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THE SEDIMENTOLOGY AND URANIUM MINERALIZATION OF THE BEAUFORT GROUP IN THE BEAUFORT WEST - FRASERBURG - MERWEVILLE AREA, CAPE PROVINCE.

Markus Kübler.

A Dissertation Submitted to the Faculty of Science
University of the Witwatersrand, Johannesburg
for the Degree of Master of Science.

Johannesburg, January, 1977

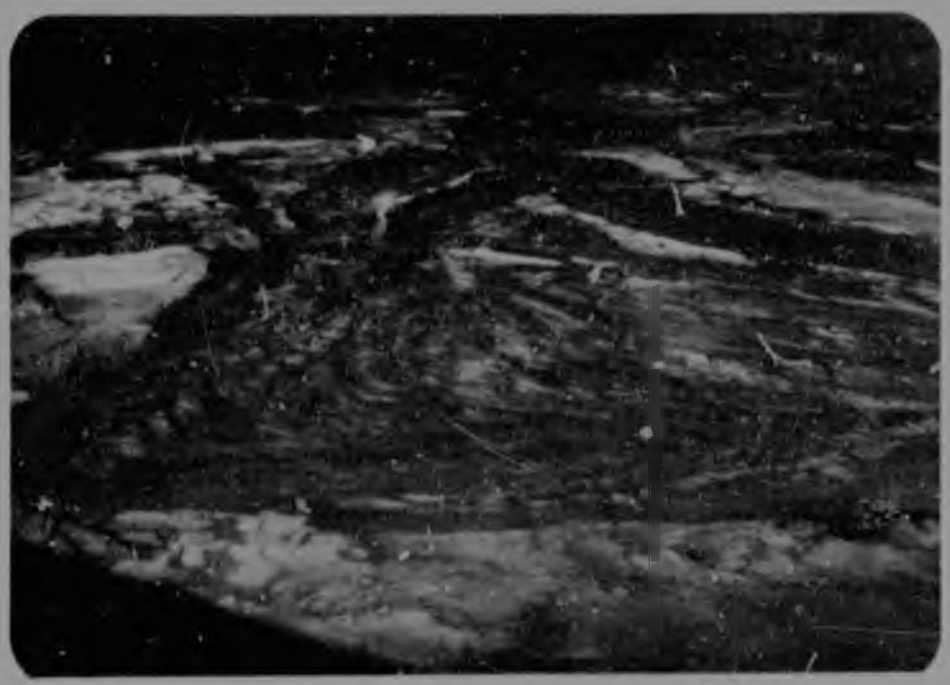
DECLARATION.

This dissertation is my own unaided work, except as acknowledged in the text. Neither the substance nor any part of it has been submitted in the past, or is being submitted for a degree in any other university. The information used in the dissertation was obtained by me while employed by Union Carbide Exploration Corporation during the period in which I was registered as a student at the University of the Witwatersrand.

M. Kübler

M.KÜBLER

25th February, 1977



Frontispiece : Beaufort Group sandstone forming a low ridge, which, in plan, resembles a contemporary point bar, Reyers Valley 401 (width of photograph about 2,5 km)

ABSTRACT

The sediments of the lower part of the Beaufort Group (Permian) consist of mudstones, siltstones, fine- to very fine-grained sandstones and small amounts of intraformational conglomerate. The mudstones are generally a brownish-purple colour, and are massive. The siltstones are generally greyish-green coloured, and are sometimes ripple cross-laminated. The sandstones vary in colour from green to grey. Horizontally-bedded, trough cross-bedded and ripple cross-laminated sandstone subfacies were recognized. All the sandstones found in the area studied may be described as fine- to very fine-grained, moderately sorted, arkosic wackes.

The stratigraphic interval studied was found to have a thickness of about 850 m. No readily mappable subdivisions were found. The sandstone to siltstone and mudstone ratio for the stratigraphic interval is about 1:4.

The sandstones and finer sediments are generally arranged in upward-fining sequences. The most commonly occurring sequence commences with an intraformational conglomerate, and is overlain by trough cross-bedded or horizontally-bedded sandstone, followed by ripple cross-laminated sandstone, siltstone and mudstone. This sequence of lithologies and sedimentary structures is typical of sediments deposited by meandering streams. The sediments in the area studied are thought to have been deposited by strongly meandering rivers, separated by large flood basins on a low-lying flood plain. An arid, temperate climate is inferred to have prevailed during the deposition of the sediments.

The sedimentary units in the interval studied are laterally impersistent. The sandstone lenses were

found to have a maximum thickness of about 25 m. Away from the thickened or channeled areas, the lenses thin rapidly and ir erfinger with argillaceous sediments. The lenses are generally elongated in the direction of sedimentary transport.

A palaeocurrent analysis of the sandstones, based on the measurement of trough cross-beds, rib-and-furrow structures and of primary current lineations, showed that the provenance area lay to the south-west (the mean palaeo-transport direction was found to be towards N 29 E). Moving average palaeocurrent maps of selected sandstone units showed that the palaeocurrent directions closely follow the outcrop patterns of the sandstones, which are thus thought to approximate the original geometric shapes of the units. The consistency ratios of the mean palaeocurrent directions were found to be largest along the edges of the sandstone units, and lowest in the areas of maximum sandstone development. This is probably the result of the thicker sandstones having been deposited by an actively meandering stream over a relatively long period of time. The somewhat bimodal distribution of palaeocurrent directions seen in the rose diagrams constructed for some of the sandstones is thought to reflect deposition by strongly meandering streams, rather than deposition by more than one dispersion system.

Uranium mineralization was found in the thickest sandstone units, and is distributed throughout the entire stratigraphic interval studied. The uranium mineralization occurs as small lenticular bodies, commonly only a few tens of metres in length with thickness varying from a few cm to a maximum of about 5 m. The mineralized lenses are generally separated by large areas of barren sandstone. The lenses are peneconcordant to the bedding, and are elongated in the direction of sandstone thickening. The localization of the uranium in the host sandstones was found to be controlled by the presence of permeability

boundaries and coalified plant remains. An isopach map of a mineralized sandstone unit showed that the thickest portions of the unit (areas with a sandstone thickness of over 17 m) are preferentially mineralized. Parts of the unit having the thinnest mudstone and siltstone intercalations, and thus the highest sandstone to siltstone and mudstone ratios, were found to be favourable for mineralization.

The major ore minerals are uraninite (UO_2) and coffinite ($U(SiO_4)_{1-x}(OH)_{4x}$). They are most commonly found replacing coalified plant remains, as well as the sandstone matrix and cement. The uranium was probably derived by the leaching of that element from the feldspars and volcanic rock fragments found within the host sandstones. It was probably transported by ground waters that were mildly reducing, had an alkaline to neutral pH and contained abundant CO_2. When the flow-rate of these waters through the host sandstone was reduced, by a local lowering in permeability, in the vicinity of a strong reductant, the ore minerals were precipitated. The resulting ore deposits are similar to the peneconcordant deposits found on the Colorado Plateau.

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I. INTRODUCTION.

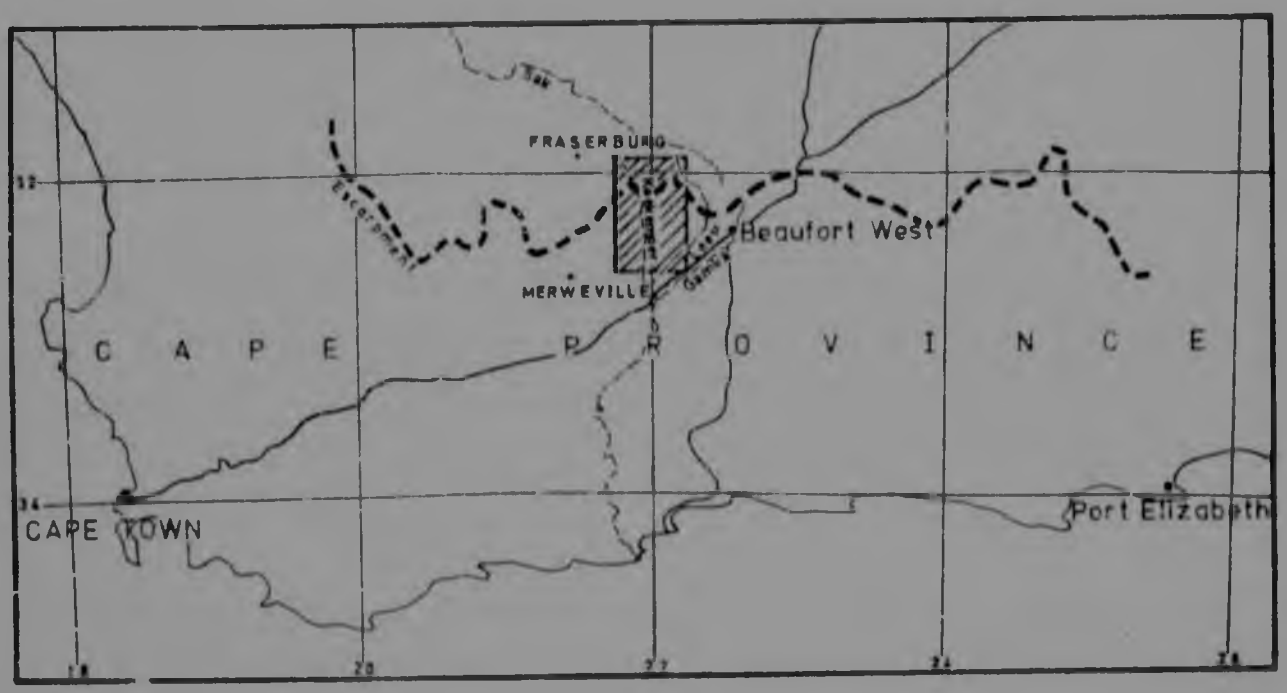
A. GENERAL.

The Beaufort Group sediments were selected as a target area for uranium exploration by the technical staff of Union Carbide Exploration Corporation because they were found to be similar to the rocks hosting the sandstone-type uranium deposits in the United States of America. The factors considered were that the sediments were deposited in a fluvial environment, and comprise a sequence of sandstone and shale, the sandstones are arkosic and calcareous, carbonaceous fragments are common, and that they are of late-Palaeozoic to early-Mesozoic age. Systematic car-borne radiometric traversing of the Beaufort Group sediments was then undertaken. This resulted in the location of the uranium mineralized outcrop on the farm Grootfontein 180, in the Beaufort West district, in 1970. More detailed radiometric surveys located many more radiometric anomalies in the area. By 1976, about nine different companies had become actively involved in uranium exploration in an area extending some 400 km in an east-west direction and 150 km in a north-south direction, centred on Beaufort West.

The writer was introduced to the area in 1974, as a geologist of Union Carbide Exploration Corporation. Very little was known about the geology of the Beaufort Group sediments which are the host to the uranium mineralization. This study was commissioned and sponsored by Union Carbide Exploration Corporation to provide a basic sedimentological and stratigraphic framework within which detailed exploration might be undertaken.

FIG 1

LOCATION MAP



SCALE 1:5 000 000

0 100 200 300 400 KM

B. AIMS.

The principal aims of this study were the following :

(1) to describe the nature and distribution of the sediments;
(2) to establish the stratigraphy of the area;
(3) to determine the environment of deposition and the provenance area of the sediments;
(4) to determine the nature and origin of the uranium mineralization; and,
(5) to relate the occurrence of the mineralization to the lithology and sedimentology of the host strata.

C. GEOGRAPHICAL SETTING.

The area selected for study lies between the towns of Beaufort West, Fraserburg and Merweville in the Cape Province. It extends between longitudes 21°45'E and 22°15'E and latitudes 31°54'S and 32°33'S (Figure 1). The area was selected so as to include as much property held under option by Union Carbide Exploration as was possible, and to cover a large stratigraphic interval.

Secondary provincial roads linking the towns of Beaufort West, Fraserburg and Merweville provide ready access to the area. Numerous tertiary provincial and private farm roads allow further access. Much of the area along the escarpment is inaccessible to vehicles.

The Nuweveld Mountains form the Great Escarpment in the area, and are the dominant topographic feature. They separate two relatively flat plains, the northern at an elevation of about 1370 m and the southern, the Great Karroo, at between 610 and 730 m. Dolerite capped mountains in the area attain elevations of up to 1900 m.

The resistance of the dolerite to weathering is responsible for much of the rugged topography. Dolerite and sandstone-capped mesas and buttes are common features of the plains. The escarpment is steep, and affords many good cross-sectional exposures of the sediments.

The Great Escarpment forms a watershed in the area. The southward flowing rivers, such as the Leeu and the Koekemoer, are deeply incised and have steep gradients. The streams flowing to the north have lower gradients and drain into the Sak River. The streams are ephemeral, flowing only after good rains.

Beaufort West has an average annual rainfall of 213 mm (Wellington, 1955). The rainfall decreases westwards, and Fraserburg and Merweville have averages of 161 mm and 128 mm respectively. The rain falls mainly as heavy showers during the late summer months (December to March).

The region is covered by sparse desert scrub. This consists of woody shrubs of the Karroo Bush type (Wellington, 1955) and succulents. Various species of grasses spring up after the rains.

D. REGIONAL STRATIGRAPHY AND GEOLOGICAL HISTORY.

The rocks of the Cape and Karoo supergroups (Karoo, when referring to the rocks of the Karoo Supergroup, is spelt with one 'r' only in accordance with the recommendation of Johnson *et al.*, 1976), underlie about half of South Africa. In the southern Cape, the two supergroups are conformable. The time span from the base of the Cape to the top of the Karoo Supergroup, is Upper Ordovician to Lower Jurassic (Truswell, 1970). The boundary between the two supergroups is generally taken at the base of the Dwyka Formation, which is Lower Carboniferous in age.

TABLE 1 : THE STRATIGRAPHY OF THE CAPE AND KAROO SUPERGROUPS IN THE SOUTHERN CAPE (Compiled from Venter (1969), Truswell (1970) and Johnson *et al.* (1976).

SUPER-GROUP	GROUP	SUBGROUP	FORMATION	PREVIOUSLY-USED AND FORMATIONAL NAMES		APPROX. THICKNESS (M)	AGE
Karoo	Drakensberg				Drakensberg Volcanics	1370	Jurassic
			Clarens Sandstone	Stormberg Series	Cave Sandstone	60 - 90	190 MY
			Elliot		Red Beds	500	
			Molteno		Molteno	610	Triassic
	Beaufort	Tarkastad / Adelaide	Burgersdorp	Beaufort Series	Upper	610	
			Katberg		Middle	300	225 MY
					Lower	2740	
	Ecca		Waterford	Ecca Series	Upper	1500	Permian
			Fort Brown Shale		Middle		
			Laingsburg				
			Vischkuil		Lower		
			Collingham				
			Whitehill Shale	Dwyka Series	White Band		280 MY
			Prince Albert Shale		Upper Dwyka Shale		
			Dwyka		Dwyka Tillite	600	Carboniferous
Cape	Witteberg		Kommadagga			750	
			Lake Mentz				345 MY
			Wittepoort				Devonian
			Steytlerville				
	Bokkeveld					750	395 MY
	Table Mountain Sandstone	Winterhoek	Nardouw			400	Silurian
			Cedarberg				
			Pakhuis				440 MY
			Peninsula				Ordovician
			Graafwater				500 MY
			Piekenier				Cambrain

A short outline of the stratigraphy of the Cape and Karoo rocks in the southern Cape is given. The subdivisions, ages and thickness of the two supergroups are given in Table 1.

(1) The Cape Supergroup.

The Cape Supergroup is divided into three conformable units, the Table Mountain Sandstone Group, the Bokkeveld Group and the Witteberg Group. The Table Mountain Sandstone Group was deposited on a planed surface of Nama and Malmesbury strata, and on Cape Granite. It consists predominantly of sandstones and minor conglomerates, but also contains a glacial horizon. Six formations within the group are recognized (Rust, 1967).

The overlying Bokkeveld Group consists of five thicker shale bands separated by four thinner sandstone bands. There is a general thickening of the succession eastwards. There is no break in sedimentation into the overlying Witteberg Group (Truswell, 1970).

The lower portion of the Witteberg Group is predominantly argillaceous, with micaceous shales being the characteristic sediment. The upper Witteberg may be divided into two formations. The lower, the Lake Mentz Formation, consists of sandstones and occasional conglomerates, siltstones and shales (Venter, 1969). The upper, the Kommadagga Formation consists of mudstones, siltstones and sandstones. The presence of the unstable minerals, feldspar, apatite and garnet, and their non-micaceous nature caused Venter (1969) to place it in the Dwyka Group of the Karoo Supergroup. Johnson *et al.* (1976), however, placed the Cape-Karoo boundary at the base of the overlying Dwyka Formation.

(2) The Karoo Supergroup.

The terminology used in describing the stratigraphy of the Karoo succession is that proposed by Johnson *et al.* (1976).

The term *Karoo Sequence* was proposed for the successions found in the different Karoo-aged basins in southern Africa because, in some cases, they are lithologically different from the rocks found in the main Karoo Basin. The rocks of the main Karoo Basin were referred to as the *Karoo Supergroup*.

The basal unit of the Karoo Supergroup is the Dwyka Formation (Johnson *et al.*, 1976). The formation is characterized by the presence of glacial material such as tillite, varved shales and fluvioglacial gravels and conglomerates (Johnson *et al.*, 1976). The tillite is a dark grey to blue-grey coloured rock containing clasts (most of which are less than 10 cm in diameter) set in an argillaceous matrix (Truswell, 1970).

The Ecca Group overlies the Dwyka Formation. In the southern Cape Province, the Ecca Group consists of seven formations (Johnson *et al.*, 1976). The Prince Albert Shale Formation is the basal unit of the group. It consists predominantly of olive-green marine shales (Truswell, 1970).

The Whitehill Shale Formation, which consists of white-weathering carbonaceous shales with occasional chert bands, overlies the Prince Albert Shale Formation (Johnson *et al.*, 1976). These two formations constituted what was previously known as the Upper Dwyka Shales. The Whitehill Formation was informally called the "White Band" (Johnson *et al.*, 1976). The Collingham Formation is a thin succession of rythmically-bedded thin bands of grey shale and yellowish-weathering clayey material which overlies the Whitehill Shale Formation (Johnson *et al.*, 1976). The Ripon Formation overlies the Collingham Formation in the south-eastern part of the Karoo Basin (Johnson *et al.*, 1976). It consists of alternating shale and sandstone. Towards the west, the upper part of the Ripon Formation intertongues with the overlying Fort Brown Shale Formation while the lower part of the Ripon Formation becomes more argillaceous and grades into the

Vischkuil Formation. In the southern Cape Province, Theron (1967) recognized the Laingsburg Formation as the lateral equivalent of the upper part of the Ripon Formation. Johnson *et al.* (1976) proposed that both the Ripon and Laingsburg Formations be retained until their lateral interrelationships are clarified. In the western part of the Karroo Basin the Laingsburg Formation pinches out. The Vischkuil Formation, which underlies the Laingsburg Formation, consists of shale with minor sandstone intercalations. The sandstones become thicker and more abundant eastwards (Theron, 1967). The Fort Brown Shale Formation, which overlies the Ripon and Laingsburg formations, consists predominantly of shales with isolated sandstone intercalations. Where the Laingsburg Formation pinches out, the Vischkuil and Fort Brown Shale formations merge, and are known as the Tierberg Shale Formation (Johnson *et al.*, 1976). The Waterford Formation, which is a thick succession of massive sandstones with interbedded, generally ripple-marked shale, overlain by a thin but laterally persistent shale, is the topmost formation of the Ecca Group.

The most significant unifying lithological features which serve to distinguish the sediments of the Ecca Group from those of the overlying Beaufort Group are given by Johnson *et al.* (1976). The argillaceous rocks of the Ecca Group are generally laminated and platy-or flaky-weathering, while those of the Beaufort Group are more massive. The Ecca Group shales are characteristically dark grey and carbonaceous, while the Beaufort Group mudstones are greenish-grey, bluish-grey or reddish. Cross-bedded sandstones are a common feature of the Beaufort Group, but are generally absent in the southern part of the Ecca Group. The fining-upward sedimentary cycles, which are ubiquitous in the Beaufort Group, are only found in the north-eastern part of the Ecca Group depository. The reptilian remains which are common in the Beaufort Group sediments are not found in Ecca Group sediments (except for one species in the Whitehill Shale Formation).

The sediments of the Beaufort Group may be divided into a lower, Adelaide and an upper, Tarkastad Subgroup (Johnson *et al.*, 1976). The Adelaide Subgroup contains a smaller amount of both sandstone and reddish mudstone than the overlying Tarkastad Subgroup. Kitching (1970) divided the Beaufort Group into the *Tapinocephalus*, *Cistecephalus*, *Daptocephalus*, *Lystrosaurus* and *Cynognathus* zones, on the basis of vertebrate fossil assemblages. The first three zones correspond to the Adelaide Subgroup of Johnson *et al.* (1976), while the other two constitute the Tarkastad Subgroup.

No formal subdivisions within the Adelaide Subgroup have been recognized because of the lateral variability displayed by the stratigraphic position of the red mudstones (Johnson *et al.*, 1976).

In the southern part of the Karoo Basin, the Tarkastad Subgroup consists of a lower, predominantly arenaceous Katberg Formation, and an upper predominantly argillaceous Burgersdorp Formation (Johnson *et al.*, 1976).

There are no unifying lithologic features in the formations overlying the Beaufort Group to justify the retention of the old "Stormberg Series" as a group (Johnson *et al.*, 1976). The Molteno Formation is composed of coarse-grained sandstones, grey and blue coloured shales and occasional coal seams (Truswell, 1970). The overlying Elliot Formation (previously known as the "Red Beds") is a succession of red or purple argillaceous rocks containing occasional beds of sandstone (Truswell, 1970). The Clarens Sandstone Formation (formerly known as the "Cave Sandstone") is the topmost sedimentary succession in the Karoo Supergroup. It is a very fine-grained, white or cream coloured sandstone, partly of aeolian origin (Truswell, 1970).

The Karoo Supergroup is capped by the Drakensberg Group volcanics. These consist of tholeiitic basalts and associated rocks (Truswell, 1970).

The Karoo Dolerites represent a widespread hypabyssal phase of the Drakensberg Group volcanics. The southern limit of their development corresponds with a compressional zone, which coincides with the northern and western limit of the Cape Folded Belt (Truswell, 1970).

3. The Palaeogeography of the Cape-Karoo Basin.

During Silurian times, southern Africa consisted of a broad shield flanked along the southern margin by a rapidly subsiding arcuate trough. To the south-west, south and east of the trough was situated a rapidly rising belt of high ground (Ryan, 1967).

The Table Mountain Sandstone Group sediments were deposited into this trough from both the stable craton and from the high ground along the outer rim of the basin. Subsidence kept pace with deposition, resulting in the formation of shallow water deposits throughout the group (Ryan, 1967). Isopach maps of the Table Mountain Sandstone Group show that the southern portion of the arcuate trough plunged eastwards while the eastern portion of the trough plunged southwards, indicating that the south-eastern portion was deeply depressed, and probably open to the sea (Ryan, 1967). The Bokkeveld Group sediments were deposited only in the axial portions of the troughs. The sediments contain an assemblage of marine fossils, which indicates that the basin was open to the sea (Truswell, 1970). During Witteberg times, deposition took place from both the north and south into the axial portions of the basin. The depositional environment changed, with time, from open-marine to shallow-marine or littoral. The abundance of coarse clastics in the Witteberg Group sediments indicated a high relief in the provenance area (Ryan, 1967).

During Dwyka times, glaciers moved basinwards from six main centres distributed around the basin (except in the south-east, Stratten, 1968). Glacial sediments were

deposited over most of the shield area, suggesting that it was low-lying during the accumulation of the Dwyka Formation (Ryan, 1967). The sediments constituting the Prince Albert Shale Formation and the Whitehill Shale Formation ("Upper Dwyka Shales") were deposited in a deep-water marine basin, which was open to the sea in the south-east and north-west (Ryan, 1967). The basin had the same overall geometry during the deposition of the Collingham, Vischkuil and Ripon-Laingsburg formations ("Lower Ecca Formation"), with most of the sediment being derived from the southern highland (Ryan, 1967). During the deposition of the Fort Brown Shale Formation ("Middle Ecca"), the eastern and western highlands were being most actively uplifted and eroded. The subsidence, which started in the southern portion of the craton, spread northwards. The fluvio-deltaic sediments of the Vryheid Formation were deposited in the northern portion of the basin at this time (Ryan, 1967).

By the beginning of Beaufort times, the continental sea which covered most of the Karoo Basin during much of the Ecca period, had largely withdrawn, and shallow-water continental conditions prevailed (Ryan, 1967). The change from deposition in a large body of water (possibly marine) to mainly fluviatile deposition, marks the change from the Ecca Group to the Beaufort Group. Since it is unlikely that this change took place at the same time everywhere, the Ecca-Beaufort boundary is probably a diachronous one (Johnson *et al.*, 1976).

Strata of the lower part of the Beaufort Group were deformed during the formation of the Cape Folded Belt, indicating that the earliest tectonism could have taken place was after the deposition of the lowermost part of the Beaufort Group. The continued uplift of the southern and eastern highlands during Beaufort times is indicated by the general northerly trend of palaeotransport directions for the Beaufort Group sediments (Theron, 1973). The major entry point of the sediment during Beaufort times was in the south-east of the basin (Theron, 1973). The

presence of Witteberg Group quartzite pebbles, derived from a southerly provenance, in the Molteno Formation, indicated that the rocks of the Cape Folded Belt had been uplifted and eroded (Ryan, 1967). The overlying Elliot and Clarens formations ("Red Beds" and "Cave Sandstone" respectively) are continental sediments deposited within a sedimentary framework similar to that of the Molteno Formation (Ryan, 1967).

Sedimentation in the Karoo Basin was brought to a close by the outpouring of the basalts and associated rocks of the Drakensberg Group, and the intrusion of the Karoo Dolerites (Truswell, 1970).

After Karoo times, the land surface was elevated, and the Gondwanaland erosional surface bevelled (King, 1963). This was an extensive smooth surface, the drainage of which was towards the north. This surface was broken up during early-Cretaceous times, when it was warped monoclinally towards the south, and the African cycle of erosion started. The start of the African erosional cycle was probably associated with the break up of Gondwanaland (King, 1963). The African erosi nal cycle rivers, which flow southwards, cut back into the Godwanaland surface forming the Great Escarpment, which is the major topographic feature of the area studied.

E. PREVIOUS WORK.

Schwartz in 1896 was attracted to the area by the "fissure coals" found in the escarpment on the farm Brandewyns Ghat 214 (known locally as Leeu River's Poort). The psuedo-coal was found in near-vertical fissures, the largest of which could be traced for over 75 m. He described the geology of both the sediments and of the igneous rocks of the area.

The stratigraphy of the Karoo rocks in parts of the Beaufort West, Prince Albert and Sutherland districts was

described by Rogers and Schwartz in 1902. They measured, and described in detail, a stratigraphic interval of about 870 m, located in the escarpment just to the west of the area of the present study.

Rogers (1910) wrote a comprehensive report on the geology of the Beaufort West, Fraserburg, Victoria West, Sutherland and Laingsburg areas. He gave thin-section descriptions of the sandstones, dolerites and other igneous rocks found in the area. He found that the sandstones consisted mainly of quartz, orthoclase and plagioclase, the orthoclase generally being more altered than the plagioclase.

Particular attention was paid to the vertebrate fauna, and their use in regional stratigraphic correlation by workers such as Watson (1914), Du Toit (1918), Von Huene (1925) and Kitching (1970).

Rossouw and De Villiers (1953) mapped an area south of latitude 32°30'S, which included the southernmost portion of the area considered in the present study. In their explanation to the map, they described the lithology, thickness and structure of the sediments. They recognized the Droëfontein Chert and Poortjie Sandstone as being stratigraphic markers some 1000 and 1800 m above the base of the Beaufort Group respectively. From their interpretation of the structure and stratigraphic sections, they concluded that the Ecca Group contact came nearer surface towards the north (i.e. stratigraphically lower units were exposed towards the north). They found that the structures had an overall easterly plunge.

Wilke (1962) studied the ground water hydrology of an area around Fraserburg. He noted that the sandstones, which occur as beds varying from about 1 to 7 m in thickness, constitute 10 to 15 percent of the stratigraphic section. He described two prominent sets of joints, one trending about north-south and the other east-west. The mineralogy

and texture of the sediments were documented.

Hotton (1967) reviewed the stratigraphy of the Beaufort Group as a whole. He gave thin-section descriptions and modal analyses of the sandstones. Lenticular and sheet-like sandstone bodies were described. The lenticular bodies are typically 3 to 5 m thick, and may pinch out laterally within about 30 m. The largest lenticular bodies may have thicknesses of over 15 m and extend laterally for about 8 km. Th sheet sandstones have thicknesses of 6 to 10 m and may be traced for many kilometres. The lenticular sandstones were thought to have been deposited "under nearly dry land conditions" while the sheet sands suggested "deposits made during the transgression of a shoreline of some sort".

Ryan (1967), on the basis of palaeocurrent studies and lithology, recognized three facies in the lowermost of the Beaufort Group sediments. The southern facies was related to a northerly-trending dispersion pattern which was found in the southern half of the basin. The sediments of this facies consisted of blue, green, grey, purple and maroon mudstones, fine - to medium-grained sandstones, and occasional lenses of chert and limestone. The western facies, which was deposited by an easterly and north-easterly-trending dispersion system, consists of medium-grained sandstones with occasional granite pebbles, green mudstone and green and purple shale. The northern facies, which was deposited along the northern and eastern margins of the basin, was found to consist of coarse- to medium-grained sandstones, grits and conglomerates, interbedded with shales. The area of the present study lies within the southern facies, which, towards the centre of the basin, interfingers the western and northern facies

Thin-section descriptions of sandstone samples taken in and around the area of the present study were given in a Union Carbide Research Report (1972). Uraninite (UO_2) and

coffinite ($U(SiO_4)_{1-x}(OH)_{4x}$) were identified as the major ore minerals. The uranium minerals were found as coatings on the detrital grains and replacing carbonaceous debris. 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.

Theron (1973) undertook a palaeocurrent study covering the whole of the Beaufort Group outcrop. He made about 11 000 measurements at some 1000 localities. This, together with grain size and heavy mineral analysis, was used to define the palaeogeography of the Beaufort Basin. The overall transport direction showed that all the units of the Beaufort Group (except part of the north-eastern outcrop area) had source areas in the south. The major entry point for sediment into the basin was in the south-east (East London area). A second entry point was in the south-west. The sediment deposited in the north-eastern part of the basin was derived from an area of local intrabasinal uplift. He concluded that the southern source consisted of basement granites, granulites and gneisses, and lay close to the present continental margin.

Von Backström (1974) outlined the geological setting of the uranium mineralization in the Karoo. He stated that the then known occurrences were in the Adelaide Subgroup ("Lower Beaufort"), but suggested that the uranium mineralization need not be restricted to this unit. The uranium was most often found associated with deposits formed in erosion channels and washouts. Syngenetic uraninite and coffinite occurs together with a complex variety of secondary minerals. The secondary minerals may have been derived from the uraninite and coffinite. He found that the grade of the mineralized sandstones from surface outcrops varied from trace amounts to over 2 percent U_3O_8, the average being 0.05 percent U_3O_8.

Moon (1974) described many uranium mineralized outcrops in the lower part of the Beaufort Group, most of them within the area of the present study. He constructed detailed radiometric maps of the outcrops. From his palaeocurrent work, he concluded that the sediments were transported from the south-west. He found that the environment of deposition was probably the lower part of a flat flood plain, or, on palaeontological grounds, a marginal marine shelf. He distinguished two major types of uranium occurrence. Both types are found in sandstone. One is calcareous and contains primary uranium minerals and sulphides. The other is limonite stained, and contains secondary uranium minerals. He recognized an intermediate type, occurring north of the escarpment, which he believed was simply the weathered counterpart of the primary type. He described thin-sections of the sediments, and from microprobe studies, identified the primary uranium minerals as uraninite and coffinite. These were found to be associated with minor quantities of arsenopyrite (FeAsS), chalcopyrite ($CuFeS_2$), bornite (Cu_5FeS_4) and galena (PbS). He considered that the most likely mode of formation of the mineralization was the reduction of uranium in carbonate complexes by carbonaceous debris.

Henderson(1974) and Roberts (1974) both measured stratigraphic sections of Beaufort Group sediments in the Beaufort West district (Henderson and Roberts) and the Prince Albert and Graaff-Reinet areas (Henderson). Both writers described the petrology and sedimentology of the rocks, from which they concluded that they were deposited by fluvial processes.

Turner (1975) carried out a sedimentological study of parts of the southern portion of the area of the present study. He found that the sediments generally consist of upward-fining cycles which are variable in nature, and may contain cyclic elements which are upward-coarsening. The environment of deposition was said to be comparable to that

developed in modern meandering streams. The shales and mudstones, with occasional siltstones, are similar to contemporary flood plain deposits. The coarsening-upward cycles probably record the accumulation of plant debris and mud in a local swamp or lagoon, later covered by coarser overbank sediments. The overall picture was found to be consistent with deposition in the lowermost reaches of a flood plain, in close proximity to a delta and deeper water, which, from his palaeocurrent work, was thought to lie to the east. The uranium mineralization was found to show "a particular affinity for the channel and crevasse-splay sandstones in the succession". He described the mineralization as being both primary and secondary. The primary uraninite was always found together with sulphides, and intimately associated with calcareous pods and lenses, and with plant material. He suggested that the uranium may have been derived by leaching of the volcanic material found within the sediments.

Horowitz (1976) conducted a palynological analysis of some 50 samples collected in and around the area of the present study. He concluded that the sediments were laid down in a wide, rather shallow delta, at the northern or north-western shore of an oceanic basin in late-Permian times. In addition, he thought that most of the plant remains were transported from the north. A considerable percentage of the organic microfossils were said to be indicative of a marine environment. The proportion of marine microfossils increases southwards. He stated that rivers flowing from the north carried soluble uranium compounds that were precipitated on contact with a saline environment, giving rise to the mineralization. Horowitz's interpretation of the depositional environment and palaeogeography strongly contradicts the interpretations of workers such as Kitching (1970), Theron (1973), Moon (1974) and Turner (1975).

II. STRUCTURAL GEOLOGY.

The Karoo sediments form a large structural basin with gentle inward dips. Along the southern margin of the basin the sediments were deformed by folding which resulted in the formation of the Cape Folded Belt (Truswell, 1970).

A. FOLDING.

The southern portion of the area studied is folded into gentle east-west-trending anticlines and synclines. This trend parallels the southern Cape Folded Belt. The intensity of the folding decreases towards the north (away from the Cape Folded Belt). In the northern portion of the area (above the escarpment), the sediments are essentially flat-lying.

The dips of the sediments in the south of the study area are generally less than 10 degrees. The fold axes plunge gently towards both the east and the west, resulting in the development of fold closures. There is a regional plunge towards the east, which results in stratigraphically higher sediments being exposed in that direction.

In the extreme south, the anticlines and synclines have wave-lengths of the order of 1 to 3 km. This increases to about 5 km towards the base of the escarpment. Most of these open folds are asymmetrical, having limbs with steeper dips towards the south. The asymmetry is extreme in some cases, with dips to the north being 2 to 3 degrees, while those to the south may be up to 50 degrees.

Asymmetrical folds with limbs dipping more steeply towards the north were also encountered locally. The northern limbs of these folds are near vertical. Their hinges are tight and are cut by quartz veins. These structures are impersistent along strike, and have maximum amplitudes of

some 20 m. In such sediments, the primary sedimentary structures tend to be masked. The folds in the sandstones are of the concentric type, which characteristically form in competent rocks under near-surface conditions (De Sitter, 1964).

A large anticlinorium is the dominant structure in the south-central portion of the area. The axis of this structure, which trends east-west, can be traced for over 30 km from the centre of Tamboersfontein 291 to the southern boundary of Rietfontein 306 (Map 1).

The sediments exposed above the escarpment appear to be horizontal. Wilke (1962), found that they have a regional northerly to north-easterly dip of 1 to 2 degrees. He also measured dips of up to 2 degrees towards the south, and ascribed them to open folding or to local disturbances due to intrusive dolerites. Small-amplitude kink folds, resulting from brittle deformation, were occasionally encountered (Plate 1).

The uranium mineralization appears to be unaffected by the folding. Mineralization is found on the limbs of the folds, and near both anticlinal and synclinal axes, as well as in the flat-lying sandstones to the north of the escarpment. These observations suggest that the mineralization predates the tectonic episode which caused the folding.

B. FISSURES AND JOINTS.

Fissures, typically 2 to 5 km, but sometimes up to 8 km long, are found to be concentrated in an area extending between $32^{o}22'S$ and $32^{o}30'S$ (Map 1). They are probably tensional features related to the major anticlinorium in the area. The fissures result from the concentration of joints. The spacing of the joints is of the order of tens of millimetres, and the openings are generally between 1 and 2 mm. This group of fissures has a strong preferred



Plate 1: Small-amplitude kink fold.



Plate 2: Brownish-black-weathering calcareous material replacing the sandstone along joints

orientation. The mean strike was found to be N 67° E. They are straight and have near-vertical dips. The fissures are clearly visible on airphotos an on the ground, being marked by lines of bushes and occasional trees. Calcite is commonly found as a filling within joints. These fissures belong to a group, recognized by Rossouw and De Villiers (1953), having strikes between N 52° E and N 89° E. A second, northerly-orientated, group of fissures recognized by Rossouw and De Villiers (1953) is not well developed in the area of the present study. Only a few fissures having this orientation were found in the extreme south of the study area.

The sandstones above the escarpment exhibit two well defined sets of joints, almost perpendicular to each other. The north-trending one is the most conspicuous, and has smooth surfaces and a high degree of both directional persistence and host rock penetration. The secondary set, which trends about east-west, interconnects the major set, but seldom cuts across more than one set of primary joints. The joint spacing increases with increase in grain size of the host rock (Wilke 1962). Local replacement of the host sandstone by brownish-black-weathering calcareous material is sometimes seen along the north-trending joints (Plate 2).

Slickensided quartz-filled shear planes, usually dipping between 15 and 30 degrees, are sometimes found near the hinge zones of the folds in some sandstones (Plate 3). Occasionally, brecciated blocks of sandstone are found within these shear planes. The thickness of the shear zones varies from less than 1 up to about 25 cm. No displacement was observed along them.

Primary uranium mineralization does not appear to be in any way related to the joints and fissures. However, secondary uranium minerals, formed by surface weathering, are occasionally found along joints and fissures in the



Plate 3: Slickensided quartz filled shear plane. No displacement along these planes was noted.



Plate 4: Displacement resulting from dolerite intrusion. The section to the left (west) of the sill/dyke has been uplifted.

mineralized sandstone.

C. THE STRUCTURAL EFFECT OF THE DOLERITE INTRUSIONS.

The sediments in the area of the escarpment and to the north of it are intruded by numerous dolerite dykes and sills. The intrusion of the dolerite results in the displacement of the sediments by a distance equal to the thickness of the intruding dolerite.

The sills are discordant, change in attitude and in thickness, and thus cause relative displacement of the stratification. A spectacular example of displacement resulting from the change in attitude of a sill may be seen in the escarpment on the northern portion of the farm Brandewyns Ghat 214. Here a near-horizontal sill with an estimated thickness of some 20 m changes to a vertical attitude, causing the sediments underlain by the sill in the west to be uplifted by a distance equal to the thickness of the sill relative to those in the east (Plate 4).

Sills are often intruded at the same stratigraphic levels as sandstone units. The dolerite appears to intrude preferentially along the upper and lower sandstone-siltstone contacts, but also invades the sandstone units. The invading dolerite displaces the sandstone mainly along the bedding planes and joints. The contacts between the dolerite and sandstone are sharp. A good example of this may be seen in the lowermost sill in the north-eastern corner of the farm Hottentots River 296 (Map 1).

Associated with the dolerite dykes are two sets of joints in the country rock, one parallel to the dyke margin and the other perpendicular to it. These are best developed, and have the closest spacing, near to the dyke (Wilke, 1962).

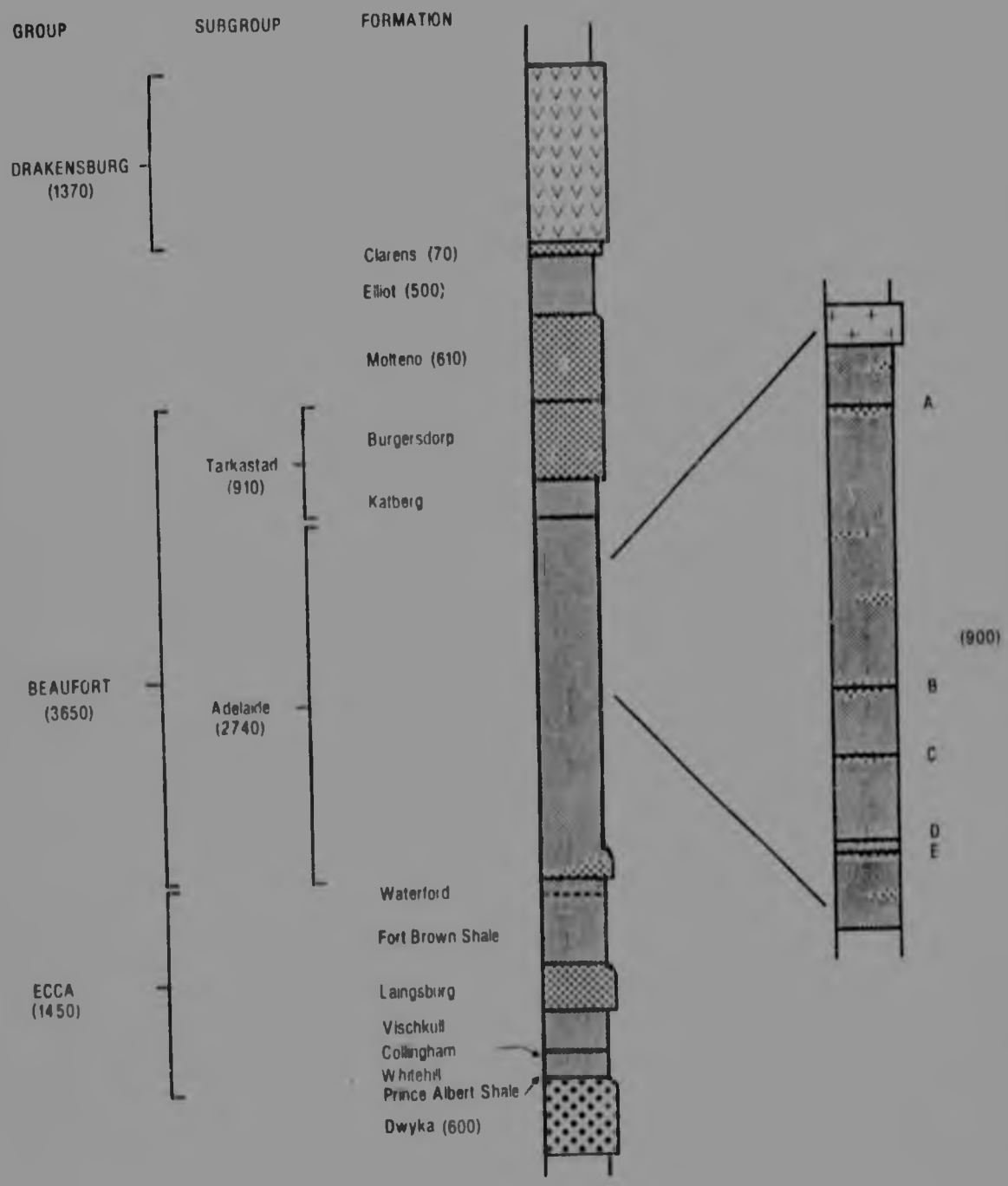
The dykes generally trend in more-or-less northerly or sometimes easterly directions. These directions correspond to the joint directions in the sandstones to the north of the escarpment.

D. FAULTS.

No faults large enough to be mapped at 1 : 100 000 were encountered in the area. The only displacements observed were those caused by the dolerite intrusions. Faults with small throws are present in the succession to the south of the area of the present study (Rossouw and De Villiers, 1953). Strike faults were found where folds are very closely spaced. Normal faults, associated with northward-trending fissures, were observed. These have throws of 1 to 5 m. The faults are usually marked by the presence of quartz veins.

FIG. 2

STRATIGRAPHY IN RELATION TO THE KAROO SUPERGROUP



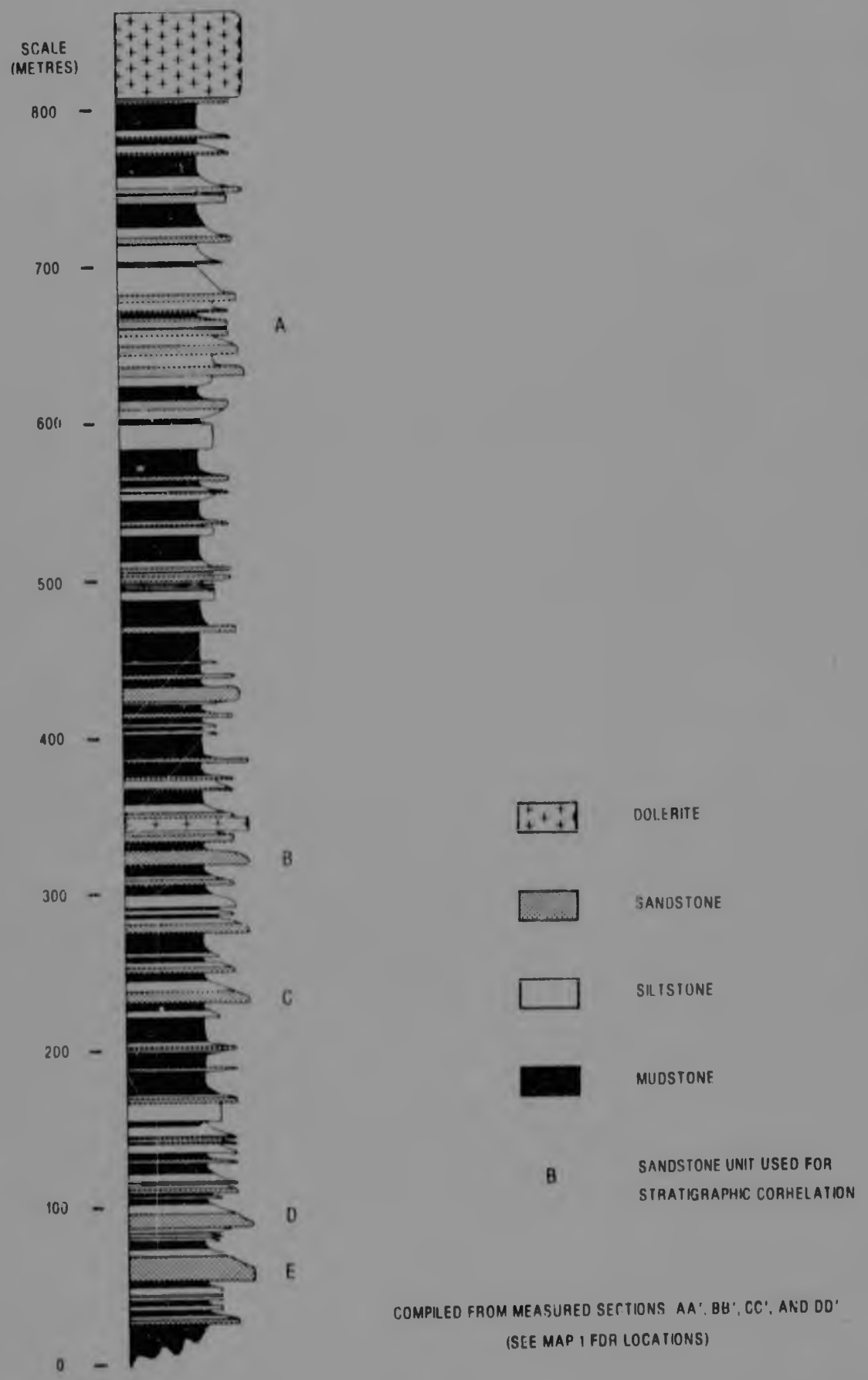
III. THE STRATIGRAPHY OF PART OF THE BEAUFORT GROUP.

The stratigraphic position of the interval studied in relation to the rocks of the Karoo Supergroup is shown in Figure 2. The Poortjie Sandstone, a prominent sandstone unit, was mapped and used as a stratigraphic marker occurring some 1800 m above the base of the Beaufort Group in an area to the south-east of the area of the present study by Rossouw and De Villiers (1953). The "B" sandstone unit (Figure 2 and Map 1) was found by airphoto interpretation to be equivalent to the Poortjie Sandstone. This correlation was used to fix the position of the stratigraphic interval studied. The "A", "B", "C", "D" and "E" sandstone units (Figure 2 and Map 1) are amongst the thickest and most continuous sandstones found in the area studied. They were used for the stratigraphic and structural interpretation of the area. The total stratigraphic interval exposed was estimated at between 800 and 900 m by drawing cross-sections using the South Africa 1 : 50 000 topographic sheets and aerial photographs. Stratigraphic sections were measured with a Jacobstaff so as to include most of the stratigraphic interval exposed in the area (measured sections AA', BB', CC' and DD' of Map 1). A total thickness of 840 m for the stratgraphic interval was obtained by this method.

The succession consists essentially of mudstones and siltstones with interbedded sandstones. Lithological units are discontinuous, and show rapid lateral and vertical facies changes. The typical vertical distribution of the lithological units is shown in Figure 3 which was compiled from the measured sections. The figure shows that the sediments generally form upward-fining sequences. None of the sedimentary units is distinctive, thus lithostratigraphic mapping is unreliable. The stratigraphic interval studied was not subdivided because no marked changes in

FIG. 3

THE STRATIGRAPHY OF PART OF THE LOWER PORTION OF THE BEAUFORT GROUP



COMPILED FROM MEASURED SECTIONS AA', BB', CC', AND DD'
(SEE MAP 1 FOR LOCATIONS)

lithological character were observed. More detailed lithostratigraphic mapping, over an area larger than that considered in the present study, may prove the existence of mappable units with significantly different sandstone to shale ratios. A unit with a higher sandstone to shale ratio than that of the sediments above and below was noted in the vicinity of the "A" sandstone (Figure 3) but its lateral persistence was not investigated.

The argillaceous rocks consist of siltstones, mudstones and shales. The siltstone is usually greyish-green and rarely purple or reddish in colour. It is found as bands varying in thickness from 0,05 to a few metres. The mudstones and shales are usually brown, red, purple or grey and occasionally green in colour. They are often mottled. The colour changes cannot be used for stratigraphic correlation, since colour boundaries transgress lithologic units.

Bands of calcareous concretions were found in siltstones and mudstones throughout the stratigraphic section. The bands consist of discreet ovate concretions 0,1 to 0,2 m in diameter (Plate 5). The concretions occasionally merge to form near-continuous calcareous bands. They are found in the argillaceous sediments, and have the same colour as them. The concretion bands cannot be used for stratigraphic correlation because of their discontinuous nature and their wide vertical distribution.

The sandstones have an average thickness of about 2 to 3 m, but locally may have thicknesses in excess of 25 m. They are fine- to very fine-grained. Their colour varies from green to grey, with occasional purples and browns. On surface, the sandstones weather to a more yellowish or pinkish colour. Intraformational conglomerates are found near the bases of some of the sandstones. These have thicknesses from 0,1 to more than 1 m. They generally consist of mudstone or siltstone

clasts set in a sandy matrix. Occasionally, the conglomerates have carbonate or sandstone pebbles. Some of the former represent re-worked calcareous concretions. Bone fragments are sometimes found in the conglomerates.

Some of the more persistent sandstones, although they vary considerably in thickness and in grain size, can be traced for several kilometres. Although much of the outcrop in the area is sandstone, the sandstone only forms a small part of the stratigraphic section. A sandstone to shale ratio of 1:4 was determined for the lower part of the Beaufort Group sediments to the south of the area of the present study (Henderson, 1974, and Roberts, 1974). Measurement of a section just south of the town of Beaufort West gave a similar result (Roberts, 1974). From the data of Rogers and Schwartz (1902), Wilke (1962) found that the sandstone in a 870 m section up the escarpment just to the west of the area of the present study, constitutes only 10 to 15 percent of the section. Measurement of sections near the top of the escarpment to the north of Beaufort West, gave sandstone to shale ratios of 1:4 (Henderson, 1974) and 1:3,5 (Roberts, 1974). A sandstone to siltstone and mudstone ratio for the stratigraphic interval exposed in the area (along measured sections AA', BB', CC', and DD', Map 1) was found to be 1:4. Over a stratigraphic interval of about 100 m, which includes the "A" sandstone, on the farm Bloemfontein 406, the sandstone to mudstone ratios were found to vary between 1:1 and 1:2 for sections measured every 200 m along an exposure of about 2 km. The same stratigraphic interval exposed further to the south on the farm Leeuwe Kloof 402 was measured, and sandstone to mudstone ratios were found to vary between 1:2 and 1:6 for two measurements of the same stratigraphic interval separated by only 200m. This shows that a considerable variation in sandstone to mudstone ratios is found in the succession. A large number of measurements along the strike of a stratigraphic interval would have to be made if reliable ratios are to be determined.

Sandstone to shale ratios in the range of 1:1 and 4:1 are found in the major sandstone-type uranium districts of the United States (Grutt, 1975). The average for the Lower Beaufort sediments is considerably below this. Even in selected more arenaceous horizons, such as the one exposed in the area between the farms Bloemfontein 406 and Leeuwe Kloof 402 (Map 1), the ratios are still below those of the rocks which are hosts to the major uranium deposits in the United States.

Uranium mineralization is found in sandstones distributed throughout the entire section. There appears to be no regional stratigraphic control on mineralization. On a more local scale, sandstones which are characteristically thick and have a complex internal structure (with channels or washouts), are preferentially mineralized.

The amount of dolerite intruded into the section is difficult to determine because the sills are generally discordant and show considerable changes in thickness and in attitude. The most prominent sill is the one capping the Nuweveld Mountains, which has a thickness of about 70 m at Steenkampsberg just to the west of the area of the present study (Wilke 1962).

IV. DEPOSITIONAL FACIES AND SEDIMENTARY PETROLOGY.

A sedimentary facies has been defined as "a mass of sedimentary rock which can be defined and distinguished from others by its geometry, lithology, sedimentary structures, palaeocurrent pattern and fossils" (Selly, 1970). A sedimentary facies results from deposition in a specific environment, and since only relatively few depositional environments are recognized, it is possible to use facies relationships to determine the palaeoenvironment.

The sediments of the lower part of the Beaufort Group in the area studied can readily be divided into a conglomerate, sandstone, siltstone and mudstone facies. The sandstone facies may be conveniently further divided on the basis of primary sedimentary structures into a trough cross-bedded, a horizontally-bedded and a ripple cross-laminated subfacies. Bedding in some sandstones was not visible. This was not regarded as constituting a separate subfacies since "most homogeneous looking sediments show internal laminations if special techniques are applied" (Reineck and Singh, 1973). Homogenizati of the sediment may also result from dewatering and from biological activity. The petrology of the various sandstone subfacies was found to be similar, and is thus described for the group as a whole.

A. THE INTRAFORMATIONAL CONGLOMERATE FACIES.

Intraformational conglomerate lenses were commonly found interbedded with fine-grained sandstone at, or just above, the base of the arenaceous units. Typically, the conglomerates consist of well-rounded pebbles of mudstone, siltstone or carbonate set in a fine-grained sandstone matrix. Very rarely, sandstone-pebble conglomerates were encountered.



Plate 5: Ovate calcareous concretions in a mudstone unit.



Plate 6: Carbonate clast conglomerate overlying horizontally-bedded sandstone.

The siltstone and mudstone pebbles tend to be oblate, while the carbonate pebbles are more spherical (Plate 6). The diameters of the clasts vary from about 1 mm to over 20 mm. A complete gradation from sandstones containing only isolated mudstone clasts, to conglomerates composed almost entirely of pebbles with only interstitial sand-sized material, was noted. Volume percentages of clasts (estimated by point counting in thin-section) were found to vary between 14 and 66 percent.

The similarity between the mudstone, siltstone and sandstone of the pebbles, and that of the sediment immediately below the conglomerates, indicates that they were derived locally. Carbonate pebbles closely resemble the carbonate found as concretions within the mudstones and the isolated limestone beds intercalated in the sequence, and were thus also intraformationally derived. Carbonaceous debris and fossilized bone (Plate 7) were often incorporated into the conglomerates. A carbonate cement was a common constituent of all the intraformational conglomerates.

The conglomerates were found in beds ranging in thickness from a few cm to over 2 m. Individual lenses could be traced along strike for tens of metres. The conglomerates have an erosional lower contact. Scours of up to 1,5 m into the underlying sediments were recorded. The upper bounding surface of the conglomerates was usually erosional, but gradations into fine-grained sandstone were also noted. The conglomerates generally pinch out laterally. Gradual lateral facies changes to fine-grained sandstone containing only isolated pebbles are fairly common.

Only a few primary sedimentary structures were found within the conglomerate lenses. The lenses are generally massive, with some indication of a vague upward decrease in pebble

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Plate 7: Mudstone clast conglomerate containing fossilized bones.



Plate 8: Horizontally-bedded sandstone.



Plate 7: Mudstone clast conglomerate containing fossilized bones.



Plate 8: Horizontally-bedded sandstone.

size and packing density. Large-scale trough cross-bedding is occasionally developed. A crude imbrication of the pebbles was observed in a few outcrops. Thin conglomerate bands were often found forming the basal unit in large-scale scour-and-fill trough cross-beds.

B. THE SANDSTONE FACIES.

1. The Horizontally-Bedded Subfacies.

The rocks of this subfacies are characterized by horizontal or gently-inclined plane bedding (Plate 8). The horizontally-bedded sets often truncate each other at very low angles (less than one degree). The thickness of the individual laminae varies from about 1 to 20 mm. The beds could be traced laterally for several metres. The horizontally-bedded sandstone constitutes about 20 percent of the sandstone making up the stratigraphic section.

The bedding results from the alternation of lighter coloured, somewhat coarser-grained bands with slightly finer, darker bands. Very fine black, platy, carbonaceous fragments and rounded oblate mudstone galls are often concentrated along the bedding planes. The grain size and composition of the horizontally-bedded sandstone facies is given in Figure 4 and Table 4 respectively.

Primary current lineation was found to be a ubiquitous primary sedimentary structure of this facies. Both the parting plane-lineation and the parting-step lineation of McBride and Yeakel (1963) are common (Plates 9 and 10 respectively)

Towards the base of the sandstone lenses, the horizontally-bedded facies was found as sedimentation units having thicknesses from about 0,1 to 1,5 m, which are bounded

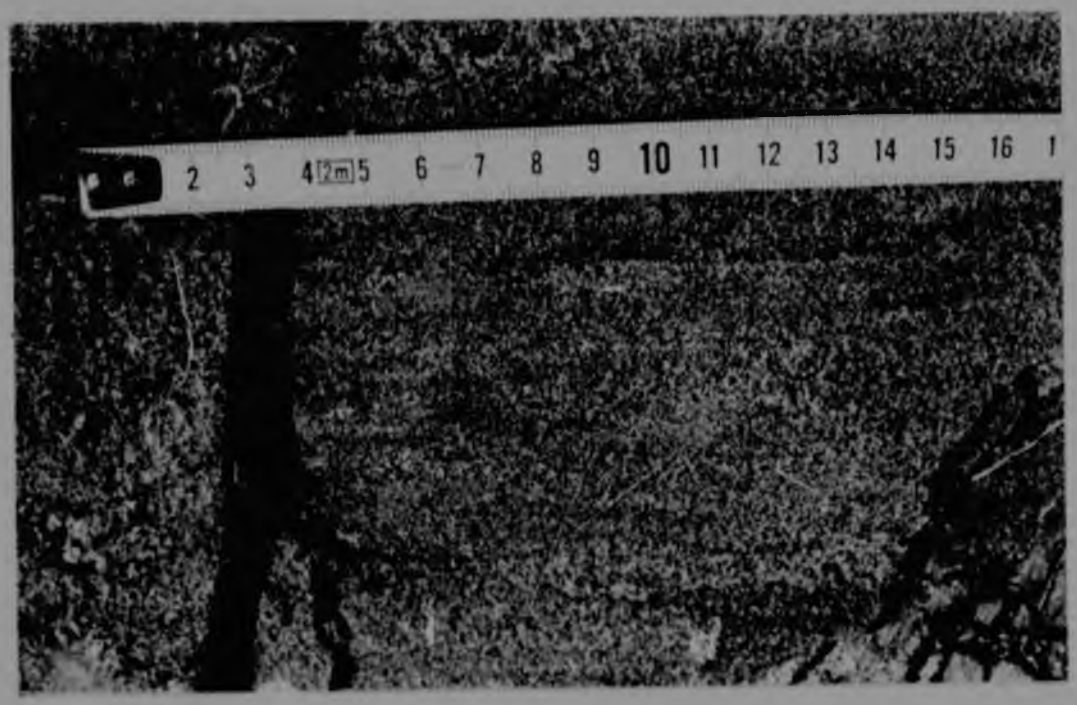


Plate 9: Horizontally-bedded sandstone with parting-plane lineation.



Plate 10: Horizontally-bedded sandstone with parting-step lineation.

by erosional surfaces. The surfaces are planar or slightly curved, and discordant to the bedding. Several of these sedimentation units are stacked, or they alternate with trough cross-bedded sandstones or intraformational conglomerates.

In the upper parts of the sandstone lenses, thinner units (about 2 to 20 cm thick) of horizontally-bedded sandstone are often interbedded with the ripple cross-laminated sandstone which predominates in this part of the lens.

2. The Trough Cross-Bedded Subfacies.

Much of the cleaner, fine-grained sandstone encountered belongs to the trough cross-bedded sandstone subfacies. This subfacies constitutes about 20 percent of the total sandstone in the stratigraphic section. Trough cross-bedded units are commonly interbedded with intraformational conglomerates, horizontally-bedded sandstones and ripple cross-laminated sandstones. The facies is best developed in the thickest portions of the sandstone lenses.

The grain size and composition of the trough cross-bedded subfacies is given in Figure 4 and Table 4. Fine-grained black carbonaceous debris is often concentrated along the lower bounding surfaces of the individual sets. Small, well-rounded, often prolate, mudstone galls were also often encountered on the foreset planes, particularly towards the base of the troughs.

The cross-bedding, using Allen's (1963) terminology, may be described as consisting of large-scale solitary or grouped sets. The thickness of the individual sets varies between 0,2 and 1,5 m. While solitary sets are most common, cosets consisting of up to about 10 sets were encountered (Plate 11). The lower bounding surfaces of the sets were seen to be both erosional and non-depositional.



Plate 11: Cosets of trough cross-bedded sandstone.



Plate 12: Large scale trough-cross beds (looking along trough axis).



Plate 13: Intraformationally deformed trough cross-bed foresets.



Plate 14: Channel-fill cross-bed. A thin mudstone conglomerate at the base of the U-shaped scour is overlain by fine-grained sandstone.

Scoop and cylindrically-shaped lower bounding surfaces are most common. Each set is made up of curved, more-or-less symmetrical beds which are discordant to the lower bounding surface. The beds are usually homogeneous, with slight increases in silt content towards their tops being discernable, in some cases. The troughs have widths ranging from about 0,3 to over 3 m (Plate 12). The dips of the foresets are usually between 15 and 25 degrees. Most of the cross-beds would thus be of Allen's (1963) Pi-type. Intraformationally deformed foresets (Plate 13) are rare.

Trough-shaped scours filled with more-or-less conformable laminae called "channel-fill cross-bedding" by Reineck and Singh (1973), were frequently encountered. The sediment filling the scours is generally upward-fining (Plate 14). In some cases, the complete range from conglomerate to siltstone is preserved. This channel-fill cross-bedding was found as isolated scours in the mudstone and siltstone facies, as well as in the horizontally-bedded sandstones.

3. The Ripple Cross-Laminated Subfacies.

The ripple cross-laminated subfacies comprises about 50 percent of the arenaceous rocks. The sandstone of this subfacies is generally finer grained than that of the horizontally-bedded and trough cross-bedded subfacies (Figure 4). It also contains slightly more matrix than the other sandstones (Figure 5 and Table 4).

The ripple cross-laminated sandstones were generally found in the uppermost portions of the larger sandstone units. Thinner units (about 0,5 to 3 m thick), composed almost entirely of ripple cross-laminated sandstone were distributed throughout the argillaceous rocks.



Plate 15: Sandstone showing rib-and-furrow structure overlying sandstone with parting step lineation. Palaeocurrent direction is the same for both structures.



Plate 16: Ripple cross-laminated sandstone; ripples show slight climbing tendencies.

The most common type of ripple cross-lamination encountered was festoon shaped small-ripple bedding (Reineck and Singh, 1973). Bottom sets of the ripples were generally preserved, while the upper bounding surfaces truncated the tops of the lee sides of the ripples. The set thickness is of the order of 2 to 3 cm, and in some cosets the set thickness was seen to decrease upwards. The bedding surfaces commonly showed rib-and-furrow structures (Plate 15), and rarely, lingoid and straight-crested ripples. Ripples showing climbing tendencies (Plate 16) of both type 1 and type 2 (Jopling and Walker, 1968) were only rarely encountered.

C. THE SILTSTONE FACIES.

About 30 percent of the total stratigraphic interval studied was composed of siltstone (Figure 3). The siltstones are generally greyish-green coloured rocks. A prominent purple mottling is locally developed. They are well consolidated. The composition of the siltstone appeared to be similar to that of the sandstones. A grain size analysis of the sample of siltstone used as a standard reference during the field-work is given in Table 2.

The siltstones are most commonly interbedded with rocks of the mudstone facies. Here, they commonly have erosional lower, and gradational upper contacts. The ripple cross-laminated sandstones often grade upwards into siltstones. The overall geometry of the argillaceous horizons was difficult to determine because of their relatively poor outcrop. The siltstones occur as more-or-less continuous beds varying in thickness from a few centimetres to several metres. In some cases, the siltstones were found in small channels cut into the mudstone (Plate 17).



Plate 17:Siltstone filled channel cut into mudstone; probably part of a crevasse-splay deposit.

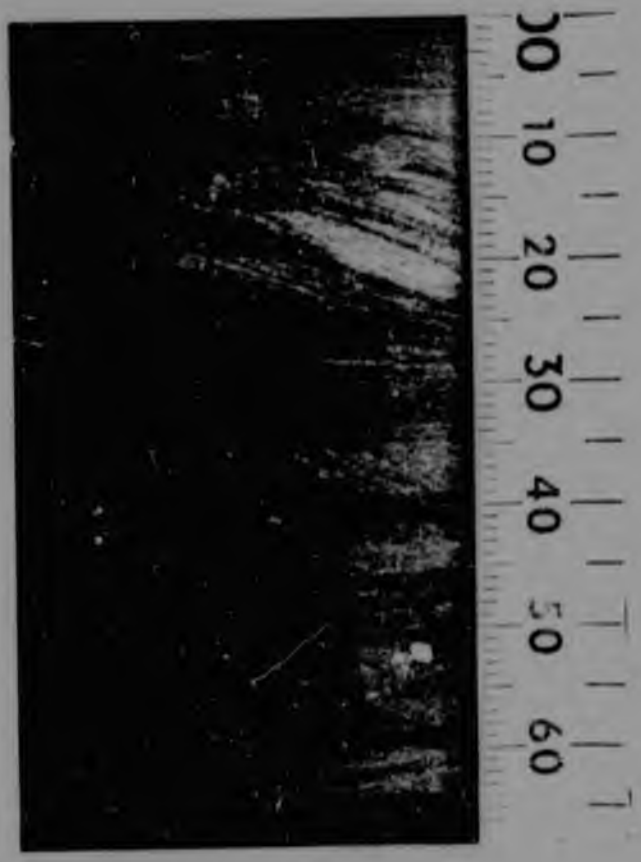


Plate 18; Small ripple cross-lamination in siltstone core (scale in mm).



Plate 19: Bioturbated sandy-siltstone (scale in cm).

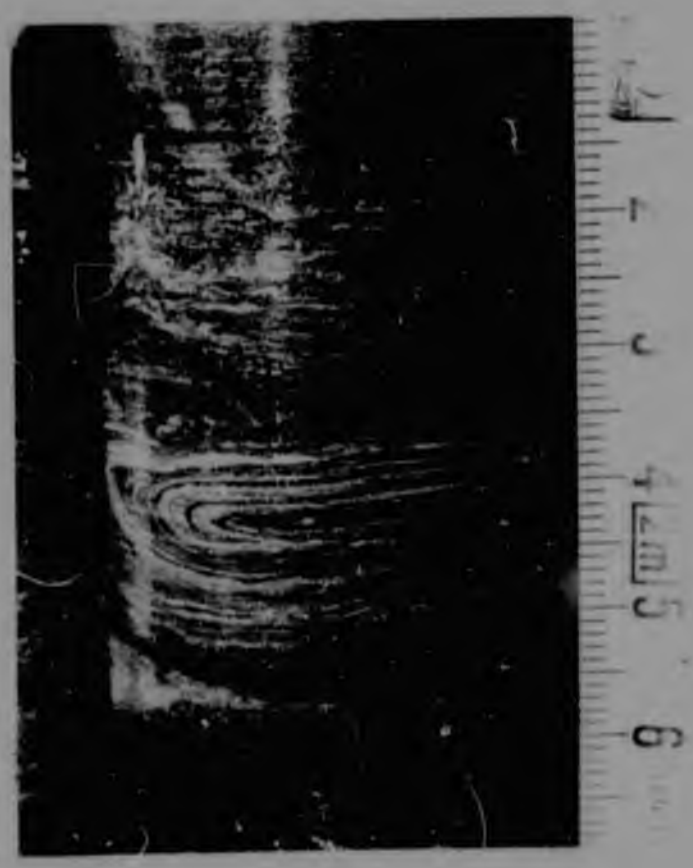


Plate 20: Convolute bedding in mud-stone core (scale in cm).

Relatively few primary sedimentary structures were observed in the siltstones. Ripple cross-lamination (Plate 18), often showing climbing tendencies (type 1 and type 2 of Jopling and Walker, 1968) are the most common structures. The set thickness of these units varies from less than 0,5 to about 2 cm. Horizontal and convolute lamination were rarely encountered. Some of the sandier siltstones are strongly bioturbated (Plate 19).

The bioturbations consist of almost cylindrical, smooth-walled, sediment filled tubes. These have diameters ranging between about 4 and 8 mm, are often curved and cut the bedding at all angles or are parallel to it. They are probably a form of "planolites", a trace fossil which is commonly attributed to the burrowing activities of worms. "Planolites" is not restricted to any particular sedimentary environment (Frey and Howard, 1970).

D. THE MUDSTONE FACIES.

Rocks of the mudstone facies constitute just under 50 percent of the total stratigraphic interval investigated. They are generally a brownish purple colour, although brownish-grey and bluish-grey varieties are common. Green mudstones are rare. In surface exposures, the mudstone is characteristically broken up into small (about 1 cm long) angular fragments. The rocks of this facies are thus very poorly exposed. X-ray diffraction analysis of a mudstone sample from the area (Moon, 1974) suggested a composition of 50 percent quartz, 35 percent feldspar and 5 percent each of chlorite, mica and montmorillonite.

Most of the mudstone appeared structureless. Occasionally, lighter and darker laminations gave it a shaley appearance. The laminae are sometimes convoluted (Plate 20). Elongate, nodular calcareous concretions were commonly developed at various stratigraphic horizons within the

mudstones. Their long axes range from about 2 to 30 cm. In some cases, the concretions merge to form continuous and near-continuous limestone bands. Mudcracks were only rarely seen.

E. SANDSTONE PETROLOGY.

The sandstones are light-to medium-grey, green and occasionally purplish in colour. On the surface, they weather to a somewhat lighter colour, with buff and pinkish hues being common. The lighter-coloured sandstones are usually cleaner and somewhat coarser grained than the darker varieties. They are tough and well compacted. The mean specific gravity of some 20 sandstone samples collected in the area was found to be 2,64.

In the field, the grain size was estimated by comparison to samples of sandstone collected in the area to represent typical fine-and very fine-grained sandstone. These, together with samples of typical siltstone and mudstone, were mounted on a piece of hardboard for convenient reference.

1. Grain Size Analysis.

For all grain size analyses 100 long axes of quartz grains per thin-section were measured, using a graduated microscope occular. An automatic point counting stage was used to give an even distribution across the thin-sections. The results were grouped into one phi units, and the mean grain size, M, for each thin-section calculated from the formula,

$$M = \frac{\sum f \quad m}{n}$$

where f is the number of measurements in each group, m the midpoint in phi units of each group, and n the total number of grains (Friedman, 1962b). The standard

deviation S, which can be used as a measure of sorting, was calculated using the formula given by Friedman (1962b).

$$S = \sqrt{\frac{\sum f \quad (m - M)^2}{100}}$$

The means and standard deviations determined for the thin-section data were then converted to results which are compatible to sieving data using the relationship determined by Friedman (1962a).

The means and standard deviations thus determined for the samples used as standards are given in Table 2.

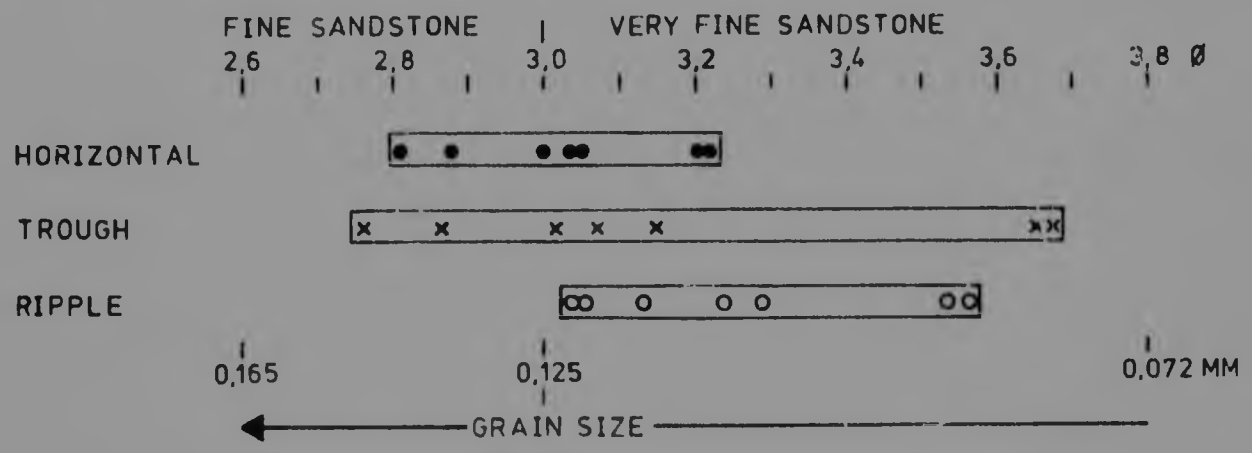
Table 2: - Grain Size and Standard Deviations of Samples used as Grain Size Standards.

	Wentworth Class Limits	Mean Grain Size		Standard Deviation
	Φ	Φ	mm	Φ
Fine Sandstone	2 - 3	3,07	0,119	1,18
Very Fine Sandstone	3 - 4	3,61	0,082	1,01
Siltstone	4 - 8	5,16	0,028	1,10

The range in mean grain sizes for the trough cross-bedded, horizontally-bedded and ripple cross-laminated subfacies were determined. The results are presented in Figure 4.

FIG 4

GRAIN SIZE DISTRBUTION



On the Wentworth scale, the mean grain size of the trough cross-bedded and horizontally-bedded sandstone subfacies ranges from fine- to very fine-grained, while the ripple cross-laminated sandstones are all very fine-grained.

The standard deviations of the sandstones of the three facies were then determined. No marked differences for the standard deviations of the three facies were noted. They range from 1,00 to 1,20 Φ, and thus all fall into the moderately sorted range, 0,80 to 1,40 Φ of Friedman (1962b).

2. Modal Analysis of the Sandstones.

The sandstones were found to be composed mainly of quartz, feldspar and a detrital matrix. Locally, carbonate cement was found to be a significant constituent of the rock.

A point count analysis of 33 thin-sections was made to determine the proportions of the major constituents present in the various sandstone subfacies. Some 1000 grains per thin-section were counted, using an automatic point counting stage. The constituents counted were quartz, orthoclase, plagioclase, chert, carbonate and matrix. The arithmetic mean of the results, together with

compositions determined from modal analyses of sandstones from the same area (Moon, 1974) and of the "Tapinocephalus Zone" (Hotton, 1967) are given in Table 3.

Table 3: Modal Analyses of Beaufort Group Sandstones.

	This Study	Moon (1974)	Hotton (1967)
Quartz	39	31	28 - 45
Chert	2	5	7 - 10
Orthoclase	30 } 33	13 } 15	11 - 19
Plagioclase	3 }	2 }	
Matrix	24	24 } 50	25 - 40
Chlorite/Mica		26 }	
Carbonate	2		

The sandstones were found to contain more feldspar and less chlorite, mica and matrix than indicated by Hotton (1967) and Moon (1974). The probable cause of this discrepancy was that the grains of feldspar, even when showing considerable alteration to chlorite and sericite, were counted as feldspar in the present study.

The average compositions of the sandstone facies (in volume percent) as determined by point count analysis is given in Table 4.

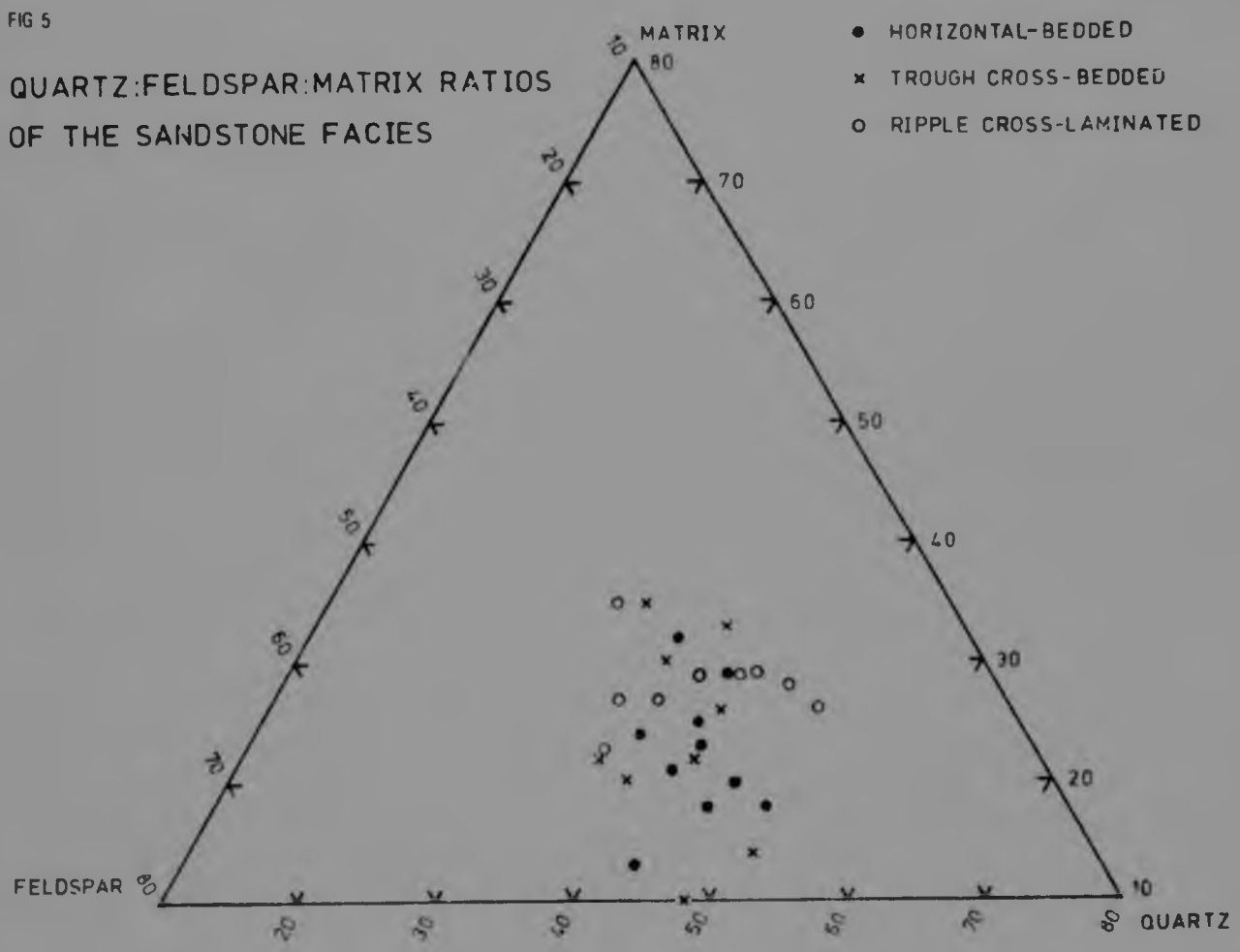
Table 4: Modal Analysis of the Sandstone Facies.

Subfacies	Quartz	Chert	Ortho-clase	Plagio-clase	Matrix	Carbon-ate
Horizontall -bedded	40,1	0,9	29,2	3,4	21,6	4,6
Trough Cross-bedded	40,0	1,4	30,6	3,7	23,0	1,2
Ripple Cross-Laminated	36,9	2,2	28,8	3,4	26,9	2,0
Massive	37,8	2,2	31,5	2,8	23,8	1,2
Mean	38,8	1,6	29,8	3,4	23,8	2,5

The ripple cross-laminated sandstone subfacies was found to contain somewhat more matrix than the other subfacies. A triangular plot (Figure 5) was prepared in an attempt to separate the sandstones of the various subfacies on the basis of their quartz to feldspar to matrix proportions.

FIG 5

QUARTZ:FELDSPAR:MATRIX RATIOS OF THE SANDSTONE FACIES



No distinct fields were found for the various subfacies. This was attributed to several factors. Small mudstone gails seen in some hand-specimen samples of trough cross-bedded and horizontally-bedded sandstones could not be distinguished from the matrix in thin-section.

In some instances, the replacement of the matrix by carbonate cement further upset the ratios. In samples where the alteration of the feldspars was strongest, some of the altered feldspar may have been counted as matrix.

3. Thin-Section Descriptions of the Main Constituents.

a) Quartz.

Quartz constitutes just less than 40 percent of the sandstone by volume. It occurs as fine to very fine detrital grains. The grains are generally subrounded to subangular single crystals. Secondary overgrowths on the grains gives them a more angular appearance.

The quartz grains are generally surrounded by matrix and maintain their original detrital shape. Where they are in direct contact with each other, they generally have straight boundaries. Some interpenetration of quartz grains was seen. In quartz-rich bands of some thin-sections, the grains are interlocked by pressure-point-solution and overgrowth into a quartzitic mosaic.

Most of the quartz is inclusion free. Where inclusions are found, they are of the acicular and irregular types, and are too small to be indentified in thin-section. A large proportion of the quartz grains show undulose extinction.

Polycrystalline quartz grains and chert are rare. The quartzitic grains often have strongly sutured inter-crystalline boundaries. Some of the cherty material is thought to have resulted from the quartzification of feldspar. The edges of some of the quartz grains have been replaced by carbonate and sericite.

b) Feldspar.

The sandstones were found to contain an average of about 33 percent feldspar. The most common feldspar is orthoclase, constituting about 30 percent of the rock, with the remainder being plagioclase. A few grains showing the typical grid-iron twinning of microcline were seen in the thin-sections. A considerable number of the more altered grains of plagioclase and microcline may have been counted as orthoclase in the point count analysis. Very strongly altered feldspars, which no longer showed distinct grain boundaries, may have been counted as matrix.

The feldspar grains have similar shapes and sizes to the quartz grains. They may have been somewhat better rounded than the quartz grains but, this is ofter obscured by the alteration.

The orthoclase was distinguished from the quartz by its dustier appearance and occasional presence of simple twins. The plagioclase was recognized in thin-section by the presence of polysynthetic twinning. The twin lamellae are often bent. The composition of the plagioclase was found to be andesine-labradorite (Union Carbide Research Report, 1972) and estimated as being albite-oligioclase by Moon (1974). The feldspars were found to be altered to various degrees. All four alteration types described by Carozzi (1960, pp. 57 - 58) were encountered, and a brief description of each is given.

Calcitization was the most common alteration seen in the plagioclase grains. The grains show small inclusions of calcite with random orientations. As the degree of alteration increases, the size and number of inclusions increases. Grains of pure calcite, having the size and shape of detrital feldspar, probably resulted from the alteration of plagioclase.

Sericitization of both the orthoclase and the plagioclase grains was seen. This varied from small unorientated flakes seen as inclusions, to a widespread sericite network in which small fresh remnants of feldspar are enclosed.

Minute quartz granules, which are often associated with sericite and calcite, formed by the quartzification of some of the orthoclase. This type of alteration was probably responsible for some of the fine-grained quartzitic and cherty grains seen in thin-section. Grains having the appearance of rock fragments may also have resulted from this process.

The dusty appearance of some feldspar grains, and the irregular kaolinitic aggregates, occasionally with a vermicular structure, probably resulted from kaolinitization.

c) Matrix.

The matrix was found to constitute an average of about 24 percent of the volume of the sandstone. It is mostly finely granular, consisting of silt-sized grains of sericite, chlorite, carbonate, feldspar and quartz. Locally, the matrix is clay. Occasionally it was seen to be stained reddish-brown by iron oxides.

The sericite, quartz and carbonate may have resulted from the alteration of detrital feldspathic mud deposited more-or-less simultaneously with the coarser clastics (Carozzi, 1960). The chlorite probably resulted from the weathering of mafic components of the source rock and the diagenesis of montmorillonitic clays. In some thin-sections, a carbonate cement was seen replacing the matrix.

d) Accessory Minerals.

No detailed work on the accessory minerals was undertaken. Biotite, hornblende, leucoxene, zircon, monazite

and various sulphides were identified from samples of sandstone taken in and around the present study area (Union Carbide Research Report, 1972). Moon (1974) found that a heavy mineral concentrate, made from a sample of sandstone collected on the farm Riet Kuil 307, consisted of about 25 percent garnet, 40 percent apatite-zircon, 25 percent magnetite-ilmenite and 10 percent monazite.

Biotite, muscovite, apatite, zircon, garnet, monazite and epidote were found in accessory amounts in the thin-sections studied. The biotite is pleochroic in shades of green and brown, and often showed some chloritization. The mica flakes are commonly distorted, indicating post-depositional compaction of the sediment. The garnet is of a colourless variety, and occures as anhedral grains showing very little or no alteration.

e) Rock Fragments.

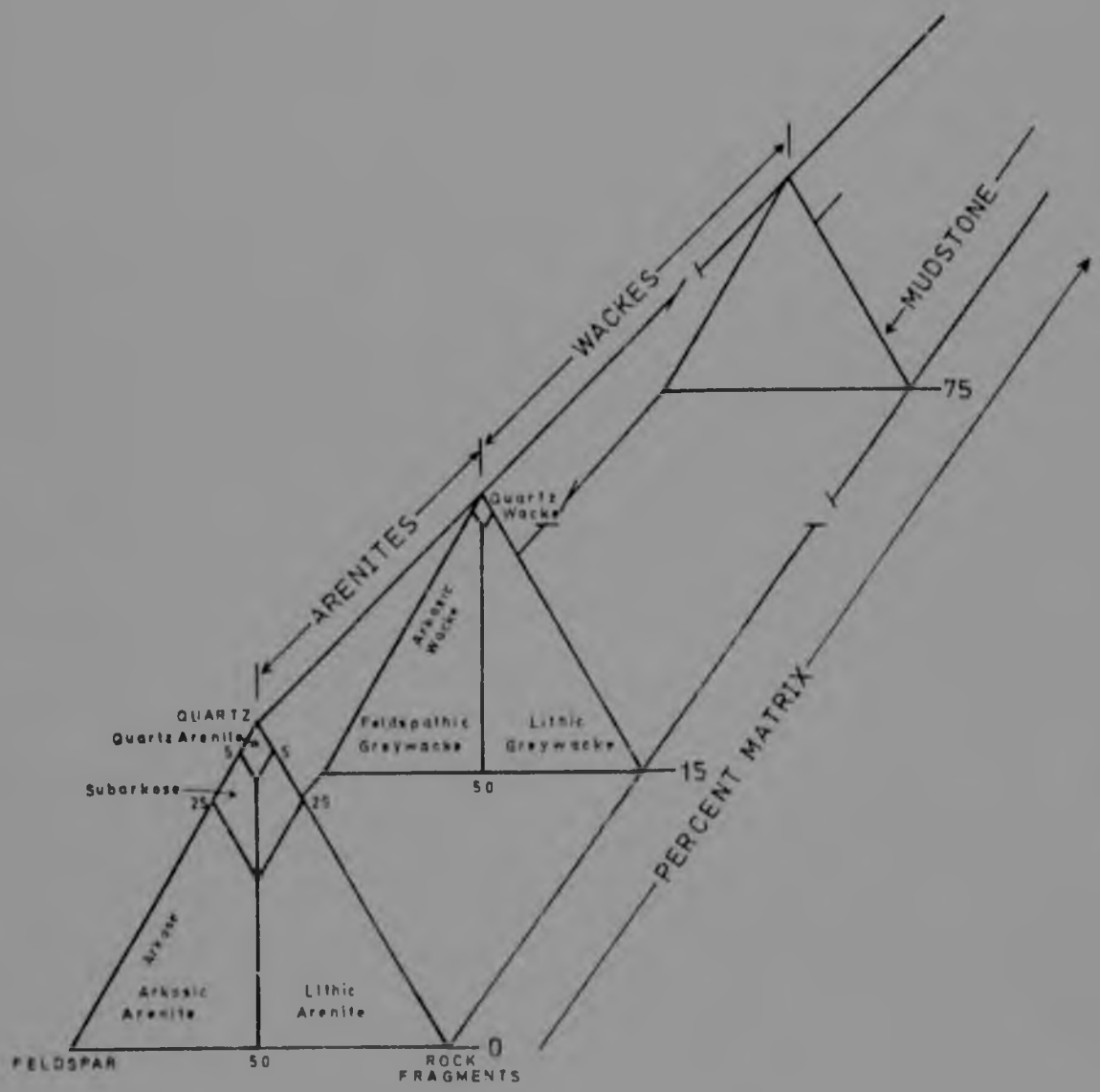
The most easily identified rock fragments found in the thin-sections studied were polycrystalline quartz grains and chert. These were only found in accessory amounts.

Martini (1974) found that greywackes from the base of the Lower Beaufort Series, to the south and south-east of the area of the present study, contained from less than 5 percent to 30 percent rock fragments. These consisted of laths of plagioclase in a chloritic matrix. They occasionally contained phenocrysts of albite, and rarely of biotite, but the general textures were trachytic and pilotaxic. He also described fragments with felsitic textures, the igneous origin of which, is in some cases, confirmed by the presence of phenocrysts.

The fine- and very fine-grained nature of the sandstones from the study area makes the positive identification of igneous rock fragments, and their differentiation from highly-altered feldspar grains in the sandstone, difficult.

FIG 6

CLASSIFICATION OF TERRIGENOUS SANDSTONES



(REDRAWN FROM PETTIJOHN et al., 1972)

J.E.J.Martini (1976, personal communication) identified fragments which are most probably of igneous origin in thin-sections of sandstones from the area studied. He indicated that the high albite content, found by him in sandstones from the lowermost part of the Beaufort Group, was typical of sandstones containing a relatively large amount of volcanic material.

4. Classification of the Sandstones.

Many classifications of sandstones have been proposed. These have been reviewed and modified by various writers, but no classification acceptable to all workers has emerged. A useful classification of terrigenous sandstones is given by Pettijohn *et al.*, 1972 (see Figure 6). The term "wacke" is used for rocks containing more than 15 percent matrix (defined as grains with diameters of less than 30 microns). Sandstones which contain more than 25 percent feldspar and in which the amount of feldspar is greater than that of rock fragments may be termed arkosic. The complete description of a sandstone should include textural terms (Pettijohn *et al.*, 1972). The sandstones found in the area studied, using the mean composition given in Table 3, may be described as fine- to very fine-grained, moderately sorted, arkosic wackes. This description is applicable to all the sandstones found in the study area.

V. VERTICAL AND LATERAL FACIES CHANGES.

The distribution of the sedimentary facies in both a vertical and lateral sense is fundamental to the recognition of the environment in which the sediments were deposited. Where sedimentary facies are repeated in a succession a "modal cycle", the most commonly occurring sequence of rock units, may be recognized (Duff and Walton, 1962). The modal cycle may then be compared to an "ideal cycle", which is the cycle predicted for a particular depositional model. Once a depositional model for the sediments has been established it may, by comparison to contemporary equivalents and well described ancient examples, be used to predict the probable extent and overall geometry of the major sedimentary units (Blatt *et al.*, 1972).

The modal cycle in a stratigraphic succession may be found by a Markov analysis. The analysis provides a statistical means for testing for the presence and degree of facies ordering in a succession.

A. MARKOV ANALYSIS.

A Markov process is defined as "a sequence or chain of discrete states in time (or space) in which the probability of the transition from one state to a given state in the next step in the chain depends on the previous state" (Harbaugh and Bonham Carter, 1970, page 98). The method of analysis used was based mainly on that of Gingerich (1969) and Harbaugh and Bonham Carter (1970).

A stratigraphic column (Figure 3), compiled from measured stratigraphic sections (AA', BB', CC'and DD', Map 1), representing the entire stratigraphic interval exposed, was used for the analysis. For the purpose of the analysis, each of the six facies given in Table 5 was taken to represent a distinct lithological state.

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Table 5: The Facies used for the Markov Analysis.

Facies	Percentage of Section	Frequency of Occurrence (s_i)
A. Horizontally-Bedded Sandstone	4,7	18
B. Trough Cross-Bedded Sandstone	4,8	20
C. Ripple Cross-Laminated Sandstone	10,3	47
D. Massive Sandstone	2,2	8
E. Siltstone	29,0	57
F. Mudstone	49,0	56

The lag conglomerate facies was only rarely encountered in the section, and thus not used in the analysis. The massive sandstone facies was used to describe sandstone with no readily visible bedding. The poor outcrop of the argillaceous rocks in some areas made the distinction of thin siltstone and mudstone bands difficult, and the facies boundaries were taken where the dominant lithology changed.

In the stratigraphic section, a total of 206 vertical changes in the lithological facies was encountered. Multistory facies (repetitions of the same facies) were not counted because, while transitions within the various sandstone facies were readily recognizable, those within the argillaceous rocks were not. The analysis does not take into account the thickness of the units. The succession was considered to be stationary, that is, the transition probabilities were considered to remain more-or-less constant throughout the succession because no major changes in the lithological associations were observed over the stratigraphic interval considered.

The frequency of occurrence in each of the six facies, s_i, is given in Table 5. The individual transitions were

counted and expressed as the transition count matrix, f_{ij}.

f_{ij} =

	A	B	C	D	E	F
A	0	4	8	1	4	1
B	4	0	9	3	3	1
C	4	4	0	2	27	10
D	0	2	3	0	2	1
E	6	1	9	0	0	41
F	5	9	18	2	22	0

An independent trials probability matrix, e_{ij}, was calculated. This assumes that the facies were deposited in a random sequence.

e_{ij} =

	A	B	C	D	E	F
A	0	0,106	0,250	0,042	0,303	0,298
B	0,097	0	0,253	0,043	0,306	0,301
C	0,113	0,126	0	0,050	0,358	0,352
D	0,091	0,101	0,237	0	0,288	0,283
E	0,121	0,134	0,315	0,054	0	0,376
F	0,120	0,133	0,313	0,053	0,380	0

The following χ^2 statistic was used to determine whether the observed transitions resulted from a random process:

$$\chi^2 = \sum_{ij}^{n} (f_{ij} - s_i e_{ij})^2 \; / \; s_i e_{ij}$$

The number of degrees of freedom, for the above statistic is given by the number of non-zero entries in the independent trials probability matrix minus the rank of the matrix. For the above given data χ^2 was found to be 65,9, and the number of degrees of freedom 24. From percentile tables for the χ^2 distribution using 24 degrees of freedom, the critical value for rejecting the hypothesis that the sediments were deposited by a random process at a 0,995 probability level is 45,6. A Markov chain process is therefore strongly indicated.

The transition probability matrix was expressed in probability form, p_{ij}.

p_{ij} =

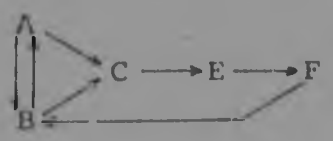
	A	B	C	D	E	F
A	0	0,222	0,444	0,056	0,222	0,056
B	0,200	0	0,450	0,150	0,150	0,050
C	0,085	0,085	0	0,042	0,574	0,213
D	0,000	0,250	0,375	0	0,250	0,125
E	0,105	0,018	0,158	0,000	0	0,719
F	0,089	0,161	0,321	0,036	0,393	0

The difference matrix, d_{ij}, was obtained by subtracting the independent trials probability matrix, e_{ij}, from the transition probability matrix.

d_{ij} =

	A	B	C	D	E	F
A	0	+0,166	+0,194	+0,014	-0,081	-0,242
B	+0,103	0	+0,197	+0,107	-0,156	-0,251
C	-0,028	-0,041	0	-0,008	+0,216	-0,139
D	-0,091	+0,149	+0,138	0	-0,038	-0,158
E	-0,016	-0,116	-0,157	-0,054	0	+0,343
F	-0,031	+0,028	+0,008	-0,017	+0,013	0

The positive elements of the difference matrix represent those transitions which have a higher than random probability of occurring. A modal depositional cycle was developed by following the positive elements through the matrix. The result may be shown schematically as:



The mean probability for the transition sequence (Allen, 1970)
A → B → C → F → F → A was 0,253, and the sequence
B → A → C → E → F → B was 0,254, thus the two sequences have an almost equal probability of occurring.

In general terms, the horizontal and trough cross-bedded sandstone is overlain by ripple cross-laminated sandstone, followed by siltstone and mudstone, forming a general upward-fining sequence. The difference matrix shows that the massive sandstone facies alternates mainly with the trough cross-bedded facies and the two may thus be closely related.

These results correlate closely with those obtained by Allen (1970) for the Old Red Sandstone of Britain and the Appalachians of North America, in that the coarser-grained facies "are highly variable in character" and the "upward transition, cross-laminated sandstone facies, alternating bed facies, siltstone facies is an essentially one-way path" (page 304).

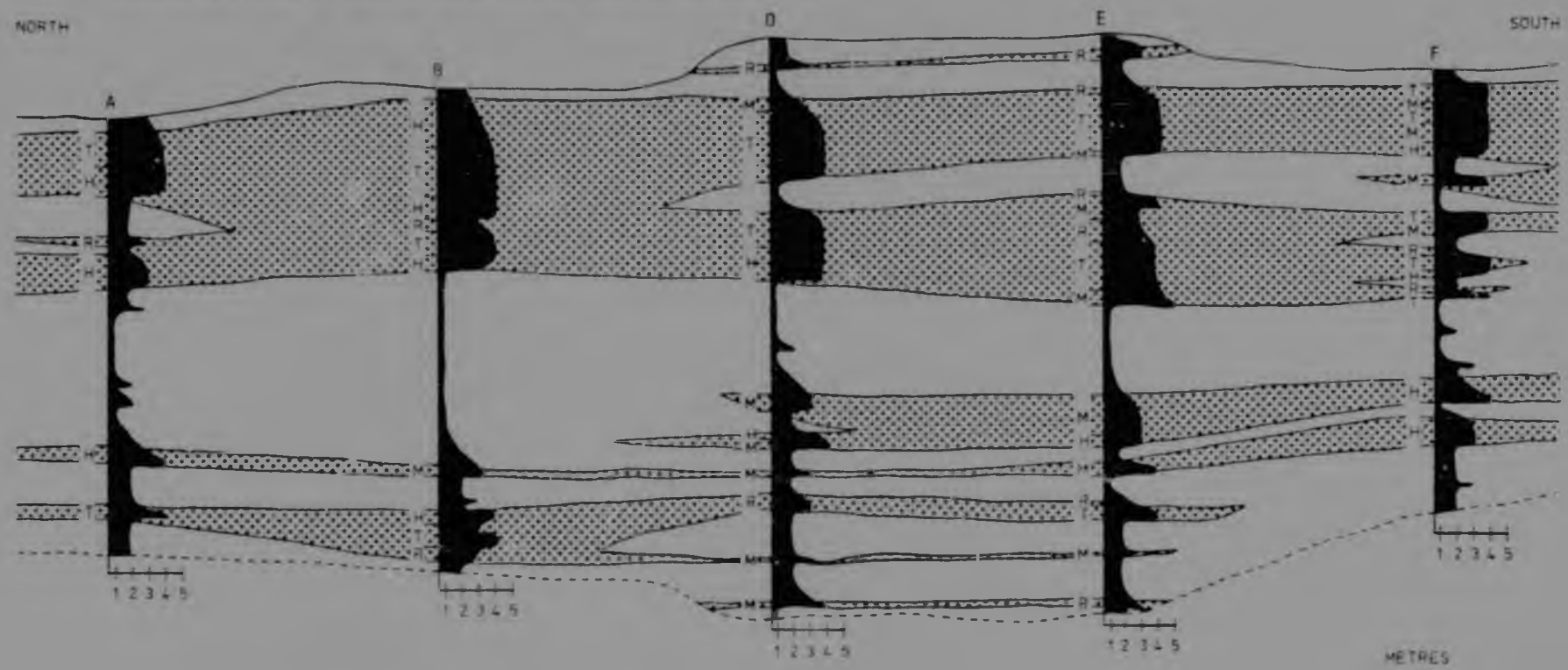
B. FIELD RELATIONSHIPS.

The sedimentary cycles in the field were considered to start at an erosional surface. This surface was cut into the rocks of the preceeding cycle, usually the argillaceous facies, but, in areas of sandstone thickening, the surface was cut on the underlying arenaceous unit. The surface generally has a low relief (less than 1 m), with local scours orientated parallel to the regional palaeotransport direction.

Intraformational conglomerates, often only 1 or 2 cm thick, commonly overlie the erosion surfaces. Thicker conglomerate lenses are impersistent and grade laterally into, and are interbedded with, horizontally-bedded and trough cross-bedded sandstones. Both horizontally-bedded and trough cross-bedded sandstone are common just above the erosional surface, but in some places the surfaces are overlain by ripple cross-laminated sandstone and siltstone. The vertical facies changes generally correspond well with those derived by the Markov analysis.

FIG. 7

CROSS-SECTION OF MAJOR SANDSTONE, BLOEMFONTEIN 406



The lateral facies changes are similar to the vertical, in that the arenaceous units give way to thinner-bedded argillaceous rocks. Cross-sections of the major sandstone units exposed on the farms Bloemfontein 406 and Leeuwe Kloof 402 (Map 1) were constructed (Figures 7 and 8 respectively). The sandstone units depicted are at about the same stratigraphic level. Stratigraphic sections were measured every 200 m along the outcrop using a Jacob-staff. Lithology and sedimentary structures were noted and the sandstone units correlated laterally. Figure 7 is orientated almost parallel to the regional palaeotransport direction, while Figure 8 is more-or-less perpendicular to it. The cross-sections show the rapid lateral variation in gross lithology, and the interfingering of the sedimentary facies.

The areas of thickening in the major sandstones, often referred to as channels (measured section line B, Figure 7, and lines A and B, Figure 8), consist of thicker cycles of which only the arenaceous units are preserved. The major sandstones may be considered as consisting of an upper and a lower arenaceous unit, separated by an argillaceous parting, which merge in the channelled areas. Away from these channelled zones, the number of cycles increases, and the sediment becomes progressively finer grained. The conglomerate and sandstone facies are less well developed. These grade laterally into a section which consists predominantly of alternating beds of siltstone and mudstone.

The arenaceous units are made up of lenses consisting of the various sandstone subfacies interbedded with occasional siltstone and mudstone lenses. The individual lenses are often bounded by curved erosional surfaces. Mudstone drapes are occasionally preserved between the lenses. The internal structure of the lenses is variable. Single trough cross-bedded sets, homogeneous horizontally-bedded units, cosets of small-ripple bedding, small massively-bedded siltstone and mudstone intercalations,

FIG 8

CROSS-SECTION OF MAJOR SANDSTONE, LEEUWE KLOOF 402

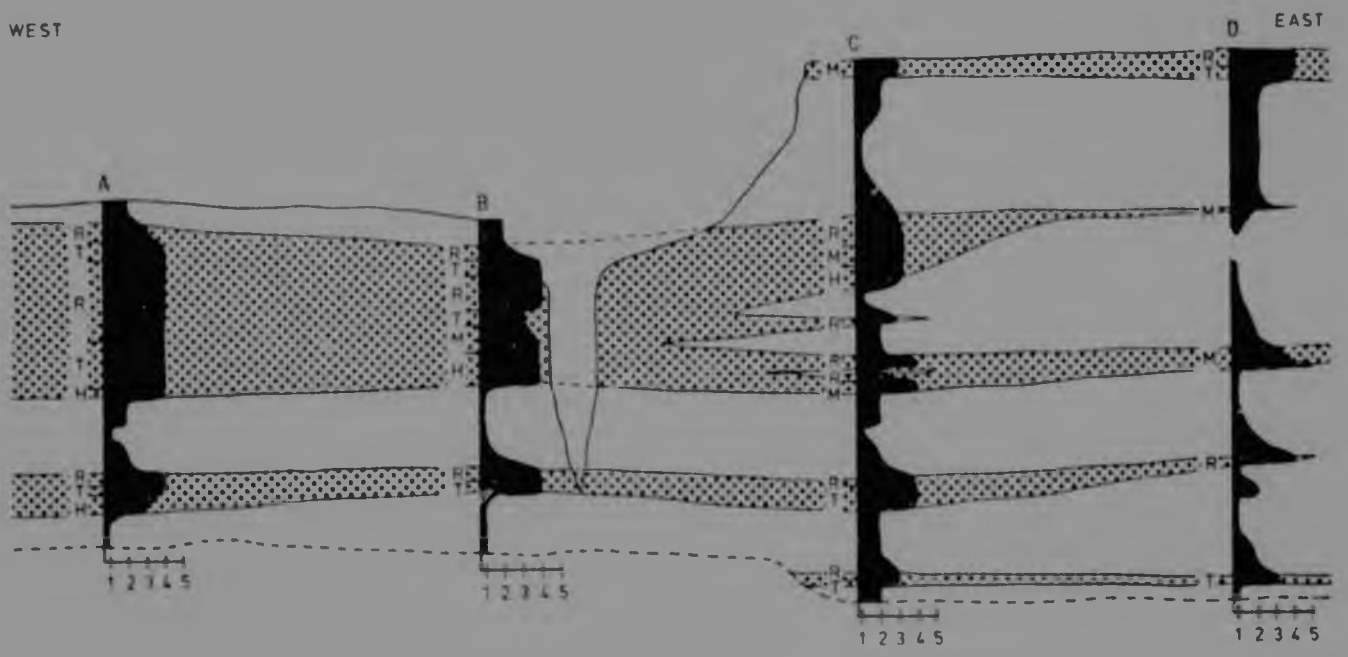




Plate 21: Upward-coarsening sequence. The darker sediment is mudstone and the lighter a sandy-siltstone.



Plate 22: Ripple-marked very fine-grained sandstone at the top of an upward-coarsening sequence. The angular fragments are typical of the weathered mudstone.

and units comprising an upward-fining sequence, commonly constitute the lenses. Figure 9 is a map of portion of a well exposed cross-section on the farm Hendrikskraal 298, which illustrates some of these features.

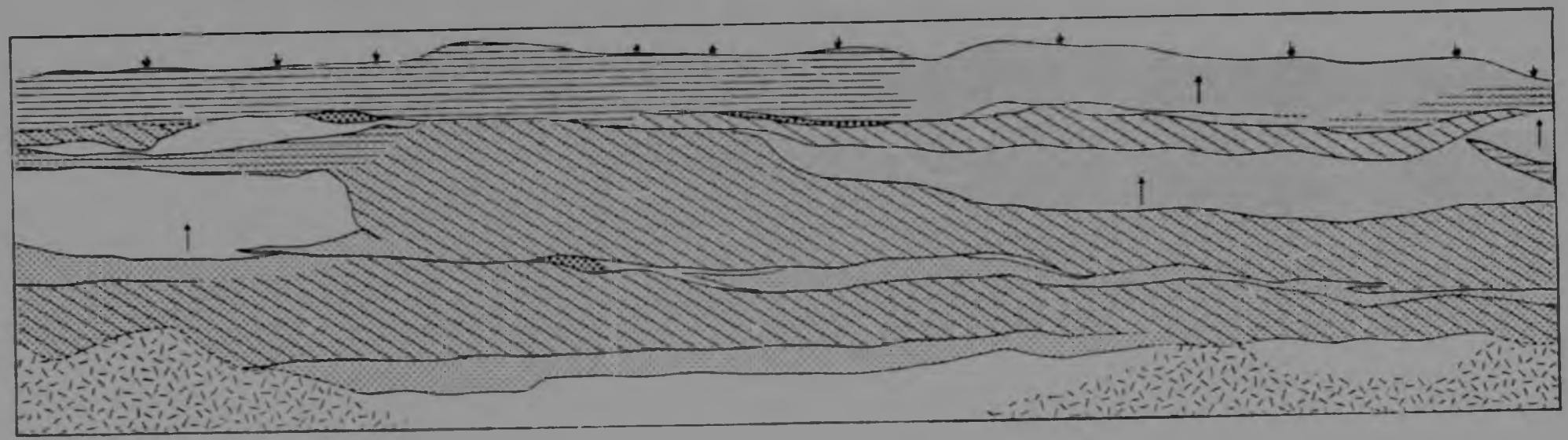
The sedimentary units are most commonly arranged so as to form upward-fining cycles, but upward-coarsening cycles were developed in some of the argillaceous rocks (Plate 21). They consist of very fine mudstones which grade continuously upwards into a siltstone or very fine sandstone, at the top of which there is a sharp break. This is overlain by mudstone of the following cycle. The siltstone or very fine sandstone often shows small-ripple bedding and the surface upon which the overlying mudstone was deposited is often ripple-marked (Plate 22). The thickness of the cycles varies from about 0,3 to 2,5 m. The lateral continuity of these cycles was not established because of the poor outcrop of the argillaceous rocks.

C. SANDSTONE GEOMETRY.

The distribution of the sedimentary facies in plan view was difficult to establish. The cross-sections of sandstone units parallel and perpendicular to the regional palaeotransport directions (Figures 7 and 8 respectively) show that the units tend to be elongate in the direction of palaeotransport. The units of the individual sandstone subfacies also follow this trend. The elongate nature of a thickened portion of a sandstone unit, is shown by an isopach map of part of the "C" sandstone unit, on the farms Riet Kuil 307 and Lang Leegte 304 (Figure 10). The sediments in the area are folded into a shallow syncline. The map was constructed from drill-hole data (about 600 holes). The contours represent the total sandstone thickness of what was considered to constitute the "C" unit. The drilling was aimed at the thickest portions of the sandstone unit, thus drill-hole control over the thinner

FIG.9

CROSS-SECTION SHOWING FACIES RELATIONSHIPS IN AN ARENACEONS UNIT



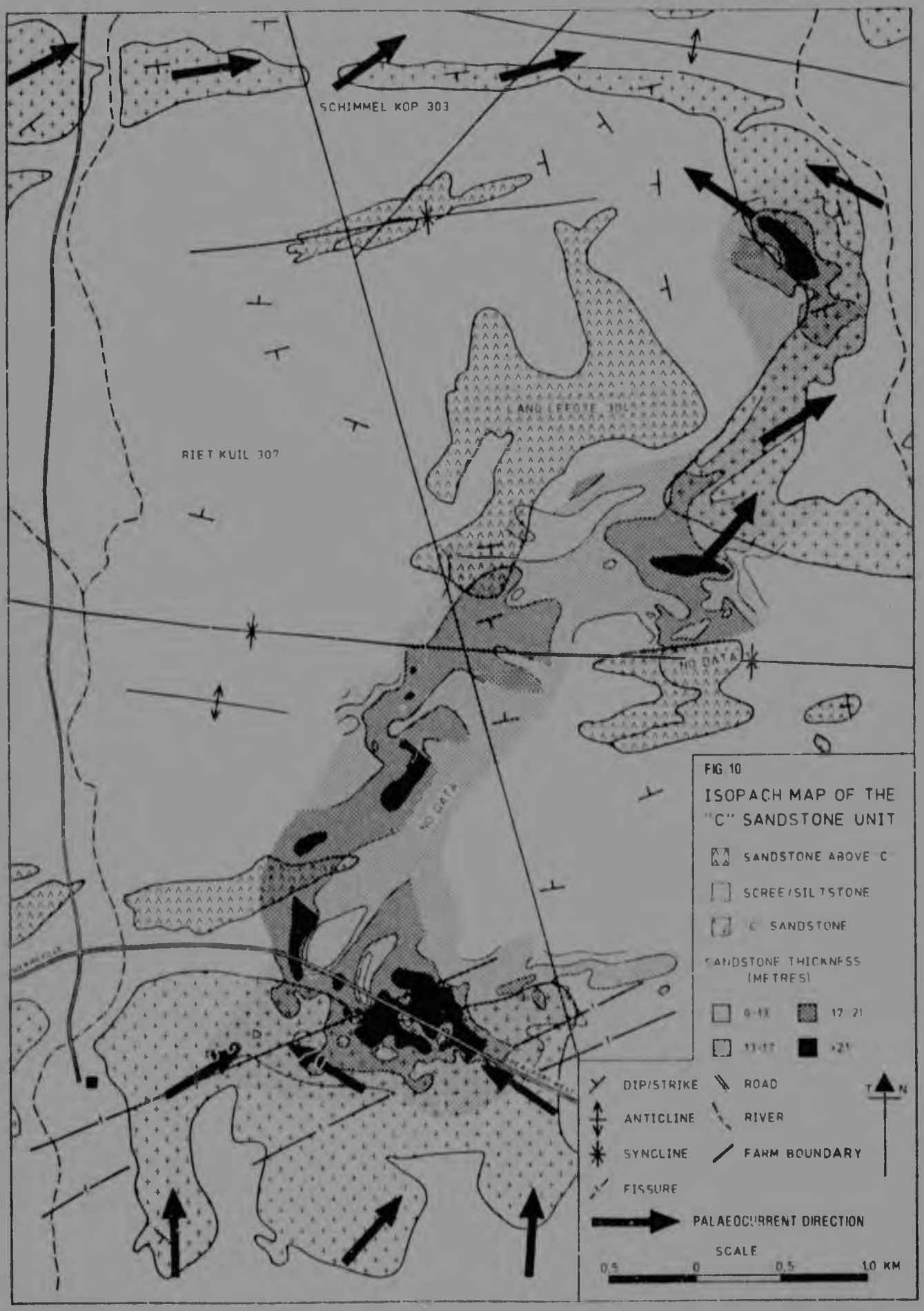
KEY

- CONGLOMERATE
- FINE SANDSTONE
- VERY FINE SANDSTONE
- SILTSTONE/MUDSTONE
- SCREE
- HORIZONTAL BEDDED
- TROUGH CROSS-BEDDED
- RIPPLE CROSS-LAMINATED
- UPWARD FINING SEQUENCE

SCALE

0 1 2 3 4 5 10 METRES

portions was less dense. The outcrop pattern and the structure were derived from airphoto interpretation. The thickened sandstone trends in a more-or-less north-easterly direction, which is parallel to the regional palaeotransport direction. The decrease in sandstone thickness away from the channelled area is rapid, and is accompanied by the interfingering of the sandstone with the argillaceous facies. A single unit was thus no longer easily recognized.


SCHIMMEL KOP 303
RIET KUIL 307
NO DATA
NO DATA
FIG 10
ISOPACH MAP OF THE
"C" SANDSTONE UNIT
SANDSTONE ABOVE C
SCREE/SILTSTONE
SANDSTONE
SANDSTONE THICKNESS
(METRES)
17-21
>21
DIP/STRIKE
ANTICLINE
SYNCLINE
FISSURE
ROAD
RIVER
FARM BOUNDARY
PALAEOCURRENT DIRECTION
SCALE
0.5
0
0.5
1.0 KM

VI. DEPOSITIONAL MODEL FOR THE LOWER PART OF THE BEAUFORT GROUP.

A. INTRODUCTION.

The lower part of the Beaufort Group is characterized by upward-fining sedimentary cycles. Upward-fining cycles most commonly form by lateral accretion on point bars in meandering channels, on alluvial plains and on tidal flats (Reineck and Singh, 1973). The absence of sedimentary structures formed by bipolar current action (which are characteristic of the tidal environment) in the sediments studied, suggests that they were deposited by fluvial processes. Middle tidal flat sediments are composed of vertical alternations of bed load, and suspension load sediments. Tidal flats are characterized by very abundant ripple-marks and desiccation features, which are not common in the sediments studied. The lower part of the Beaufort Group was thus thought to have been deposited by meandering streams ir a fluvial environment.

B. REVIEW OF THE FLUVIAL ENVIRONMENT.

Literature reviews of the hydraulic conditions pertaining to fluvial sedimentation, the resulting sedimentary facies, and their recognition in ancient rocks have been given by Leopold *et al.* (1964), Allen (1965), Visher (1972) and others.

In the fluvial environment, sediment may be deposited by either lateral or vertical accretion, which results in the formation of three major types of deposit (Reineck and Singh, 1973). These are:

(1) channel deposits, formed mainly by the action of river channels, and include channel lag, point bar, and channel fill deposits;

(2) bank deposits, which formed on the river bank during floods, and include crevasse-splay and levee deposits; and,
(3) flood basin deposits, which are essentially fine-grained deposits formed during heavy floods when the river water flowed over the levees into the flood basin.

The geometry and nature of fluvial deposits depends on the type of stream channel. The three common types of channel are braided, straight and meandering (Leopold, *et al.*, 1964). All transitions between the three types exist. A river often has all three types along its length, and the type of channel may vary within the same reach, depending on the river stage (Leopold *et al.*, 1964).

Allen (1965) proposed facies models for braided, low sinuosity and strongly meandering streams, an outline of which is given below. The deposits resulting from braided streams generally consist of coarse bed-load material. Little fine-grained overbank sediment is preserved because of the rapid lateral migration of the stream. The individual sedimentary units are lenticular, and occupy channel forms. The fine sediment may represent channel fill during low stages. The resulting deposit would be elongate in the direction of stream flow, and would extend the entire width of the flood plain.

The deposits formed by low sinuosity streams consist of arenaceous to rudaceous sediment, which was transported as bed load. Each unit is upward-fining. The stream is not confined to a meander belt, thus very little overbank material is preserved. Fine-grained channel fill is occasionally found. The resulting deposit is elongate in the direction of stream flow, and more-or-less continuous across the entire flood plain.

Strongly meandering streams are confined to meander belts

by well defined alluvial ridges. The meander belts are narrow compared to the width of the flood plain. Superimposed and adjacent channel fill deposits (erosion-resistant silt and clay) form at the edges of the meander belt, and inhibit further channel migration. Channel migration is generally by avulsion. The bed load deposits of meandering channels are narrow, linear, bodies and are elongated in the direction of stream flow. The sandstone units have erosional lower contacts, but, towards the top, interfinger with the fine-grained sediments. The argillaceous flood plain deposits separate the meander belt sediments laterally, and to some extent, vertically.

The sedimentary facies and their distribution in the study area are best explained by the strongly meandering model. The more continuous nature of some of the sandstone units toward the top of the stratigraphic interval studied, and the somewhat lesser development of siltstone and mudstone, indicate that the streams had lower sinuosities. There is no evidence for the existence of any major braided channels.

Fluvial deposits are best recognized by the sequence of sedimentary structures formed by unidirectional confined flow (Visher, 1972). These are trough and planar cross-bedding, horizontal bedding with primary current lineation and ripple cross-lamination. These sedimentary structures may be formed individually in other environments, but the upward gradation from trough cross-bedding, to horizontal bedding and ripple bedding, all showing unidirectional sediment transport, is developed only in fluvial channels (Visher, 1972).

Large-scale trough or festoon cross-bedding probably only forms in confined channels by unidirectional flow, and thus is a powerful tool in the recognition of this regime (Visher, 1972). Harms and Fahnestock (1965) suggested that trough cross-bedding is formed by the filling of scours, caused by vortices moving slowly downstream. The downstream

migration of lunate dunes or megaripples would also produce trough cross-bedding. The amplitude of large ripples was found by Allen (1965) to be 10 to 20 percent of the stream depth.

Ripple cross-lamination of the festoon type is formed by the downstream migration of linguoid ripples (Harms and Fahnestock, 1965). Ripple cross-lamination is common both in marine and fluvial environments (Visher, 1972). Small-ripple bedding indicates lower rates of sedimentation and more sediment reworking than climbing ripple-lamination (Reineck and Singh, 1973).

Visher (1972) indicated that horizontal bedding or current lamination formed only under upper flow-regime conditions, but was not restricted to environments of unidirectional flow. Harms and Fahnestock (1965) found that horizontal bedding formed during high discharge stages. The preservation potential of the horizontally-bedded sandstone was found to be low, because of disruption by ripple migration at lower river stages (Harms and Fahnestock, 1965). This caused the interbedding of the ripple cross-laminated and horizontally-bedded subfacies. McBride *et al.* (1975), using flume experiments, found that horizontal lamination was only produced by the migration of low-amplitude waves and ripples in water depths of less than 5 cm. A slight increase in water depth caused the formation of ripples. Under their rather restricted experimental conditions, they found that aggradation under plane-bed conditions did not produce lamination, because no sorting of the sediment took place.

The thickness of a complete point bar sequence is approximately equal to the channel depth. The thickness of the sequences in smaller streams would be 1 to 3 m, while major rivers such as the Mississippi may have bars which are up to 25 m thick (Reineck and Singh, 1973). The uppermost part of the sequence is commonly eroded before the deposition

of the following sequence (Reineck and Singh, 1973).

The features of fluvial sedimentation which may be recognized in ancient deposits are erosion surfaces formed along the cut banks of ancient rivers, channel lag, point bar, channel fill, natural levee, crevasse-splay and flood basin deposits. A short description of the characteristics of each feature is given below.

C. THE EROSIONAL SURFACE.

The erosional surface, which is taken as the base of a fluvial cycle, is thought to have been cut by river migration across a flood plain. Allen (1964) found that the low relief features commonly encountered on these surfaces were comparable to those found on the beds of modern day streams. The small-scale surface features, load casts and irregular depressions, found in the area studied were non-directional. Small scours with a 10 to 30 cm relief were found to be elongate parallel to the palaeocurrent directions. The surfaces, when traced laterally, were often seen to be erosional disconformities with an overall channel-like geometry scouring several metres into the underlying sediment (Plate 23).

D. CHANNEL LAG DEPOSITS.

The intraformational conglomerate which often overlies the scoured surface was interpreted as a channel lag deposit. These typically accumulate in the deeper parts of the stream beds, as lenticular deposits, which, in the course of time, became buried by finer grained alluvial bar sediments (Allen, 1965). The lag conglomerates were generally found to be the basal units of the point bar sequences. Where lag deposits were found within the fluvial bar sediments, they occurred as thin sheets of pebbles. These were probably concentrated by the winnowing of sand from the initial deposits (Allen, 1965). The deepest portions



Plate 23: Cross-section showing an erosional disconformity at the base of a sandstone unit.



Plate 24: Typical point bar sequence with lag conglomerate at base (in shadow) overlain by horizontally-bedded and trough cross-bedded sandstone.

of the scours occasionally found within the sandstone units, sometimes contain small intraformational conglomerate lenses. These possibly represent material derived from the cut bank of the stream, which was deposited as a lag conglomerate on the point bar during flood stages.

The lag conglomerates represent the coarsest material available for deposition (Visher, 1965). Since the conglomerates in the area studied consist entirely of intraformationally derived siltsone, mudstone and carbonate clasts, the rocks and the weathering processes in the provenance area must have been such as to give only fine, sand-sized and smaller detritus.

E. POINT BAR DEPOSITS.

The sandstone facies of the lower part of the Beaufort Group is considered to have been deposited mainly as alluvial point bars. This is indicated by the upward-fining cycles (Plate 24) which were found to be common in the study area. The sequence of sedimentary structures, starting at the base of the sandstone units with trough cross-bedding and horizontal-bedding, overlain by ripple cross-lamination, showing unidirectional palaeotransport directions, is typical of the point bar sequence (Visher, 1972).

Complete upward-fining sequences, where found, have thicknesses of the order of 2 to 5 m, which corresponds roughly to the depths of the streams which deposited them (Reineck and Singh, 1973). This indicates that most of the sediment was deposited by smaller streams. The largest trough cross-beds found had set thicknesses of about 1,5 m which indicates, using the relationship given by Allen (1965), that the largest streams had depths of 7 to 15 m. The development of trough cross-bedding, and the general absence of planar cross-bedding, suggests that the streams which deposited the sandstones had relatively high stream

velocities (Allen, 1965).

The horizontally-bedded sandstone subfacies is thought to have been deposited under upper flow-regime conditions (Visher, 1972), where it was found near the base of the point bar sequences. Where the horizontally-bedded and ripple cross-laminated sandstones alternate (in the upper parts of the sandstone units) the shallow water, low-amplitude wave mechanism of McBride *et al.* (1975) may have been operative.

The most convincing evidence for deposition of the sandstones on point bars is the close similarity of the outcrop pattern of some sandstone units to contemporary point bars (see frontispiece). The sandstone units are more resistant to erosion than the surrounding siltstones and mudstones and thus, in areas with flat dips and low relief, may be exposed as to show the depositional pattern.

F. CHANNEL FILL DEPOSITS.

Channel fill deposits result from sedimentation in abandoned river channels. Where abandonment was by chute cut-off (the new channel is cut along one of the swales on the point bar) the channel which is being abandoned gets plugged, mainly by bed load sediment (Allen, 1965). The final filling is with overbank material. Neck cut-off is primarily responsible for the abandonment of well developed meander loops (Allen, 1965). This results in the formation of ox-bow lakes, which are very slowly filled by overbank sedimentation. The resulting deposits are composed of sediment which is similar to that of the flood plain deposits. The channel fill deposits resulting from neck cut-off were not readily recognized in the study area because of the poor outcrop of the argillaceous rocks.

G. NATURAL LEVEE DEPOSITS.

The natural levees which commonly border meandering streams

are sinuous ribbon-like deposits of triangular cross-section (Allen, 1965). The levee has its maximum elevation near the stream channel, from which it slopes gently towards the flood basin. They are best developed on the concave river bank. On the convex side, levees are often gradational with the upper point bar deposits (Reineck and Singh, 1973). Deposition on the levees takes place during floods (Allen, 1963). The coarser sediment is deposited nearest the channel, while the finer is carried further into the flood basin. As the flood recedes, finer sediment is deposited on the levee. During lower river stages the levee is no longer inundated, and may support vegetation.

One of the most characteristic features of levee deposits is the small-scale vertical alternation of coarser and finer sediments. Sandy and silty layers, a few decimetres thick, alternate with muddy layers only a few centimetres thick (Reineck and Singh, 1973). Primary sedimentary structures consist of small-ripple cross-lamination, climbing-ripple lamination and parallel lamination. The formation of soil horizons within the deposits causes some homogenization and mottling of the sediments (Allen, 1965). Suncracks may be developed in the more clayey beds.

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. This was supported by the presence of the primary sedimentary structures commonly associated with levees, as well as occasional colour-mottling. The three-dimensional geometry of the deposits could not be established.

H. CREVASSE-SPLAY DEPOSITS.

At high river stages some of the flood water leaves the

channels through isolated breaks, termed crevasses, in the natural levees. They are most common on the concave banks of meandering streams. The crevasse channels are commonly only a few decimetres to a few metres wide (Reineck and Singh, 1973). The resulting crevasse-splay deposits are tongue shaped, and taper off into the flood basin. They commonly have thicknesses of up to a few metres. The sediments constituting the crevasse-splay deposits are generally somewhat coarser than those of the corresponding levees. The most common sedimentary structures of these deposits are small-scale cross-bedding, climbing ripple-lamination and some horizontal lamination. Channel-fill cross-bedding may be developed locally. In ancient deposits, they are best recognized as sandy channels within finer grained natural levee deposits (Reineck and Singh, 1973).

Small coarser grained channels, which were thought to be crevasse-splay deposits, were commonly found within the sediments interpreted as natural levee deposits in the study area. These ranged from small, broad, U-shaped channels filled with apparently homogeneous siltstone (Plate 17) to larger, channel shaped, deposits with widths of 8 to 10 m and depths of 1 to 2 m. The larger deposits usually showed the channel-fill type cross-bedding of Reineck and Singh (1973). The channel fill was commonly upward-fining, from very fine sandstone to mudstone.

I. FLOOD BASIN DEPOSITS.

The lowest lying portion of a river's flood plain is the flood basin. The edges of the flood basins are generally valley walls or existing alluvial ridges. The basins are thus generally elongated parallel to the active stream. They are best developed in the lowest reaches of the rivers. During flood stages, water flows over the levees and through the crevasses into the flood basins. The coarser sediment is deposited on the natural levees and as

crevasse-splay deposits,while the suspended fines settle in the flood basins (Allen, 1965). The flood basin deposits are composed of uniform finely-laminated muds, with some sandy and silty intercalations. Desiccation features, mottling due to soil forming processes and organic debris are common in flood basin deposits. In humid regions, peat bogs may develop, while under more arid conditions, carbonate nodules, iron concretions and alkali salts may form (Reineck and Singh, 1973).

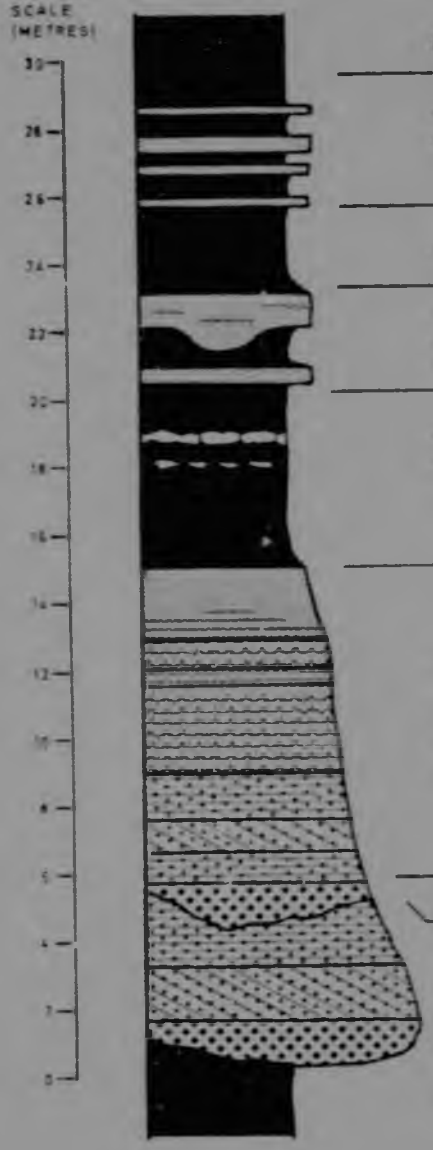
The rocks of the mudstone facies,which predominated the stratigraphic section in the study area,were considered to be flood basin deposits. Mud-cracks were only very rarely seen in the mudstones,but this may have been the result of the poor exposure of these rocks. Colour-mottling, generally in browns and reds,is a common feature of the mudstones studied.

Carbonate nodules were often found within the mudstones. They are generally ellipsoidal bodies of impure limestone with diameters of 10 to 30 cm. Occasionally, septarian nodules (nodules with radiating cracks which get thicker towards the centre) were seen. Calcareous nodules were described as being a common feature in the upper parts of fluvial upward-fining cycles by Pettijohn (1975). A cross-section of what appeared to be a continuous limestone band showed concentric structures with dimensions similar to those of the concretions, suggesting that the limestone bands formed by concretionary processes. The abundance of carbonate nodules,and the general absence of organic layers, indicate that the sediments accumulated under fairly arid conditions. Keyser (1966) described gypsum and barite crystals having a "desert rose" shape, from the lower part of the Beaufort Group, which are indicative of arid conditions during sedimentation.

The upward-coarsening cycles were considered by Turner (1975) to have formed by the accumulation of muds in local

FIG 11

GENERERALIZED DEPOSITIONAL SEQUENCE FOR THE LOWER PART OF THE BEAUFORT GROUP



FACIES DESCRIPTION	INTERPRETATION
ALTERNATING MUDSTONE AND SILTSTONE BEDS. SOME SILTSTONES SHOW CLIMBING-RIPPLE LAMINATION	BANK DEPOSIT PROBABLY FORMED ON A LEVEE
MASSIVELY BEDDED MUDSTONE AND SILTSTONE	FLOOD BASIN OR POSSIBLY CHANNEL FILL DEPOSIT
INTERBEDDED SILTSTONE, SANDY SILTSTONE AND MUDSTONE. SILTSTONE UNITS OFTEN WITH EROSIONAL LOWER SURFACES. SILTSTONES SOMETIMES RIPPLE CROSS-LAMINATED	BANK DEPOSIT. SCOURED SURFACES INDICATE CREVASSE-SPLAYS
MASSIVELY BEDDED MUDSTONE, SHOWING COLOUR MOTTLING AND CONTAINING CALCAREOUS CONCRETIONS	FLOOD BASIN DEPOSIT. OCCASIONAL EXPOSURE FLUCTUATING GROUND WATER LEVEL
FINE-GRAINED SANDSTONE WITH TROUGH CROSS-BEDDING AND HORIZONTAL BEDDING SHOWING PRIMARY CURRENT LINEATIONS, OVERLAIN BY RIPPLE CROSS-LAMINATED VERY FINE GRAINED SANDSTONE. HORIZONTALLY-BEDDED SANDSTONE IS COMMONLY INTERBEDDED WITH THE RIPPLE CROSS LAMINATED SANDSTONE, WHICH FINES UPWARDS INTO SILTSTONE	COMPLETE POINT BAR SEQUENCE FORMED BY LATERAL ACCRETION IN A MEANDERING CHANNEL
EROSIONAL SURFACE, OVERLAIN BY INTRAFORMATIONAL CONGLOMERATE	RIVER CHANNEL CUT ON EARLIER POINT BAR SEQUENCE. LAG CONGLOMERATE
FINE-GRAINED, TROUGH CROSS-BEDDED AND HORIZONTALLY-BEDDED SANDSTONE	TRUNCATED POINT BAR SEQUENCE
EROSIONAL SURFACE OVERLAIN BY A DISCONTINUOUS INTRAFORMATIONAL CONGLOMERATE	EROSION ON CUT BANK OF CHANNEL. LAG DEPOSIT
MASSIVELY BEDDED MUDSTONE AND SILTSTONE	FLOOD BASIN DEPOSIT

swamps or lagoons by vertical accretion This was followed by the gradual silting up of the depositional site by currents competent enough to cause small-scale rippling. Incursions into the flood basin of channel or overspill material, or the breaching of the channels by crevasse-splays, was thought to be the mechanism.

J. SUMMARY.

A generalized depositional sequence for the sediments of the Beaufort Group in the study, area as found from the Markov analysis and from field relationships, is given in Figure 11. An interpretation of the major units of the generalized sequence, in terms of a fluvial meandering model, is given in the figure.

VII. PALAEOCURRENT ANALYSIS OF SOME BEAUFORT GROUP SANDSTONES.

A. INTRODUCTION.

A palaeocurrent analysis was made to determine the direction of sediment transport during Beaufort times in the study area. Any major changes in palaeotransport direction found within the stratigraphic interval studied, would be useful in understanding the depositional history of the sediments. The possibility of more than one dispersion system having been operative at a given time was investigated. An insight into the relationship between palaeocurrent directions and the directions of elongation of the sandstone units (and thus of the uranium orebodies) should be useful in exploration.

Directional structures were measured on a regional grid covering the entire thesis area to determine the regional palaeotransport direction, any major changes in the palaeotransport directions, and the nature of the dispersion system operating during deposition. A more detailed study was made of a few selected sandstone units to establish the usefulness of palaeocurrent studies in predicting sandstone geometry.

B. FIELD PROCEDURE.

The most common sedimentary structures in the sandstones of the lower part of the Beaufort Group are primary current lineations, rib-and-furrow structures (Pettijohn, 1957) and trough cross-bedding. In areas where all these structures were present and were well exposed, trough cross-beds were measured in preference to rib-and-furrow structures. Primary current lineations were only measured where the other structures were not common.

The azimuths of the trough axes were measured for the cross-bed sets and rib-and-furrow structures. Measurements of primary current lineations were only used where they occurred together with trough cross-beds or rib-and-furrow structures. At a given outcrop, the lineations were assigned the sense found from the other directional structures measured.

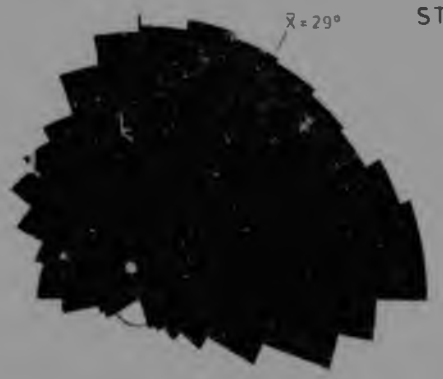
The sediments in the study area generally dip at less than 5 degrees. It was thus not necessary to correct the data for tectonic tilt (Potter and Pettijohn, 1963). Areas with dips of more than 5 degrees were avoided in the palaeocurrent study.

For the regional palaeocurrent study, the entire thesis area was divided into blocks, each 25 square km in area. In each square (except those covered by the detailed study) three outcrops of sandstone were selected from aerial photographs. Where possible, the outcrops were chosen so as to lie along public roads, and to be reasonably spread across the square. At each outcrop 5 to 10 directional structures were measured. The results were plotted on to a rose diagram for each outcrop, which was used to give an indication as to whether enough measurements had been made at that outcrop.

The two areas selected for detailed palaeocurrent studies were divided into one kilometre squares. Traverses were made across each square to take measurements on most of the outcropping sandstone. Fifteen or more directional structures were measured in each square. Where more than one sandstone unit outcropped within a square, structures were measured in each unit, and the results recorded separately.

FIG 12

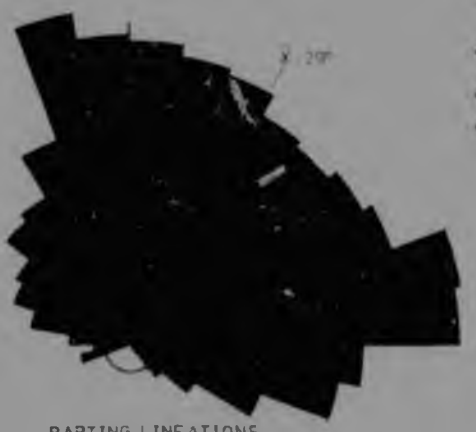
CURRENT ROSE DIAGRAMS OF THE DIFFERENT DIRECTIONAL STRUCTURES



TOTAL DIRECTIONAL STRUCTURES
(N=5896)



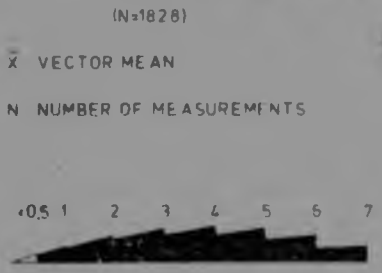
TROUGH AXES
(N=1808)



PARTING LINEATIONS
(N=1828)

X̄ VECTOR MEAN

N NUMBER OF MEASUREMENTS



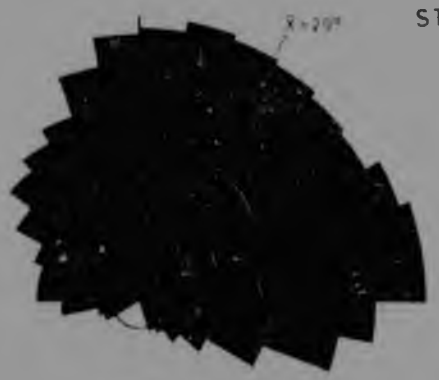
PERCENTAGE IN CLASS INTERVAL



RIB AND FURROW
(N=2260)

FIG 12

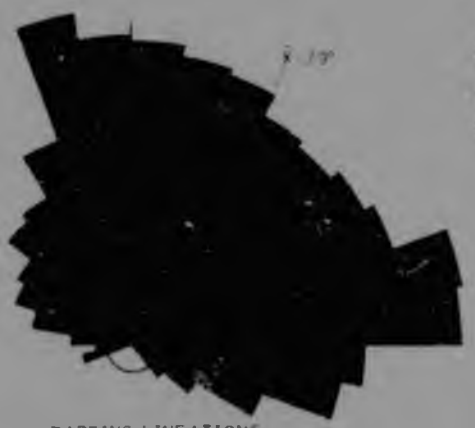
CURRENT ROSE DIAGRAMS OF THE DIFFERENT DIRECTIONAL STRUCTURES



TOTAL DIRECTIONAL STRUCTURES
(N=5408)



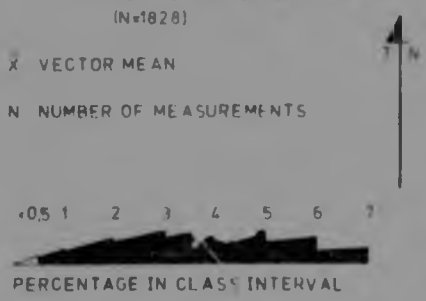
TROUGH AXES
(N=1808)



PARTING LINEATIONS
(N=1828)

$\bar{X}$ VECTOR MEAN

N NUMBER OF MEASUREMENTS



PERCENTAGE IN CLASS INTERVAL



RIB AND FURROW
(N=2260)

C. TREATMENT AND PRESENTATION OF DATA.

Current rose diagrams were constructed for all the trough cross-beds, rib-and-furrow structures, primary current lineations and a combination of these structures (Figure 12). Vector means and consistency ratios were calculated for the data grouped into 10 degree intervals, using the procedure given by Potter and Pettijohn (1963). The results are given in Table 6.

The vector means, as determined from the different structures all fall within 12^{o} of each other. From the current rose diagrams (Figure 12) it can be seen that, although the spread of the measurements is large, the distribution about the vector means for the different structures is similar. This is also shown by the similarity of the consistency ratios for all the structures (Table 6).

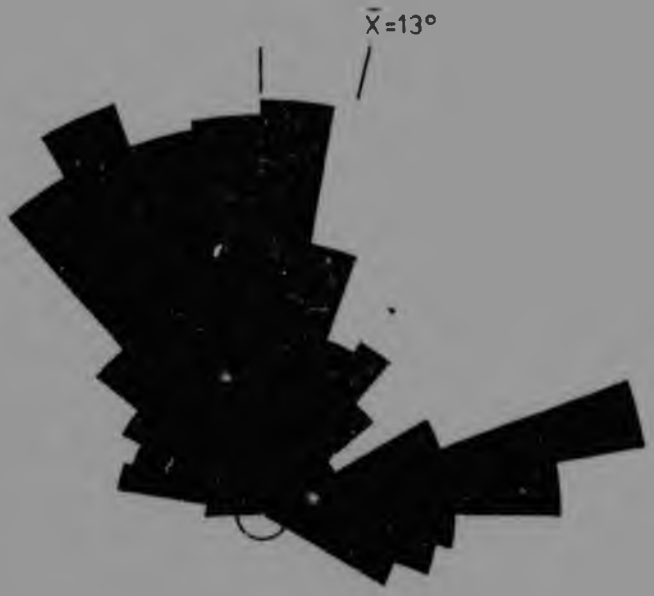
Table 6: Vector Means and Consistency Ratios of all the Directional Structures Measured.

Structure	No. of Measurements.	Vector Mean (Bearing, Degrees)	Consistency Ratio (Percent)
Trough Cross-beds	1808	023	54
Rib-and-Furrow	2260	035	48
Parting Lineations	1828	029	54
Total	5896	029	52

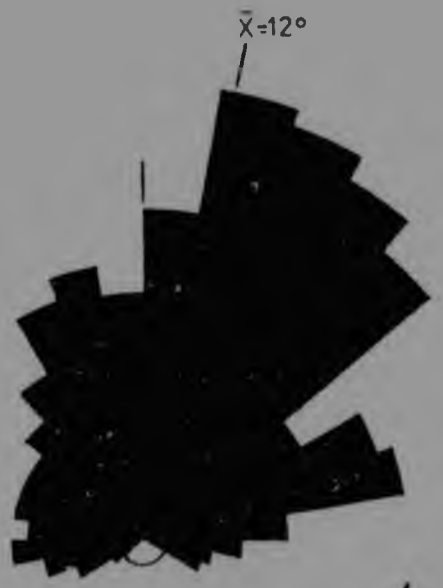
To determine if there was any significant change in palaeotransport direction during the deposition of the sediments in the study area, data from sandstones occurring in the

FIG. 13

CURRENT ROSE DIAGRAMS FOR THE "A3","A2","A" AND "C" SANDSTONES



"A3" SANDSTONE
N=407
CR=61



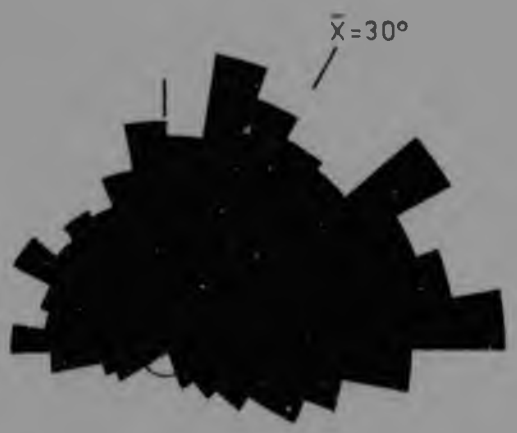
"A2" SANDSTONE
N=520
CR=62

T N

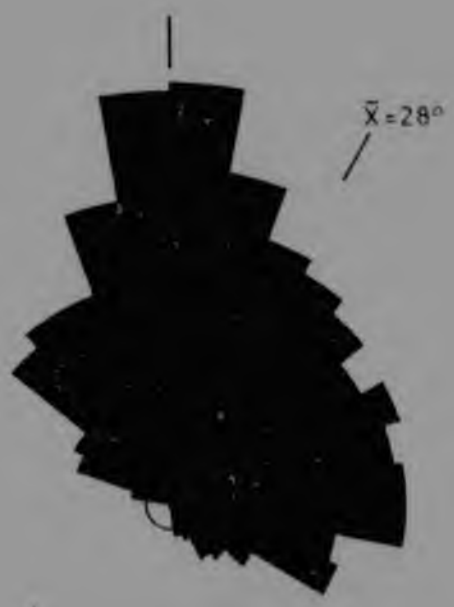
X̄ VECTOR MEAN
N NUMBER OF MEASUREMENTS
CR CONSISTEN' ' RATIO(%)



PERCENTAGE IN CLASS INTERVAL



"C" SANDSTONE
N=1935
CR=47



'A" SANDSTONE
N=903
CR=58

upper half of the stratigraphic section investigated (above the "B" sandstone) and the "B" and lower sandstones were grouped separately, and the vector means and consistency ratios calculated. Table 7 gives the results.

Table 7: Vector Means and Consistency Ratios for the Sandstones in the Upper and Lower Portions of the Stratigraphic Section Studied.

Structure	No. of Measurements.		Vector Mean (Bearing, Degrees)		Consistency Ratio (Percent)	
	Upper	Lower	Upper	Lower	Upper	Lower
Trough Cross-beds	1162	646	020	024	61	46
Rib-and-Furrow	981	1279	029	035	48	45
Parting Lineations	798	1030	017	037	54	51
Total	2941	2955	021	033	56	47

To gain some insight into the orientations of the directional structures measured in the single sandstone units, current rose diagrams (Figure 13) were constructed for the "A3", "A2", "A" and "C" sandstones (Figures 14 and 15 for locations). All the structures measured in each sandstone unit were grouped into 10 degree intervals. Vector means and consistency ratios were calculated for each sandstone unit (Figure 13).

In the construction of the palaeocurrent maps, the data from the various directional structures were combined. No weighting for the different structures was used. The combination of the structures was useful because a significant number of measurements could generally be made, even at outcrops where only a few structures were preserved. The measurements made within each grid square were combined in different ways for the regional and detailed palaeocurrent studies to obtain mean palaeotransport directions for the grid squares.

For the regional study, vector means were calculated for the data obtained at each outcrop. A vector mean and consistency ratio for each grid square was then calculated using the means obtained for the individual outcrops. The resultant direction was then plotted as an arrow at the centre of the block (Map 1). The length of the arrow is proportional to the consistency ratio. Each arrow represents about 15 to 20 measurements. This method of obtaining vector means was used in preference to one in which all the structures measured at the different outcrops within a given square are used to calculate the vector mean directly. The latter method would have weighted the vector mean towards the direction obtained for the outcrop within the grid square at which the largest number of measurements was made. In the areas covered by the more detailed study, each square kilometer block was treated as an outcrop, and a vector mean and consistency ratio calculated and plotted for the 25 square kilometer block as outlined. Areas where no palaeocurrent arrows are shown on Map 1 either contained no sandstone outcrop or were inaccessible to the writer.

A moving average technique was used to calculate the average palaeocurrent directions over the sandstone units studied in detail. The moving average technique was used because it provides a simple method for smoothing results, which facilitates the interpretation of more regional trends. A vector mean and consistency ratio were calculated for all the individual directional measurements within a 4 square km block of a given sandstone. The resultant directions were plotted as arrows at the centres of the blocks, the lengths of the arrows being proportional to their consistency ratios. The progression used to calculate the moving average was one square kilometer, (i.e. the grid squares used for the measurement of the directional structures). The results are given in Figures 14 and 15.

FIG. 14

PALAEOCURRENT MAP OF THE 'A' AND OVERLYING SANDSTONES

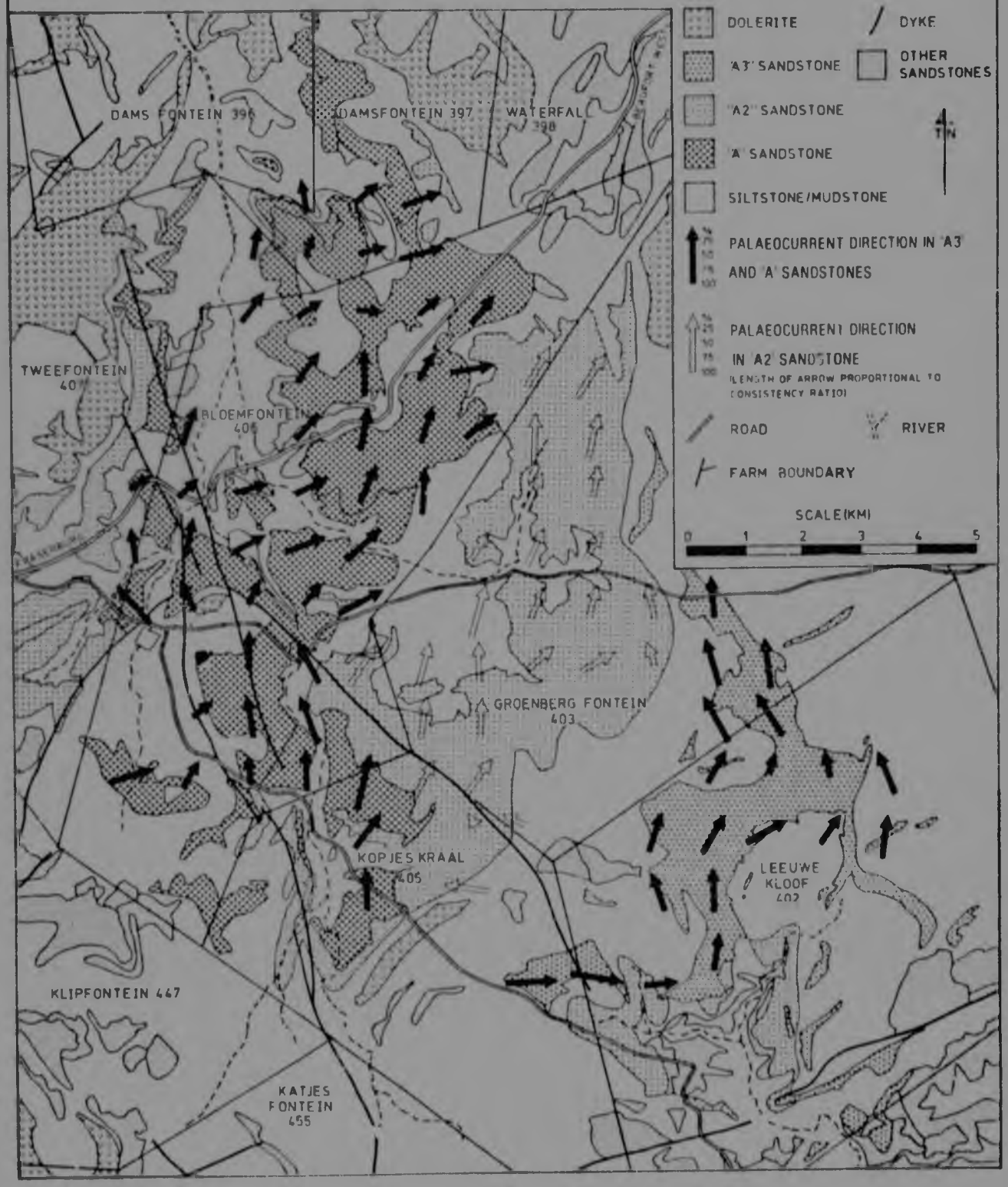
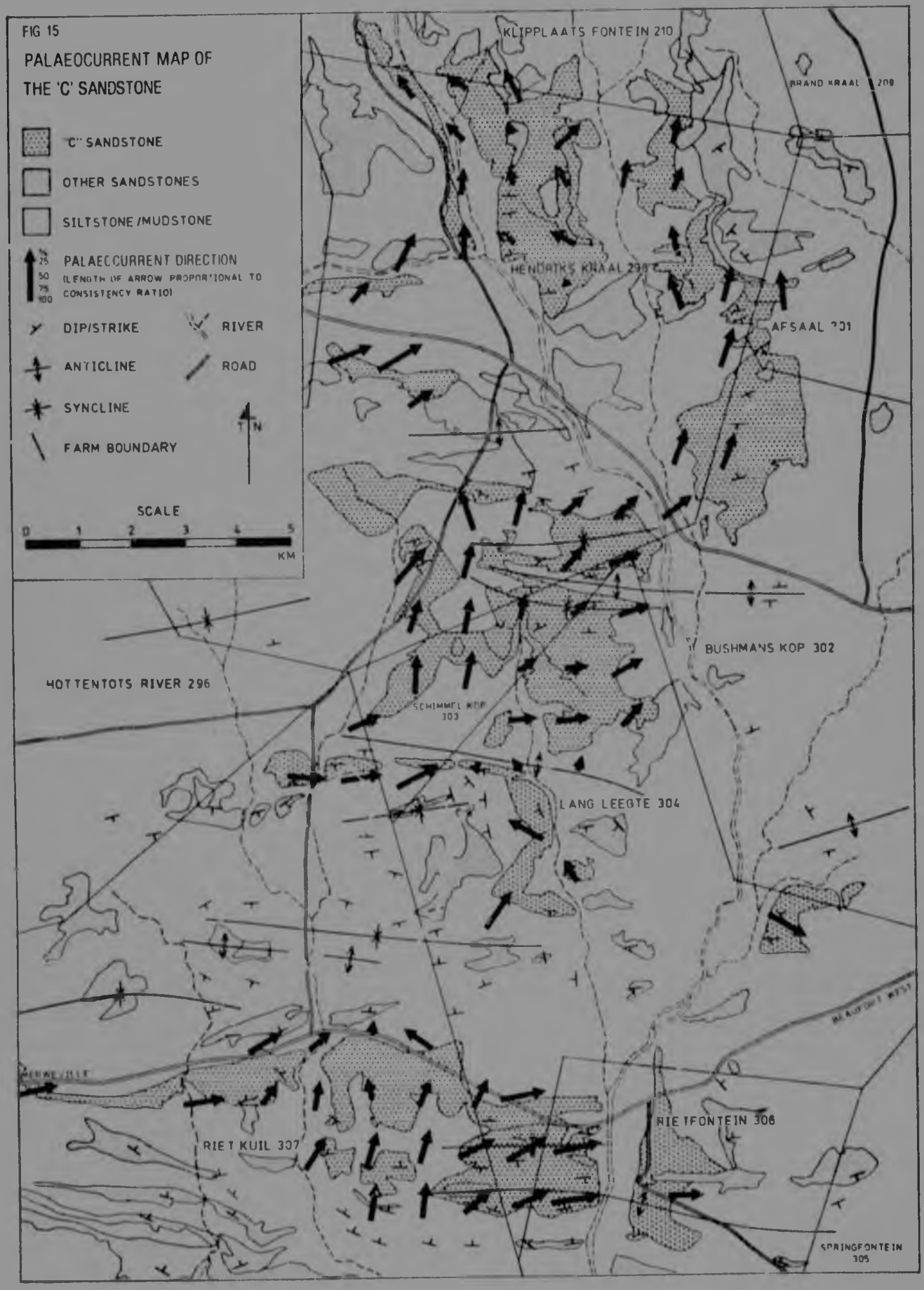


FIG 15

PALAEOCURRENT MAP OF THE 'C' SANDSTONE



5. RESULTS AND CONCLUSIONS.

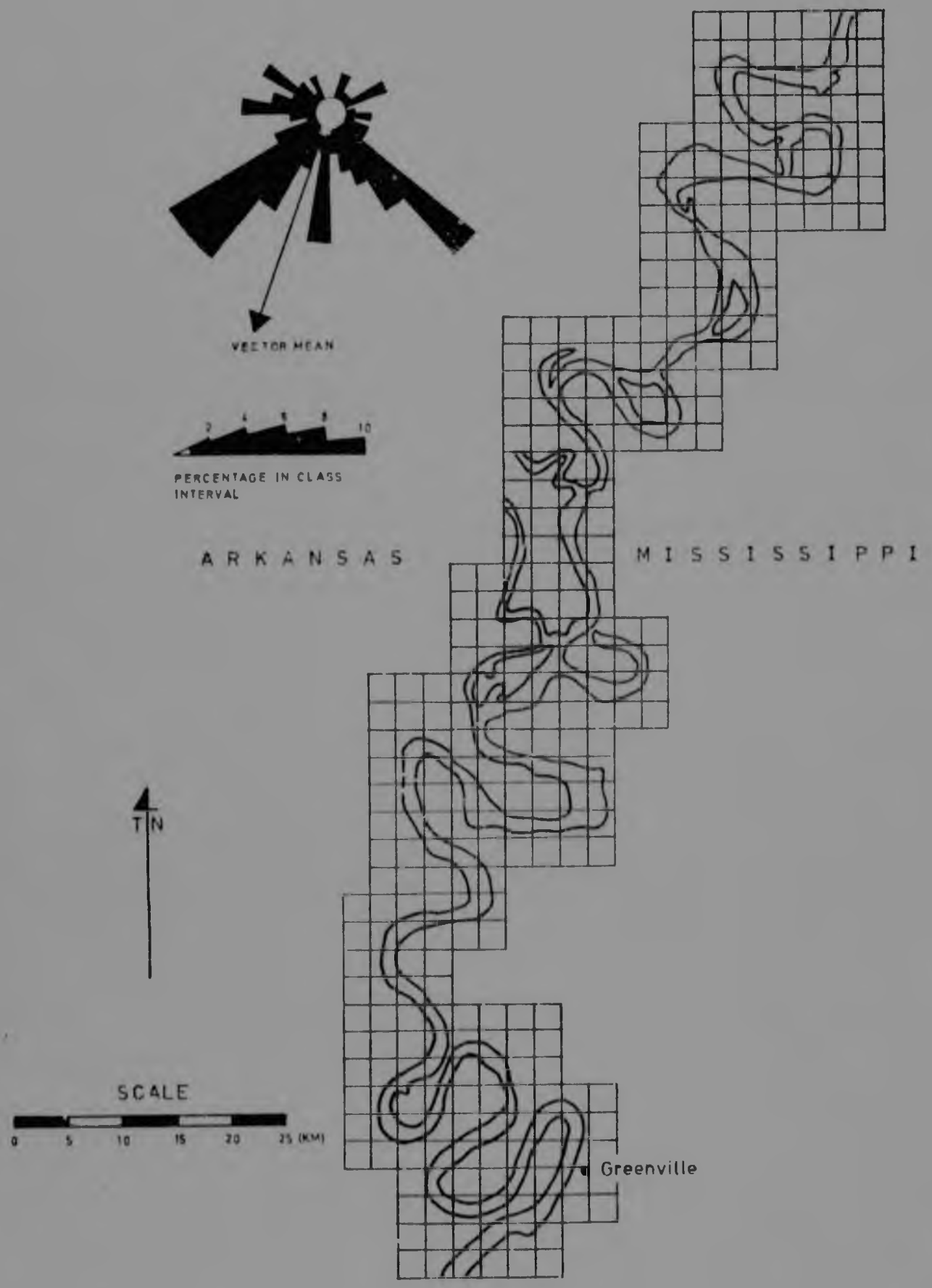
In sediments deposited by fluvial processes, the mean palaeotransport direction will coincide with the palaeoslope. The consistent northerly trend in the regional palaeocurrent directions as shown on Figure 12 and Map 1, indicates that a northerly palaeoslope existed during the deposition of the entire stratigraphic interval exposed in the area. This corroborates the findings of Theron (1973), who showed, on a regional scale, that a northerly palaeoslope persisted during the deposition of the entire Beaufort Group. The current rose diagrams for the whole area, and the vector mean calculated for all the measurements made, indicate that the overall sediment transport direction was about N30°E.

No major changes of sediment transport direction were observed within the stratigraphic interval. The vector means calculated for the measurements made in the lower half of the stratigraphic interval and the upper half (Table 7) indicate that there may have been a small change in palaeoslope from N33°E to N21°E going up the section. The wide scatter of readings as shown on the rose diagrams, and indicated by the low consistency ratios, suggest that this small change in direction is not of any significance.

The current rose diagrams for all the structures measured show that the transport direction was essentially unimodal despite the scatter of readings over some 180 degrees. The slight bimodality (transport towards the north and east) indicated by some of the current rose diagrams is not thought to have resulted from deposition by two dispersion systems, but rather from deposition by strongly meandering streams. This is borne out to some extent by the bimodal distribution of palaeocurrent directions within some of the individual sandstone units of the detailed study (Figure 13).

FIG 16

CHANNEL DIRECTIONS OF PART OF THE MISSISSIPPI RIVER



To gain some insight into the possible distribution of current directions in a meandering stream, a grid with lines spaced at 2,5 km intervals was placed over a map of part of the Mississippi River (Figure 16). An average flow direction was estimated for each grid square. Some 126 flow directions were obtained and plotted on to a current rose diagram. The rose diagram (Figure 16) shows a bimodal distribution, which is comparable to that obtained from the palaeocurrent analysis of the lower part of the Beaufort Group. A vector mean of the flow direction and a consistency ratio were calculated for the data grouped into 10 degree intervals. The consistency ratio of 45 percent obtained for the channel orientations of part of the Mississippi River is similar to those obtained for the palaeocurrent directions in the area studied. These factors confirm that the sediments of the lower part of the Beaufort Group were deposited by meandering streams. A single dispersion system for the entire stratigraphic interval is indicated.

Moving average palaeocurrent maps for the "A" and overlying "A2" and "A3" sandstones, and the "C" sandstone were drawn (Figures 14 and 15 respectively). The outcrop pattern and structure were determined from aerial photographs. The sandstones are more resistant to weathering than the surrounding siltstones and mudstones. Consequently, they often form low mesas which have an overall shape which approximates that of the original sandstone body. A good example is the "A3" sandstone of Figure 14. The moving averages of the palaeocurrent direction measurements are shown in the figures to follow the outcrop patterns of the sandstone bodies.

The consistency ratios, determined for the palaeocurrent directions in Figures 14 and 15, appear to be largest along the edges of the sandstone bodies. The lowest consistency ratios were found in areas of maximum sandstone development (as seen in mesa edges and determined from drill-hole data).

This may reflect the deposition of the thicker sandstones over a relatively long period of time in an actively meandering stream. The thicker parts of the sandstone units have a complex internal morphology. They generally consist of several point bar sequences which overlie and truncate each other. Since each point bar sequence results from the deposition in a channel as it migrates across its meander belt,and the streams were strongly meandering, it is likely that the transport directions for the individual sequences preserved in the composite sandstones would vary markedly. The thinner units were probably deposited as single point bar sequences during times when the streams may have migrated across their flood plains, and the channels were not localized for any considerable period of time. The transport directions would have tended to be more uniform in these areas.

Palaeocurrent measurements should be useful in predicting the subsurface continuation of sandstone bodies. The correlation between the palaeotransport direction and sandstone channel geometry is shown by the isopach map of part of the "C" sandstone unit (Figure 10). The palaeocurrent directions shown on the figure are the vector means for all the measurements made within one kilometer squares.

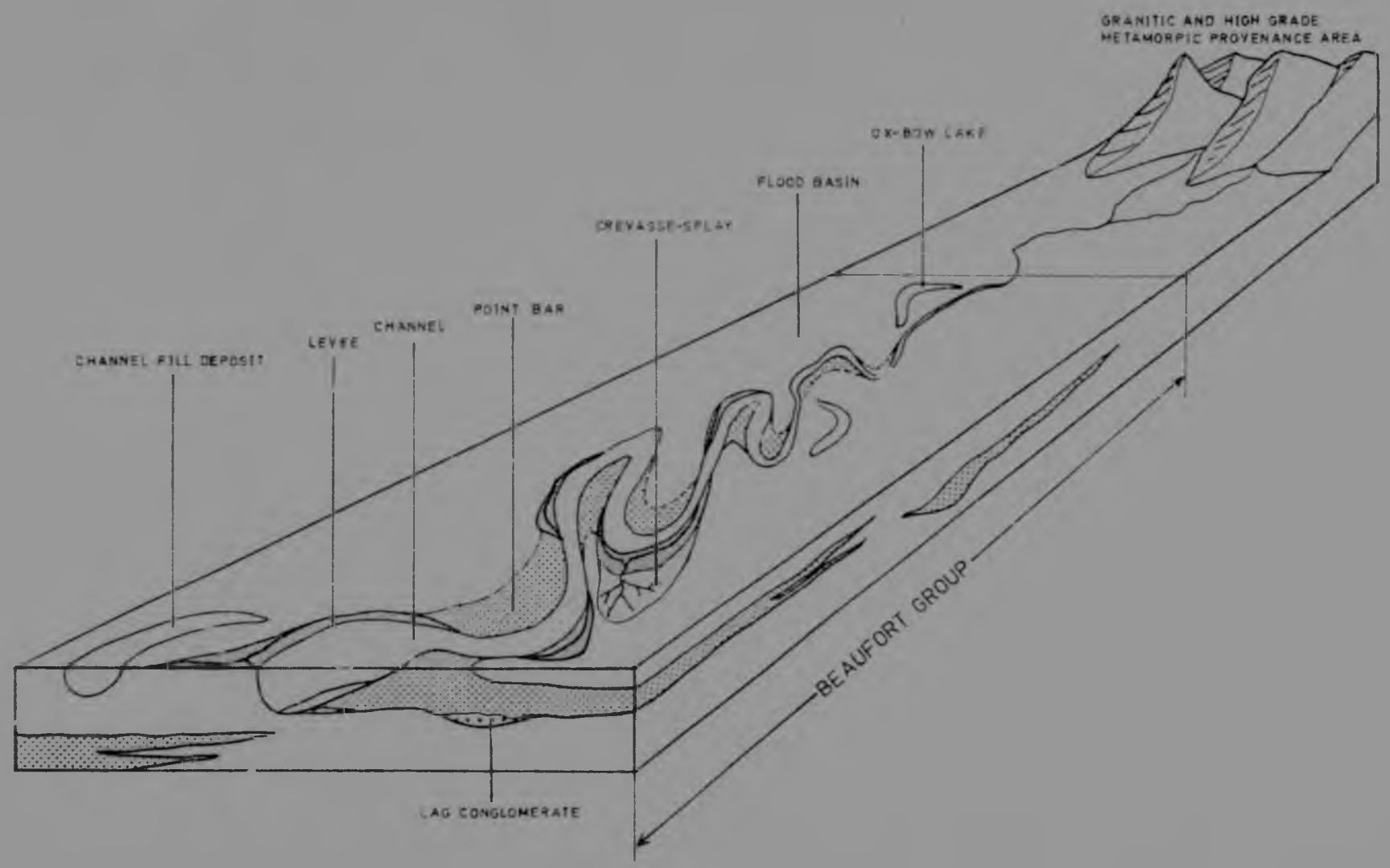
E. PALAEOGEOGRAPHICAL RECONSTRUCTION.

The palaeocurrent analysis of the sandstones showed that the sediments of the entire stratigraphic interval studied were derived from a south-westerly provenance area. The highland area probably consisted of high grade metamorphic and acid igneous rocks (Theron, 1973). Igneous activity in the provenance area is indicated by the presence of rock fragments of a probable volcanic origin in the sandstones (Martini, 1974).

The quartz to feldspar ratio of the sediments studied was found to be 1,2:1. They thus have a low maturity

FIG.17

DIAGRAMMATIC GEOMORPHOLOGICAL SETTING DURING THE DEPOSITION OF THE BEAUFORT GROUP



index (Pettijohn, 1957). Immature sediments generally form under conditions of rapid erosion and associated limited chemical weathering. Fluvial sandstones consisting essentially of immature components form in areas which have a high relief and mature topography or in areas which have a low rainfall and low temperatures (or a combination of the above conditions). Immature sandstones containing numerous bits of carbonized wood reflect high relief and mature topography conditions, since cold, arid climates do not favour abundant plant growth (Pettijohn 1957). Areas of very high relief would tend to shed coarse-grained detritus. The more proximal facies of sedimentation in which the coarser detritus would have been deposited, are not preserved in the lower part of the Beaufort Group.

The sediments of the area studied were probably deposited on a very large, flat, flood plain by meandering streams (Figure 17). The streams were thought to best fit the strongly meandering model proposed by Allen (1965). The meander belts of the streams were narrow compared to the width of the flood plain. Stream depths, as indicated by the sedimentary structures, probably ranged from a few metres to about 15 m. During high river stages some water left the main river channels through crevasses in the levees and inundated the flood basins. At lower river stages, the flood basins were partially or completely dry. This is suggested by the presence of calcarecus concretions, colour-mottling and occasional mud cracks and gypsum desert roses (Keyser, 1966) in the overbank deposits. The general aridity is also indicated by the absence of coals and organic rich layers in the stratigraphic record. Evidence for a temperate climate during the deposition of the Beaufort Group, cited by King (1961) was the presence of a "Taeniopteris" flora (as opposed to the "Glossopteris" flora typical of the colder climate during Ecca times) and the abundance of reptilian remains. Arid and temperate climatic conditions

would be expected in the interior of very large landmass (Gondwanaland) at a lattitude of about 45 degrees (Creer, 1965). No basinal (inland sea or marine) facies of the Beaufort Group has been recognized in South Africa. The Ecca Group basin probably regressed northwards during the deposition of the Beaufort Group sediments (Ryan, 1967 and Theron, 1973). Thus argillaceous sediments assigned to the Ecca Group in the northern part of the basin, may be time equivalent of the Beaufort Group in the south. Theron (1973) suggested that the basinal area into which the rivers, that deposited the Beaufort Group drained, was well beyond the present northern limit of the Beaufort basin (possibly in Zambia).

VIII. DISTRIBUTION AND PETROLOGY OF THE URANIUM IN THE LOWER PART OF THE BEAUFORT GROUP.

A. OUTCROP DESCRIPTIONS.

Uranium occurrences are found throughout most of the area studied. The locations of 37 surface occurrences, found by both ground and airborne radiometric surveys by Union Carbide Exploration Corporation, are shown on the geological map of the area (Map 1). Since only portions of the area shown on the map were investigated in detail, the existence of many more uranium occurrences is postulated. The mineralization is generally found in the thickest portions of the sandstone lenses. Where the sandstones are thickest, they characteristically contain only thin, discontinuous, siltstone and mudstone intercalations. Away from the thickened zones the sandstones interfinger with the argillaceous rocks. The uranium is generally found in the lower halves of the sandstone units, often near to where they interfinger with the argillaceous rocks.

The mineralized outcrops vary greatly in size. The smallest consist of a single pod of only a few metres in length, e.g. mineralized outcrop number 11 (Map 1), while the largest are discontinuous bodies which may be traced for distances of up to about 1 km,e.g. number 24 of Map 1. The individual mineralized bands range in thickness from a few centimetres to a maximum of about 5 m.

The uranium-mineralized sandstones are generally calcareous, and weather to a dark grey or black colour. Some of them have a bleached, white to brownish or yellowish colour. The different colours of the mineralized sandstones are thought to result from the variation in the

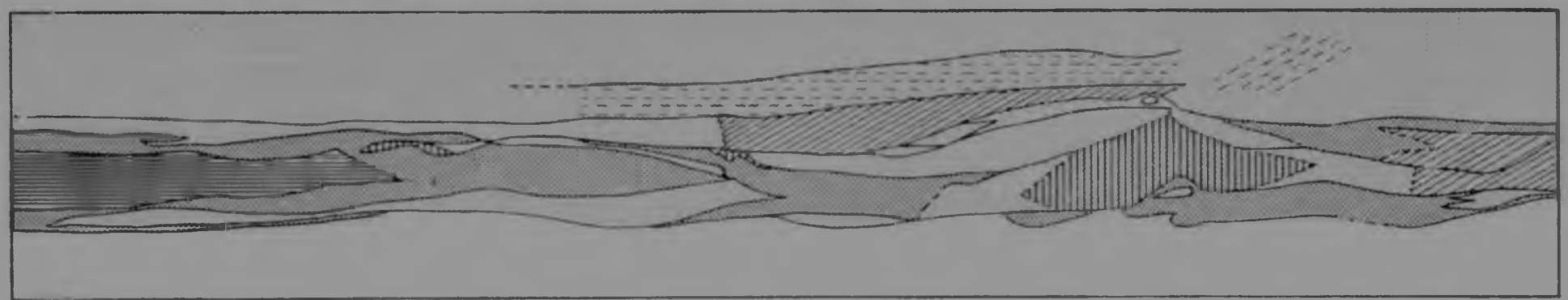
degree of surface weathering. The darker-coloured mineralized outcrops are more calcareous and less strongly weathered than the lighter-coloured ones. This suggests that the calcite cement rendered the outcrops less susceptible to surface weathering. The sandstones, both mineralized and unmineralized, found in the northern part of the area studied (above the escarpment) are more strongly weathered than those occurring below the escarpment. This may be the result of more effective chemical weathering (caused by slightly higher rainfall) and a slower rate of erosion (suggested by lower stream gradients) in the area north of the escarpment. The mineralized sandstones outcropping in the south-western portion of the study area appear to be more strongly oxidized than those in the south-east. The two distinct types of uranium occurrence, a primary and a secondary, described by Moon (1974) were not recognized during the course of this investigation. The morphological similarity between the two types, and the existence of intermediate types, suggests that the one type is simply a highly oxidized form of the other.

The location of the uranium in the sediments is best determined by radiometric methods, because the primary mineralization is not generally visible. Bright green and yellow secondary uranium minerals are found at the mineralized outcrops. They are most commonly found along bedding planes and joints in the sandstone, as well as encrustations on coalified plant remains. Carbonaceous debris, ranging from large logs to twigs and leaves to very fine platy fragments, is commonly associated with the mineralization.

Sandstones of the horizontally-bedded, trough cross-bedded and ripple cross-laminated facies were found to be mineralized. Occasionally, mineralized intraformational conglomerates were encountered.

FIG. 18

CROSS-SECTION OF MINERALIZED OUTCROP NO.3 BLOEMFONTEIN, 406



KEY

- CONGLOMERATE
- FINE SANDSTONE
- VERY FINE SANDSTONE
- SILTSTONE/MUDSTONE
- HORIZONTAL-BEDDED
- CROSS-BEDDED
- URANIUM MINERALIZATION

SCALE

0 1 2 3 4 5 METRES

Detailed maps of portions of the good cross-sectional exposures of the mineralized outcrops numbered 3,4 and 7 on Map 1 were made to illustrate the typical lenticular nature of the mineralization, and its relationship to the sedimentary facies (Figures 18, 19 and 20 respectively). The mineralized zone shown in Figure 18 is found in the basal portion of the sandstone lens, just above the conglomerate. The bedding of the sandstone hosting the largest mineralized zone appears to have been disrupted. This is probably the result of penecontemporaneous deformation. The mineralization is concentrated near the crest of a small intraformational anticline. The sandstone unit, when traced laterally away from the mineralized zone, is seen to be trough cross-bedded.

At the surface, the mineralized sandstone is white with brown and yellow limonite staining. Fresher samples are light grey, and contain black carbonaceous debris. Secondary uranium minerals are visible within the sandstone. The two smaller mineralized zones are similar. Both are closely associated with small mudstone intercalations. The conglomerates, which underlie the mineralized sandstone, consist of carbonate clasts set in a fine sandstone matrix.

The uraniferous lenses shown in Figure 19 are located about 3 m above the base of the sandstone unit which has a total thickness of at least 13 m (the upper contact has been eroded). The mineralized sandstone overlies a siltstone parting which separates a very fine-grained horizontally-bedded sandstone from a fine-grained one. Locally, the siltstone has been reworked into an intraformational conglomerate. The mineralized sandstone contains abundant carbonaceous debris, consisting mainly of large pieces of fossilized leaves. It is pale yellow in colour. The bedding is no longer discernable in the mineralized zone.

FIG 19

CROSS-SECTION OF MINERALIZED OUTCROP NO 4 BLOEMFONTEIN, 406



KEY

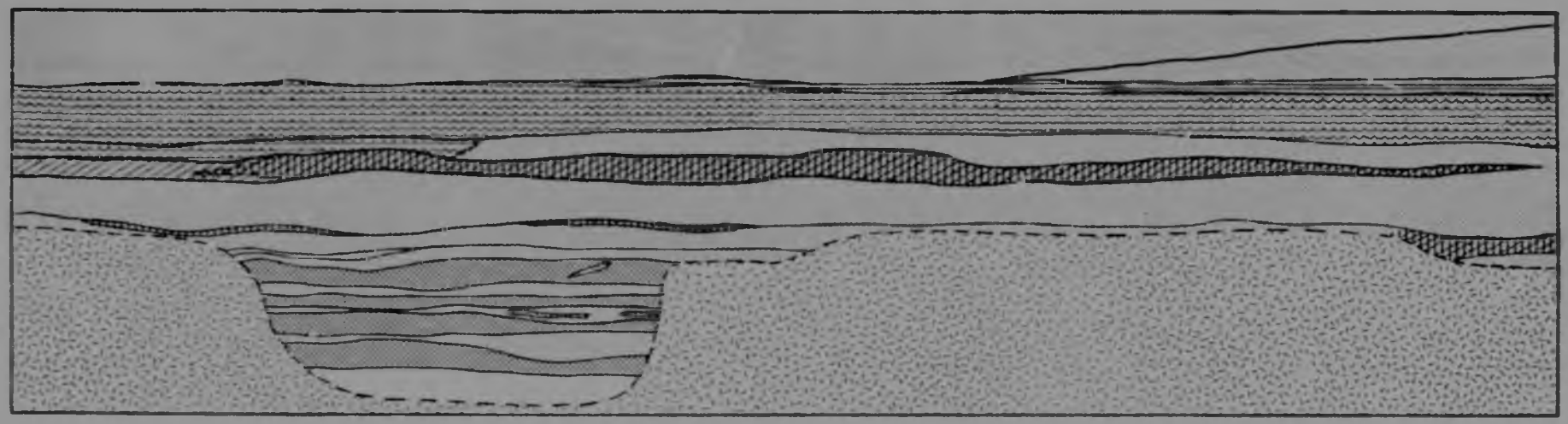
- CONGLOMERATE
- FINE SANDSTONE
- VERY FINE SANDSTONE
- SILTSTONE/MUDSTONE
- HORIZONTAL-BEDDED
- CROSS-BEDDED
- SILTSTONE PARTING
- URANIUM MINERALIZATION

SCALE

0 1 2 3 4 5 METRES

FIG. 20

CROSS-SECTION OF MINERALIZED OUTCROP NO.7 LEEUWE KLOOF, 402



KEY

- CONGLOMERATE
- FINE SANDSTONE
- VERY FINE SANDSTONE
- SILTSTONE/MUDSTONE
- SCREE
- HORIZONTAL-BEDDED
- CROSS-BEDDED
- RIPPLE CROSS-LAMINATED
- URANIUM MINERALIZATION

SCALE

0 1 2 3 4 5 METRES

From Figure 20 it can be seen that the trough cross-bedded sandstone is preferentially mineralized. The mineralized sandstone is a pale-brownish colour, and is more strongly weathered than the apparently massive sandstone surrounding it. The two thin lenses of mineralized sandstone shown are also cross-bedded. In other portions of the sandstone lens at the same locality, the horizontally-bedded facies is preferentially mineralized. No large carbonaceous fragments were found in the mineralized sandstone.

From the descriptions of the mineralized outcrops given above, it appears that there are two major controls on the location of the uranium in the sandstone units. The first is the presence of marked permeability changes, which are found where the sandstone units have mudstone and siltstone intercalations. The silty parting overlain by mineralized sandstone shown in Figure 19 probably acted as a barrier to, and effectively confined, ground water movement. The intraformational conglomerates may have been channel-ways for the movement of ground water. Penecontemporaneous deformation structures may have caused inhomogeneities in the permeability of the sediments by disrupting the bedding. The second major controlling feature appears to be the presence of carbonaceous debris, as seen at the mineralized outcrops 3 and 4 (Map 1). At the mineralized outcrop 7 (Map 1) no carbonaceous material was seen. Fine platy carbonaceous debris, as seen at several other mineralized outcrops, may have been present but later destroyed by oxidation resulting from surface weathering.

B. THE DISTRIBUTION OF URANIUM IN PART OF THE "C" SANDSTONE UNIT.

The logs of some 600 holes drilled by Union Carbide Exploration Corporation to intersect the "C" sandstone unit on the farms Riet Kuil 307 and Lang Leegte 304 were used to construct maps showing the position of the mineralization relative to the thickness of the sandstone (Figure 21),

From Figure 20 it can be seen that the trough cross-bedded sandstone is preferentially mineralized. The mineralized sandstone is a pale-brownish colour, and is more strongly weathered than the apparently massive sandstone surrounding it. The two thin lenses of mineralized sandstone shown are also cross-bedded. In other portions of the sandstone lens at the same locality, the horizontally-bedded facies is preferentially mineralized. No large carbonaceous fragments were found in the mineralized sandstone.

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B. THE DISTRIBUTION OF URANIUM IN PART OF THE "C" SANDSTONE UNIT.

The logs of some 600 holes drilled by Union Carbide Exploration Corporation to intersect the "C" sandstone unit on the farms Riet Kuil 307 and Lang Leegte 304 were used to construct maps showing the position of the mineralization relative to the thickness of the sandstone (Figure 21),

the thickness of the siltstone and mudstone intercalated within the sandstone (Figure 22), and the sandstone to siltstone and mudstone ratio (Figure 23). The drill hole spacing is highly variable, and only a small portion of the areal extent of the "C" sandstone unit has been drilled. Although the picture is incomplete, it illustrates the relationships between the uranium mineralization and the gross lithology. The geological and cadastral features of the area considered are shown in Figure 10.

The sandstone isopach map shows that the mineralization is found within the thickest portions of the sandstone lens. The mineralized sandstones generally have thicknesses in excess of 17 m, however, sandstones of only 10 m are occasionally mineralized. The mineralized zones are generally elongate in the direction of the sandstone thickening. The thickest parts of the sandstone unit, which contain the uranium mineralization, are commonly arcuate. This possibly reflects the meander pattern of the stream which deposited the unit.

The association of the uranium with the cleanest and most continuous portion of the sandstone is shown by the isopach map of the total siltsone and mudstone contained within the "C" sandstone. In the mineralized areas the combined siltstone and mudstone thickness is generally less than 1 m (Figure 22). There is a close correlation between areas of maximum sandstone development, and areas with thin siltstone and mudstone intercalations. This probably reflects the interfingering of the sandstones with the argillaceous rocks towards the edges of a meander belt.

The sandstone to siltstone and mudstone ratio map (Figure 23) again shows that the mineralization is found within the cleanest portions of the sandstone lens. Areas where the ratio is larger than 50:1 are the most favourable.

FIG 21

ISOPACH MAP OF PART OF THE "C" SANDSTONE UNIT SHOWING THE POSITION OF THE MINERALIZATION



FIG. 22

ISOPACH MAP OF THE TOTAL SILTSTONE AND MUDSTONE WITHIN THE "C" SANDSTONE UNIT

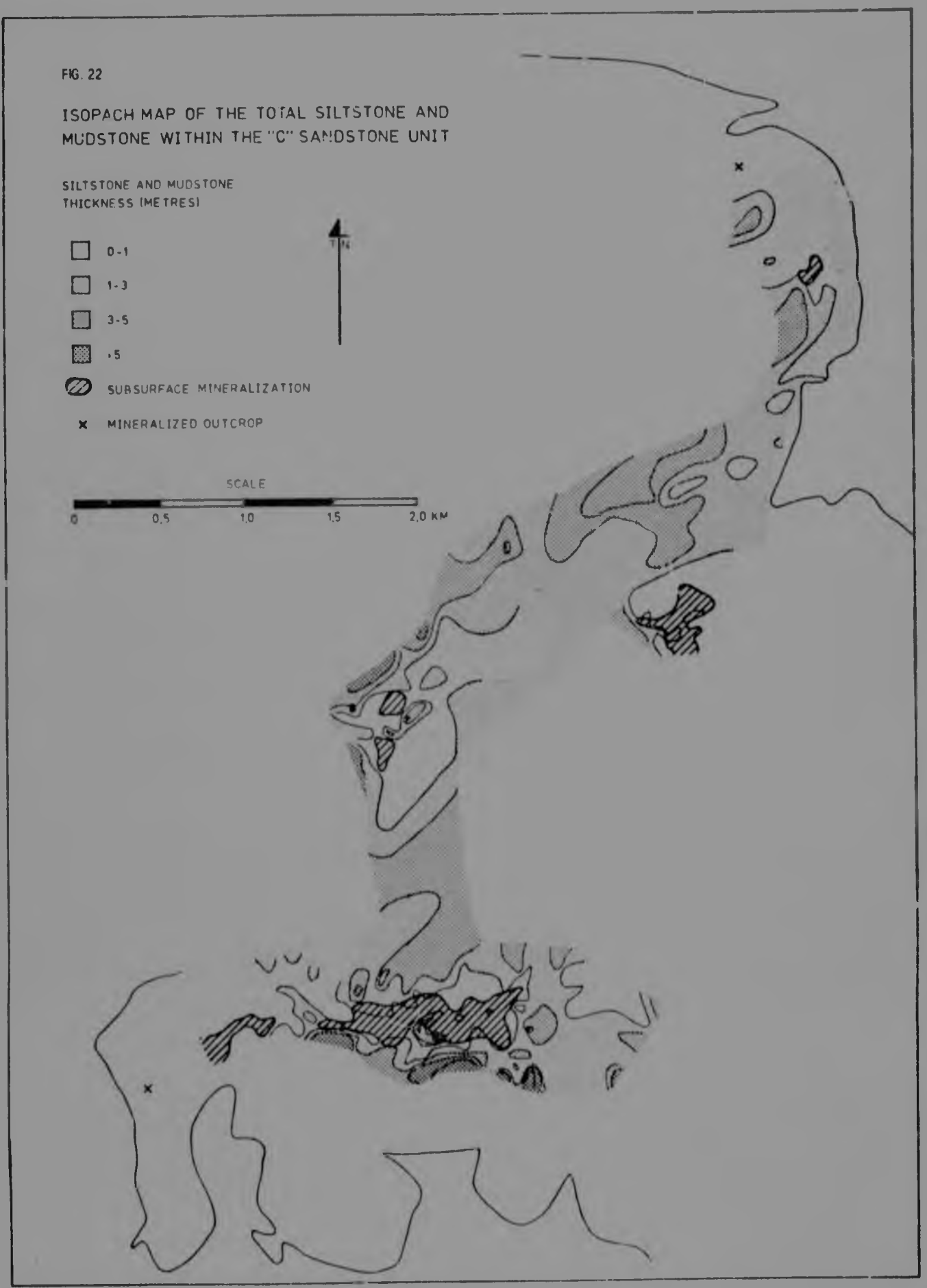


FIG 23

SANDSTONE TO SILTSTONE AND MUDSTONE RATIO MAP OF THE "C" SANDSTONE



The cross-sections of the "C" sandstone (Figure 24) show that the mineralization is most commonly found within the lower third or half of the sandstone unit. The association of the mineralization with the thickest portions of the sandstone, the absence of major siltstone or mudstone intercalations, and hence the areas with the highest sandstone to siltstone and mudstone ratios is also shown by the cross-sections. Small siltstone and mudstone intercalations are commonly found in close proximity to the mineralized zones.

C. ORE PETROLOGY.

1. Petrology of the Host Sandstone.

The textures, grain sizes and compositions of the sandstones hosting the uranium mineralization studied were found to be similar to those of the unmineralized sandstones. The mineralized sandstones were found (by point count analysis) to contain between 5 and 20 percent calcite while the unmineralized ones generally contain less than 5 percent calcite. The mineralized sandstones were found, on average, to contain slightly more matrix.

In thin-section, the feldspar of the mineralized sandstones generally appears more altered. The lower feldspar content of the mineralized sandstone is probably the result of both replacement of the feldspar by calcite, and its alteration to clay minerals. The mineralized sandstones commonly contain small amounts (estimated to constitute up to about 1 percent of the rock) of fine, platy, coalified plant material. Small amounts of sulphide are associated with the uranium minerals. The yellow mottling often found in the mineralized sandstone, is thought to have resulted from the local oxidation of the sulphides to ferric oxides, by both surface weathering and aerated ground waters.

FIG 24

CROSS-SECTIONS OF THE "C" SANDSTONE

(FOR LOCATIONS SEE FIG. 21)

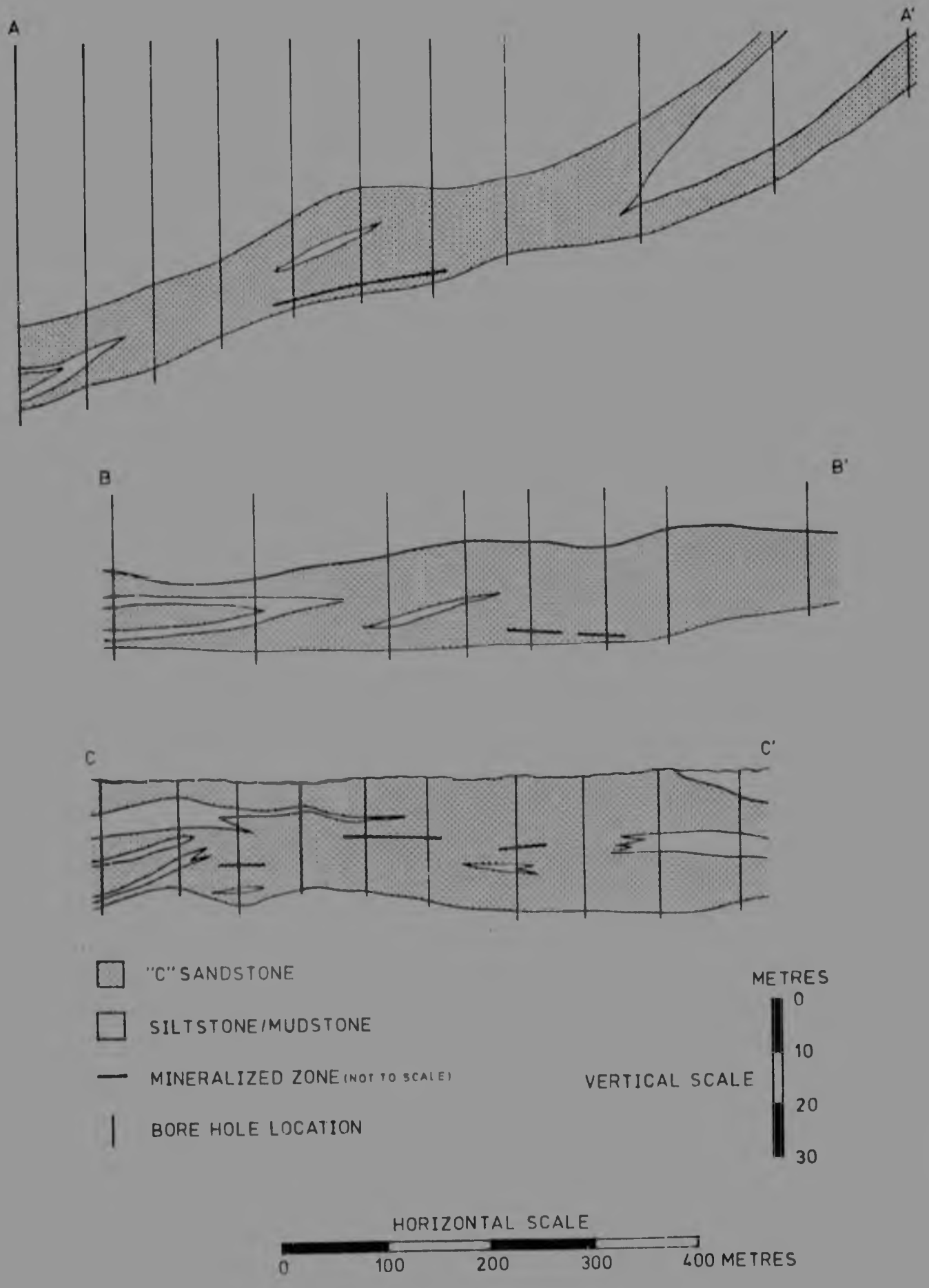




Plate 25: Uraninite-coffinite replacing woody fragment. Note undeformed cell structure (photomicrograph of polished section).



Plate 26: Uraninite-coffinite (light grey) replacing matrix and carbonate cement (photomicrograph of polished section).

2. The Uranium Minerals.

Uraninite (UO_2) and coffinite ($U(SiO_4)_{1-x}(OH)_{4x}$) were identified as the major ore minerals in the area (Union Carbide Research Report, 1972, and Moon, 1974). In polished-section, both minerals are grey and have a moderate to low reflectivity which varies considerably from grain to grain, even within a single section. The uraninite is isotropic, while coffinite appears to be so because of isotropization caused by radiation. The two minerals cannot readily be differentiated in polished-section. Coffinite was more abundant than uraninite in samples from the area studied (Union Carbide Research Report, 1972). An X-ray powder photograph showed that the mineral replacing the carbonaceous debris consisted of both uraninite and coffinite.

The ore minerals were most commonly found replacing woody fragments. Undeformed cell structures are a characteristic feature of these replaced fragments (Plate 25). The uraninite and coffinite often replace the detrital matrix and sometimes the carbonate cement (Plate 26). In some cases the detrital matrix and cement were preferentially replaced by the uranium minerals immediately adjacent to the replaced carbonaceous fragments. Occasionally, irregular grains of uraninite or coffinite about the same size as the detrital grains were seen. Moon (1974) found uranium minerals in iron rich veinlets, replacing sulphide minerals, in concretions which replace the matrix, and in irregular veinlets.

The uranium minerals were in some cases cut by narrow calcite filled veins. Sulphide grains, often too small to be identified microscopically, were found both as inclusions in, and surrounding the ore minerals.

Oxidation of the uraninite and coffinite by surface weathering or aerated ground water resulted in the

formation of a complex assemblage of secondary minerals. Metatorbernite($Cu(UO_2)_2(PO_4)_2.8H_2O$) a light green platy non-fluorescent mineral, uranospinite ($Ca(UO_2)_2(AsO_4)_2.10H_2O$) a light yellow earthy-to-waxy arsenate which fluoresces a brilliant green, and uranophane ($Ca(UO_2)SiO_3(OH)_2.5H_2O$) which is similar to uranospinite but non-fluorescent were identified (Union Carbide Research Report, 1972).

3. The Sulphide Minerals.

Small amounts of different sulphide minerals are commonly associated with the uranium mineralization. Arsenopyrite (FeAsS) was found to be the most abundant sulphide. It occurs as anhedral to subhedral grains which commonly have diameters of less than 0,1 mm. Irregular aggregates of arsenopyrite grains, up to 0,8 mm in diameter were rarely encountered. The arsenopyrite content of the host sandstone was estimated as being less than 0,5 percent in all the polished-sections studied. The other sulphides identified were bornite (Cu_5FeS_4), chalcocite (Cu_2S), covellite (CuS), chalcopyrite ($CuFeS_2$) and pyrite (FeS_2). In addition to the above, Moon (1974) found small amounts of galena (PbS), sphalerite (ZnS) and loellingite ($FeAs_2$). Although no molybdenum minerals were seen in the sections studied, anomalous amounts were found associated with the uranium minerals (Union Carbide Research Report, 1972, and Moon, 1974). The sulphides were seen to replace the detrital grains, the matrix and the cement.

4. Paragenesis of the Mineralization.

The small grain sizes and low concentrations of the uranium minerals and the sulphides make paragenetic studies difficult. Dark radioactive haloes often mask the contacts between the uranium and gangue minerals.

The calcite was found to be contemporary with or post

uranium emplacement (Union Carbide Research Report, 1972). The early formation of the calcite cement in the paragenetic sequence is indicated because it is replaced by uraninite and coffinite, as well as by the sulphides. Inclusions of calcite in the uranium minerals and arsenopyrite also indicate the early formation of the calcite. The presence of sulphides, both as inclusions in the uraninite and coffinite grains, and as rims around them suggests that these minerals formed more-or-less contemporaneously. The arsenopyrite commonly forms rims around the copper sulphides, which suggests that it formed after them. Calcite veins cutting across the uranium minerals and the sulphides are indicative of later remobilization of the calcite.

IX. THE ORIGIN AND CONCENTRATION OF THE URANIUM.

A. SOURCE OF THE URANIUM.

Review papers on the sandstone-uranium districts of the United States by Fisher (1970 and 1974) and Grutt (1975) indicate that the uranium may have been derived from any of several sources. A magmatic hydrothermal source which was postulated at various stages, has now generally been abandoned because of the discovery of uranium in sandstones far removed from sites of plutonic activity. The *in situ* weathering and leaching of granitic rocks may, by deep oxidation and ground water leaching, solubilize much of the loosely-bound uranium from the granites, which then migrates into the aquifer system. The uranium may also have been leached from the arkosic sandstone which hosts the orebodies. Tuffaceous sediments within or above the host sandstone may present a further possible source of uranium, which may have been leached, enriching the ground water in uranium.

Fisher (1970) indicated that any of the three last-mentioned sources could yield sufficient uranium to form economic deposits. The leaching of uranium from tuffaceous sediments is currently the hypothesis most favoured by geologists working in the United States. Grutt (1975) found that tuffaceous sediments in the stratigraphic section above the host rocks are a feature of all of the major sandstone-uranium districts of the United States considered in his review. He cited as further evidence in support of a tuffaceous source the observations of Garrels (1957) and work by Denson *et al.* (1956), that reported the high uranium content of waters in streams draining tuffaceous terrains. These waters also contained abnormal amounts of selenium, arsenic, vanadium, phosphorous

and molybdenum, which are elements commonly found associated with the uranium.

No tuffaceous sediments are known to immediately overlie the lower part of the Beaufort Group. The fact that the mineralization is found distributed throughout a stratigraphic interval of some 800 m in the area studied suggests that, if the mineral was derived from tuffaceous rocks, they would have to be found within the sequence. Rock fragments, probably of volcanic origin, are found in the sandstones of the area studied (Martini, 1976, personal communication).

The high feldspar content (over 30 percent)of the sandstones and the presence of volcanic rock fragments, suggests that the uranium was derived by the leaching of these components in the host sediments.

B. THE MOBILITY OF URANIUM AND THE NATURE OF THE MINERALIZING SOLUTIONS.

The mobility of uranium in permeable sandstones is governed by the stability of its two valence states, U^{4+} and U^{6+}. In the major ore minerals, uraninite and coffinite, the uranium is in the tetravalent state. These minerals are stable under reducing conditions. There is no appreciable dissolution of these minerals in oxygen depleted ground waters. Oxidation of the uranium to the hexavalent state at or near the surface, or by the oxidizing ground waters, allows the uranium to form soluble complexes (Adler, 1974).

Hostetler and Garrels (1962) have shown that the uranium can be transported as uranyl carbonate complexes in a solution that is mildly reducing, has a neutral to alkaline pH, and contains abundant carbon dioxide. The mildly reducing solutions can pass through the host sandstones without markedly altering them. When the solutions come

into contact with strong reductants in the sandstone, the uranium may be precipitated. Penecontemporaneous ore bodies, which are tabular or lenticular in shape and are almost parallel to the bedding, may have formed by this mechanism (Adler, 1974).

Oxygenated ground waters can also transport uranium (Adler, 1974). They commonly react with the pyrite in the sandstone to produce roll or roll-like uranium deposits. Roll-type uranium deposits are sinuous bodies, generally of c-shaped cross-section, which are discordant to the bedding. They occur at the interface between oxidized and reduced sandstone within a single unit.

The solutions which formed the deposits in the area studied were probably of the reducing type. This is indicated by the close association of the uranium with the fossil plant material, sulphides and carbonate cement. The absence of roll type orebodies and large areas of oxidized sandstone also indicate reducing conditions. The overgrowths on the quartz grains seen in thin-section show that silica was remobilized, which is suggestive of alkaline conditions.

C. THE PERMEABILITY OF THE HOST ROCK.

For sufficient mineralizing solution to come into contact with the reductant to form an orebody, the host rock must be permeable. An interruption or delay of fluid flow is apparently required to allow time for the precipitation of the uranium (Gabelman, 1971). In parts of the host rock where continuous flushing by the mineralizing solution takes place, leaching will probably predominate over fixation (Doi *et al.*, 1975).

The ideal host rock would thus have discontinuous permeability zones in both the lateral and vertical dimensions. The discontinuous permeability in fluvial sandstones results from the highly varied lithologies, textures, porosities,

sedimentary structures and jointing found within these units. Several features affecting permeability which may exercise control on the location of the uranium deposits, were discussed by Gabelman (1971). The interfingering of sandstones with mudstone, and intercalated mudstone lenses provide areas where fluid flow is delayed sufficiently to allow precipitation of the uranium (in the presence of a suitable reductant). Penecontemporaneous deformation structures probably aid the concentration of uranium by disrupting the bedding, and thus forming permeability boundaries within the host sandstones. Intraformational diastems, where coarser sediments overlie finer within a sandstone unit, may provide suitable sites for mineralization. Intraformational conglomerate lenses commonly provide more permeable channelways giving the ground waters access to different portions of the sandstone.

The sandstones of the Beaufort Group acted as channelways for the mineralizing ground waters. Their highly varied lithologies and sedimentary structures provided favourable hydrodynamic conditions for the transport and precipitation of the uranium. The relatively fine grain and poor sorting of most of the sandstones possibly somewhat restricted the volume of mineralizing ground water which flowed through the sediments. The intraformational conglomerates, which would form good aquifers, generally occur only as thin, discontinuous lenses. However, in the few places in which they are well developed, they may have been important as passages for the mineralizing ground waters.

D. REDUCTANTS AND THE PRECIPITATION OF URANIUM.

Uranium deposits in sandstone are formed by the precipitation of uranium from solution by reduction, adsorption, ion exhange, ionic substitution or the formation of insoluble ionic complexes (Gabelman, 1971).

Carbonaceous material appears to have been the most

important precipitant in the major uranium districts of the United States (Gabelman, 1971, Fisher, 1974, Grutt, 1975). Poorly-coalified plant remains are good adsorbants of uranium. Replacement of wood by uraninite and coffinite is common. Hydrogen sulphide, formed from organic matter by anaerobic bacteria, is a strong reductant. Fisher (1968) reported that isotopic studies on the sulphides associated with the uranium mineralization on the Colorado Plateau indicated that the sulphur was of organic origin.

The presence of humates (viscous plant-derived oils) appears to be the major control in the Ambrosia Lake District, New Mexico. The humates have three possible origins (Adler, 1974). They may have been derived from vegetation decaying in a bog or swamp which overlay the mineralized sandstone, they may have been dissolved from plant matter syngenetically incorporated in the sandstone, or they may have been present in the same streams which deposited the sandstone. Uranium is inferred to have been precipitated directly by the humates or hydrogen sulphide produced by bacteria in the humate.

Hydrogen sulphide bearing gas or water associated with oil in the underlying rocks is postulated to be the most important reductant in areas like the Texas Gulf Coast (Grutt, 1975). Adsorption and co-precipitation of uranium by and with limonite is a mechanism proposed for the formation of some of the ore deposits of Japan (Doi *et al.*, 1975). Uranium concentrations, formed possibly by ion exchange within irregularly shaped bodies of clay isolated in massive sandstone, are reported by Gabelman (1971). Uranium may be fixed by the formation of uranyl vanadates (e.g. carnotite and tyuyamunite, Fisher, 1968). These minerals are stable under oxidizing conditions. In the absence of vanadium, other secondary minerals, such as uranyl phosphates and arsenates may form, some of which are not very stable. Migration of uranium and impoverishment of the deposits thus generally occurs

under oxidizing conditions in the absence of vanadium.

The close association of the uraninite and coffinite with carbonaceous debris in the occurrences studied indicates that this was the major precipitant. The replacement of the carbonaceous material by ore minerals is common. The interstitial uraninite and coffinite was probably precipitated by the reduction of the mineralizing ground waters by hydrogen sulphide, produced from the coalified plant remains. Some of the interstitial ore may also have formed by the replacement of the clay matrix, carbonate cement and sulphides in the sandstone. There is no evidence that oil-derived reductants precipitated any of the uranium in the area. The pseudo-coals found in fissures on the farm Brandewyns Ghat 214 and in the Merweville District (Rossouw and De Villiers, 1953) are not radioactive. The sandstone in fissures found cutting, or in close proximity to mineralized outcrops (e.g numbers 18, 19 and 25 on Map 1) is not preferentially mineralized, as would probably have been the case if they were the paths along which hydrogen sulphide was introduced.

E. REMOBILIZATION OF URANIUM AND THE PRESERVATION OF THE DEPOSITS.

The major uranium ore minerals, uraninite and coffinite, are readily soluble in an oxidizing environment. Gruner (1956) proposed a mechanism whereby concentration of uranium in sediments can take place by multiple migration and accretion. The uranium is concentrated by precipitation from ground water encountering a suitable reductant. A change in hydraulic regime allows oxidizing ground water to dissolve the uranium. Uranium is again precipitated when this enriched ground water comes into contact with a suitable reductant. By repeating this process, large deposits of uranium may accumulate. Gruner (1956) envisaged tha' this process could form peneconcordant as well as roll-type deposits, while Adler (1974) suggested

that remobilization was more likely to form roll-type deposits only. The *in situ* formation of the ore deposits in the area studied is suggested by the peneconcordant nature of the deposits, the absence of large redox fronts and the fact that the uranium is not concentrated in synclines and along fissures.

The mineralized outcrops investigated were all subjected to contemporary surface oxidation. This resulted in the formation of secondary uranium minerals at all the outcrops. Uraninite and coffinite were found associated with secondary minerals at some surface outcrops, while others were completely oxidized. The various degrees of oxidation are attributed to the amount of calcite cement. Abundant calcite cement renders the sandstone relatively impermeable, and thus protects the deposits from surface oxidation. Wood (1968) attributed the unoxidized nature of the uranium mineralized sandstones in the Lisbon Valley area, Utah, which are "hundreds of feet above the water table" to the calcite cement, which rendered the host rocks impermeable.

F. STRUCTURAL SETTING.

Beds dipping at less than 5 degrees at the time of mineralization are considered favourable for the formation of uranium deposits (Grutt, 1975). This assures that the migration of ground waters is slow enough to prevent flushing of the reductants which fix the mineralization, but still allows ample uraniferous ground water throughput for the formation of deposits. The low dips also assure a large area of outcrop for ground water recharge. In areas where the mineralized sediments dip at more than 5 degrees the deformation was thought to have taken place after the formation of the deposits.

G. THE AGE OF MINERALIZATION.

From field relationships, it is apparent that the uranium mineralization formed shortly after the deposition of the host rocks. The absence of any discernable control on the mineralization by the folding of the sediments (which is generally thought to have terminated towards the end of Beaufort times) indicates that the mineralization predates the deformational event.

A sandstone unit (near mineralized outcrop 4, Map 1) was found (by drilling) to be mineralized on either side of a dolerite dyke which cuts through it. The dyke would have been an impermeable barrier to the mineralizing ground water. This suggests that the mineralization pre-dates the intrusion of the dolerite.

The replacement, by ore minerals, of unflattened cell structures in plant fossils was commonly seen in the polished-sections. This indicates that the mineralization took place before deep burial of the sediments (Fisher, 1968).

H. THE CLASSIFICATION OF THE URANIUM DEPOSITS.

The major features used for the classification of the uranium occurrences in the area studied are:

(1) they are found in the channel facies of a fluviatile sequence;
(2) the mineralized zones are peneconcordant to the bedding;
(3) they are associated with carbonaceous debris and small mudstone intercalations;
(4) the primary minerals are uraninite and coffinite, which are associated with sulphides and calcite;
(5) the uranium minerals occur in small patches which are separated by large areas of barren sandstone;

(6) the individual mineralized lenses generally have sharp boundaries; and,
(7) there is no apparent structural control on the mineralization.

Uranium deposits in fluvial sandstones are generally classified on the basis of their morphological relationship to the host rock, as being either peneconcordant or roll-type. The features of the occurrences outlined above indicate that they are typical peneconcordant deposits. Roll-type deposits were not found in the area studied.

Adler (1974) suggested that, although speculative, a genetic classification could be useful. The deposits can be considered primary when they formed as an original accumulation of uranium not obviously derived from pre-existing ore. Secondary orebodies are those which formed by the redistribution or reconstitution of pre-existing orebodies. Commonly, the redistribution forms roll-type deposits. These definitions can be applied to both oxidized and unoxidized bodies. The uranium deposits in the lower part of the Beaufort Group appear to be primary. They are oxidized to varying degrees.

The nature and source of the reductant may be used to further classify the deposits (Adler, 1974). The two types recognized are a static indigenous reducing environment, such as is generated by carbonaceous plant material accumulated by stream action during sedimentation, and later introduced reductants, such as water-borne humic substances or hydrogen sulphide. The abundant carbonaceous debris associated with the mineralization in the area studied, indicates that a static reducing environment was responsible for the precipitation of the uranium.

The deposits are not truly syngenetic. They are best described as epigenetic, formed by supergene ground waters.

I. GENERALIZED MODEL FOR THE FORMATION OF THE URANIUM DEPOSITS IN THE LOWER PART OF THE BEAUFORT GROUP.

The uranium was probably leached by surface and ground waters from the feldspars and volcanic rock fragments of the host sandstone. It is thought to have been transported as uranyl carbonate complexes in mildly reducing supergene solutions having a neutral to alkaline pH. The mineralizing ground waters moved through the most permeable units in the stratigraphic succession. Where these solutions came into contact with a strong reductant (probably H_2S formed from coalified plant remains by anaerobic bacteria), in areas where a lowering in permeability delayed fluid flow, the uranyl complexes were reduced, and uraninite and coffinite precipitated. Coalified plant remains were often replaced by the ore minerals. The mineralizing ground waters, which were carbonate rich, probably also cemented the host sandstones. During the present erosional cycle the deposits were subject to oxidizing conditions. This probably resulted in the removal of some of the uranium by solution, lowering the grade of the deposits, and the formation of the secondary mineral assemblage.

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X. SUMMARY AND CONCLUSIONS.

A. STRATIGRAPHY.

The sediments in the area studied are a sequence of mudstones, siltstones and fine-grained sandstones. The thickness of the stratigraphic interval exposed is about 850 m. The mudstone constitutes about 50 percent of the stratigraphic interval, the siltstone 30 percent and the sandstone 20 percent. This gives a sandstone to mudstone and siltstone ratio of 1:4. No laterally persistent mappable units were found in the area studied. More detailed lithostratigraphic mapping over an area larger than that considered in the present study may, however, prove the existence of a mappable unit with a sandstone to mudstone ratio which is higher than that of the strata above and below. This unit would be located near the top of the escarpment in the study area (in the vicinity of "A" sandstone of Figure 3). The thickest sandstones, although laterally impersistent, were found to be the most useful units for interpreting the stratigraphy and structure of the area.

B. FACIES OF SEDIMENTATION AND THE DEPOSITIONAL MODEL.

A conglomerate, sandstone, siltstone and mudstone facies were recognized in the study area. The sandstone facies was subdivided, on the basis of primary sedimentary structures, into a trough cross-bedded, a horizontally-bedded and a ripple cross-laminated subfacies. A Markov analysis of a random stratigraphic section through the sediments in the study area showed that the facies are ordered. The most commonly occurring facies sequence, as determined by the Markov analysis and field observations,

was an intraformational conglomerate overlain by trough cross-bedded or horizontally-bedded sandstone, succeeded by ripple cross-laminated sandstone, siltstone and mudstone (Figure 11). This sequence of sedimentary facies and structures is typically found in sediments deposited by meandering streams on an alluvial plain. The high percentage of mudstone preserved in the stratigraphic section indicates that a large amount of sediment was deposited in flood basins, and that the streams were confined to well defined meander belts. The depositional pattern would thus best fit the strongly meandering model proposed by Allen (1965). A palaeocurrent analysis of the sandstones in the study area confirmed, by comparison to the channel orientations of part of the Mississippi River (which is strongly meandering), that the sandstones were probably deposited by meandering streams (Figures 12 and 16).

C. SANDSTONE GEOMETRY.

The mapping of well exposed stratigraphic cross-sections in the study area showed that the sandstones are lenticular (Figures 7 and 8). The lenses are elongated in the direction of stream flow (as determined by palaeocurrent analysis). The largest sandstone lenses were found to have maximum thicknesses of about 25 m. When traced laterally away from the thickest portions, the lenses were found to thin rapidly, and to interfinger with the argillaceous facies. Many of the sandstones were found to consist of an upper and a lower unit separated by an argillaceous parting several metres thick. In the thickened, channelled areas, the two sandstones merge to form a single unit.

D. SANDSTONE PETROLOGY.

The sandstones studied were found to have mean grain sizes ranging from fine-to very-fine grained. They are moderately sorted and the grains were found to be subangular to subrounded. The sandstones, on average, contain 39

percent quartz, 33 percent feldspar, 24 percent matrix and 2 percent each of chert and carbonate. The accessory minerals found were biotite, muscovite, garnet, apatite, zircon, monazite and epidote. Rock fragments, of a probable volcanic origin, are a minor constituent of the sandstones. All the sandstones found in the area studied can be described as fine-to very fine-grained, moderately sorted, arkosic wackes (Pettijohn *et al.*, 1972). The mineralogy of the sediments studied is consistent with the granitic and high grade metamorphic rock provenance area proposed by Theron (1973) for the Beaufort Group sediments.

E. PALAEOCURRENT ANALYSIS.

The most common directional sedimentary structures found in the area studied were trough cross-beds, rib-and-furrow structures and primary current lineations. Current rose diagrams plotted for the different types of structures measured throughout the area studied, showed that the vector means, and the distribution of the measurements about the vector means, obtained for the different structures are similar (Figure 12 and Table 7). The results of the measurements of the different sedimentary structures were combined for use in the analysis. The palaeoslope (which is given by the palaeocurrent direction in sediments deposited by fluvial proccesses) was found to be towards the north-east (029°) during the deposition of the entire stratigraphic interval studied (Map 1 and Figure 12).

For the interpretation of the palaeocurrent measurements made in some selected sandstone units, a moving average technique was found to be useful. The moving average palaeocurrent maps (Figures 14 and 15) of selected sandstone units show that the palaeocurrent directions closely follow the outcrop configuration (in plan view) of the individual sandstone units. The consistency ratios of the palaeocurrent vectors were found to be largest along the edges of the sandstone units, and lowest in the areas

of maximum sandstone development. This was thought to reflect the deposition of the thicker sandstones over a relatively long period of time, by an actively meandering stream. The thinner sandstone deposits reflect shorter time-spans, and probably formed during periods when the streams migrated across the flood plains.

The bimodal distribution of palaeocurrent directions shown on some of the current rose diagrams (Figures 12 and 13) are thought to reflect deposition by strongly meandering streams, rather than deposition by more than one dispersion system. This is shown by the bimodal distribution of palaeocurrent directions found in some of the single sandstone units studied (Figure 13) which were deposited as point bars in a single stream. The channel orientations of a portion of the Mississippi River, when plotted on a rose diagram (Figure 16), show a similar distribution.

F. PALAEOGEOGRAPHICAL SETTING.

Stratigraphic, petrological, sedimentological and palaeocurrent studies were used to gain some insight into the geographical setting of the area studied during sedimentation. The low quartz to feldspar ratios of the sandstones, and the presence of fine coalified plant remains in them, indicates that they were derived from a provenance area with a high relief and mature topography (Pettijohn, 1957). The palaeocurrent analysis showed that the provenance area lay to the south-west. Theron (1973) found that the provenance area of the Beaufort Group sediments consisted of granitic and high grade metamorphic rocks. The sediments of the area studied were probably deposited by strongly meandering rivers, separated by large flood basins, on a low-lying flood plain (Figure 17).

The climatic conditions during the deposition of the sediments were probably temperate and fiarly arid. The abundant reptilian fossils and the "Taeniopteris" flora indicate temperate conditons (King, 1961), while arid conditions are indicated by the presence of calcareous concretions, colour-mottling of the argillaceous rocks, and the general absence of organic rich and rootlet penetrated layers in the stratigraphic succession. The basin into which the Beaufort Group streams drained probably lay to the north of the present day Beaufort Basin.

G. THE DISTRIBUTION AND LOCALIZATION OF URANIUM IN THE LOWER PART OF THE BEAUFORT GROUP.

Uranium mineralized sandstones were found throughout the entire stratigraphic interval studied. There appeared to be no regional stratigraphic control on the localization of the mineralization. The thickest and most persistent sandstone units, which characteristically have a complex internal structure, were found to be preferentially mineralized. Uranium was found in sandstones of the trough cross-bedded, horizontally-bedded and ripple cross-laminated subfacies. Mineralized intraformational conglomerates were occasionally encountered. Where mineralized, the sandstones are generally calcareous, and weather to a dark-grey or black colour. The bleached white to brownish or yellowish colour of some mineralized outcrops is attributed to the more intense weathering which appeared to be associated with sandstones having a lower calcite content.

The uranium mineralization occurs as small lenticular bodies, commonly only a few tens of metres in length. The lenses have thicknesses varying from a few centimetres to a maximum of about 5 m. The mineralized lenses are generally separated by large areas of barren sandstone. In some places, they may almost merge to form near continuous mineralized zones which occasionally can be traced

for distances of up to 1 km. The lenses are concordant or nearly concordant to the bedding. They are commonly elongated in the direction of sandstone thickening.

Maps of well exposed cross-sections of three mineralized outcrops (Figures 18, 19 and 20) show that the uranium is commonly found in the lower portions of the sandstone units. The uranium was found just overlying intraformational conglomerates, associated with penecontemporaneous deformation structures, overlying and adjacent to mudstone and siltstone intercalations, and within well developed cross-bedded and horizontally-bedded sandstone units. In most places, the mineralization was seen to be closely associated with coalified plant remains. This suggests that the two major controls on the localization of uranium in the well developed sandstone units are marked permeability changes and the presence of coalified plant remains.

Drill hole data was used to study the location of the uranium mineralization in the "C" sandstone unit in relation to the thickness of the sandstone, the thickness of the siltstone and mudstone intercalated within the sandstone, and the sandstone to siltstone and mudstone ratio (Figures 21, 22 and 23 respectively). The thickest portions of the sandstone unit were found to be preferentially mineralized (areas having a sandstone thickness of over 17 m being the most favourable). In the mineralized areas of the sandstone, the combined thickness of the mudstone and siltstone intercalations was generally found to be less than 1 m.
A close correlation between areas of maximum sandstone development and areas with thin siltstone and mudstone intercalations was generally found. The mineralized portions of the sandstone lens commonly have sandstone to siltstone and mudstone ratios which are larger than 50:1, again reflecting the affinity of the mineralization for the cleanest,most permeable portions of the sandstone lens.

H. PETROLOGY OF THE MINERALIZATION.

The mineralized and unmineralized sandstones were found to have similar textures and compositions. A comparison between the composition of the mineralized and barren sandstones indicated that the mineralized sandstones contain more calcite and slightly more matrix. The lower feldspar content of the mineralized sandstone is attributed to both the replacement of the feldspar by calcite, and its alteration to clay minerals. The clay minerals would have been counted as matrix in the modal analysis. The mineralized sandstones were found to contain small amounts of fine, platy, coalified plant material and sulphide minerals.

The ore minerals found were uraninite and coffinite. The two minerals are not easily distinguished in polished-section, and are thought to commonly occur as mixtures. The uraninite and coffinite were found replacing the carbonaceous debris, detrital matrix and carbonate cement. Undeformed cell structures are a characteristic feature of replaced coalified plant remains. Accessory amounts of sulphide minerals (mainly arsenopyrite and lesser amounts of pyrite, bornite, covellite and chalcopyrite) were found associated with the ore. The sulphide grains, which generally have diameters of less than 0,1 mm, were found replacing the detrital minerals, matrix and cement.

Oxidation of the mineralized sandstones resulted in the formation of a complex assemblage of secondary minerals. The most commonly occurring ones were identified as metatorbernite, uranospinite and uranophane (Union Carbide Research Report, 1972).

I. THE ORIGINS AND CONTROLS OF URANIUM DEPOSITS IN THE LOWER PART OF THE BEAUFORT GROUP.

The sources most commonly postulated for the uranium which

goes into solution in ground waters are granitic rocks in the provenance areas, arkosic sandstones which host the mineralization and tuffaceous sediments overlying or within the host sandstone. The uranium for the deposits of the Beaufort Group was probably derived by the leaching of the feldspars and the volcanic rock fragments found within the host sandstones.

The uranium is thought to have been transported as uranyl carbonate complexes which were shown by Hostetler and Garrels(1962) to be stable in solutions which are oxidizing or mildly reducing, have a neutral to alkaline pH, and contain abundant CO_2. The reducing nature of the solutions which formed the deposits is indicated by the close association of the uranium with the carbonaceous debris and sulphides, and the absence of large areas of oxidized sandstone.

The mineralized ground waters moved through the most permeable sedimentary units. Intraformational conglomerates and the coarser grained sandstones, particularly where trough cross-bedded or affected by penecontemporaneous deformation, acted as channels for the mineralizing solution. Gabelman (1971) found that an interruption or delay in fluid flow is required to allow time for the precipitation of the uranium. Siltstone and mudstone intercalations in the sandstones would thus provide favourable sites for mineralization.

Reduction of the uranyl carbonate complexes causes the precipitation of the ore minerals. A suitable reductant for the precipitation of the uranium is hydrogen sulphide,which may be formed by anaerobic bacteria in the organic material.

The uraninite and coffinite commonly replace the carbonaceous debris. The close association of the uranium with the coalified plant remains in the area studied indicates that they were the most important reductants. No evidence for significant redistribution of the uranium after the

formation of the deposits was found.

The uranium deposits were probably formed shortly after the deposition of the host rocks. This is indicated by the absence of any control on the location of the deposits by the folding or the distribution of dolerite dykes, and the presence of unflattened cell structures in the plant fossils which have been replaced by the ore minerals.

The uranium deposits of the lower part of the Beaufort Group in the area studied appear to be similar to the peneconcordant deposits of the Colorado Plateau and elsewhere. Peneconcordant deposits were found to be rather uniform in grade (having an average of 0,25 percent U_3O_8) and consistent in habit, but to vary greatly in size (Fisher, 1968). They have been described as discrete masses distributed throughout the host sandstone "like rasins in a loaf of bread" (Fisher, 1970)

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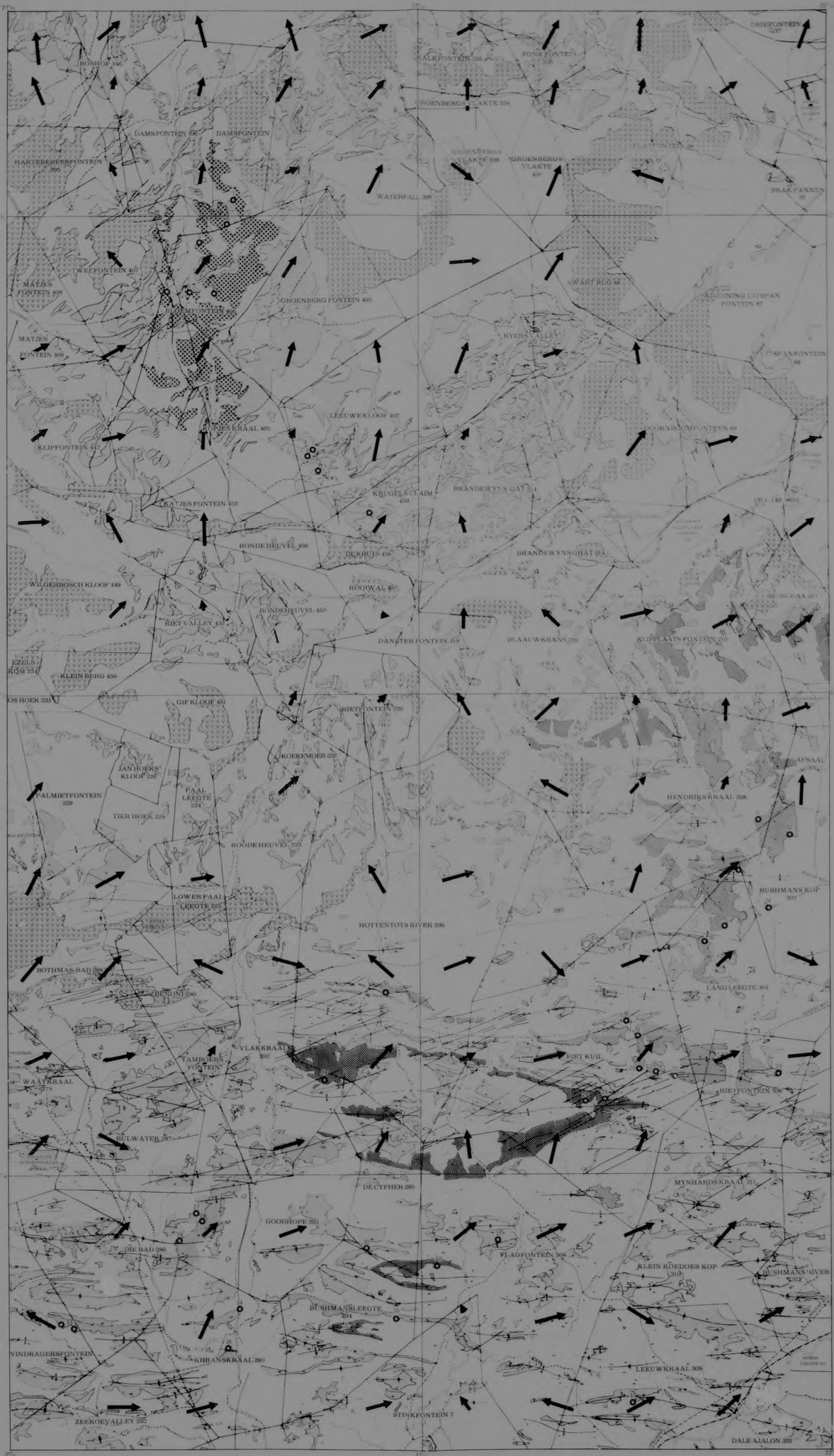
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MAP 1

THE GEOLOGY OF AN AREA BETWEEN BEAUFORT WEST, FRASERBURG AND MERWEVILLE



LEGEND

- SILTSTONE/MUDSTONE/ALLUVIUM
- DOLERITE
- DYKE
- SANDSTONE (UNDIFFERENTIATED)
- 'A' SANDSTONE
- 'B' SANDSTONE
- 'C' SANDSTONE
- 'D' SANDSTONE
- 'E' SANDSTONE
- FISSURE
- ANTICLINAL AXIS
- SYNCLINAL AXIS
- DIP (ESTIMATED AT LESS THAN 5°)
- DIP (ESTIMATED AT MORE THAN 5°)
- URANIUM MINERALIZED OUTCROP
- RIVER
- FARM BOUNDARY
- ROAD
- RAILWAY LINE
- PALAEOCURRENT DIRECTION (LENGTH OF ARROW PROPORTIONAL TO CONSISTENCY RATIO) 25, 50, 75, 100
- MEASURED SECTION

SCALE 1:100 000

0 1 2 3 4 5 6 7 8 9 10 KILOMETRES

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