precipitant in the major uranium districts of the United States (Gabelman 1971; Fisher, 1974). Some small- but very valuable - deposits have consisted almost entirely of the replacement of a single large fossil log (Stanton, 1972) by uraninite and coffinite. Coalified plant remains are also good absorbants of uranium. Hydrogen sulphide generated by the anaerobic breakdown of organic material is also a strong reductant and Fisher (1968) reported that isotopic studies on the sulphides associated with uranium mineralisation of the Colorado Plateau suggested an organic origin for the Sulphur. Grutt (1975) postulates that in the Texas Gulf Coast uranium occurrences, hydrogen sulphide generated in oil-bearing strata migrated up growth faults and acted as a reductant in overlying aquifers.

Garrels (see Jensen, 1958, p.615), suggests that the 'greyness' of many uranium ore zones in comparison with the adjacent 'red-beds' (red due to Fe_2O_3) is due to organic reduction. This is borne out by an isotope lightness (negative $\delta^{34}S$) and extreme variability of $^{32}S/^{34}S$ ratios in the sulphide sulphur. A reaction such as:-

$$4H_2S + Fe_2O_3 \longrightarrow 2FeS_2 + 3H_2O + H_2$$

is envisaged by Garrels and Jensen.

The pH range of minimum solubility of the uranyl minerals is also the pH range of maximal uranyl sorption on most important natural colloidal materials, including organic matter, Fe (III) oxyhydroxides, Mn and Ti oxyhydroxides, zeolites and clays. Once uranyl has been adsorbed it may be reduced to U (IV) in uraninite and coffinite by mobile reductants such as H_2S or CH_4 or by the sorbent itself if the latter is organic matter (Langmuir, 1978). Doi et al (1975) suggest such a mechanism for some of the ore deposits of Japan.

Ionic exchange and ionic substitution as discussed by Gabelman (1971) are mentioned for completeness but, not being important processes in the formation of ore bodies, they will not be considered further.

The fifth process - that of the formation of insoluble ionic complexes, can be important, particularly in the roll-front type of uranium deposits where uranyl vanadates (e.g. carnotite and Tyuyamunite) can form (Fisher, 1968). Such minerals are stable under oxidising conditions (Kübler, 1977).

The close association found between carbonaceous debris (dominantly macerals) and the uranium mineralisation at Matjieskloof suggests that it was the major reductant and in sub-chapter 9.2, this association will be considered further.

8.4 PERMEABILITY AND WATER MOVEMENTS

So far in the discussion on uranium, it has been tacitly assumed that uranyl complexes have been free to move throughout the sandstone bodies discussed in earlier sections, and clearly for mineralisation to develop to any degree, substantial volumes of water must have been able to migrate through these sands. At the same time the petrology of the sediments is not conducive to high through-flows of water due to a small grain size (fine to very fine) and substantial amounts of primary mud matrix.

Gabelman (1971) suggests that an interruption or delay of fluid flow is required to allow time for uranium fixation - a requirement fulfilled by the fine grain size and matrix. However any model for mineralisation of Beaufort type sediments must take cognisance of this low permeability since water cannot be passed in large volumes; this could partly account for the generally low uranium grades found in the Karoo.

Where the permeability is higher or oxidation predominates, continuous flushing by the mineralising fluid takes place and leaching will probably predominate over fixation (Doi et al, 1975).

Clearly therefore the ideal host rock is fairly permeable, with discontinuous permeability, and/or permeability barriers to slow fluid flow. Gabelman (1971) and Kübler (1977) suggest that changes in permeability are caused by variable lithologies, textures, porosities, sedimentary structures and jointing (the latter suggesting a belief in epigene fluid flows - a belief not shared by the author). Further, Gabelman (1971) suggests that control on uranium bodies can be exercised by the interfingering of sandstones and mudstone, the presence of mudstone lenses (which delay fluid flow), by penecontemporaneous deformation structures (since they disrupt bedding and create permeability barriers), by diastems, which create vertical grain-size changes and create fluid pathways, and by intra-formational conglomerates, which can provide more permeable channel-ways.

The sandstones of the Beaufort acted as fluid pathways for mineralising fluids and fulfilled most if not all of the criteria suggested by Gabelman (1971) and Kübler (1977). However the small grain size and poor sorting must have limited fluid flow - a point which cannot be over emphasised.

9 URANIUM MINERALISATION - A NEW MODEL

9.1 CURRENT MODELS FOR URANIUM MINERALISATION

Sandstone-type uranium deposits can be divided into two broad groups:- roll front-type deposits; and URAVAN-type deposits. Each type will now be considered.

9.1.1 Roll Front Deposits

Typically these deposits occur in Tertiary sandstones overlain by tuffaceous sedimentary units. These units have been truncated and bevelled by erosion prior to further deposition. The ore bodies lie some 20-30 km downdip from the bevelled edges and dating suggests that their formation was closely related to the age of the bevelling event. The sandstones are arkosic and generally contain abundant pyrite, which is typically biogenic although some may be derived from fault-leaked sour gas from underlying formations: the H_2S present reacts with iron minerals to form the pyrite.

Within the sandstones, lies an oxidised "tongue" which projects downdip as much as 30 km. Ore bodies, where present, follow the surfaces of the oxidised tongue, being thicker and richer along the discordant or roll surfaces of the tongue margins. Ore deposits are randomly scattered along the leading and lateral edges of the oxidised tongue. Ore body axes can be parallel to or at any angle to the sedimentary trends in the host rock.

Uraninite and coffinite are typical ore minerals. Pyrite and marcasite are almost always more concentrated in the ore than in barren unoxidised rock. Permeability of the rocks is not impaired. Mineral zoning is commonly present.

It is inferred that meteoric water percolated down the sandstone, gaining access at the bevelled edges. Uranium was transported after leaching from adjacent tuffaceous sediments in oxygenated ground water, which then reacted with the pyrite, generating a geochemical cell. Here oxidation of pyrite in waters with limited free oxygen resulted in soluble, metastable, partly oxidised sulphur species, which could spontaneously undergo a disproportionation reaction. This reaction generated oxidised species, e.g. $SO_4^{=}$, and reduced species, e.g. H_2S, which controlled the Eh of the environment. Elements such as uranium were then precipitated. Ore bodies therefore formed where optimum conditions of oxygen supply, pyrite and uranium content occurred, together with favourable pH, perhaps controlled by calcite (Granger and Warren, 1979).

The ore bodies generated in roll-fronts have therefore a very distinct geometry and geochemistry, being characterised by a strong Redox front. Such a geometry has never to my knowledge been noted in Beaufort Group sediments and the ore bodies at Matjieskloof (the study area) are not considered to be allied to a roll-front model.

9.1.2 URAVAN-type deposits

URAVAN deposits (URA - uranium, VAN - vanadium) are found in the Salt Wash member of the Jurassic Morrison Formation, U.S.A., in thin, discontinuous sand lenses intercalated with red mudstones. Ore bodies are enclosed in pale-grey, pyrite-bearing and coalified fossil wood-bearing zones. They are dominantly tabular, peneconcordant layers but occasionally show crude ' C' or 'S' shapes. Roll axes may be controlled by permeability, and primary structures. Distribution of the ore zones appears very random: there is no evidence for one side of the ore zone having been first oxidised and then reduced; both sides appear bleached and reduced, although some zoning may be present.

Uraninite and coffinite are the major uranium ore minerals, but the most abundant element is vanadium, occurring as vanadium clays and micas, which fill interstices and corrode sand grains. Trash zones with coalified wood tend to have the richest grades of uranium.

Ore layers and rolls typically contain asymmetric distribution of uranium and vanadium across the dark ore layers, the vanadium being richest to one side and uranium to the other. Molybdenum (as Jordisite) also occurs at some distance from the uranium. A primary zoning is therefore present.

These deposits probably formed early in the history of the host rock from the mixing of ore-forming solutions and stagnant, diagenetic - stage connate (?) waters which were permitted into more permeable channel sand units of the enclosing reduced host rocks. At the interface between the connate waters and ore solutions, ore bodies were formed. The formation of the vanadium-rich clays lowered the permeability but allowed diffusion. Because the conduits of the ore-forming solution generally conformed to broad, horizontal-channel sand units, the resulting ore bodies developed a similar shape.

'In conclusion it appears that the geochemical reactions that resulted in deposition of ore did not directly depend on alteration of minerals of the host rock. Rather, it was a reaction between the components of two unlike solutions which was instrumental in forming the ores', (Granger and Warren, 1979).

That the Matjieskloof ore body is of the URAVAN type is indisputable. At the same time it must be recognised that there are major differences between the two: one that is very apparent is the low vanadium content at Matjieskloof. A modified model of the URAVAN type is proposed for Matjieskloof in Chapter 9.2.

9.1.3 Preservation Potential

The differences between the Roll-front and URAVAN type systems are thus marked. Roll-front type uranium ore bodies continue to exist for as long as there is sufficient pyrite present in the system to maintain a strong geochemical cell. In a sense, these are systems which are never 'preserved' since the system is dynamic and continues to migrate slowly down the permeable sandstone host (Gruner, 1956). It is thus a process of multiple migration and accretion and Gruner (1956) suggests it could form both Roll front - and peneconcordant (URAVAN) - type ore bodies. Adler (1974) feels that multiple migration and accretion could only form Roll-front-type bodies. URAVAN-type sandstone bodies are clearly different in that their preservation is dependent on the continuance of reducing conditions (Granger and Warren, 1979).

Should reducing conditions be lost in either type of sandstone deposit then oxidation of the minerals present, mobilisation and solubilisation would take place, assuming that the permeability is fairly high. If cementation has occurred then uraninite and coffinite may be found in association with secondary minerals in outcrop (Kübler, 1977).

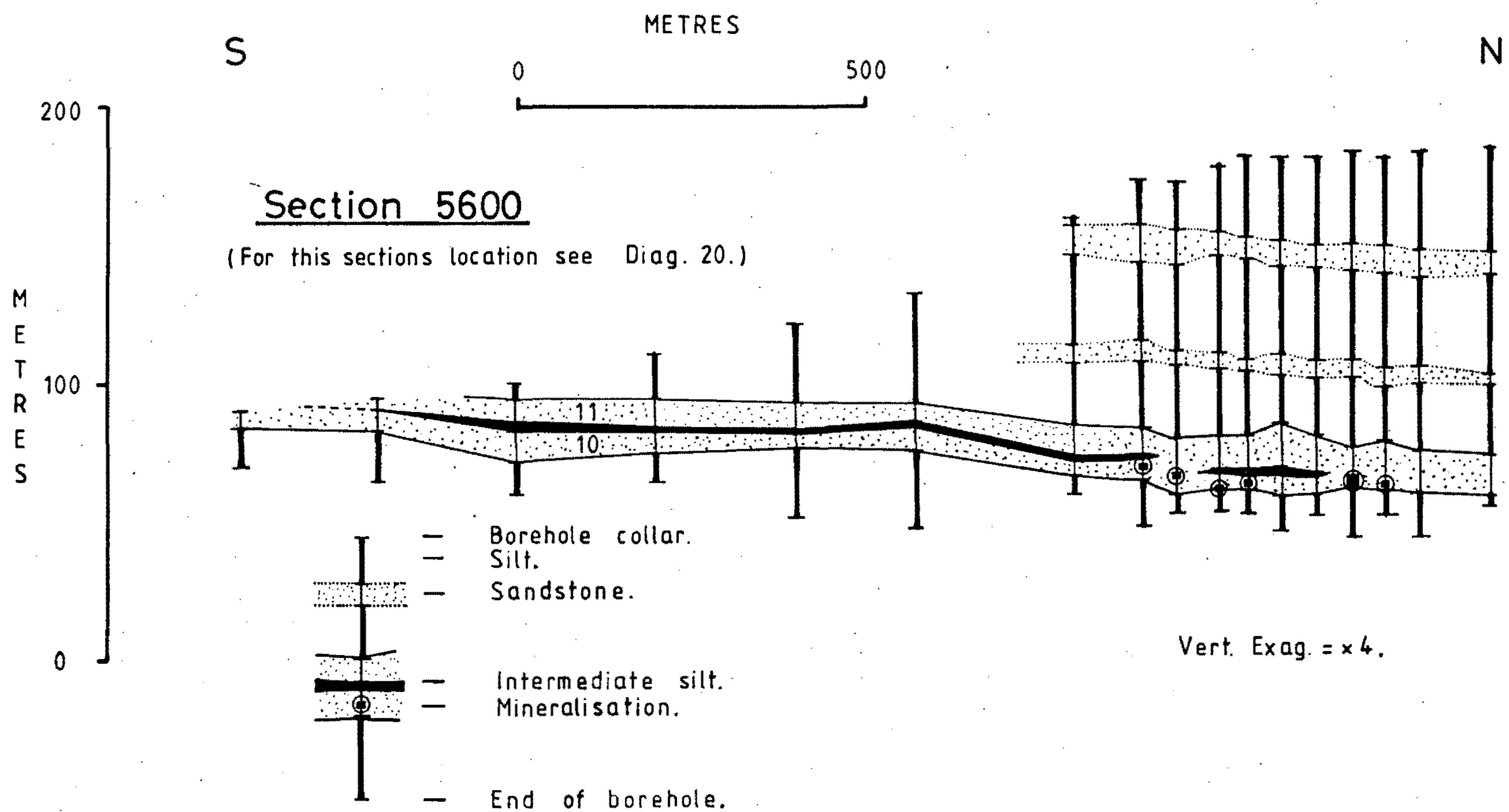
9.2. A MODEL OF URANIUM MINERALISATION AT MATJIESKLOOF

Before discussing any model of mineralisation it is worth examining the data that led up to its proposal.

Diagram 15, is a south to north drill section which demonstrates many of the features typifying Matjieskloof uranium mineralisation. Firstly, two discrete sandstones are present (numbered 10 and 11) separated by a thin silt, shown in black. Secondly, mineralisation is almost entirely confined to the lower sand and has a tendency to dip down palaeoflow (i.e. the mineralisation dips northward at a slightly higher dip then that of the host sandstone). Thirdly, mineralisation is present only at 'holes' in the silt, i.e., at points where the two sands coalesce. This is well illustrated in Diagram 15, where the mineralisation is at or immediately adjacent to points of coalescence between sandstones 10 and 11. Lastly, since the northern two boreholes are clearly drilling a coalesced sand (i.e. sandstones 10 and 11 combined) which is not mineralised, it could be suggested that mineralisation occurs only in the immediate vicinity of the point of coalescence and not throughout

Diag. 15.

A Typical South to North Drill Section.



the entire lower sand of the coalesced zone. Knowing that the palaeoflow is northward, it could also be inferred that mineralisation occurs only on the down palaeoflow side of points of sandstone coalescence (see Table 9 for the palaeoflow direction of sandstone 10).

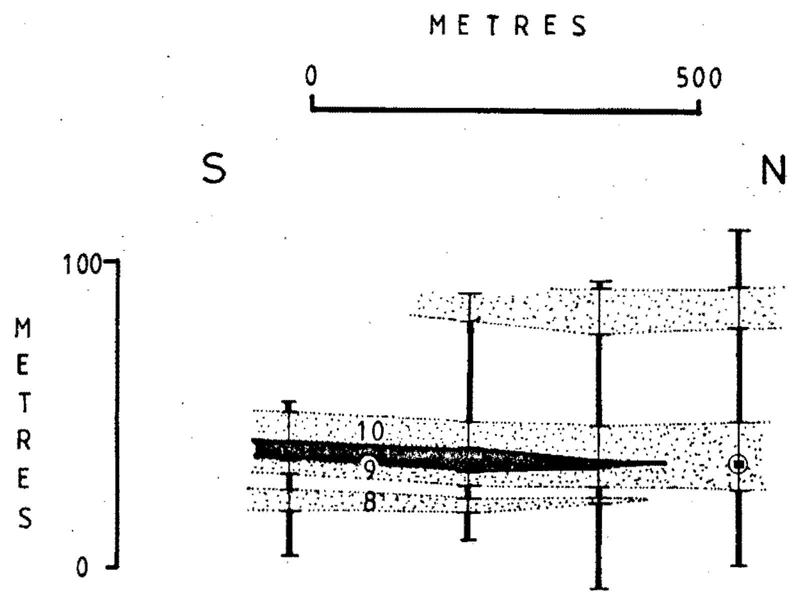
Diagrams 16 and 17, show exactly the same phenomena between pairs of discrete sands, but note that all these mineralised zones are in stratigraphically different sands. This suggests that mineralisation is not confined to any one sandstone but is present throughout the entire stratigraphy (as suggested by Kübler, 1977, and Von Backström, 1974).

The fact that all the mineralised sandstones at Matjieskloof (even where stratigraphically separated) showed such a similar geometry of their mineralisation, indicated that a common mode of uranium mineralisation was present. It is the aim of this sub-chapter to examine the model for uranium mineralisation developed at Matjieskloof.

Diagram 18, shows the model. If it is compared with Diagram 15, the same basic geometry observed in the drill-sections can be seen to be present. Thus in Diagram 18, two sandstones are present (numbered 10 and 11) separated by an intermediate silt; the zone of potential mineralisation dips, lies only in the bottom sand (sandstone 10) and terminates going away from the siltstone parting.

Diag. 16.

A Second South to North Section.



Section 11000

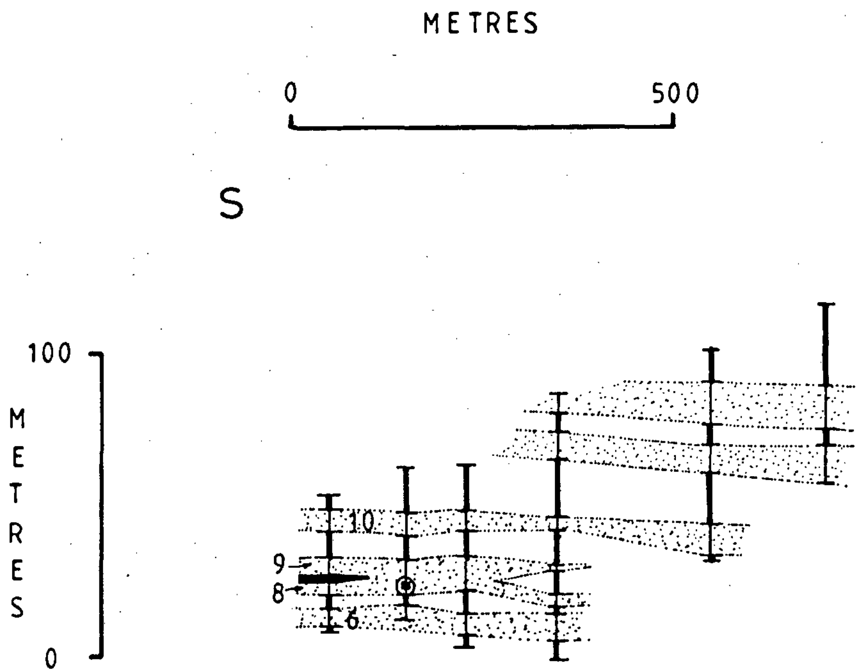
Vert. Exag. = × 4.

(For legend see diagram 15.)

Note here how the nature of the coalescence is identical to that of the previous section but is occurring between different sands.

Diag. 17.

A Third South to North Section.



Section 10800

Vert. Exag. = × 4

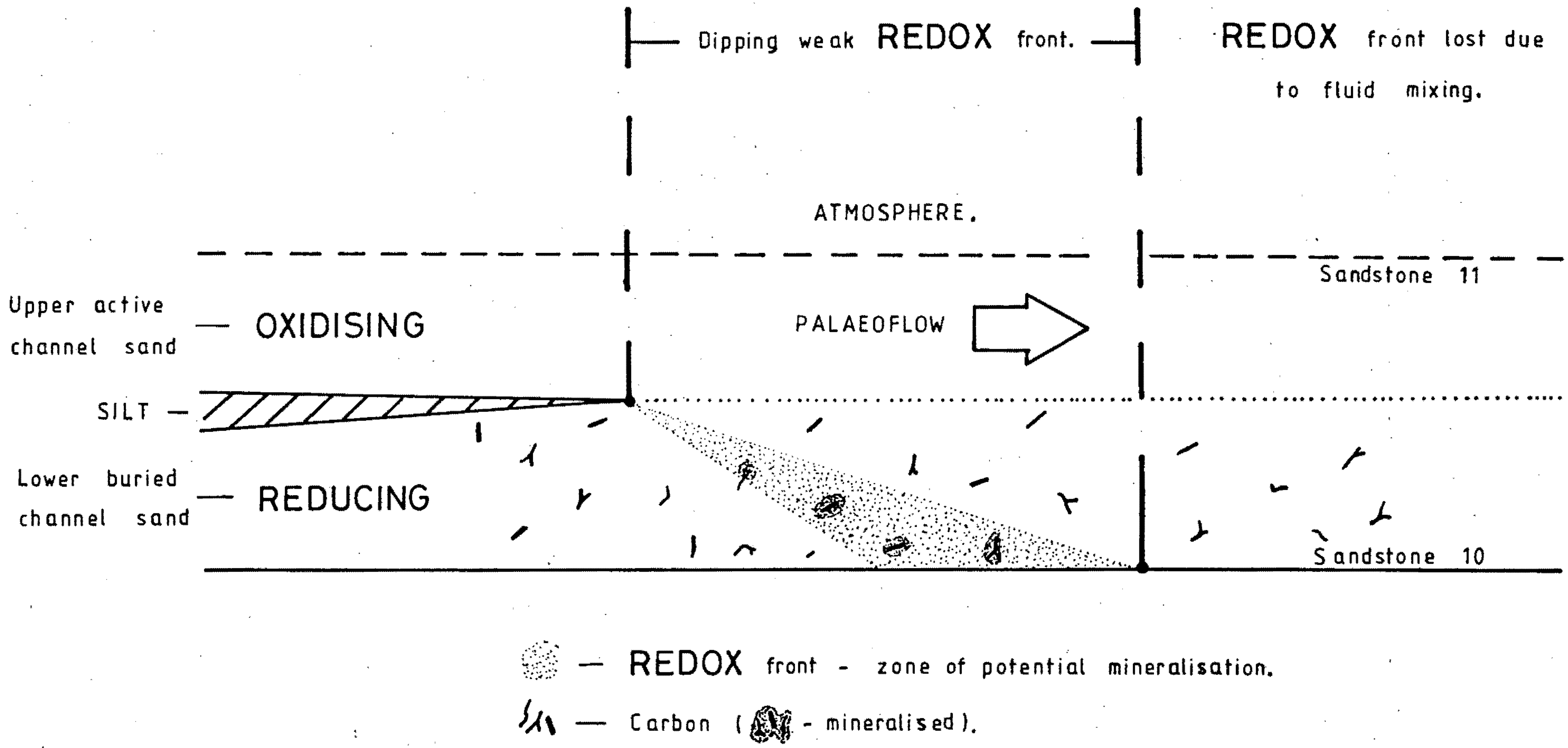
(For legend see diagram 15.)

Note once again the type of coalescence present and also that it is again between different sandstones.

Diag. 18.

The Model for Syngenetic Mineralisation at Matjieskloof.

See text for discussion.



However, there the similarity ends because Diagram 18 illustrates the inferred conditions required for uranium mineralisation. The most important point to note is the presence of two discrete fluids (one oxidising, the other reducing), developed in the upper and lower sandstones respectively.

The upper sandstone (which contains the oxidising fluid) is open to the atmosphere in an arid environment, and therefore tends to be strongly oxidising and rich in carbonates. For this reason and taking cognisance of the earlier discussion on uranyl carbonate transport mechanisms (see sub-chapter 8.2), this upper active fluvial channel is believed to have been the major conduit for uranium transport.

The lower sandstone was originally identical to the upper, in that it would have been an active channel open to the atmosphere. However, avulsion and switching and subsequent aggradation by flood-plain sediments have buried it. Due to this and its very fine grain size (see sub-chapter 3.4) fluid flow within this lower sand is extremely slow. This, in association with small amounts of carbonaceous material, has generated a weakly reducing, slightly acidic fluid. The acidity of this fluid is dependent on the carbon content of the sand, and since these sandstones are in general carbon-poor, the fluid is assumed to have been only weakly acidic and mildly reducing.

At the point of coalescence between the two sandstones these two discrete fluids are allowed to mix. This mixing will progressively penetrate deeper into the coalesced sand down palaeoflow from the point of coalescence, such that at some position the entire sandstone package (sandstones 10 and 11) will become oxidising. This point is shown in Diagram 18, by the right-hand vertical dashed line.

Between the end of the siltstone parting and the point where the entire sandstone package becomes oxidising, a REDOX front must be generated (such a front is shown stippled, in Diagram 18). It is however not the intention to generate a REDOX front of the type found in roll-front uranium deposits (see sub-chapter 9.1.1). As noted in an earlier paragraph the fluids are only considered to be weakly oxidising or reducing and could not precipitate uranyl carbonate

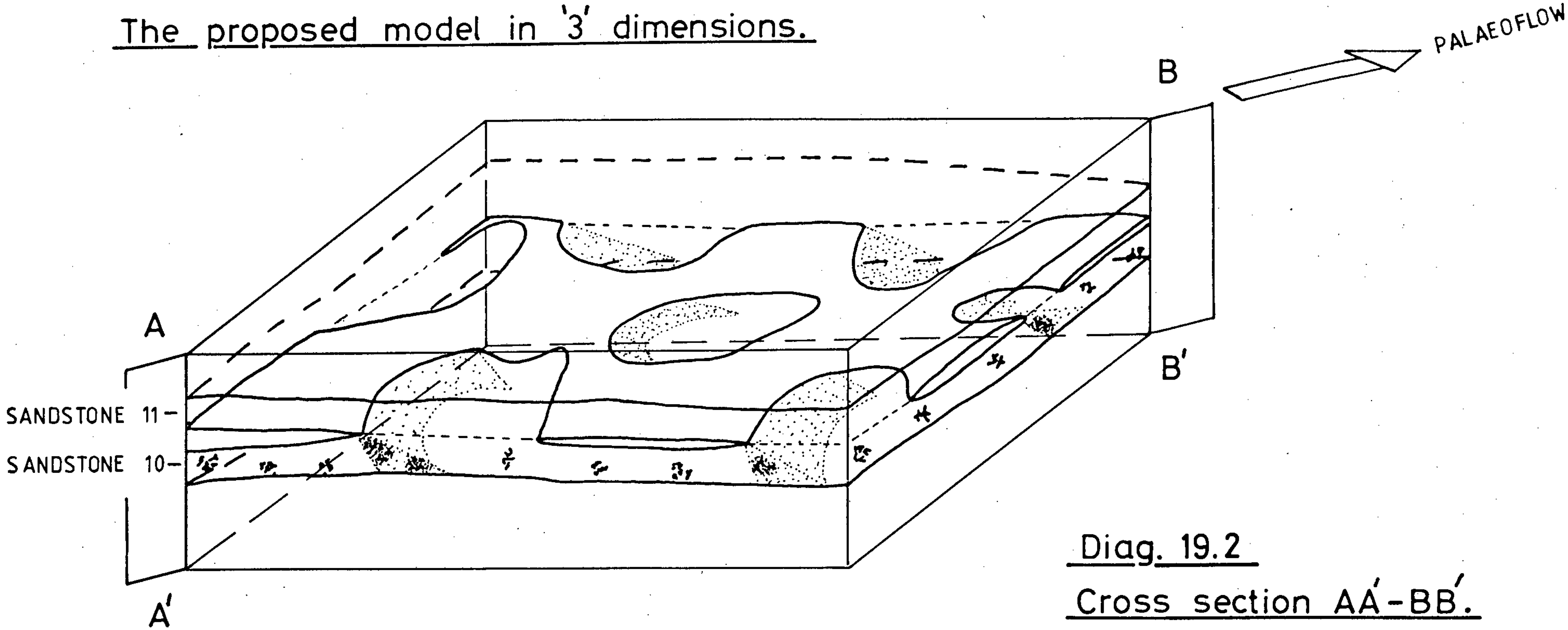
However, if free carbon is present in the zone of mixing (REDOX front), then uranium in transport as a carbonate complex could be reduced, on the carbon. Once reduced this uranium will remain stable for as long as conditions remain reducing. The dipping weak REDOX front shown in Diagram 18 is thus vitally important in that it provides a mechanism whereby mineralised carbon may remain in a weakly reducing environment. The distribution of mineralisation within the REDOX front is therefore carbon dependent, so much so that ore grade is essentially carbon-controlled.

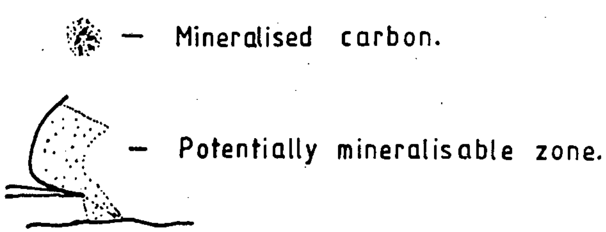
As sedimentation continues, the upper sand will in turn be buried through aggradation, and both sands will become reducing, developing the typical grey colour of all Beaufort Group transitional sandstones. This subsequent reduction of the upper sand is important for two reasons. Firstly, this total reduction of the sand pile ensures the permanent stabilising of all carbon-fixed uranium. Secondly, it means that the upper sandstone (sandstone 11 in Diagram 18) may in turn be mineralised by a coalescing higher sandstone. Thus stacked mineralisation is a clear possibility. Note that stacked mineralisation is generated in discrete sandstones, whereas zoned mineralisation is a function of carbon inhomogeneity in a single sand.

In Diagram 18, the model is only developed as a direct interpretation of drill data, such as seen in Diagram 15. It should be possible however to remodel it in three dimensions. This has been done in Diagram 19. Diagram 19.1 shows the zones of potential mineralisation stippled, whilst the actual mineralised zones are shown adjacent to carbon blebs within the zone of potential mineralisation. Obviously the shape of the mineralisation in plan is dependent on the carbon distribution, the shape of the coalesced zone and the palaeoflow direction. An examination of Diagram 19.1 will demonstrate how the changing of any one of these three parameters can affect the distribution of the mineralisation.

Diag. 19.1

The proposed model in '3' dimensions.





Diag. 19.2

Cross section AA'-BB'.

Note the dipping REDOX fronts down palaeoflow.

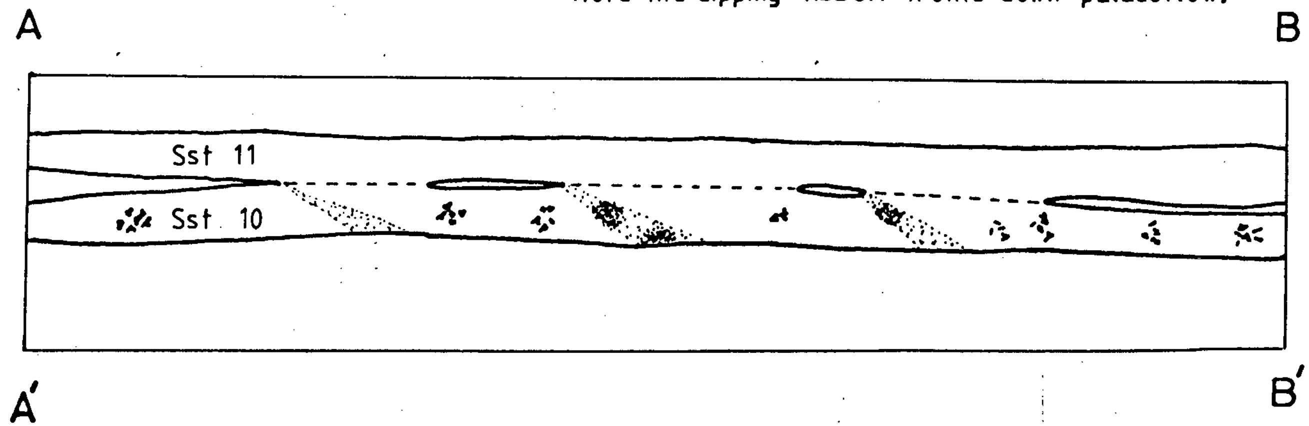


Diagram 19.2 is a cross section down palaeoflow depicting how the model can repeat itself almost 'ad infinitum' as long as sufficient separation is present between the upper and lower sand to allow generation of two discrete fluids.

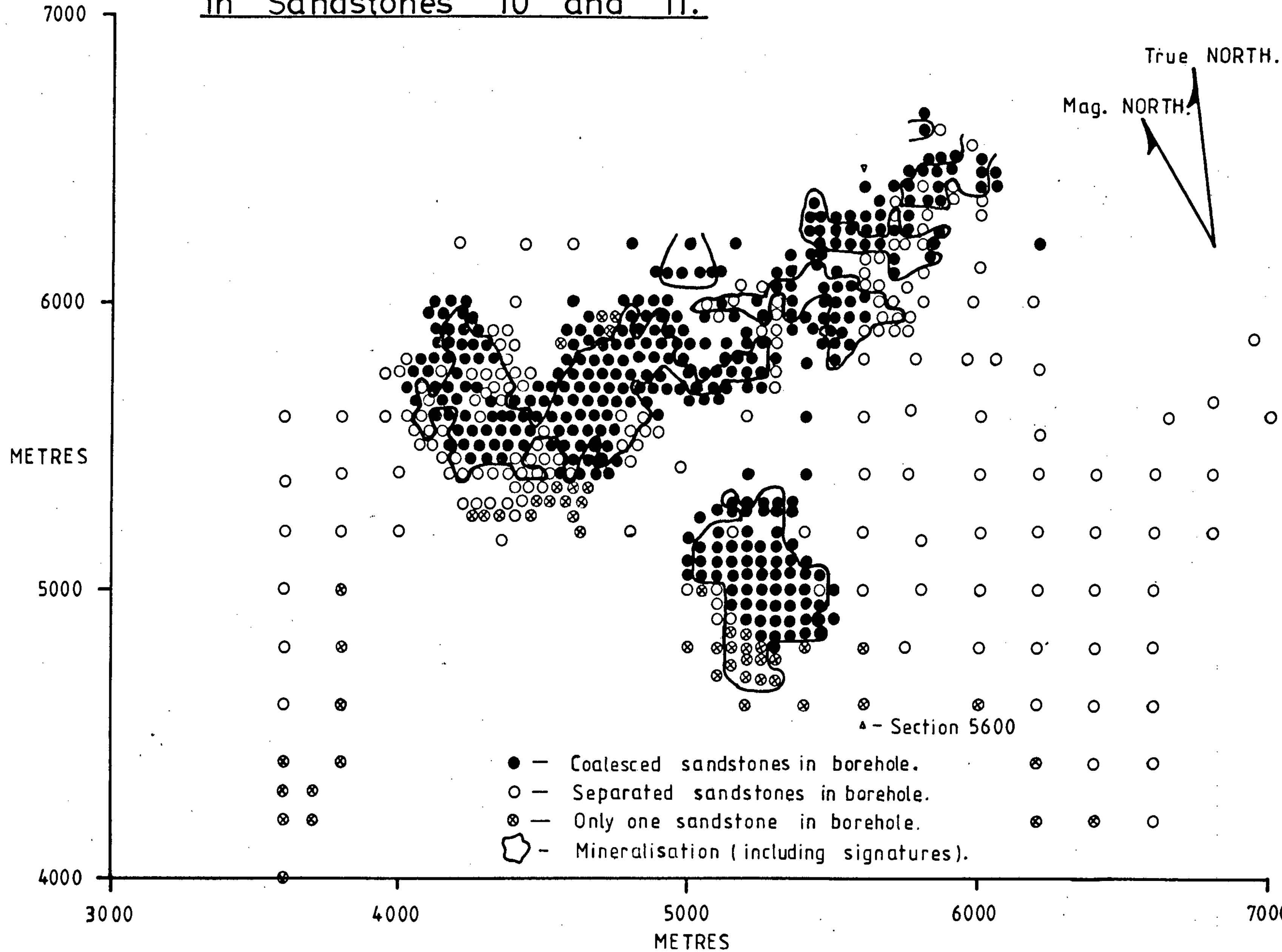
Having examined the 'COALESCENCE MODEL OF URANIUM MINERALISATION' in both two and three dimensions, the drill data should also be examined. Diagram 20 illustrates the relationship between the coalescence of sandstones 10 and 11 and mineralisation. The correlation between the coalescence and mineralisation is so strong that coalescence between two discrete sandstones must be considered a vital factor in the mineralisation of Beaufort sands.

It is also noteworthy that the coalescence is total to the north of the mineralised zone and yet the mineralisation does not continue. This suggests that the point of sandstone coalescence is critical (i.e. the termination of the siltstone parting), but NOT the presence of coalescence as has been suggested by previous workers. The distinction may seem pedantic, but if the coalescence model is correct, then it is ONLY the sandstone within the immediate vicinity of the termination of a major silt-parting that will mineralise, and not the entire coalesced sandstone unit.

9.3 DISCUSSION OF THE MODEL

It was pointed out earlier (Chapter 9.1.2) that a major difference between URAVAN deposits and those at Matjieskoof is the lack of

Diag. 20. The Relationship between Coalescence and Mineralisation in Sandstones 10 and 11.



vanadium at Matjieskloof. It is now felt that this lack of vanadium is simply the reflection of a vanadium deficiency in the provenance area. A second obvious difference is the emphasis on syngenetic mineralisation at Matjieskloof rather than diagenetic and epigenetic mineralisation, as was proposed for URAVAN deposits in North America. It should be noted that a syngenetic ore deposit is considered to have formed contemporaneously with the enclosing rocks.

Kübler (1977) states, "the deposits are not truly syngenetic, they are best described as epigenetic, formed by supergene ground waters". That Kübler (1977) was thinking of an early stage of development is apparent, since he also states, quoting from a Union Carbide Research Report (1972), that 'the report suggested that the deposits may have been formed by the precipitation of uranium from alkaline, aerated ground waters carrying uranyl complexes, by a change in pH conditions, or by direct adsorption onto carbon.' The report was prepared from drill cuttings and core from Beaufort West anomalies.

Kübler (1977) also noted that replacement of woody material had taken place with little or no deformation: this he suggested indicated that ore formation took place before deep burial (an idea proposed by Fisher (1968) for Colorado sandstone uranium deposits).

Anderson and Fraenkel (1979) said that the Rietkuil sandstone (which is stratigraphically very similar to the study area) was mineralised prior to folding, burial and dolerite intrusion; the mineralisation therefore could have been either syngenetic or epigenetic. However, in my view there are two points (ignoring those presented in the model -Chapter 9.2) which argue in favour of a SYNGENETIC formation.

The first of these is the small grain-size. This subject was raised in the introduction (Chapter 1.1) and in Chapter 8.4, where it was stated that the average grain size was fine to very fine. It was further pointed out (Chapter 3.3.4) that the matrix content was very high, and that the sandstone therefore had a very low primary permeability. This is at variance with the models discussed earlier (Chapter 9.1), which have relatively large grain sizes and fairly high permeabilities. This low permeability would clearly limit the volume of water that could potentially move long distances through these buried sand bodies.

The second point in favour of syngenetic mineralisation is the presence of free carbon which is not mineralised. Clearly, if the mineralising fluid was moving epigenetically or diagenetically, all carbon in or adjacent to fluid pathways should mineralise. The fact that it clearly has not, and that only carbon in coalesced zones has mineralised, suggests that some form of syngenetic process was active.

To state categorically that no secondary movement of uranium mineralisation has occurred is incorrect, for in rare instances cross-cutting veinlets of uraninite were noted, and these are believed to relate to remobilisation of uraninite during metamorphism. This in no way detracts from the original suggestion that the primary mineralisation was syngenetic.

Assuming that ore formation was syngenetic, it is worth comparing the coalescence model proposed against the area studied by Kübler (1977). One of his remarks stands out clearly, "the uranium is generally found in the lower halves of the sandstone units, often near to where they interfinger with the argillaceous rocks". Such a remark is explained by the model.

Further, Kübler (1977) notes that "The mineralised sandstones were found (by point count analysis) to contain 5-20% calcite whilst those not mineralised generally contain less than 5% calcite". It is now suggested that if the uranium is transported as a uranyl complex, then on reduction the carbonate released in the ore zone reacts with calcium in the adjacent feldspars to form calcium carbonate. This could explain the typical 'Koffie Klip' high background radioactivity and its association with mineralised zones, noted for example by Eddington and Harrison (1979) and Moon (1974). The words 'Koffie Klip' are Afrikaans, meaning 'coffee rock', and alludes to a brown surficial weathering phenomenon which forms a crust some millimetres to centimetres thick of iron and manganese oxides and carbonates (Eddington and Harrison, 1979).

The association of mineralisation with apparent rapid thickening of the sandstones is also explained, since mineralisation is found only in coalesced zones. However the term 'sandstone thickness' needs clarifying. During section-measuring no discrete single sandstone body greater than 15 m thick was measured. This is not to say that thicknesses exceeding 15 m generated by coalescence, are not present. This point is raised because all too frequently geological publications on the Beaufort Group discuss tremendous thicknesses of sand which the writers call sandstone 'X'. In reality they are discussing several units coalesced into a multi-storied sandstone. Clearly, in view of the model proposed, the recognition of multi-storied sandstones becomes imperative if any worthwhile interpretation of them is to be made, in respect of this model.

Not mentioned previously but present at Matjieskloof is a clear Molybdenum zoning above the uranium ore. In the proposed model a pH/Eh gradient is envisaged across the Redox front. Since not all complexes in transport will reduce at identical Eh's, a primary zoning will be produced for the differing complexes. It is therefore suggested that the molybdenum complex reduces more easily than the uranyl complex, and that the zoning in these ore bodies is a direct result of transport across a weak Redox zone. A similar molybdenum zoning is known to be present at Union Carbide's Rietkuil prospect.

As far as can be judged, coalescence is random (coalescence in this case being that between discrete sands). The process of sand-stocking must relate to the relative rates of aggradation and to avulsion and switching, as described by Allen (1978) and Leeder (1978). Avulsion and stacking are seen as being more likely to generate the type of coalescence required than lateral migration, since field evidence suggests that the sands are relatively narrow with little lateral movement.

It is also apparent that the degree of separation of the two sands is critical. If the sands are too close, then coalescence is total and no mineralisation will be found. Equally, if the sandstones are too far apart, coalesced zones will be too small and too isolated to be of any economic importance. The optimal thickness for the mudstone/siltstone parting cannot be given, but Diagrams 15 - 17 would suggest some 2 - 4 m.

If two discrete sandstones are stacked and coalescence is generated, mineralisation will only occur if the bottom sand contains a) a reducing fluid and b), free carbon. This suggests that the bottom sand must be a transitional-type sand (as discussed in earlier Chapters) since only this type is believed to generate sufficient carbon. The upper sand is probably not so critical, and there is evidence (Diagram 15, Sandstone 11) that low sinuosity sandstones may comprise the upper sand of the couplet.

If the upper sand is transitional (high sinuosity), then deeper scour at meander loops is likely to occur, generating crescent-shaped zones of coalescence. Riffle zones would be less likely to coalesce. The southern and western ore zones at Matjieskloof are clearly related to deeper scouring in meander loops 2 and 3 (see Diagram 12); loop 3 is probably responsible for mineralisation of both parts of the southern and northern zones (note the continuous coalescence in Diagram 20).

It should be pointed out that not only is the basal topography of the upper sand important in coalescence, but so is the surface topography of the lower sand. Field evidence suggests that surprisingly the surface topography of the lower sand appears the more critical, being in excess of 5 m on sandstone 10.

The model proposed is only relevant to what may be considered sub-economic to economic grades and tonnages or uranium ore. It cannot be stated to represent all Matjieskloof uranium anomalies. Some other types will be considered in the following section.

9.4 OTHER MODELS FOR URANIUM MINERALISATION AT MATJIESKLOOF

Beyond the model already proposed, two other types of uranium occurrence can be recognised.- the sump model, and a resistate mineral model.

Typically sump-style uranium occurs in the B_2 lithofacies as discussed in Chapter 2.4. The anomaly is normally low in the sandstone body, frequently in deeply-scoured hollows, and lies above a basal lag conglomerate. Carbonaceous material is abundant, as leaves and stems of size ranging from 10 cm or more down to carbon macerals. On weathering, the sandstone weathers along the bedding plane producing a classic bleached white sandstone with very brown ferrous iron staining. Oxidised vegetable matter is found lying on the bedding plane. Uranium grades may be very high. The units are podiform and when carefully examined, seldom have a continuous anomaly length of much over 5 m.

It is felt that this type of anomaly is generated in stagnant water lying deep in the sandstone of an ephemeral channel system, through which small volumes of fluid are moving. This fluid contains uranyl carbonates which are reduced on the carbonaceous material. This material preferentially mineralises because of a) its extremely low position in the sandstone, b) a reduced fluid flow (due to the material being low in the scoured channel base), c) abundant carbonaceous material and d) because of the generally large size of this material, which gives it a large surface area and good preservation potential.

The 'sump' type anomalies can occur in other positions, and are chiefly dependent on the presence of a sufficiently large piece of carbon. They frequently appear to be of interest because of their high grade - but are seldom of any economic value.

A second very minor type of uranium occurence is also found at Matjieskloof. Weak anomalies are found associated with the resistate minerals of the black sands found on sandstone 10. The ore-grade of these anomalies is so low that they are of no economic value.

10 INTERPRETATION OF THE DEPOSITIONAL ENVIRONMENT

10.1 INTRODUCTION

The predominantly unimodal nature of the Beaufort Group sandstones has always led writers to consider them as being deposited by fluvial processes. Thus authors such as Ryan (1967), Theron (1973), Kübler (1977), Turner (1978) and McPherson and Germs (1979) considered the Beaufort to be of fluvial origin.

The study area is in fact in a 'high sinuosity channel facies association' (see Chapter 1.7). This term was coined by Turner (1978) and is unfortunate because it detracts attention from the other types of channel which are also present. The purpose of this chapter is therefore to produce a model of the depositional environment which accounts for the low and high sinuosity elements seen in the portion of the Pristerognathus/Diictodon Assemblage Zone that was examined.

10.2 REVIEW OF THE FLUVIAL ENVIRONMENT WITH SPECIAL REFERENCE TO THE BEAUFORT GROUP

Straight channels are those which have, at the bankfull stage a negligible sinuosity over a distance many times that of the channel width (Allen, 1965). An example is the Palmietfontein sand (Diagram and Photograph 8). It is suggested by Schumm (1968) that such channels are commonly mixed - or suspension -load streams which occur on relatively gentle slopes. Modern straight rivers are rare and little is known regarding their deposits (Miall, 1977); however the low sinuosity deposits described by Moody-Stuart (1966) may well be of this type.

Straight channels are transitional into 'classic' braided streams. These are defined by Allen (1965) as 'being marked by a succession of diversions and rejoinings of the flow around fluvial islands'. The presence of only one island is sufficient to make the channel braided although most braided reaches show several islands in a cross-section. Such a definition would also make the Palmietfontein sand a braided system, as longitudinal bars were clearly present (see Photograph 11).

Low sinuosity systems can be transitional into meandering systems. Meandering systems are defined by Allen (1965) as showing 'more or less regular inflections in the directions of the channels', and for this reason many workers have explored the geometrical properties of meanders. Langbein and Leopold (1966) demonstrated that meandering is the most probable form of channel geometry and thus is more stable than a straight or non-meandering aligment.

It is apparent from the last three paragraphs that transitional channel systems can be developed between each of the three basic fluvial types (Kübler, 1977, p.51; Leopold and Wolman, 1957). Thus

Miall (1977) quotes the Amite River (Louisiana, U.S.A.) which is a bed-load river with sedimentary deposits and bedforms similar to those of a braided river, yet is essentially a non-braided meandering stream, with a sinuosity (P) of 1,4 - 1,7.

Since all three channel types are present in the study area, the implication is that there must be a complete transition between the three types (if it is assumed that they all flow from the provenance area), or that there are tributaries and main channels (see Chapter 5.8), or some combination of these two ideas.

The following sub-chapters will attempt to demonstrate that Sandstone 10 does in fact display a number of features suggestive of a more ephemeral and transitional nature than previously suspected; however the intention is not to in any way discount or discredit the presence of tributary channels as discussed in Chapter 5.8.

10.3 IS SANDSTONE 10 A TRANSITIONAL SAND?

Rather than describing Sandstone 10 in detail it is necessary to describe only those features which appear to differ from typical fluvial models proposed for high sinuosity systems, such as those suggested by Allen (1965), Turner (1977) and Visher (1972). These differing features are:-

A) Some evidence that bedload transport may be evident (see Chapter 7.3).

B) The dominance of the flat-bedded lithofacies B_2, and apparent subordinate position of the trough cross-bedded B_1 lithofacies (see Frontispiece, Photographs 18 and 19).

C) No cut banks are observed (see Photograph 17).

D) Point-bar surfaces when located are seldom seen with any structure other than B_2 lithofacies. Further, the palaeoflow trends on these surfaces suggest that the water at peak flow, flowed directly across these surfaces.

E) Very little vegetation is in evidence. In general the sandstones are not bioturbated, no seat earths are present, and the bulk of vegetation found is allocthonous - suggesting that the channels failed to carry perennial water.

F) No exotic pebbles are found, clasts being exclusively from reworked adjacent material.

G) Lithofacies C is seldom developed.

H) Many of the sandstones have sharp rather than gradational upper contacts.

Each of these points has been discussed in the various sub-chapters. Viewed individually, none apppear sufficient to argue against a typical high sinuosity system. However when viewed together they strongly suggest (to the author at least) an element of transitionality between high and low sinuosity sandstones. I believe that these 'transitional' sandstones, being in an arid environment, showed a fairly high degree of ephemerality accompanied by fairly extreme changes in flow regime, sufficient that they periodically 'gutted' their beds and developed sheet flow giving the dominance of B_2 lithofacies, and removing the C lithofacies. This ephemerality also limited the development of vegetation, and created fairly common falling-water marks as noted by Stear (1978) and located in at least two places in the study area.

10.4 TRANSITIONAL SYSTEMS

Transitional systems such as the Amite River (Miall, 1977) were mentioned earlier. Such systems are rare and tend to be only poorly developed. Owing to this they have not been extensively examined in the literature. Probably the most detailed examination carried out recently was that by Schwarz (1978), who examined the braided-to-meandering transition of the Red River in Oklahoma and Texas, U.S.A.

Schwarz (1978) found that three types of flow combined to form a sedimentation cycle. They are:-

A) channel flow at low discharge,

B) sheet flow during flood, and

C) post-sheet flow associated with a falling discharge.

These three could be differentiated on the basis of their characteristic sedimentation load, flow pattern, channel morphology and bed-form occurrence. Photographs 25 and 26 (from Schwarz, 1978) clearly

PLATE VIII

Photographs

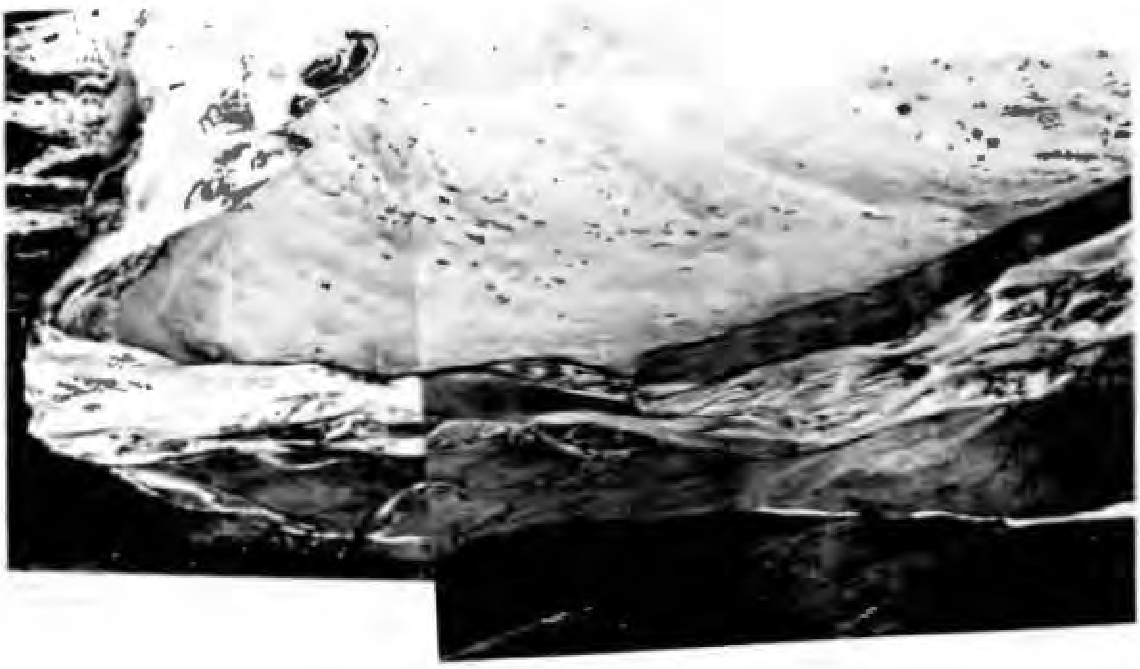
25 and 26 These two photographs show all the features characteristic of transitional fluvial systems. Note the generation of accretion surfaces on point bars, the high sinuosity and strong element of bedload transport (linguoid bars - dotted; transverse bars - dashed).

The point-bar surface (particularly in photograph 26), can be seen to be mainly lithofacies B_2 with small goz 'like' features. Vegetation is minimal and cut banks are either weakly developed or absent.

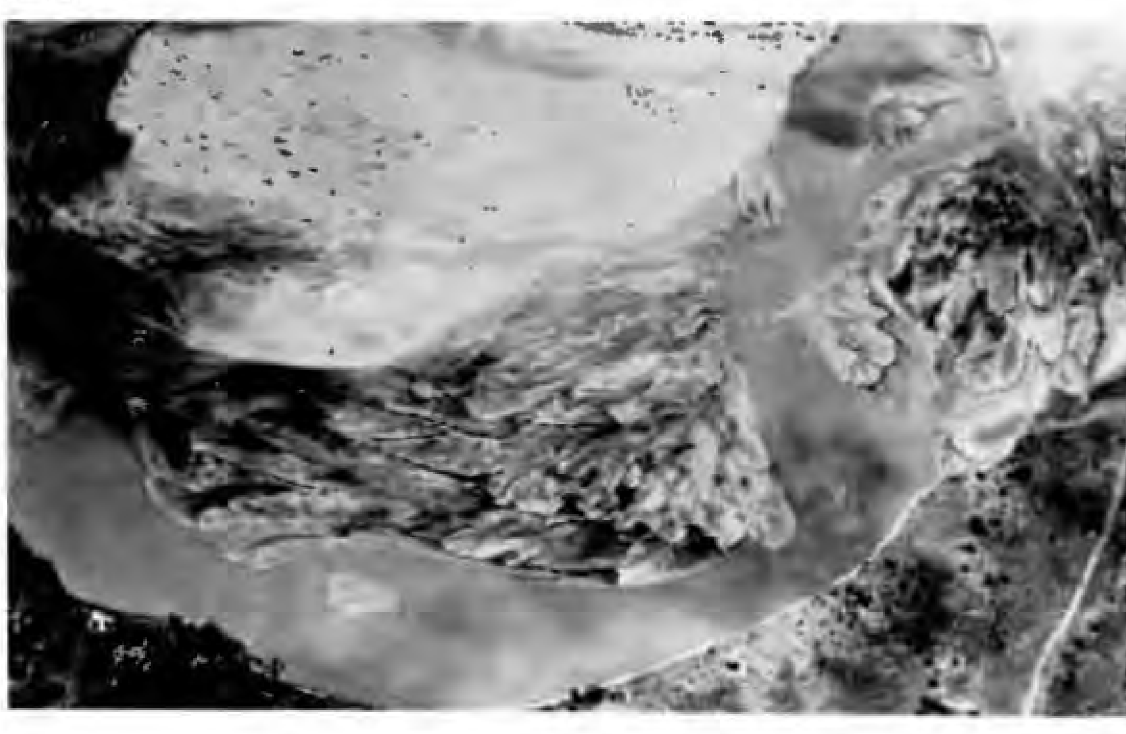
Ridges and swales are weakly developed - see Photograph 25, and can be seen to curve with the point-bar surface. Lithofacies C would be only poorly developed in this environment.

PLATE VIII.

25



26



show the type of fluvial system envisaged for the high sinuosity sandstones in the study area.

In these two photographs, many of the features noted as being present in the Beaufort Group sandstones of the study area are visible.

Linguoid bars are visible in Photograph 26 and although not photographed on Sandstone 10, can be demonstrated to be present. The limited nature of the vegetation is apparent and the weak banks can be seen, cut-banks being only weakly developed. Horizontally-bedded (flat-bedded) sands of the B_2 lithofacies dominate point bar surfaces as was the case on Sandstone 10 (see Photographs 25, 26, 19 and the frontispiece). Lithofacies C is only weakly developed, partly due to limited vegetation and partly to removal during flood. The proposed ephemerality, coupled with regular avulsion, accounts for the sharp upper contact of many of the sandstones. Gozes can be clearly seen on the point bar surfaces (see Photographs 25 and 26), very similar to their fossil equivalents (Photograph 23 and the frontispiece). Meandering is clearly present, in Photograph 26, through over 180^{0}. A tendency for development of ridge and swale features can also be seen, particularly in Photograph 25, and is easily comparable to that seen as a Beaufort equivalent (Photograph 20).

From this photograph it can thus be seen that the Red River displays all the features of the Beaufort Group sandstones even though some of these features are not typical of more 'classic' high sinuosity systems. The hydrology and palaeoflow variability of these systems should now be examined in more detail.

10.5 THE HYDROLOGY OF TRANSITIONAL SYSTEMS

Schwarz (1978) examined a 100 km stretch of the Red River between Burkburnett and Terral (both in Oklohoma). The section that he examined was the central portion of a 230 km transitional zone which begins some 50 km upstream of Burkburnett and ends some 80 km below Terral. The drainage area above Terral is some 74 393 km^{-2} and the overall channel sinuosity (P) for the 100 km is 1,60. The channel gradient for the study reach is 0,00076 above the Wichita River and 0,00044 below it.

At Burkburnett the mean daily discharge in the period 1960 - 1976 was 23,14 m^3/S with a maximum discharge of 1780 m^3/S. Frequently, channel flow is <u>zero</u>.

At Terral, over a period from 1938 - 1976 the mean daily discharge was 62,11 m^3/S with a maximum of 5580 m^3/S. Minimum flow was 1,22 m^3/S.

Water depths during low discharge are 0,033 - 0,88 m at Burkburnett and 0,265 - 3,47 at Terral. During flood discharge, water depths of 2,95 - 3,493 m are typical at Burkburnett, whilst Terral has water depths of 5,051 - 8,571 m.

Channel widths also change drastically between high and low discharge. Thus at Burkburnett the range is 13,88 - 621,05 m, averaging 216,45 m and at Terral 31,53 - 308,71 m, averaging 109,46 m. During sheet flow the entire river bed may be water covered.

The system is thus essentially ephemeral. However the figures given here cannot be directly compared with assumed flows in Beaufort Group sandstones because the gradient of the Red River is clearly much higher than that which must have existed during Beaufort Group formation. Although no precise figures have been generated the presence of straight channels in a very muddy environment must indicate a very low fluvial gradient for these sediments. This point will be considered again later.

10.6 CURRENT VECTOR ORIENTATION IN TRANSITIONAL SYSTEMS

Schwarz (1978) did a two-dimensional analysis of the current orientations in the Red River in that he conducted his current vector analysis using aerial photographs. From the photographs he identified the bed forms in the river, i.e. linguoid, longitudinal, braided, transverse and scroll-like bars; sand waves; and caternary, sinuous and straight dunes; and estimated the flow directions. This meant that only the larger bedforms, (rank 4; after Miall, 1974) could be used. For each bedform he allowed a 10^{o} variability - no weighting factor was used.

He found, from 533 current orientations measured in 6 river segments, that the range in mean direction (of the six segments) was 097^{o} for channel flow bedforms and 160^{o} for sheet and post sheet flow deposits. These gave standard deviations of 38^{o} and 56^{o} respectively with azimuthal spreads of 285^{o} and 332,5^{o}. Bearing in mind the rank of bedforms being measured, these figures compare well with those presented in sub-chapter 5.4, (Table 9 - transitional sandstones). It is also interesting to note that many of the river reaches measured by Schwarz (1978) gave good bimodal distributions.

10.7 TRANSITIONAL SANDSTONES IN RELATION TO BEAUFORT GROUP SANDSTONES

That transitional systems can then have a wide azimuthal variation has been clearly demonstrated by Schwarz (1978). This suggests that the assumption that a high palaeovariability in a sandstone is indicative of derivation from a classic high sinuosity channel is falacious, and allows the consideration of alternatives such as transitional systems. It would further appear that transitional systems can and do display many of the features associated with 'classic' high sinuosity systems and that their recognition in the field is dependent on the recognition of features such as some evidence of bedload dominance in association with a high sinuosity.

That Beaufort Group sandstones display many of the features of transitional sandstones cannot be denied. It is however not correct to compare directly a degradational transitional system (the Red River) with one which was progradational (Sandstone 10), nor one where the gradients are clearly very different. Both of these problems will be considered in sub-chapter 10.9.

10.8 TRANSITIONAL SYSTEMS AND THE MUDSTONE + SILTSTONE: SANDSTONE RATIO

In the case of the Red River transition, the river is changing from fully braided to meandering. Such a transition is clearly proximal and is unlikely to produce the major flood plain deposits which dominate the stratigraphy of the study area. In fact the presence of abundant muds and silts, and development of numerous soil horizons suggests a very distal nature and slow progradation - atypical of a proximal environment.

However the transition being observed could also represent high-sinuosity to low-sinuosity, and in view of the arid environment and presence of numerous small, oxidised, muddy-sand tributaries (as suggested in sub-chapter 5,8) such a belief may not be ill-founded. This suggests that the transitionality may not be a function of gradient (as it was in the Red River) but a function of ephemerality induced by aridification along its length. This aridification generated a more variable seasonal (?) discharge in the distal portions of the system, than would have been found more proximally.

If aridification were total then this would suggest that the Beaufort Group could represent a major terminal fan. This is not implied here but the concept of terminal fans must be examined.

10.9 TERMINAL FANS AND BEAUFORT GROUP SANDSTONES

Classically a terminal fan as described by Mukerji (1976) is formed by the repeated bifurcation of distributaries and master channels, due to water loss, and in-channel sediment build up. The fans as described by Mukerji (1976) of the Sutlej-Yamuna Plain in India are small, but Williams (1971) in his discussion of the ephemeral streams of Central Australia, notably the Eyres Basin, discusses terminal fans (although he does not use this terminology) of much larger dimensions. The ephemeral streams of the Eyres Basin drain towards the basin centre but dry out totally before ever reaching it.

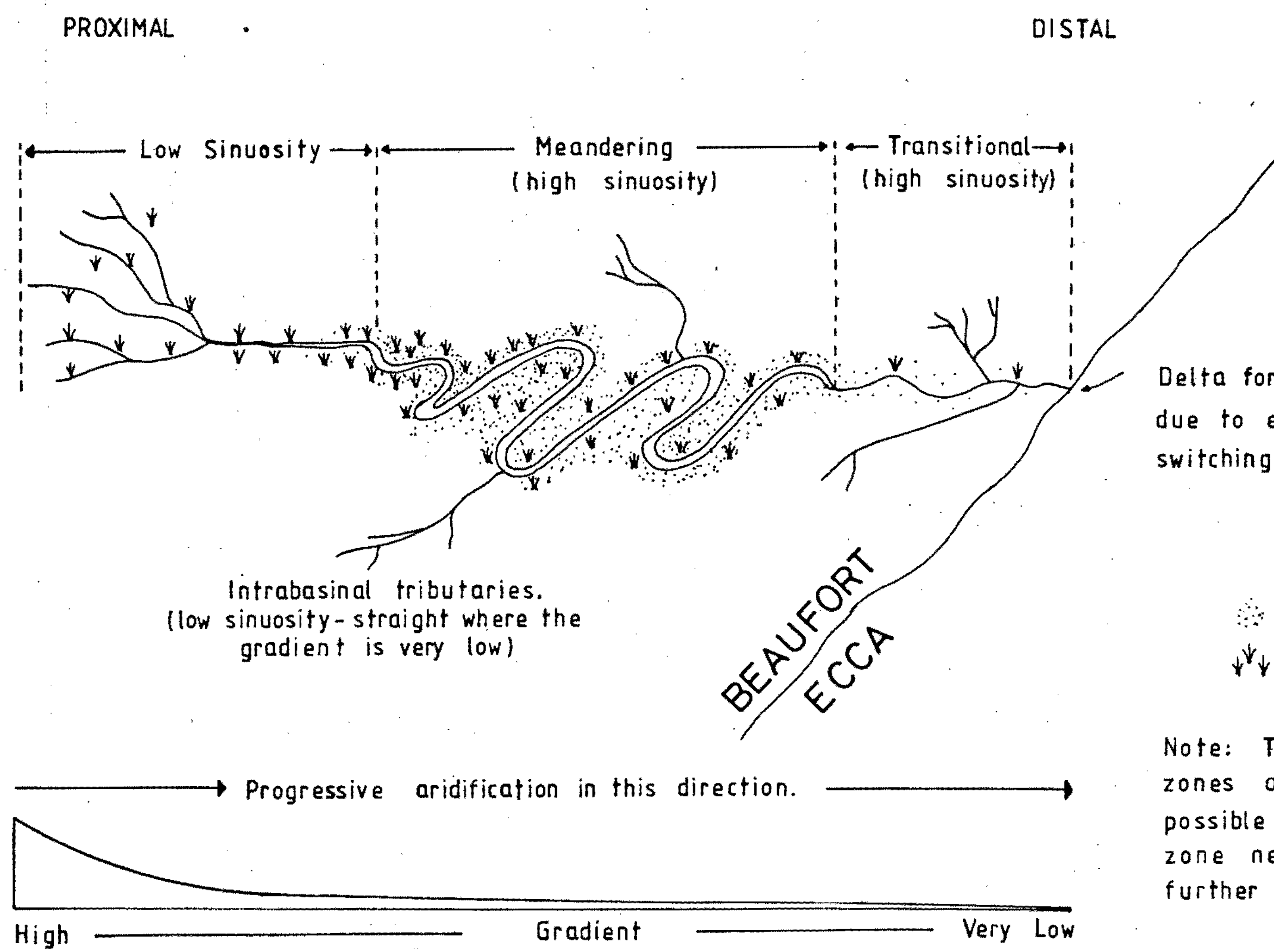
Such a suggestion of total aridification, for the Beaufort Group of the study area and elsewhere is obviously ill-founded. If total aridification had occurred then a nett progradation of the Beaufort and Ecca as proposed by Turner (1978) could never have occurred, since no sediment would have been fed into the Ecca Basin. At the same time Wickens (pers.comm.) mapping the Beaufort-Ecca contact, states that he has observed no major sandstone at the Ecca-Beaufort contact (and this is borne out by the authors own - admittedly limited observations). This lack of major fluvial systems (as evidenced by the lack of major sandstones), is strange in what is obviously a major distal-fluvial environment.

However the problem may be resolved by suggesting that Beaufort Group sandstones sit at the distal end of a partially aridifying system which gave the high sinuosity sandstones a transitional nature. A model of the system envisaged is shown in Diagram 21 (the study area being assumed to be in the transitional-distal system).

The more proximal part of the system is visualised as having permanent but variable flow, with subsequent development of a more stable fluvial system with accompanying generation of levees and vegetation. This vegetation was flushed down-stream during flood and it is felt that this may account for the vegetation (which is accumulated allocthonous material in 'trash' zones) found accompanying uranium mineralisation.

Downstream from this more stable meandering portion of the fluvial system, dessication (aridification) generated a more variable flow regime - quite possibly even ephemeral. In this zone, the sediments would be distal and very fine-grained. No exotic lithoclasts would be likely due to reduced flow rates and their removal and stabilisation in more proximal meander belts. Mudstones would be the dominant rock type due to the distal nature of the sediment and would probably be formed by vertical accretion associated with major flood events. Their accumulation would be fairly slow since flooding would be more sporadic than in a 'classic' high sinuosity system. Palaeosols would be common, since the climate would be moisture-deficient. Seasonal wetting could well occur and the topography would be

Diag. 21.
A Model of the Fluvial System Envisaged.



Delta formation likely to be limited due to ephemeral flow and frequent switching.

- Levees

- Vegetation

Note: The meandering and transitional zones are not shown to scale. It is even possible that the true meandering zone never develops. See text for further details.

minimal, allowing time for generation of the numerous pedocals seen (McPherson and Germs, 1979). Thin extensive cherts could be laid, probably after flooding when shallow sheets of standing water would be present.

The red-beds are thus likely to have been hydrated brownish iron oxides, altered to haematite within the soil horizons, or during diagenesis. This red suggests that the sediments had abundant iron and argues against the presence of organics in these sediments, which would either have leached the iron or reduced it.

The apparently very flat, featureless topography was thus an ideal environment for the development of ephemeral straight channels such as the Palmietfontein sandstone. These channels probably represent tributary channels which drained storm water in areas of very low gradient.

10.10 SUMMARY

It is therefore suggested that the transitional sandstones (as defined in sub-chapter 5.6) are major perennial to ephemeral fluvial systems fed from the provenance area whilst the straight and low-sinuosity channel sandstones are tributaries draining interfluves in an arid environment, which only flowed sporadically.

The entire drainage network is situated in an arid enviromment and all the drainages are undergoing aridification, a factor which creates the features of transitionality in the larger fluvial systems. This aridifcation creates sediment build up in the major channels, which, combined with an extremely low gradient, allows easy and rapid avulsion tending to generate fairly simple sand bodies, and extensive mud and silt interfluves.

That the climate was arid is demonstrated by mud-cracks, desert roses, and the generation of numerous pedocals. The abundant haematite may also bear witness to a warm climate. The lack of major development of vegetation is also attributable to the arid climate and variability of river flow.

Such a model would also suggest that no deltas are likely to be generated at the Beaufort-Ecca contact since flow rates at the distal end of the fluvial system would be very variable, quite possibly ephemeral, avulsion and switching would be common and sheet flooding would occur. This would suggest that deltas may never have formed on a large scale, at the Ecca-Beaufort contact. Flow during flood would tend tocross the contact on a broad front while only weakly channelised and this could account for the major sands of the Waterford having only smaller counterparts in the lower Abrahamskraal Formation. Such a major flood input could also account for the numerous turbidites seen in the Ecca Group of the Western Karoo basin.

11 APPENDIX

11.1 PROGRAMMES FOR PALAEOCURRENT TREATMENT USING THE HP - 33 E

11.1.1 Programme 'A' which Converts Magnetic Compass Bearings to True Bearings.

This is a very simple programme. The only key-strokes which can be varied are 01, 02 and 03, which represent the magnetic declination at the geographical location where the readings were taken. No account is taken in this programme of magnetic declinations of less than a whole degree.

Step	Key-Stroke	Comment
00	F clear PRGM	
01	2	Magnetic Declination
02	3	" "
03	-	" "
04	g x < 0	
05	GTO 07	
06	GTO 00	
07	3	
08	6	
09	0	
10	+	
11	GTO 00	

Whilst working in the field this programme was used to correct all magnetic azimuths as a first step prior to data handling. Ideally this step would be incorporated into programmes B and C. Unfortunately the calculator programme storage is not large enough and precludes the inclusion of this programme.

11.1.2 Programme B which gives a vectoral mean ($\bar{X}_v$) for 'n' vectoral readings (no weightings used).

This programme initially stores the newest entry (step 01), then determines the Sine and Cosine of that newest entry (steps 02 - 06) and sums these in separate stores. It thus generates

$$W = \sum_{i=1}^{n} \text{Sin } \theta \qquad \text{in store 1}$$

and

$$V = \sum_{i=1}^{n} \text{Cos } \theta$$

and since no weighting is used, assumes each vector of equal weighting (and unity). θ is the true bearing of the magnetic bearing after using Programme A. The vectoral mean ($\bar{X}_v$) is the arctan of $^W/V$

i.e. $\bar{X}_v = \arctan {}^W V$

Since Sine and Cosine can be -ve and +ve, this process produces four possible quadrants. The 1st quadrant is where both are +ve, in the second W is +ve and V is -ve, in the third both are -ve and in the fourth V is +ve and W is -ve. This programme must therefore differentiat the quadrant and then determine the bearing. This will not be discussed in detail and the interested reader need only work through the comments.

Step	Key-Stroke	Comment
00	f clear PRGM	
01	STO 0	Newest entry in stor
02	f Sin	Sin of newest entry
03	STO + 1	" to Store 1
04	RCL 0	Recall newest entry
05	f Cos	Cosine of newest entry
06	STO + 2	Cosine to Store 2.
07	RCL 1	Recall $\sum$ Sines
08	g x < 0	If -ve

Step	Key-Stroke	Comment
09	GTO 27	Go to step 27
10	g $x > 0$	If +ve
11	RCL 2	Recall Cosines
12	g $x < 0$	If -ve
13	GTO 18	Go to step 18
14	g $x > 0$	If +ve
15	÷	Divide step 10 by step 14
16	g Tan^{-1}	Find the arctan. Thi quadrant is W+ve and V+ve
17	GTO 00	Go to step 00. Programme stops and the vector is displayed for the 1st quadrant
18	÷	Divide step 10 by step 12.
19	CHS	Change the sign
20	g Tan^{-1}	Find arctan
21	1	
22	8	180
23	0	
24	$x \rightleftarrows y$	Rotate x and y register
25	-	Subtract (i.e.180 - step 20)
26	GTO 00	Programme stops and displays vector in second quadrant
27	RCL 2	Recall Store 2
28	g $x > 0$	if +ve
29	GTO 38	Go to step 38
30	g $x < 0$	if -ve
31	÷	Divide step 8 by step 30

Step	Key-Stroke	Comment
32	g Tan^{-1}	Arctan
33	1	
34	8	180
35	0	
36	+	Add (180 + step 32)
37	GTO 00	Programme terminates and displays vector in third quadrant
38	÷	
39	CHS	
40	g Tan^{-1}	Arctan
41	3	
42	6	360
43	0	
44	x ⇄ y	Rotate x and y register
45	-	Subtract (360 - step 40)
46	GTO 00	Programme terminates and displays vector in fourth quadrant

Once programmed this programme works well. Only one problem is found and that is if the first bearing entered is 000^o, 090^o, 180^o, 270^o or 360^o. In each case either the sine or cosine of these is 0,00, and thus either W or V is nought and the division of W by V becomes impossible. If one of these numbers is encountered in a situation where it would be entered first, then it should be changed with the adjacent bearing and no problem will be found.

11.1.3 Programme 'C' which gives a Vectoral Mean ($\bar{X}_v$), the Magnitude of the Resultant Mean Vector (R), the Magnitude of the Resultant Vector in Percent (L) and the Standard Deviation of the Population of Vectors (S). As with programme 11.1.2, this programme finds V and W and then R, where

$$R = (W^2 + V^2)^{\frac{1}{2}}$$ (after Potter and Pettijohn, 1977)

The magnitude of the resultant vector in percent (L) is found from:-

$$L = \frac{R}{n}(100)$$ (after Potter and Pettijohn,1977)

where 'n' is the total number of vectors measured. Note that R/n is the consistency ratio, which is never displayed.

The standard deviation (S) is found from

$$S = [2(1 - r)]^{\frac{1}{2}}$$ (after Turner, 1975)

where

$$r = (\bar{x}^2 + \bar{y}^2)^{\frac{1}{2}}$$

and

$$\bar{x} = \sum_{i=1}^{n} \text{Sin } \theta/_n$$

and $\bar{y} = \sum_{i=1}^{n} \text{Cos } \theta/_n$

This formula assumes a circular normal distribution (von Mises distribution) discussed in Till (1974, p.38-43).

It should be noted that this programme does NOT give a true bearing for the vectoral mean but only a bearing in one of the four possible quadrants discussed in 11.1.2. For a true bearing, programme 11.1.2 can be entered, without clearing the 'stores' and a true bearing will be displayed.

Step	Key-Stroke	Comments
00	f clear PRGM	As per programme 11.1.2
01	STO 0	" " "
02	f Sin	" " "
03	STO + 1	" " "

Step	Key-Stroke	Comment
04	RCL 0	As per programme 11.1.2.
05	f Cos	" " "
06	STO + 2	" " "
07	1	Generates 'n'
08	STO + 3	'n'
09	RCL 1	Recall $\sum \text{Sin}\,\theta$
10	g x^2	$(\sum \text{Sin}\,\theta)^2$
11	RCL 2	Recall $\sum \text{Cos}\,\theta$
12	g x^2	$(\sum \text{Cos}\,\theta)^2$
13	+	Add steps 10 and 12
14	f $\sqrt{x}$	$(\sum \text{Sin}\,\theta^2 + \sum \text{Cos}\,\theta^2)$
15	STO 4	This is R
16	RCL 3	Recall 'n'
17	÷	Divide R by 'n'
18	1	
19	0	100
20	0	
21	X	Multiply $^R/n$ (consistency ratio) by 100 = L
22	STO 5	Store L.
23	RCL 1	Recall $\sum_{i=1}^{n} \text{Sin}\,\theta$
24	RCL 3	Recall 'n'
25		This is $\bar{X}^2$
26	g x^2	This is $\bar{X}^2 = (\sum_{i=1}^{n} \text{Sin}\frac{\theta}{n})^2$
27	RCL 2	Recall $\sum \text{Cos}\,\theta$
28	RCL 3	Recall 'n'
29	÷	This is $\bar{y}$
30	g x^2	This is $\bar{y}^2 = (\sum \text{Cos}\frac{\theta}{n})$
31	+	
32	f $\sqrt{x}$	This is $r = (\bar{x}^2 + \bar{y}^2)^{\frac{1}{2}}$
33	1	

Step	Key-Stroke	Comment
34	x ⇄ y	
35	-	This is (1 - r)
36	2	
37	X	
38	f $\sqrt{x}$	This is $2(1-r)^{\frac{1}{2}}$
39	g ⇨Deg	Converts step 38 which is in radians to degrees
40	STO 6	Standard Deviation S (in degrees to store 6)
41	RCL 1	Recall $\sum_{i=1}^{n} \sin\theta$
42	RCL 2	Recall $\sum_{i=1}^{n} \cos\theta$
43		
44	g $\tan^{-1}$	Arctan
45	STO 7	Vectoral mean ($\bar{X}_v$)
46	GTO 00	Programme terminates

As with programme 11.1.2. directional azimuths 000°, 090°, 180°, 270° and 360° should be avoided as initial entries.

11.2 CONTINUITY INDEX

Before considering the continuity index itself it is worth examining the premises on which it is based. Initially when section measuring began it was felt that the sandstones were randomly located in the sediment pile and that no such features, as broadscale fluvial and interfluvial zones were present, each sandstone being considered as a separate system in time. However as section-measuring continued it became very apparent that certain groups of sections were sand-dominant and others clearly sand-deficient. This suggested that some type of primary control was acting on the sandstones and that possibly the sandstones were not random in the sediment pile but tended to be concentrated in a central zone. Further, it appeared likely that the major sandstones were almost exclusively developed in a central portion of the study area and that only small minor sandstones occurred towards the margins.

If the sandstones with the longer strike lengths were concentrated in a central zone then clearly some form of measurement of sandstone continuity should demonstrate this. Also if sandstone strike length relates to the size of the primary fluvial system the sandstone : mudstone ratio should change in favour of the sand. Thus by comparing the sandstone : mudstone ratio with the sandstone continuity index it should be possible to identify fluvial and interfluvial zones.

A very simple continuity index was evolved, where:-

$$\text{C.I. (continuity index)} = \frac{\text{Sum of continuities to left and right}}{\text{Number of Sandstones}}$$

A continuity to the left or right is found where a sandstone continues from the section being considered to an adjacent section on the left or right (west or east). If the sandstone continues to the left it scores 1 and if to the right again 1. It therefore will have a C.I = 2 if the sandstone under consideration is continuous between both adjacent sections. If the sandstone fails to reach either of the adjacent sections it scores C.1 = 0.

In the case of end sections (i.e. section 4 and section 26 in Diagram 2) a slightly different treatment is required - since there can only be one adjacent section. In this case each sandstone only scores a ½, thus

$$\text{C.I} = \frac{\text{Sum of continuities}}{\frac{1}{2} \times \text{Number of sandstones}}$$

and thus preserves the ratio.

The values of the continuity index for sections 4 to 26 are tabulated in Table 8, and shown graphically in Diagram 6.

12 ACKNOWLEDGEMENTS

Johannesburg Consolidated Investment Co. Ltd., supported all aspects of this dissertation and they are particularly acknowledged for allowing the publication of borehole data. Mr. P.G. Cochran and Mr. E. H. Jones must be especially thanked for allowing the author the opportunity to complete this thesis. Mr. R.G. Wadley and Mr. C.M. Taylor are also cordially thanked for their assistance and for many useful discussions and suggestions. Without Mr. C.M. Taylor's caustic wit many of the ideas about uranium mineralisation may never have reached fruition.

Professor A.O. Fuller of the University of Cape Town who supervised this dissertation is thanked for his support. Without his faith and confidence it is likely that this thesis may never have been completed.

My family and parents-in-law are thanked for their support and patience.

Lastly, my special thanks go to the typists of Lucy's Typing and Secretarial Services, Rondebosch, for braving my writing and typing this thesis.

13 REFERENCES

Adler, H.H., (1974). Concepts of uranium ore formation in reducing environments in sandstone and other sediments, p.141 - 168. In: Formation of Uranium Ore Deposits. International Atomic Energy Agency, Vienna, 748 p.

Allen, J.R.L., (1963). The classification of cross-stratified units with notes on their origin. Sedimentology, 2, 93 - 114.

______ (1964). Primary current lineation in the lower Old Red Sandstone (Devonian),Anglo Welsh Basin. Sedimentology, 3, 89 - 108.

______ (1965). A review of the origin and characteristics of recent alluvial sediments. Sedimentology, 5, 89 - 191.

______ (1968). The nature and origin of bed-form hierarchies. Sedimentology, 10, 161 - 182.

______ (1970). Studies in fluviatile sedimentation: A comparison with fining upward cyclothems, with special reference to coarse member composition and interpretation. J. Sedim. Petrol, 40, 298 - 323.

______ (1978). Studies in fluviatile sedimentation: An exploratory quantitative model for the architecture of avulsion - controlled alluvial suites. Sedim. Geol., 21, 129 - 147.

Anderson,R., and Fraenkel, H.C., (1979). The geology and mineralisation of a uranium occurrence at Rietkuil farm, Beaufort West district, South Africa. Paper presented at the 18th Congress of the Geological Society of South Africa.

Bagnold, R.A., (1954). The physics of blown sand and desert dunes, 265 p. Methuen : London.

Bain, A.G., (1845). On the discovery of the fossil remains of bidental and other reptiles in South Africa. Proc. Geol. Soc. Lond., 4, 499 - 500.

Beeson, R., (1978) The geochemistry of surface uranium mineralisation in the south west Karoo basin. Open file Rep. Geol. Surv. S. Afr., 75, 12 p.

Beukes, N.J., (1970). Stratigraphy and sedimentology of the Cave Sandstone Stage, Karoo System. Proc. 2nd Int. Gondwana Symp., I .U.G.S., South Africa. p.321 - 341.

Boonstra, L.D., (1969). The fauna of the Tapinocephalus zone (Beaufort beds of the Karoo). Ann. S.Afr. Mus., 56 (1), 1 - 75.

Boothroyd, J.C., and Nummedal, D., (1978). Proglacial braided outwash: A model for humid alluvial fan deposits. In: Miall, A.D., (Ed.), Fluvial Sedimentology, Can. Soc. Petrol. Geol., Memoir 5, 641 - 668.

Brice, J.C., (1964). Channel patterns and terraces of the Loup Rivers in Nebraska. U.S. Geol. Surv. Prof. Paper 422 - D.

Broom, R., (1905). Notes on the localities of some type specimens of the Karroo fossil reptiles. Rec. Albany Mus., 1., 275 - 278.

______ (1907). On the geological horizons of the vertebrate genera of the Karroo Formation. Rec. Albany Mus., 2, 156 - 163.

Case, E.C., (1926). Environment of tetrapod life in the late Palaeozoic of regions other than North America. Publ. Carnegie Instn. Wash., 375, 141 - 167.

Cole, D.I., (1979). The sedimentology of uranium bearing sandstones on the farm Ryst Kuil 351, Beaufort West area. Open File Rep. 1980 - 0020. Geol. Surv. S. Afr.

Conybeare, C.E.B., and Crook, K.A.W., (1968). Manual of sedimentary structures. Australian Dept. National Development, Bur. Min. Resources, Geology and Geophysics, Bull., 102, 327 p.

Curray, J.R., (1956). The analyses of two dimensional orientation data. J. Geol., 64, 117 - 131.

Dapples, E.C., (1967). Diagenesis of sandstones, p. 91 - 125. In: Larsen, G., and Chilingar, G.V., (Eds.), Diagenesis in Sediments. Amsterdam, Elsevier Pub. Co., 551 p.

Doi, K., Hirono, S., and Sakamaki, Y., (1975). Uranium mineralisation by ground water in sedimentary rocks, Japan. Econ. Geol., 70, 628 - 646.

Dott, R.H., Jr., (1973). Paleocurrent analysis of trough cross-stratification. J. Sedim. Petrol., 43, 779 - 783.

Du Toit, A.L., (1918). Zones of the Karroo System and their distribution. Proc. Geol. Soc. S.Afr., 21, 17 - 36.

______ (1954). The Geology of South Africa, 3rd. edit. Oliver and Boyd, 576 p.

Eddington, S.M., and Harrison, D., (1979). Ryst Kuil uranium deposit - a case history. Paper presented at the 18th Congress of the Geological Society of South Africa.

Elliot, D.H., and Watts, D.R., (1974). The nature and origin of volcaniclastic material in some Karroo and Beacon rocks. Trans. Geol. Soc. S. Afr., 77, 109 - 111.

Ferm, J.C., and Cavaroc, V.V., (1968). A non-marine model for the Allegheny of West Virginia. In: G. de V. Klein, (Ed), Late Paleozoic and Mesozoic Continental Sedimentation, Northeastern North America. Geol. Soc. Amer., Spec. Pap., 106, 1 - 19.

Fisher, R.P., (1968). The uranium and vanadium deposits of the Colorado Plateau region, 734 - 746. In: Ridge, J.D., (Ed), Ore deposits of the United States, p. 1933 - 1967. Vol. 1. American Institute of Mining, Metallurgical and Petroluem Engineers, New York, 991 p.

______ (1974). Exploration guides to new uranium districts and belts. Econ. Geol., 69, 362 - 376.

Folk, R.L., Andrews, P.B., and Lewis, D.W., (1970). Detrital sedimentary rock classification and nomenclature for use in New Zealand. New Zealand J. Geology and Geophysics, 13, 937 - 968.

Frey, R.W., and Howard, J.D., (1970). Comparison of Upper Cretaceous Ichnofossils from Siliceous Sandstones and Chalk, Western Interior Region, U.S.A., p.141 - 165. In: Crimes, T.P., and Harper, J.C., (Eds.), Trace Fossils. Geol. J. Spec. Issue 3.

Gabelman, J.W., (1971). Sedimentology and uranium prospecting. Sedimentary Geology, 6, 145 - 186.

Granger, H.C., and Warren, C.G., (1979). The importance of dissolved free oxygen during formation of sandstone type uranium deposits. U.S. Geol. Surv., Open File Rep., 79 - 1603, 22 p.

Greenshields, H.D., (1978). A palaeoenvironmental analysis of the Beaufort Group along the Transkei and parts of the Ciskei Coast. M.Sc. Thesis (unpub.), Pietermaritzburg.

Gruner, J.W., (1956). Concentration of uranium in sediments by multiple migration - accretion. Econ. Geol., 51, 495 - 520.

Grutt, E.W., (1975). Prospecting criteria for sandstone type uranium deposits. Paper presented at the International Atomic Energy Agency Symposium, Vienna.

Hamblin, W. K., (1961). Micro-cross-lamination in Upper Keweenawan sediments of northern Michigan. J. Sedim. Petrol. 31, 390 - 401.

Harbaugh, J., and Bonham Carter, G., (1970). Computer simulation in geology, Wiley and Sons, New York, 575 p.

Henderson, R.E., (1974). The geology and hydrodynamic interpretation of the Lower Beaufort Series north of Beaufort West, Price Albert and Graaff-Reinet. B.Sc. (Hons) diss.(unpub.), Univ. Witwatersrand, 83 p.

Ho-Tun, E., (1979). Volcaniclastic material in Lower Beaufort Group Karroo rocks. Paper presented at the 18th Congress of the Geol. Soc. S. Afr.

Horowitz, A., (1976). Environment of deposition, and stratigraphy of the uranium bearing strata around Beaufort West, South Africa. Atomic Energy Board Publ., PEL 251.

Hotton, N., (1967). Stratigraphy and sedimentation in the Beaufort Series, 390 - 428. In: Teichert, C., (Ed.), Essays in paleontology and stratigraphy. University of Kansas Press.

Hostetler, P.R., and Garrels, R.M., (1962). Transportation and precipitation of uranium and vanadium at low temperatures with special reference to sandstone type uranium deposits. Econ. Geol., 57, 137 - 167.

Ingram, R.L., (1954). Terminology for the thickness of stratification and parting units in sedimentary rocks. Geol. Soc. Amer., Bull, 65, 937 - 938.

Jensen, M.L., (1958). Sulfur isotopes and the origin of sandstone type uranium deposits. Econ. Geol., 53, 598 - 616.

Johnson, M.R., (1966). The stratigraphy of the Cape and Karroo systems in the Eastern Cape Province. M.Sc. thesis, Rhodes Univ. (unpub.).

______ Botha, B.J.V., Hugo, R.J., Keyser, A.W., Turner, B.R., and de la R. Winter, H., (1976). Preliminary report on lithostratigraphic nomenclature in the Karoo Sequence. S.Afr. committee on stratigraphic nomenclature, Unpub. report, 21 p.

______ and Keyser, A.W., (1979). Expl. sheet 3222 (The geology of the Beaufort West area). Geol. Surv. S.Afr.

Jones, T.R., (1867). Some secondary fossils from South Africa. Quar. J. Geol. Soc. Lond., 23, 139 - 175.

Keyser, A.W., (1966). Some indications of arid climate during the deposition of the Beaufort series. Ann. Geol. Surv. S.Afr., 5, 77 - 79.

______ (1970). Some ecological aspects of the Cistecephalus zone of the Beaufort Series of South Africa. I.U.G.S., 2nd Gondwana Symp., Pretoria, p. 687 - 689.

______ (1978). Notes on the Ecca-Beaufort boundary in the Western Karoo. Ann. Geol. Surv. S. Afr., 12, 69 - 72.

______ and Smith, R.M.H., (1978). Vertebrate biozonation of the Beaufort Group with special reference to the Western Karoo Basin. Ann. Geol. Surv. S. Afr., 12, 1 - 35.

Kitching, J.W., (1970). A short review of the Beaufort zoning in South Africa. In: I.U.G.S., 2nd Gondwana Symp. (S.H. Haughton, Ed.), Pretoria.

______ (1973). On the distribution of the Karroo vertebrate fauna with special reference to certain genera and the bearing of this distribution on the zoning of the Beaufort Beds. Unpub. Ph.D. thesis, University of the Witwatersrand, Johannesburg, 256 p.

______ (1977). The distribution of the Karoo vertebrate fauna. Mem. Bernard Price Inst. Palaeont. Res., Univ. Witwatersrand, 1.

Kübler, M., (1977). The sedimentology and uranium mineralisation of the Beaufort Group in the Beaufort West - Fraserburg - Merweville Area, Cape Province. M. Sc. Thesis (unpub.), Univ. Witwatersrand.

Kuenen, Ph. H., (1963).. Turbidites in South Africa. Trans. Proc. Geol. Soc. S.Afr., LXVI, 191 - 195.

Langbein, W.B., and Leopold, L.B., (1966). River Meanders - Theory of Minimum Variance. U.S. Geol. Surv. Prof. Paper 422 -H, 15 p.

Langmuir, D., (1978), Uranium solution - mineral equilibria at low temperatures with applications to sedimentary ore deposits. Geochimica et Cosmochimica Acta, 42, 547 - 569.

Leeder, M.R., (1978). A quantitative stratigraphic model for alluvium, with special reference to channel deposit density and interconnectedness. In: Miall, A.D., (Ed.), Fluvial Sedimentology. Canad.Soc. Petrol. Geol.,Memoir 5, 587 - 596.

Leopold, L.B., and Wolman, M.G., (1957). River channel patterns: braided, meandering and straight. U.S. Geol. Surv. Prof. Paper 282 - B, 35 - 85.

______, Wolman, M.G., and Miller, J.P., (1964). Fluvial Processes in Geomorphology. San Francisco and New York, W.H. Freeman and Co., 522 p.

Le Roux, J.P., (1979). Classification of palaeoriver types in the Karoo and their significance with regard to uranium mineralisation. Atomic Energy Board Publ., PER-42, 5 p.

Martini, J.E.J., (1974). On the presence of ash beds and volcanic fragments in the graywackes of the Karoo System in the southern Cape Province. Trans. Geol. Soc. S.Afr., 77, 113 - 116.

McBride, E.F., and Yeakel, L.S., (1963). Relationship between parting lineation and rock fabric. J. Sedim. Petrol., 33, 779 - 782.

McPherson, J.G., and Germs, G.J.B., (1979). Calcrete (caliche) in the Beaufort Group of the Southern Karoo basin and its palaeoclimatic significance. Paper presented at the 18th Congress of the Geological Society of South Africa, Port Elizabeth.

Miall, A.D., (1973). Markov chain analysis applied to an ancient alluvial plain succession. Sedimentology, 20, 347 - 364.

______ (1974). Paleocurrent analysis of alluvial sediments: a discussion of directional variance and vector magnitude. J. Sedim. Petrol., 44, 1174 - 1185.

______ (1976). Paleocurrent and paleohydrologic analysis of some vertical profiles through a Cretaceous braided stream deposit, Banks Island, Arctic Canada. Sedimentology, 23, 459 - 484.

______ (1977). Fluvial Sedimentology. Notes to accompany a lecture series on fluvial sedimentology, held at the Calgary Inn, 19th October, 1977.

______ (1977a). A review of the Braided - River Depositional Environment. Earth-Science Reviews, 13, 1 - 62.

Moody-Stuart, M., (1966). High and low sinuosity stream deposits, with examples from the Devonian of Spitzbergen. J. Sedim. Petrol. 36, 1102 - 1117.

Moon, C.J., (1974). The geology and geochemistry of some uraniferous occurrences in the Beaufort West Area, Cape Province. Geol. Surv. Report, Dept. Mining S. Afr., G.234 (unpub.), 73 p.

Mukerji, A.B., (1976). Terminal fans of inland streams in Sutlej-Yamuna Plain, India. Z. Geomorph. N.F., 20 (2), 190 - 204.

Potter, P.E., and Pettijohn, F.J., (1977). Paleocurrents and Basin Analysis. Springer-Verlag; Berlin, Heidelberg, New-York, 425 p.

Powers, M.C., (1953). A new roughness scale for sedimentary particles. J. Sedim. Petrol., 23, 117 - 119.

Qidwai, H.A., and Jensen, M.L., (1979). Methodology and exploration for sandstone type uranium deposits. Mineral. Deposita (Berl.), 14, 137 - 152.

Reeves, C.C., Jr., (1970). Origin, classification and geologic history of caliche on the southern High Plains, Texas and eastern New Mexico. J. Geol., 78, 352 - 362.

Reineck, H.E., and Singh, I.B., (1973). Depositional Sedimentary Environments. Springer - Verlag, Berlin, 439 p.

______ (1975). Depositional Sedimentary Environments with reference to terrigenous clastics. Springer-Verlag, Berlin, 439 p.

Roberts, D.L., (1974). A stratigraphical and sedimentological analysis in selected areas from the Lower Beaufort Series. B.Sc. (Hons) diss. (unpub.), Univ. Witwatersrand, 59 p.

Rogers, A.W., (1905). An introduction to the geology of Cape Colony. Longmans Green, London.

______ (1910). Geological survey of parts of the divisions of Beaufort West, Fraserburg, Victoria West, Sutherland and Laingsburg. 16th Ann. Rept. Geol. Comm. Cape Good Hope, 66 p.

______, and Schwartz, E.H.L., (1902). Report on a survey of parts of the Beaufort West, Prince Albert and Sutherland Divisions. 7th Ann. Rept. Geol. Comm. Cape Good Hope, 99 - 129.

Rossouw, P.J., and De Villiers, J., (1952). The geology of the Merweville area, Cape Province. Expl. Sheet Geol. Surv., Dept. Mines S. Afr., 189, 78 p.

Rowsell, D.M., and De Swardt, A.M.J., (1976). Diagenesis in Cape and Karroo sediments, South Africa, and its bearing on their hydrocarbon potential. Trans. Geol. Soc. S.Afr., 79, 81 - 145.

Ryan, P.J., (1967). Stratigraphic and palaeocurrent analysis of the Ecca Series and the lowermost Beaufort beds in the Karroo Basin of South Africa. Ph. D. thesis (unpub.), Univ. Witwatersrand, 210 p.

Schumm, S.A., (1968). Speculations, concerning paleohydrologic controls of terrestrial sedimentation. Geol. Soc. America, Bull., 79, 1573 - 1588.

Schwartz, D.E., (1978). Hydrology and current orientation analysis of a braided-to-meandering transition: the Red River in Oklahoma and Texas, U.S.A. In: Miall, A.D., (Ed.), Fluvial Sedimentology. Can. Soc. Petrol. Geol., Memoir 5, 231 - 255.

Schwartz, E.H.L., (1896). Geological Survey of the Beaufort West District. 1st Ann. Rept. Geol. Comm. Cape Good Hope, 18 - 33.

Simons, D.B., Richardson, E.V., and Nordin, C.F., Jr., (1965). Sedimentary structures generated by flow in alluvial channels. In: Middleton, G.V., (Ed), Primary Sedimentary Structures and their Hydrodrynamic Interpretation - a Symposium. Soc. Econ. Paleont. Mineral., Spec. Publ., 12, 265 p.

Smith, N.D., (1974). Flume experiments on the durability of mud clasts. J. Sedim. Petrol., 42 (2), 378 - 383.

Smith, R.M.H., (1978). The sedimentology and taphonomy of flood-plain deposits of the Lower Beaufort (Adelaide Subgroup) strata near Beaufort West, Cape Province. Annals. Geol. Surv. S. Afr., 12, 37 - 57.

Stanton, R.L., (1972). Ore Petrology. McGraw-Hill Book Co., 713 p.

Stapleton, R.P., (1974). Dinoflaggelates from the Lower Beaufort Stage. Annals. Geol. Surv. S. Afr., 9, 87 - 89,

______ (1978). Organic metamorphism and uranium occurrences in the Beaufort Group of South Africa. Econ. Geol., 73, 283 - 285.

Stear, W.M., (1978). Sedimentary structures related to fluctuating hydrodynamic conditions in flood-plain deposits of the Beaufort Group near Beaufort West, Cape. Trans. Geol. Soc. S. Afr., 81, 393 - 399.

Stokes, W.L., (1953). Primary sedimentary trend indicators as applied to ore finding in the Carrizo Mountains, Arizona and New Mexico. U.S. Atomic Energy Comm. RME - 3043, 48p.

Stuart-Williams, V. Le Q., (1979). A facies model analysis of the Upper Pristerognathus/Diictodon Assemblage Zone of the Abrahamskraal Formation, Karoo Supergroup, in the Fraserburg District. B.Sc. (Hons) thesis (unpub.),University Cape Town.

Tanner, W.F., (1967). Ripple mark indices and their uses. Sedimentology, 9, 89 - 104.

Theron, J.C., (1973). Sedimentological evidence for the extension of the African continent southwards during Late Permian - Early Triassic times, p.61 - 71. In: Campbell, K.S.W., (Ed.), Gondwana Geology: Papers from the 3rd Gondwana Symposium., Aust. Nat. Univ. Press.

Till, R., (1974). Statistical Methods for the Earth Scientist. Macmillan, 154 p.

Truswell, J.F., (1977). The Geological Evolution of South Africa. Purnell, 218 p.

Turner, B.R., (1975). Depositional environments and uranium mineralisation in the Permian Lower Beaufort beds (Tapinocephalus Zone) of the Karroo (Gondwana) System in South Africa. Paper presented at IX^me Congress International de Sedimentologie, Nice.

______ (1978). Sedimentary patterns of uranium mineralisation in the Beaufort Group of the Southern Karoo (Gondwana) basin, South Africa, p.831 - 848. In: Miall, A.D., (Ed.), Fluvial Sedimentology. Can. Soc. Petrol. Geol. Memoir 5, 859 p.

Turner, J.R., (1977). Palaeoenvironmental study of the Lower Beaufort in the northeast Karoo basin. M.Sc. thesis (unpub.). Univ. Natal. Pietermaritzburg, 138 p.

Union Carbide Research Report, (1972). Lithologic and petrographic considerations of drill cutting and core from Beaufort West anomalies. Union Carbide Research Report, (unpub.), 17 p.

Venter, J.J., (1969). Stratigraphy and correlation of the Cape and Karroo Supergroups in the southern Cape Province. Soekor Interim Report (unpub.), 33 p.

Visher, G.S., (1972). Physical characteristics of fluvial deposits, 84 - 97. In Rigby, J.L., and Hamblin, W.K., (Eds.), The Recognition of Ancient Sedimentary Environments. Soc. Econ. Palaeont. Mineral., Spec. Publ., 12, 340 p.

Von Backström, J.W., (1974). Uranium deposits in the Karroo Supergroup near Beaufort West, Cape Province, South Africa, p.419 - 424. In: Formation of uranium ore deposits. Internat. Atomic Energy Agency, Vienna, 748 p.

Von Huene, F., (1925). Die Südafrikanische Karroo - Formation als geologisches und faunistishes Lebensbild, Doergel, Tübingen, 124 p.

Watson, D.M.S., (1914). The Beaufort Beds of the Karroo System of South Africa. Geol. Mag. Decade VI, 203-208.

Wilke, P. P., (1962). Ground water geology of the Fraserburg area. M.Sc. thesis. Ann. of the Univ. Stellenbosch. 37, Ser. A. No.9.

Williams, G.E., (1971). Flood deposits of the sand-bed ephemeral streams of central Australia. Sedimentology, 17, 1 - 40.

Winter, H. DE LA R., and Venter, J.J., (1970). Lithostratigraphic correlation of recent deep boreholes in the Karroo-Cape sequence. In: Proc. and Papers, 2nd I.U.G.S. Symposium, p.395 - 408. (Ed. Haughton, S.H.; publ., C.S.I.R., Pretoria).

Wyley, A., (1859). Report of the geological surveyor upon a journey by him during the year 1858 in two directions across the colony and its results. Parliamentary Rept. G 54, Cape of Good Hope, Cape Town.

Yeakel, L.S., (1959). Tuscarora, Juniata and Bald Eagle paleocurrents and paleogeography in the central Appalachians. Ph.D. thesis (unpub.), The Johns Hopkins University, 454 p.