

FOSSIL WOOD FROM THE BRANDVLEI AREA, BUSHMANLAND AS AN INDICATION OF PALAEOENVIRONMENTAL CHANGES DURING THE CAINOZOIC

by

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ABSTRACT

Remnants of Cainozoic fluvial deposits occur along the northerly flowing Sak River in Bushmanland, between Brandvlei and Sak River Station. The terraces can be subdivided into older and younger deposits, and occur approximately 60m and between 20m and 30m above the present-day river respectively. The older deposits are found to the east of the Sak River in the Geelvloer palaeo-valley. Most of the older 'terraces' are either hill-slope deposits or fans, and represent reworked fluvial sediments. A rounded vertebrate bone and several pieces of sub-rounded fossil-wood were found in these deposits, which indicate a mid Miocene age for the original older deposits. Some of the fossil-wood samples have been positively identified as extant angiospermous families. The occurrence of fagaceous wood in two samples is of great interest biogeographically. Both the vertebrate fossil and the wood suggest that the mid Miocene climate was subtropical. At the end of the Miocene the wet period changed to arid conditions, and mature calcretes developed. This dry period was interrupted by pluvials during which the younger gravels were deposited. These alluvial terraces are interpreted as an aggradational sequence of braid bars associated with a wandering river, deposited under semi-arid conditions. Two well-rounded fossil-wood clasts, presumably reworked from the older terraces, were found in these sediments. One of which is identified as Polygalaceae. Based on similarities of lithofacies and style of diagenesis with the Van Wyksvlei sequence to the east, the younger terraces are probably Plio-Pleistocene in age.

KEY WORDS: Fossil wood, terraces, Cainozoic, Bushmanland.

INTRODUCTION

The Sak River is a north-flowing ephemeral river which meets up with the Vis River at Sak River Station, 65km south of Brandvlei in the western Cape. The Sak has its headwaters near Loxton, and the Vis originates near Sutherland. Below the confluence the Sak continues northwards following a prominent north-north-easterly orientated lineament and flows into the Grootvloer depression, approximately 50km north of Brandvlei. The mean gradient of the Sak River is 0.00063.

Several Cainozoic deposits, along the Sak River in Bushmanland, have been investigated as part of a regional study of Cainozoic drainage systems in the north-west Cape Province (Figure 1).

These deposits can be divided into erosional alluvial terraces, hill slope deposits and fans. Some of these deposits were exploited for diamonds in the 1930's. They can be grouped into older and younger deposits, depending on their positions above the present-day Sak River. The older deposits, which partly comprise reworked fluvial sediments, are hillslope deposits and fans. These occur between 35m and 65m above and west of the Sak River, in a palaeo-valley referred to as the Geelvloer valley (De Wit 1993).

The younger deposits are remnants of bedrock

alluvial terraces and are between 20m and 30m above the Sak River, either central to, or east of, the Sak River.

REGIONAL GEOLOGY

The area occupied by the Sak River in the study area is underlain by Lower Ecca Group argillaceous sediments (Prince Albert, Whitehill and Tierberg Formations), intruded by Karoo-aged dolerite sills and dykes. The Sak River flows perpendicular to the general strike of the Karoo rocks. The headwaters of the Vis and Sak Rivers comprise Beaufort Group sediments, which are predominantly arenaceous.

The dolerite sills have selectively intruded the Karoo Sequence along the contact of the Whitehill and Tierberg Formations, halfway up the Tierberg Formation, and in the lower part of the Beaufort Group (Rogers and Du Toit 1908). The presence of these sills has had a significant influence on the river's behaviour. Where it flows over dolerite the river is confined to a single, relatively narrow channel with an average gradient of 0.00031. When flowing over shale the river occupies a wide floodplain with a mean gradient of 0.0012. Most terraces are situated directly below the sills and resemble expansion bar complexes, which form at abrupt widening of channels (Baker 1984).

GEOMORPHOLOGY

A geomorphological study of the region revealed several denudational landsurfaces outside the Sak River Valley. The oldest surface is referred to as the Highveld surface (SHV) (Lockett 1984), and equates with the African surface of King (1962) and the Bushmanland plateau of Reuning (1930). It forms isolated remnants which are associated with mature pedogenic calcrete (Mabutt 1955, De Wit 1988). This calcrete, which is regionally widespread (De Wit 1988), can on geomorphic and petrographic grounds (De Wit 1993), possibly be correlated with calcretes from the Namib that were described by Ward and Corbett (1990). Based on stratigraphic correlation this calcrete, which represents an arid to semi-arid climate with minimal rainfall, developed between Late Miocene and Late Pliocene (Ward and Corbett 1990; De Wit 1993).

METHODS

Six terrace deposits were mapped using 6x enlargements of 1:50,000 scale aerial photographs. Bedrock

morphology and gravel thickness were outlined using a "down-the-hole" percussion drill rig. Holes were drilled every 50m on lines 100m apart. Trenches were subsequently dug in the deepest part of the deposits down to bedrock, and these range in depth from 1.5m to 7.9m and in length from 7m to 60m.

OLDER DEPOSITS

Facies description and interpretation

Higher elevated, and hence older, deposits were investigated on the farms Paarde Kolk 247, Nels Kop South 245 and Piet Louws Vlei 302 (Figure 1). All occur in the palaeo-Sak or Geelvloer Valley.

The facies of all three older 'terraces' represent mostly reworked deposits. Remnants of undisturbed fluvial facies (Gm) are only preserved at the base of the deposit on Nels Kop (Figure 3).

Gm facies

These represent clast-supported massive gravel facies (Gm), that developed as an accumulation of fluvial gravel

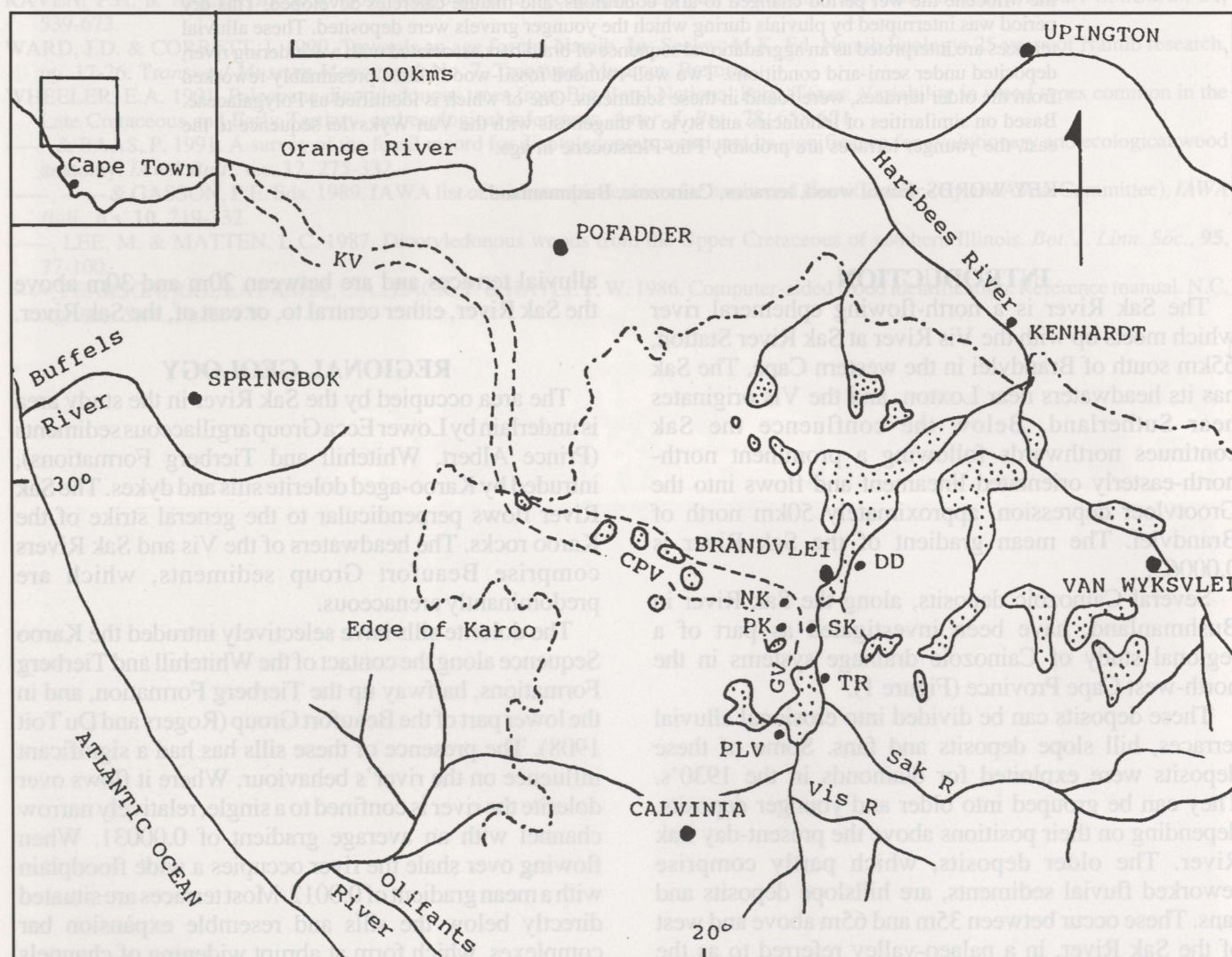


Figure 1: Location map of study area. DD = DikDoorns, NK = Nelskop, PK = Paardekalk, PLV = Piet Louws Vlei, TR = Twee Rivieren, SK = Swartkop. KV = Koa Valley, CPV = Commissioners Pan Valley, GV = Geelvloer Valley.

in a channel, and resemble cores of longitudinal bars such as described by Boothroyd and Ashley (1975) and Kraus (1984). The fluvial facies occur in a bedrock channel almost 7m wide and indicates that erosion under fluvial conditions did occur. The clasts are generally well-rounded, and are composed of dolerite, shale and sandstone. Palaeoflow direction, based on pebble imbrication, was to the north-east (323° N, $n=47$).

Gms facies

The overlying Gms facies on Nelskop, as well as those occurring on Paarde Kolk and Piet Louws Vlei, have a

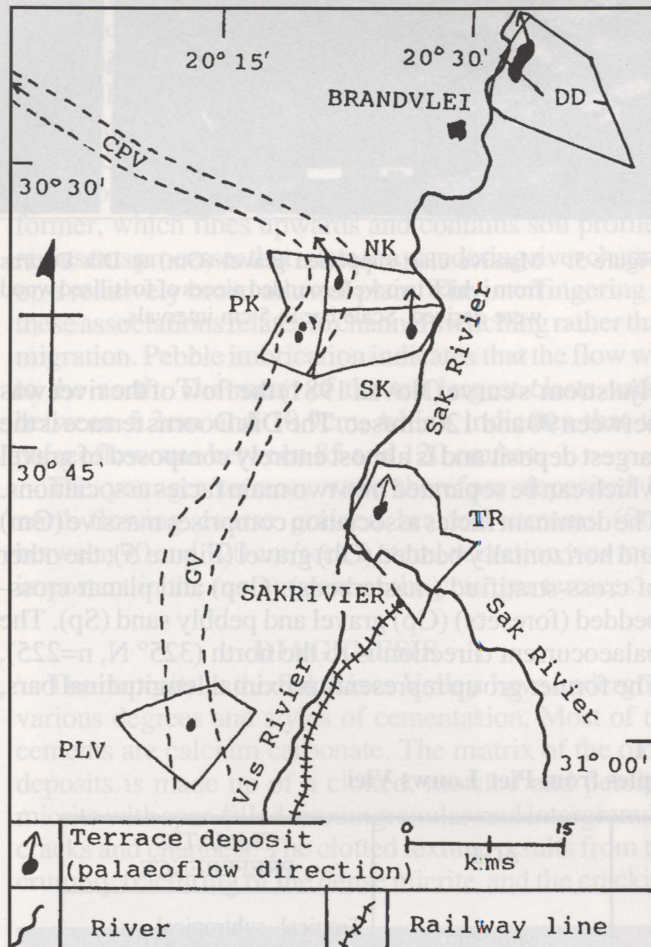


Figure 2: Locality plan of Brandvlei Cainozoic deposits and palaeo-Sak River drainage. DD = Dik Doorns, NK = Nelskop, PK = Paardekolk, PLV = Piet Louws Vlei, TR = Twee Rivieren, SK = Swartkop, GV = Geelvloer Valley, CPV = Commissioners Pan Valley, KV = Koa Valley.

bimodal clast population (Figure 4); sub-angular locally derived shale and dolerite boulders on the one hand, and well-rounded sandstone (Beaufort Group?), rare green volcanic pebbles and very rare diamonds on the other hand. These gravels are mainly unstratified, matrix-supported and generally coarsen upwards (Gms). The ratio of the coarsest 1-percentile particle size (C) and the medium particle size (M) of the Gms facies are more characteristic of alluvial mudflows than bedload deposits (De Wit 1993). These gravels and those on Paarde Kolk

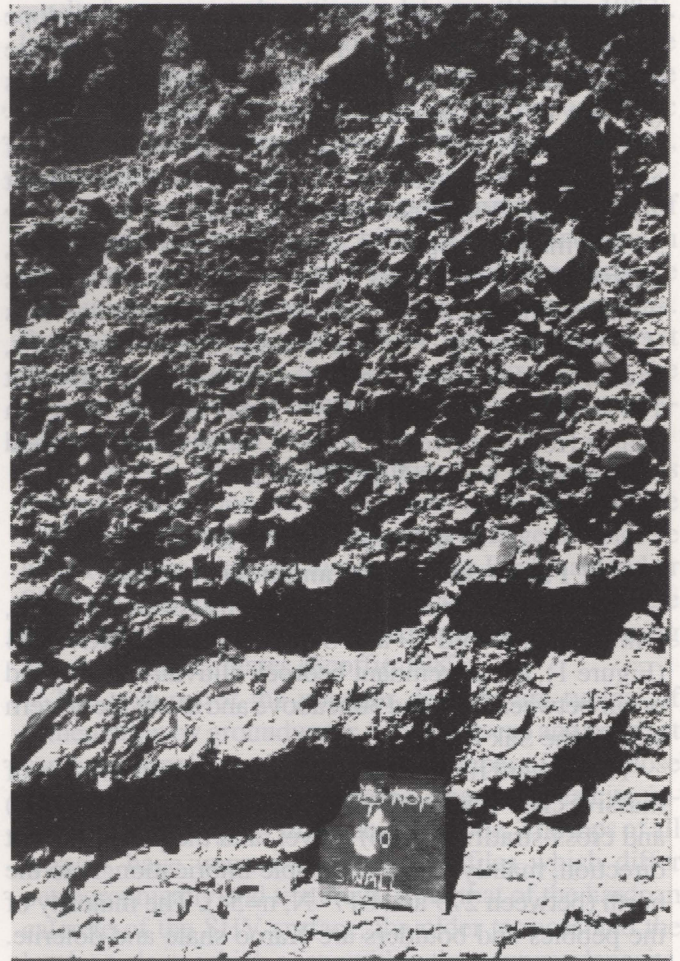


Figure 3: Original Gm facies preserved at the base and overlain by Gh facies, Nelskop South 245. Scale bar in 5cm intervals.

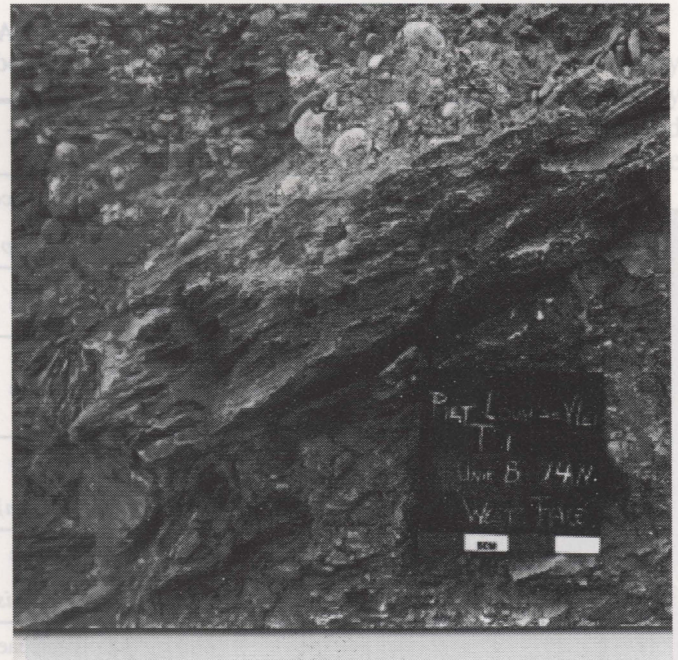


Figure 4: Poorly sorted matrix-supported gravel (Gms) at Piet Louws Vlei 302 from which five pieces of fossilised wood were recovered. Scale bar in 5cm intervals.

and Piet Louws Vlei are, therefore, interpreted as hillslope deposits that were derived from local shale and dolerite mixed with fluvial sediments rich in sandstone pebbles (De Wit 1993). The deposit at Paarde Kolk has a sheet-like geometry and is typical of the proximal part of alluvial fans (Middleton and Hampton 1976). The deposit at Piet Louws Vlei is dominated by poorly- to very poorly sorted matrix-supported gravels (Gms) (Figure 4), interbedded with slightly better sorted massive gravels (Gm) and horizontally stratified pebbly sands and silts (Gh and Sh facies). These are interpreted as debris flow, stream flood and sheet flood facies respectively (De Wit 1993). One well-rounded fossil jawbone was found on Paarde Kolk and five (5) pieces of sub-angular fossilised wood on Piet Louws Vlei (Table 1).

YOUNGER DEPOSITS

Facies description and interpretation

The younger deposits on the farms Zwart Kop 246, Dik Doorns Noord 30 and Suid 31 and Twee River 84 (Figure 1), are all remnant bedrock alluvial terraces and occur between 20m and 30m above and along the eastern side of the Sak River.

The upward fining sequence on Zwart Kop consists of massive clast-supported (Gm), horizontally bedded (Gh) and cross-stratified (Gep) gravel, and the palaeocurrent direction, mainly based on pebble imbrication, is to the north (between 279 and 017° N, n=54). The majority of the pebbles and boulders are Karoo shale and dolerite. Only a few sandstone and hardpan calcrete pebbles are present. This coarse grained deposit is interpreted as braided river facies where lateral accretion was not uncommon. The mean diameter of the ten largest clasts varies from 6.8cm to 10.9cm, and based on the revised

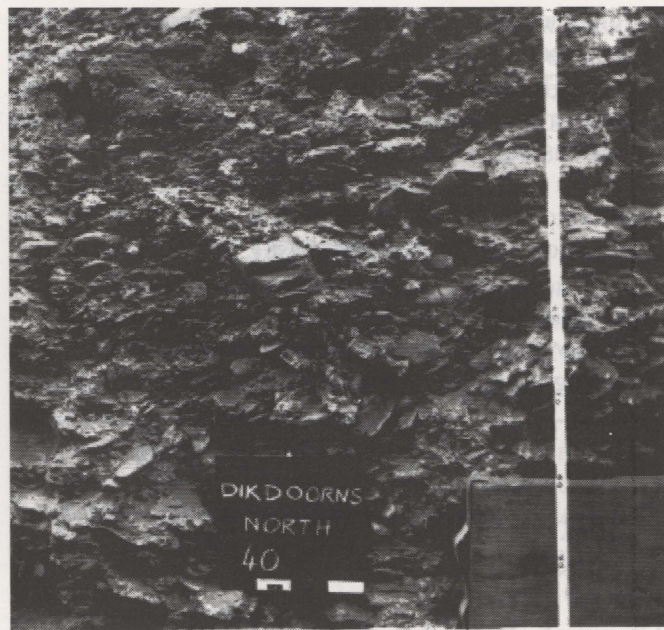


Figure 5: Massive clast-supported gravel (Gm) at Dik Doorns from which two well-rounded pieces of fossilised wood were derived. Scale bar in 5 cm intervals.

Hjulstrom's curve (Novak 1981) the flow of the river was between 90 and 120 cm/sec. The Dik Doorns terrace is the largest deposit and is almost entirely composed of gravel which can be separated into two main facies associations. The dominant facies association comprises massive (Gm) and horizontally bedded (Gh) gravel (Figure 5); the other of cross-stratified (masterbeds) (Gep) and planar cross-bedded (foresets) (Gp) gravel and pebbly sand (Sp). The palaeocurrent direction is to the north (325° N, n=225). The former group represents proximal longitudinal bars,

TABLE 1
Identification of fossil wood samples from Piet Louws Vlei

SAMPLE	BPI No	FAMILY	AGE	CLIMATIC PREFERENCE
PLVA	BP/3/4	Dipterocarpaceae <i>Monotes sp.</i>	Mio-Plio	Tropical, subtropical especially savannas
PLVB	BP/3/5	Fagaceae	Tertiary	Temperate/ tropical, excluding Africa.
PLVC	BP/3/6	Rutaceae	Tertiary	Tropical/subtropical, especially southern Africa and Australia.
PLVD	BP/3/7	Oleaceae (<i>Ligustrum</i>)	Tertiary	Tropical/subtropical, very few temperate.
PLVE	BP/3/8	Fagaceae (<i>Castanopsis</i>)	Tertiary	Temperate/tropical, excluding Africa.
DD	BP/3/2	Polygalceae (<i>Xanthophyllum</i>)	Mio-Plio	Lowland tropical rainforest
DD	BP/3/3	Unidentified	?	-

which are initiated during the falling stages by deposition of the coarser fraction of the bedload in mid-channel. The Gep and Gp facies are interpreted to have formed as modifications of the longitudinal bars by lateral and downstream progradation respectively. Flow velocities based on the largest clasts were nearly 100 cm/sec (De Wit 1993).

Two pieces of silicified wood (Table 1) were recovered from the base of the trench. These are more abraded and polished than those recovered from Piet Louws Vlei.

The deposit on Twee River is only 20m above the present river. The sequence here can be subdivided into two lithofacies associations. Association A is composed predominantly of horizontally bedded gravel (Gh) and sand (Sh) and cross-stratified gravel (Gep) facies, and Association B is composed mainly of massive (Gm) and cross-bedded (Gp) gravel. The latter is typically part of a cyclic braided river (Donjek type; Miall 1978), and the former, which fines upwards and contains soil profiles, represents processes that relate to a wandering river channel on a relatively broad alluvial plain. The interfingering of these associations relates to channel switching rather than migration. Pebble imbrication indicates that the flow was to the north. The mean of the ten largest clasts varies between 5.3cm and 10.9cm, which indicates that the palaeoflow was between 85 and 120 cm/sec.

The younger terraces were therefore deposited by north-flowing coarse grained braided streams (flow between 90 and 120 cm/sec). Lateral accretion was more important in the more recent of the younger terraces.

DIAGENESIS

The deposits in the Sak River Valley have undergone various degrees and styles of cementation. Most of the cements are calcium carbonate. The matrix of the older deposits is made up of a clotted, mottled and peloidal micrite with spar-filled circumgranular and intergranular cracks and channels. The clotted texture results from the crumbly fracturing of the dense micrite and the cracking

results from repeated wetting and drying (Scoffin 1987). Detrital grains, which 'float' in the micritic matrix, are severely etched (Figure 6). Samples taken from the mature hardpan calcrete clasts from the SHV geomorphic surface and from calcrete pebbles in the younger terraces, have identical textures.

The cement of the younger gravels consists mainly of equant calcite spar (Figure 7). These crystals increase in size to the pore centres, and the edges of the clasts are surrounded by isopachous bladed calcite crystals. Precipitation of small sparry calcite cement also occurs at grain contacts where liquids have been held in the meniscus position. Pendant cements occur on the under-surfaces of grains.

These two types of cementation are interpreted as follows. The clotted micritic textures of the matrix of the older deposits form part of the mature pedogenic calcrete which equates with the calcretes on the Bushmanland or SHV geomorphic surface. The calcretes result from the epigenetic accumulation of calcium carbonate during warm and dry climates (Scoffin 1987).

The textures of the younger deposits are typical of cementation by groundwater. The meniscus and pendant cements form in the precipitation member of the vadose zone, just above the phreatic zone. The sparry calcite, infilling the voids, grew in the phreatic zone. The tops of all terraces have immature calcrete profiles which differ petrographically and texturally from that of the hardpan calcrete of the SHV surface, the older terraces and the hardpan clasts which occur within the younger deposits.

The mature calcrete phase, therefore, post-dates the deposition of the gravels on Nels Kop and Paarde Kolk but pre-dates the younger terraces. The immature calcrete post-dates all Cainozoic deposits.

FOSSIL WOOD

Because the cell structures of the wood are faithfully replaced by silica in these samples, it is possible to identify the wood by comparing it with structures of living and fossil trees. Some of the characteristics studied are the size

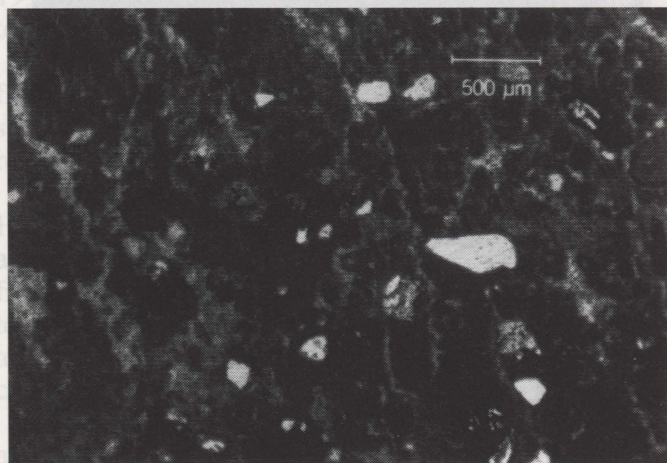


Figure 6: Photomicrograph of matrix of calcretised gravel from Nelskop, showing clotted texture with etched grains.



Figure 7: Photomicrograph of equant sparry calcite from calcified gravel from Twee Rivier.

and distribution of the vessel elements in transverse section (Figures 8 & 9), and in tangential longitudinal sections, the ray width, height, number and cell type (Figure 10). Minute details such as pitting on the cell walls are also important characters. Comparing the cell structure and its climatic distribution, and the distribution of the extant trees, it is possible to define the palaeoclimate.

The fossil wood is described in detail by Bamford (1990, unpublished report) and Bamford and De Wit (this volume). Two different computer aided wood identification packages were used (Ilic 1987; Wheeler *et al* 1986) and the results were cross-checked in the relevant literature (Metcalf and Chalk 1950; see below). Of the seven logs found (Fig. 11), only one was too poorly preserved to be identified. The others were identified to family level and three of them to generic level.

Of the two pieces of fossil wood found at Dik Doorns only one was identifiable: *Xanthophyllum* of the family Polygalaceae. The modern genus *Xanthophyllum* occurs in lowland tropical rainforest and submontane rain forests of Asia (Bridgwater and Baas 1982). The genus is no longer present in Africa. This fossil wood is similar to *X. cuddalorensis* from Mio-Pliocene deposits in India (Awasthi 1986). The Indian wood occurs with other woods which indicate excessively humid conditions.

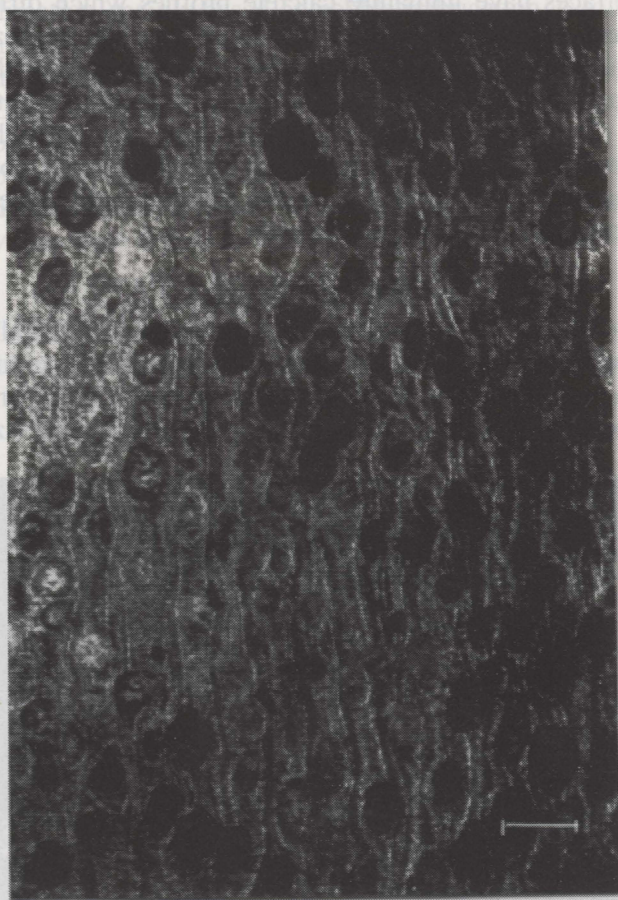


Figure 8: Transverse section of wood of *Xanthophyllum* sp. (Polygalaceae) showing exclusively solitary vessels. Scale bar represents 400 μ

Of the five pieces of wood collected from Piet Louws Vlei, two have been identified as members of the Fagaceae, one of which is *Castanopsis*. The other three are *Ligustrum* of the Oleaceae, one member of the Dipterocarpaceae, *Monotes* sp., and one member of the Rutaceae.

The fagaceous wood is of considerable interest because the family no longer occurs in southern Africa. One member of this family, *Nothofagus* or the southern beech, occurs on all the southern hemisphere continents except Africa and has been used as an example in several biogeographic theories (Van Steenis 1971; Melville 1978). *Castanopsis* has a present day northern hemisphere distribution. Crepet and Nixon (1989) consider the subfamily Castaneoideae to be more ancestral within the family, and they exclude *Nothofagus* from the family. More wood needs to be collected before any biogeographical statements can be made. The Fagaceae are distributed in temperate and tropical regions of the world.

Ligustrum, of the family Oleaceae, is now restricted to Asia, Malaysia and Australia and grows in temperate and tropical regions (Baas *et al* 1988). The wood structure of this fossil is similar to the two tropical species in that it is diffuse porous, has large, solitary vessels and no spiral thickening.



Figure 9: Transverse section of wood of Rutaceae showing vessels arranged in radial groups of 2-3, and solitary. Scale bar represents 260 μ

Members of the Monotoideae (Dipterocarpaceae) occur in tropical and subtropical parts of Africa (Bancroft 1935). Their presence in the fossil record is no surprise but means that the climate was wetter than at present. This sample of wood compares with samples from India of Mio-Pliocene age (Bande and Prakash 1984). The particular suite of fossil woods in the Indian deposits is the same as occurs in their extant forests in Assam (Prakash and Awasthi 1969).

The last piece of wood belongs to the family Rutaceae which is widespread in tropical and subtropical regions of the world (Record and Hess 1949; Cronquist 1981; Gregor 1989). It has radial rows of vessels, a feature which does not occur before the Tertiary (Wheeler and Baas 1991).

The present vegetation of the region is arid Karoo and false desert grassveld and there is no indication of tropical or subtropical vegetation or rainforest (Acocks 1951).

AGE OF DEPOSITS

The fossil bone from Paarde Kolk was identified as an incomplete edentulous lower jaw of a hippopotamus-like animal *Antracotheriidae* (Hendey 1984), which is known to have inhabited Africa between the Early Oligocene and Late Miocene (Black 1978).

The original older fluvial deposits are therefore most likely Miocene in age, which is similar to the basal part of the sequence at Bosluispan in the Koa valley, Namaqualand (De Wit 1990). Furthermore, geomorphological studies, palaeoflow measurements and provenance of the heavy minerals of the basal gravels strongly suggest that the Geelvloer River was connected with the Koa valley (Figures 1 and 2), and hence the Bosluispan deposit (De Wit 1990), during the Middle Miocene (De Wit 1993). The fossil wood samples from Piet Louwsvlei also suggest that the older terraces, although reworked, are Tertiary and probably middle Miocene in age (Table 1, Bamford 1991).

These deposits along with the general area were probably calcretised at the end of the Miocene (De Wit 1993). Clasts of this calcrete are present in the younger terraces.

The degree of abrasion of the fossil wood samples from Dik Doorns suggests that they have undergone substantial transport and it is likely that they were reworked from the older deposits.

No other fossils were found in the younger terraces. However, based on similarities of lithofacies, facies associations and diagenesis of these gravels with those from the Van Wyksvlei sequence in the Carnarvon Leegte to the east (De Wit 1993), it seems likely that the younger terraces and the Van Wyksvlei sediments, which also contain hardpan calcrete clasts, are of similar age.

The Van Wyksvlei sequence produced several *Equus* and antelope teeth and the age of this deposit has been assigned to the Plio-Pleistocene (De Wit 1993). These fossils also indicate a more grassland type of environment (Hendey 1983).

PALAEOENVIRONMENTAL CHANGES

There is no Early Tertiary geological record in the north-west Cape Province. However it has been inferred from the offshore record that erosion was minimal during this period (Dingle and Hendey 1984; Partridge and Maud 1989). The preservation of crater facies over ultrabasic intrusions and the results of apatite fission track analyses of basement samples, suggest that the region has been relatively stable since the end of the Cretaceous (De Wit 1993). The main geomorphological surfaces, which had developed by the end of the Cretaceous, matured during the Early and Middle Tertiary (De Wit 1988) when a semi-arid to arid climate prevailed (Ward and Corbett 1990).

Climatic change was experienced in the Miocene from semi-arid to more tropical conditions, which can be deduced from the macro-fossils in Brandvlei and Bosluispan (De Wit 1990), but more significantly from the fossil wood samples from Brandvlei (Bamford 1991). The latter indicate that the area was well-wooded with a tropical to sub-tropical type of vegetation. Interpretation of the basal facies at Bosluispan conform with a major low-sinuosity river and palaeontological material from here suggests that the river was active during a period of humid conditions (De Wit 1990). The

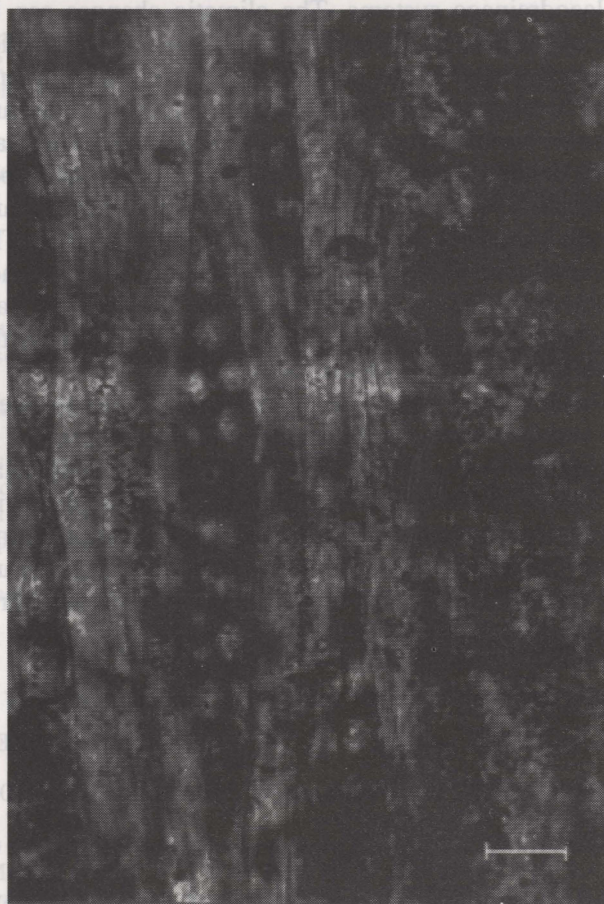


Figure 10: Tangential longitudinal section of wood of Rutaceae showing uniseriate and biserate rays. Scale bar represents 45μ

concentration of diamonds, both at Bosluispan and in the older Brandvlei deposits, suggests that degradation may have carried on for some time during the Middle Miocene. However, deterioration of the climate at the end of the Miocene is evident from the sequence of evaporites and aeolian sands overlying the middle Miocene fluvial facies at Bosluispan (De Wit 1990). In fact, it is believed that this arid phase was responsible for the main calcrete phase (Ward and Corbett 1990), which also affected the older deposits near Brandvlei.

This arid phase was interrupted by a wet spell in the Plio-Pleistocene, when the younger terraces were deposited and clasts of this mature calcrete were incorporated in the younger deposits.

The climate here supported mainly grazers such as *Equus* and antelope (De Wit 1993). The Plio-Pleistocene wet phase also deteriorated and this is recorded in the Van Wyksvlei sequence, where ephemeral stream deposits, aeolian sands and immature calcrete overlie the basal fluvial facies (De Wit 1993).

Because the terraces occur above the Great Escarpment it is unlikely that base level changes have had a significant influence on the river behaviour. Climatic changes, re-exhumation of the pre-Karoo topography and possibly some tectonic adjustment were therefore the main factors in the development of these palaeodrainage systems. The climatic changes can be directly related to the oceanic circulation pattern, which was influenced by the relative position of the continents after breakup of Gondwana. The present-day climate and oceanic circulation pattern can be traced back to the Late Oligocene, when the circum-Antarctic current developed (Kennett 1980), following separation of Antarctica and South America, and Antarctica and Australia. The Benguela upwelling was driven by the strengthened Antarctic bottom water during the Middle to Late Miocene (Siesser 1978), reinforcing the aridity in the Late Miocene (Ward and Corbett 1990).

In the northern hemisphere these palaeo-environmental changes were complicated by the establishment of major landlinks (Middle East and the Iberian peninsula), as a result of the collision of the Afro-Arabian plate with the European plate. A 'corridor route' of floral and faunal interchange was opened between Africa and Eurasia and the faunas and floras of both continents underwent profound changes (Hendey 1984).

CONCLUSIONS

Remnants of original and reworked alluvial terraces occur along the middle reaches of the Sak River near Brandvlei in Bushmanland. Geomorphologically these deposits can be subdivided into more elevated (60m) older deposits, and younger bedrock terraces which are between 20m and 30m above the present river level. The older deposits, which are partly reworked, all occur between 7km and 11km west of the present Sak River, in the Geelvloer palaeovalley. This valley can be linked to the Koa Valley which contains fluvial sediments of similar age and facies. The younger deposits all occur within the Sak River Valley proper.

The older deposits were formed by a braided river system of the Donjek type, and contain sub-angular fossil wood and mammalian bone fragments. In the absence of older post Karoo deposits in the area, from which the fossil wood could have been derived, and based on the brittle nature of the mammalian bone it is inferred that the palaeontological material is locally derived and that this river system was of Middle Miocene age. Fossil wood fragments, which include Fagaceae, Oleaceae and Combretaceae, indicate that the environment was subtropical to tropical and that the area was covered in woodlands, and followed a semi-arid to arid Early to Middle Tertiary.

Rapid deterioration of the climate resulted in a major calcrete phase, of which only remnants are preserved and which also affected the older deposits. Clasts of this calcrete can be found in the younger alluvial terraces which were deposited during a pluvial stage in the Plio-Pleistocene. Palaeoenvironmental reconstruction suggests that the climate of this period was capable of supporting grasslands only. A gradual deterioration of the climate of this period is recorded in the Van Wyksvlei sequence, which eventually led to the present arid Karoo and false desert grassveld (Acocks 1951).

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vessel size decreases while vessel frequency increases with intensifying aridity.

ECOLOGICAL INFERENCES FROM XYLEM ANATOMY

It makes no sense to argue that xylem vessel size and frequency are the only wood anatomical characteristics which are habitat controlled. The conduction of water through a plant depends on too many factors (porosity,

size and frequency in archaeological wood samples may be related to climate when compared to the same measurements on an extant sample from areas of known temperature and rainfall (Scholtz 1986; February 1990, 1992). In assessing this technique of climate reconstruction it was necessary to determine the exact relationship between rainfall and xylem vessel size and frequency in a number of woody species. It is this