

THE SIGNIFICANCE OF THE CRETACEOUS DIAMONDIFEROUS GRAVEL DEPOSIT AT MAHURA MUTHLA, NORTHERN CAPE PROVINCE, SOUTH AFRICA

M.C.J. DE WIT

Department of Geology, University of Pretoria, Pretoria 0002, South Africa
e-mail: deWit@icon.co.za

J.D. WARD

17 Buitekring, Stellenbosch, South Africa
e-mail: jdwl3@vodamail.co.za

M.K. BAMFORD

BPI Palaeontology, University of the Witwatersrand, Private Bag 3, Johannesburg, WITS 2050, South Africa
e-mail: marion.bamford@wits.ac.za

M.J. ROBERTS

De Beers Group Exploration, Johannesburg, South Africa
e-mail: mike.roberts@debeersgroup.com

© 2009 June Geological Society of South Africa

ABSTRACT

Remnants of diamond-bearing fluvial gravels of Cretaceous age have been preserved on the Ghaap Plateau north-west of Reivilo at 1455 m above sea level. The alluvial deposit contains well preserved fossil woods representing at least four periods: Post-Permian (Upper Karoo), Early Cretaceous, Late Cretaceous and Tertiary. The Karoo specimen has been derived from Beaufort Group sediments, now eroded from the Ghaap Plateau. More significant are the presence of Early and Late Cretaceous woods, both periods believed to have been wetter in the interior of southern Africa. In addition to the diamonds, other kimberlite derived minerals such as ilmenite and garnet have also been recovered from these gravels. Detailed mineral chemical analyses of the ilmenites and those occurring in primary sources within a radius of 120 km of the Mahura Muthla area indicate that the most likely source are kimberlites occurring to the south-south-east, indicating that the palaeo-channel was flowing from the south-east to the north-west. This is supported by the presence of ironstone and red chert cobbles and pebbles derived from the Proterozoic Kanguru Member outcropping directly south of the channel. Further evidence comes from a palaeo-tributary on Laurika which joined the main Mahura Muthla trunk stream from the south-west; limited pebble imbrications; and a decrease in the sizes of wood, agate and ironstone cobbles and pebbles in a northerly direction associated with an increase of roundness of these clasts. At the start of the Cretaceous the area was covered by sandstones of the Beaufort Group with overlying flood basalts of the Drakensberg Group. First during the Early Cretaceous the Mahura Muthla channel was incising into an easterly retreating palaeo-escarpment of Karoo basalts. Group 2 kimberlites such as Finch, Darleston and Duivelskop, had already intruded these basalts around 120Ma. The north-westerly orientated drainage was directly linked to the drainage basin of the Kalahari River draining the northern part of the northern Cape and southern Botswana via the palaeo-Molopo and lower Orange River. This period of erosion would have released an abundance of agates from the basalts that are so abundantly present in the gravels and also diamonds from these Group 2 kimberlites. On comparing the mineral chemistry of the ilmenites the most likely source for these kimberlitic minerals is the area to the south east of Mahura Muthla. Kimberlites occurring in this area include the Duivelskop Group, X 154, Pienaarspoort, the Bellsbank Group, Bull Hill and Mayeng. At least some of these could have provided diamonds to the gravels. Later during Upper Cretaceous times the Karoo basalts had been removed and the drainage stripped the remaining sediments of the Beaufort Group before the sinuous channel became locked and preserved within the Transvaal dolomites. Subsequently the channel became calcretised during the development of the African Surface in the Early Tertiary. Mahura Muthla remained part of the Kalahari River basin which fed the Molopo River and the lower Orange drainage network and by the Early Tertiary the latter had captured the Vaal and the upper and middle Orange River drainage basin which had been part of the Karoo River drainage for most of the Cretaceous.

Introduction

Diamond bearing gravels have been known to occur on the Ghaap Plateau, some 25 km north-west of Reivilo and 60 km east of Kuruman in the North-West Province, since the early 1900's (Figure 1). Mining activities for

diamonds had taken place on the farms Mahura Muthla 198 and Gras Pan 773 but remnants of these agate-rich gravels can also be found to the north-west on the farms Groote Buitfontein 772, Tlaring 197 and Mooifontein 640. The first official records of the gravels and the diamonds

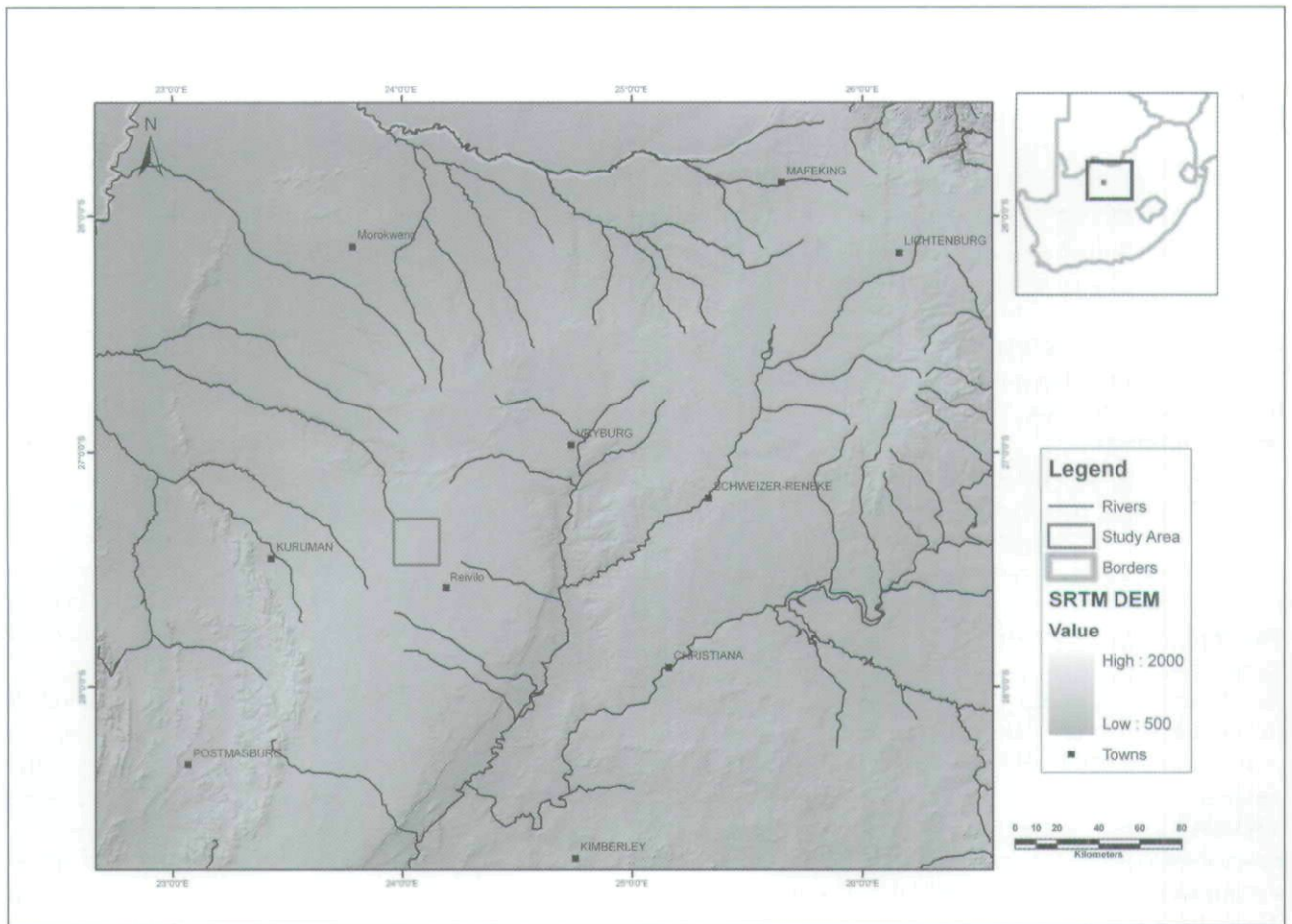


Figure 1. Location map of Mahura Muthla area located on the Ghaap plateau of the Northern Cape Province. Grey-scaled low areas (dark) to higher (lighter) areas.



Figure 2. A small parcel of diamonds extracted from the Mahura Muthla palaeo-channel in 2002. Note the unbranded nature of the stones. Scale 1 cm wide.

were by Wagner (1914) but Rogers et al (1929) also refer to some unpublished and undated notes of these deposits by A.L. Du Toit.

The gravels had yielded over 3500 ct, the bulk of which had been recovered prior to 1913 and mostly from the Mahura Muthla part of the system. The largest reported stone was 8 ct (Wagner 1914). Further diamond recoveries have been reported by: Van der Westhuizen, a previous surface owner, who had recovered 7 diamonds the largest of which was 3.4 ct (Van der Westhuizen, personal communication, 1991); Partridge who had recovered 19 stones from the dumps in 1987 which were all clear dodecahedral forms, mostly between 1 and 1.2 ct in size with the largest being 3 ct (Partridge, pers. comm., 1991); and finally by Visser who recovered 49 cts from the basal gravel in 1991 of which a 2.5 ct stone was the largest diamond (Ward, 1992). Despite the fact that it was a small population, 83% of the diamonds that Partridge recovered in 1991 were unbranded and appear to be unrelated to those found in the alluvial fields around Lichtenburg and Bloemhof well to the east (Figure 2).

The gravels are agate-rich but have also produced a wealth of fossilised wood of various ages providing important clues on the age and palaeo-environment of this deposit. Since the source for the diamonds in these

gravels has yet to be established, various workers have attempted to establish the palaeo-flow direction. Exploration geologists from De Beers including Hawthorne (1959), Stratten (1971) and Ward (1992) have always advocated a flow direction from south to north. In contrast Partridge (1990; 1998) suggested, on basis of the clasts assemblage and the orientation of the fossil logs, that the gravels had been derived from the north-west and that the original Mahura Muthla River flowed from north to south. Partridge (1998) estimated the age of this system to be Santonian-Campanian (86 to 65 Ma) and implied that it was active before the formation of the Kalahari Basin and that the drainage later would have become reversed.

Wagner (1914) lists pyrope and ilmenite as fairly common in the concentrate of the gravel. These he felt were generally un-abraded and therefore suggested that the diamonds were derived from a proximal kimberlite source (Wagner, 1914). The chemistry of the major elements of these minerals has been used in this study to establish the source area of the gravels, and ultimately to identify the primary source for the diamonds. In addition to the geochemical signature of some of the heavy minerals in the gravels, clasts lithologies, sedimentary structures and the palaeontological evidence of this deposit has been used in the overall geomorphological reconstruction. Our findings support a north-westerly flowing Mahura Muthla palaeo-channel during the Cretaceous.

Geology

The entire remnant gravel belt has been preserved on the flat lying dolomite and limestones of the Reivilo Formation in the Campbell Rand Subgroup (Ghaap Group) of the palaeo-Proterozoic Transvaal Supergroup (Eriksson et al., 2006). On a very gently north-westward sloping surface the rocks increase in age eventually exposing the underlying Allanridge Formation of the Ventersdorp Supergroup some 30 km north of Mahura Muthla. Several kilometres south-west of the outliers on Mahura Muthla is the Kanguru and uppermost Member of the Reivilo Formation. The overlying Fairfield Formation of the Campbell Rand Subgroup is found directly south again and overlies the Kanguru Member (Figure 3).

The carbonates of the Reivilo Formation comprise mainly fine-grained dolomite with giant stromatolitic domes intercalated with cycles of columnar stromatolites and fenestral facies. Oolitic beds are intercalated in places. Limestones occur in the lower sections with chert and chert breccias towards the top (Beukes, 1980).

The top of the Reivilo Formation is characterised by an ironstone member of only a few metres thick. It was mostly deposited during a transgression over the Campbell Rand platform (Beukes, 1983). This Kanguru Member, previously referred to as the Kamden Member, also contains jasper and red chert bands (Beukes, 1983) and forms a very important marker on the Ghaap plateau (Figure 3). It is at present topographically at a

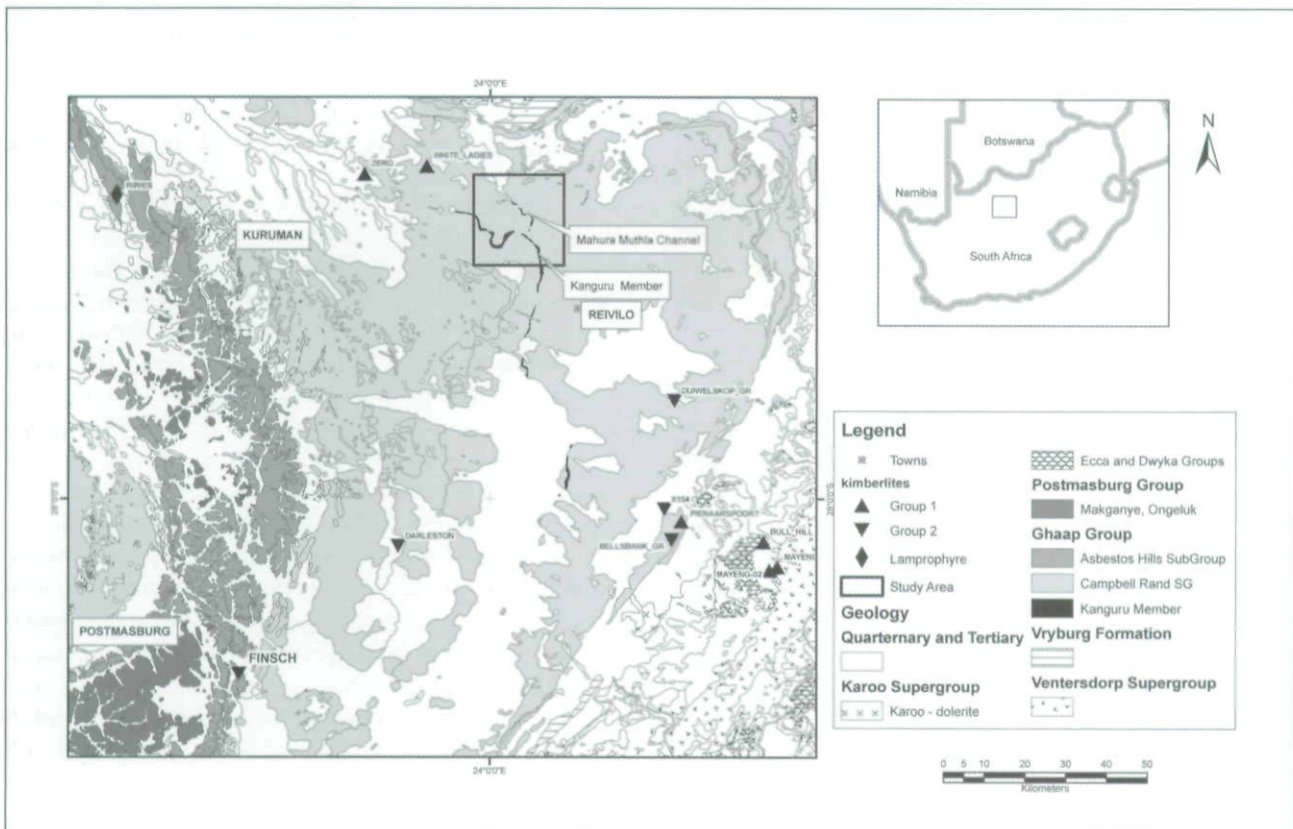


Figure 3. Regional geology of the Ghaap area.

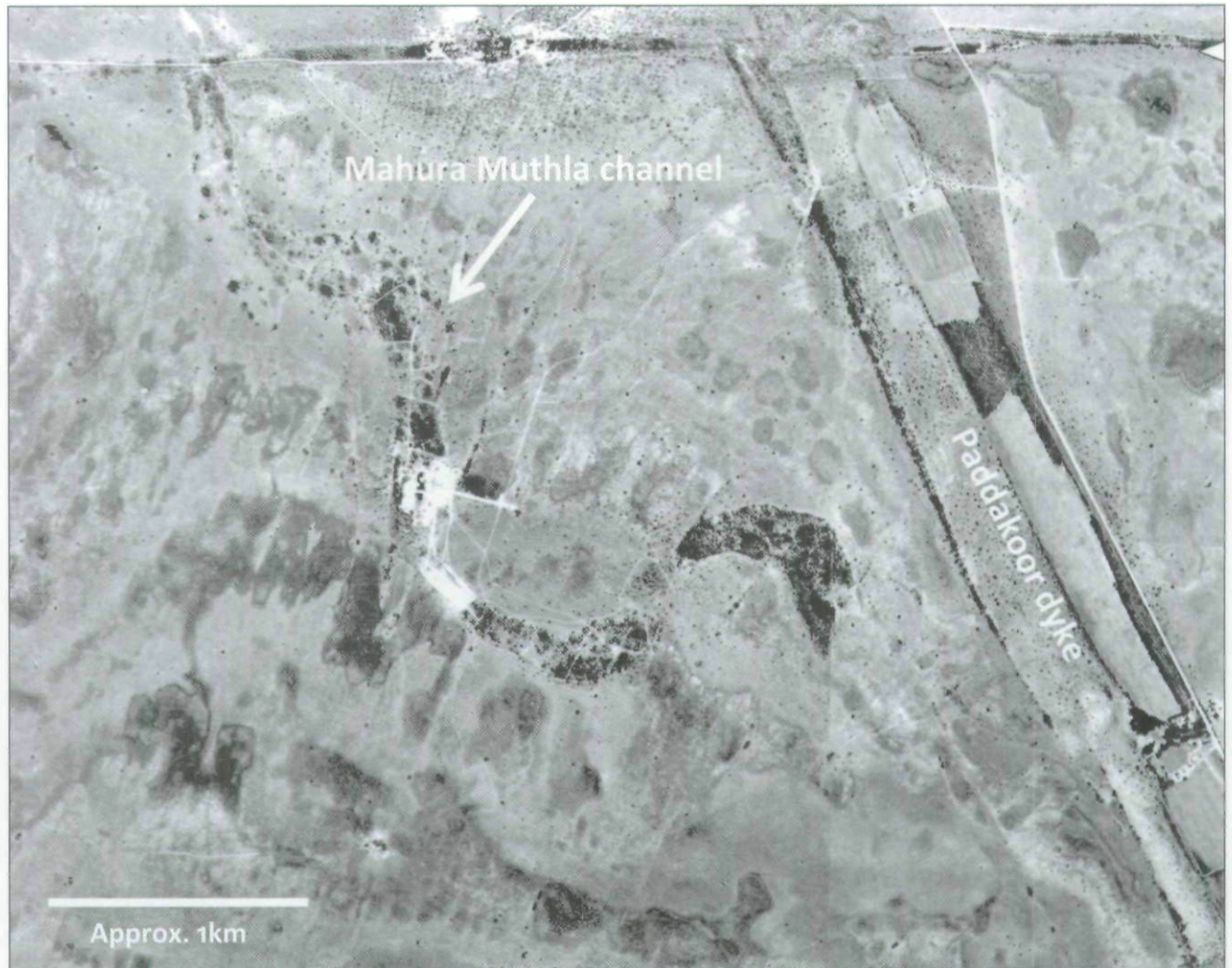


Figure 4. Aerial photo of Mahura Muthla with the sinuous palaeo-channel close to the intersection of two dykes. Also note the outline of the iron stones of the Kanguru Member just to the south of the palaeo-channel.

higher elevation to Mahura Muthla. The Kanguru Member is overlain by the Fairfield Formation clastic laminated carbonate beds passing upwards into columnar stromatolites and fenestrated laminites (Eriksson et al., 2006).

The platform carbonates have been intruded by numerous diabase dykes in various orientations. The predominant orientation is a north-north-westerly direction but others occur in a north-north-easterly and an almost east-west direction. Some form linear positive topographic features, particularly those that strike in a north-north-westerly direction (Figure 4). Although the ages of these are likely to be Karoo others may well be older possibly associated with the Ongeluk Formation extrusive igneous rocks occurring at the top of the Transvaal Supergroup.

Kimberlites within a radius of 120 km of Mahura Muthla are found to the north-west, south-southwest and south-east to south-southeast of Mahura Muthla ranging in age from Proterozoic to Cretaceous (Figure 3). Some 30 and 40 km to the north-west of the diamond-bearing gravels are the Group 1 kimberlites of White Ladies and Zero respectively, both part of the Kuruman province

(Shee et al., 1989). Almost 120 km west of Mahura Muthla is the Riries lamprophyre (Donnelly, 2008); south-southwest and 80 km from Mahura Muthla are the Darleston (Group 2) occurrences including X007 (Donnelly, 2008); and to the south-east are the Duivelskop (Group 2) pipes at 50 km, the X154 (Group 2) pipe 85 km, the Pienaarspoort (Group 2) dykes 87 km and the Bellsbank (Group 2) dykes (Smith et al., 1985) some 90 km, the Bull Hill (Group 1) kimberlites 100 km and the Mayeng (Group 1) sills and dykes (Apter et al., 1984) 110 km from Mahura Muthla (Figure 3). Except for the Bellsbank Group none of the kimberlites listed above have developed into economic deposits, and whilst some diamonds had been reported in most of these none have been significant in terms of grade.

The two types of kimberlite, Group 1 and Group 2, have distinct isotopic and petrographic signatures (Smith 1983) but more importantly they exhibit different intrusion ages. The Cretaceous Group 1 kimberlites have approximate ages of between 100 and 75 Ma whilst the Group 2 kimberlites range in age from approximately 140 to 105 Ma.



Figure 5. The calcretised part of the upper sediments within the Mahura Muthla palaeo-channel.

Local geomorphology

The Mahura Muthla gravels occur on a very gently sloping surface of the Ghaap Group. This surface, also referred to as the Ghaap Plateau, is marked by a very subtle north-eastward orientated drainage divide which separates the present day north-westward flowing Kuruman drainage from more local south-eastward draining streams towards the Dry Harts and Vaal drainage. The latter substantially increase in slope towards the edge of the Griqualand West carbonates. The Mahura Muthla gravels are located within the uppermost part of the present Kuruman drainage basin (Figure 1).

Estimates of post-emplacement erosion of Group 1 kimberlites through the study of upper-crustal xenoliths of some Cretaceous age kimberlites have suggested that in the Kimberley area this has been reduced from 1400 m (Hawthorne 1975) to approximately 850 m (Hanson 2007). According to Hanson (2007), basalt xenoliths in the Kimberley-Finsch area were found in all kimberlites over 100 Ma, generally the Group 2 variety, and suggested that the younger sequence of Karoo flood basalts (Lesotho Formation) covered the entire area from Lesotho towards Kimberley and Finsch on the Ghaap plateau at least. This is supported by the presence of upper-crustal Karoo basalt xenoliths in the Darlestone kimberlite (J. Ward, personal communication, 2009). No Lesotho basalt clasts are present in the younger Group 1 kimberlites in the Kimberley – Finch region (Hanson, 2007) which implies that this blanket of Karoo flood basalt had been removed from central South Africa by approximately 85 Ma.

Hanson (2007) also investigated the extent of the Karoo sediments and concluded that the cover around Finsch and Postmasburg had mainly been Beaufort Group rocks. This supports earlier observations that only Beaufort Group sediments had been recognised in Finsch mine (Visser 1972). 'Stormberg' Group sediments (Molteno, Elliot and Clarens Formations) had not been deposited as far west as the Ghaap Plateau (Hanson,

2007) and on the Ghaap Plateau the Beaufort would have been underlain only by thin and isolated patches of Dwyka and Ecca Group sediments.

This has important implications for the Mahura Muthla area, as only between 300 and 400 m of Beaufort sandstones and some 1200 to 1500 m of Karoo flood basalts have been modelled there at around 120 Ma (Hanson, 2007). By 85 Ma all of the basalt would have been removed leaving less than 300 m of cover of Beaufort sediments in and around Mahura Muthla.

Remnants of mature pedogenic calcretes are present on most parts of the pediplained Ghaap Plateau although these are more widespread and better preserved further south between Ulco and Douglas. The upper parts of the Mahura Muthla gravels are also highly calcretised and cemented by carbonate (Figure 5), and were probably part of the overall duricrust development on the Ghaap. According to Partridge and Maud (1987) this represents the African erosion surface and hence postdates the Campanian (~65 Ma). The development of these calcretes marked the end of the humid climatic periods of the Cretaceous (Partridge, 1998) and it has been suggested that by the end of the Cretaceous a degree of desiccation had occurred, resulting in a drier Cainozoic period (Partridge, 1998). It can therefore be assumed that the last Karoo remnants on the Ghaap plateau were removed sometime between 85 and 65 Ma.

The presence of striated bedrock near Boetsap at the edge of the Ghaap plateau (Visser et al., 1986) suggests that the pre-Karoo surface is very close to the present day surface on the Ghaap and that only minor erosion of the pre-Karoo rocks would have occurred in the Tertiary. Hence the main sediment source for Mahura Muthla type drainage would have been sands from the Beaufort Group and agates from the Karoo flood basalts. This is in agreement with Hawthorne (1959) who suggested that the yellowish, reddish and pale grey agates are considered to have been derived from the Drakensberg Group volcanics. The yellowish and reddish agates, along with green chrysoprase, are also found in abundance in the old diamondiferous gravels at Bakerville near Lichtenburg and thus may be derived from a subset of the Drakensberg Group basalts. Hawthorne (1959) on the other hand suggests that some of the green agates appear similar to those derived from the Vaal River in the Warrenton area and presumed to be derived from the Ventersdorp Supergroup possibly eroded out of the limited Dwyka Group sediments.

The Mahura Muthla distributary system

The Mahura Muthla deposit is well-cemented calcified gravel that has been preserved within the carbonates of the Reivilo Formation (Campbell Rand Subgroup) which forms the sidewalls and footwall of the channel. In places potholes have been preserved within the footwall measuring up to 3 m in diameter and between 2 and 3 m deep (Figure 6).



Figure 6. Pothole of the dolomite footwall along the edge of the Mahura Muthla palaeo-channel.

Although the exposures are poor, the channel which forms a ribbon-like feature can be traced as patchy remnants from Graspan 773 in the south across Mahura Muthla 198 onto Tlaring 197 where it disappears. This is over a distance of some 20 km but the best preserved portion of it occurs on Mahura Muthla itself (Figures. 4 and 7). Further to the north-west gravels of similar composition had been intersected at depth during a drilling programme on the portion Paddakoor of Groot Buitfontein 772 (Jackson, personal communication, 1991) and it is suggested that the channel can be traced even further north-westwards on Mooifontein 640.

The north-north-westward orientated channel is highly sinuous particularly across the Graspan 773, Mahura Muthla 198 and Tlaring 197 section. The meanders measured from Graspan 773 to Groot Buitfontein 772, a distance of 18.7 km, and expressed as the level of river sinuosity is 1.47 or 66.8%. This makes



Figure 7. Oblique aerial view of the sinuous Mahura Muthla palaeo-channel looking towards the south east. Note the workings in the fore-ground.

this section of the palaeo-channel very sinuous (Figure 7).

The depth of the channel according to Wagner (1914) is just over 9 m (30 feet) and this has been confirmed by more recent work on the deposit where the depth of the channel rarely exceeds 10 m and its width varies between 100 and 150 m (Ward 1992). The diamonds are practically confined to the lower part of the deposit which is referred to as the 'raisin-loaf' because of the abundance of carnelian (reddish agates) set in a matrix of white carbonate (Wagner, 1914).

On portion Laurika of Tlaring 197 there is a calcified gravel channel deposit trending south-south-westwards which acts as a tributary to the main Mahura Muthla channel. Importantly Ward (1992) reports that the clast assemblage of the Tlaring tributary is significantly different in that the carnelians, which are dominant in the main channel, are absent.

The infill sediments

The Mahura Muthla gravels are well-cemented sediments that display a typical fining-upward sequence from basal gravels to finer-grained and calcitised sediments on top. The abundance of agates in the smaller fraction of the gravel horizons has resulted in the above mentioned 'raisin-loaf' textures (Figure 8).

Coarse-grained basal gravel.

This is generally between 0.1 to 2.5 m thick. The boulder to cobble fraction is dominated by locally derived dolomite, black chert, red chert, shale and ironstone clasts which are not well rounded (Figure 9). The banded ironstone, red chert clasts and shale are derived from the upper Reivilo Formation and particularly the former two from the iron-rich Kanguru Member which forms such a distinct marker on the Ghaap plateau (Beukes 1983) and crops-out just to the south-west of the channel (Ward 1992). The finer pebble



Figure 8. Smaller fraction of the gravel is rich in carnelian (agates) set in a matrix of white carbonate.

Table 1 XRD analyses (in %) from selected samples (Council of Geoscience).

Sample no	Description	Quartz	Plagioclase	K-Feldspar	Dolomite	Calcite	Kaolinite	Illite	Smectite	Palygorskite
CKO 038	Whitish-grey clayey clast	34							59	7
CKO 039	Grey clayey clast	54	10				20	5	11	
CKO 040	Reddish-green clast (upper)	24		2	3	2			52	17
CKO 041	Clayey matrix (basal)	30	1	1	42	9			2	15

**Figure 9.** Basal gravel rich in locally derived dolomite, chert and iron stone clasts overlain by cross-bedded sands. Hammer for scale.

to small cobble fraction of the gravel is mainly composed of resistates which is dominated by siliceous clasts including, agates (yellow, red, blackish, grey and dark green to yellow-brown), well-rounded sandstones/quartzites, rare amygdaloidal volcanic material and fossil wood. Rare diamonds are also present.

Hawthorne (1957) noted that the agates decrease in size from the south to the northwest. This decrease is particularly evident from Graspan 773 in the south to Mooifontein 640 in the north-north-west. Similarly the ironstone clasts become smaller and more rounded over the same section. The sub-rounded and smaller ironstone clasts in the main channel on Tlaring 197 in the north-west display percussion scars, as does the black chert in the Tlaring tributary.

X-Ray Diffraction analyses were undertaken by D. Buhmann of the Council of Geoscience in Pretoria on selected samples of unusual clayey clasts within the gravels as well as the matrix of the gravels (Table 1).

The occurrence of kaolinite and smectite-rich clasts in the gravels that are cemented largely by carbonate and the related palygorskite clay probably reflects a palaeo-climatic change from wetter to drier conditions. Kaolinite is usually a product of more intense weathering whilst smectite is a common derivative of the weathering of potassium-poor mafic rocks, such as basalt (Blatt et al 1980). The smectite-rich clasts preserved in the gravels are probably weathered basalt pebbles and cobbles, derived from the Karoo volcanics now removed from the Ghaap, that have been altered under wetter climatic conditions during the Cretaceous.

The digging operations on Graspan 773 have also recovered several large unabraded tree trunks some with branches still attached. Smaller pieces of more abraded silicified wood have been found in these gravels on Graspan 773, Mahura Muthla 198, and portion Laurika of Tlaring 197.

Pebble imbrication in the basal gravels was only observed on Graspan 773 and measurements of the former are summarized in table 2 suggesting that the palaeo-flow was mainly from the south.

Table 2. Imbrication measurements on Grasfontein 773

	Imbrication	Source Quadrants
Graspan 773	208° (n=17):	south-southeast 6%
	range 166-262°	south 24%
		south-southwest 29%
		southwest 29%
		west-southwest 6%
		west 6%.

Upper gravel units.

The basal gravel is overlain by a series of fining-upward and finer grained gravel units (Figure 9). Directly overlying the coarse basal gravel is a coarse pebble to cobble gravel upward-fining unit with sandy matrix. This unit is generally 1 m thick and has a gradational contact with the basal gravel.

Several finer grained gravel units of between 0.1 to 1.3 m thick are found higher up and mark the upper gravel portion of this package. Tabular cross-stratification in the upper parts of the more sandy part was only seen in one section on Gras Pan 773. The planar cross beds of the latter are directed towards the south-south-east (175°). These occur in the upper sandy units and are interpreted as sands avalanching laterally on migrating sandy bars moving downstream in a direction associated with the palaeo-current direction of the basal gravels.

Calcrete

The whole sequence is overlain by a thick and mature calcrete which can be up to 7 m thick (Figure 5). Sedimentary structures are rare and have obviously been affected by the pedogenic calcretisation process of the sands and gravels. This process, which not only alters the matrix diagenetically by carbonate replacement, also results in a significant increase in volume disturbing the original textures by physical expansion (Netterberg, 1980). Secondly and much later, small scale karstification

Table 3. Fossil wood from Mahura Muthla 198 and Graspan 773. Numbers are the catalogue numbers and should be preceded by "BP/16/" (BPI collection)

Family	Genus, Species	Age	Sample	Mahura Muthla	Graspan
Conifer	<i>Agathoxylon africanum</i>	Paleozoic – Mesozoic	Pebble	206, 207	198c, 198d, 198e, 198f, 198g
Conifer	<i>Agathoxylon karooensis</i>	Permian	Log	336	
Gymnosperm	<i>Agathoxylon sp.</i>	Paleozoic – Mesozoic ?	Pebble	330, 335, 343-348,	
Conifer	<i>Brachyoxylon sp.</i>	Upper Jurassic – lower Cretaceous and older?	Pebble	333	198a, 198b, 198h
Podocarpaceae	<i>Podocarpoxyylon mababalei</i>	Mio-Pliocene ?	Log	339, 340	
Podocarpaceae	<i>Podocarpoxyylon umzambense</i>	Upper Cretaceous	Log	327	197b, 197c
Podocarpaceae	<i>Podocarpoxyylon sp.</i>	Mesozoic	Log	106, 205, 326, 328, 329, 331, 334, 337, 338, 341, 342	
Angiosperm	unidentified	Upper Cretaceous – Early Tertiary	Log	204	197a

processes of the calcrete would have influenced post-depositional processes particularly in the upper sections of the deposit. The latter has produced some solution cavities or 'makondos' in the calcrete surface preserving few textures and structures of the original deposit. The decalcification process is likely to be considerably younger than the cementation of the original deposit indicating that the calcrete is indeed fossil. In places the calcrete is overlain by reddish-brown sand.

Fossil wood

Silicified tree trunks and pebbles have been recovered from the gravels at Mahura Muthla 198 and Graspan 773. By identifying the woods based on their internal cellular anatomy, and making comparisons with fossil woods of known age ranges, it was possible to date the woods and, therefore, the gravels and associated drainage. This has been successfully applied for instance to terraces along the Sak River in the Brandvlei area in Bushmanland (de Wit and Bamford 1993).

Seven (7) types of wood were recognised: three (3) from Permian to Lower Jurassic (Karoo age), one from the Upper Jurassic-Lower Cretaceous, one Cretaceous, one exclusively Upper Cretaceous and one from the Tertiary (Table 3). The older wood types represented are mostly well-rounded and show evidence of transportation and/or reworking. The younger ones are mainly tree trunks and logs which have not been transported far. Mahura Muthla 198 and Gras Pan 773 have similar complements of wood types and deposition history but at Gras Pan 773 there are also angiosperm tree trunks which are of Tertiary age and are relatively unabraded.

Materials and methods

Each piece of silicified wood was cut with a diamond blade to form three faces, a transverse section, radial longitudinal section, and a tangential longitudinal section. Each face was then polished, and mounted on petrographic glass slides. The rest of the block was cut off using a discoplan saw and the remaining section

ground and polished to a thickness of about 40µm. The thin sections were studied, measured and photographed. Measurements of cell dimensions are based on an average of at least 25 cells with the ranges given. Pits are often less abundant so the average is given. Woods were compared with other fossil woods in the Bernard Price Institute Palaeobotany Collection in Johannesburg and with woods described in the literature.

Systematic description of fossil woods

Protopinaceae Kräusel, *Brachyoxylon* Hollick and Jeffrey (1909), *Brachyoxylon sp.*

<i>Specimen No</i>	BP/16/198b
<i>Locality</i>	Graspan, sample no. BPX 444, GP 772
<i>Collector</i>	M.C.J. de Wit
<i>Other specimens</i>	BP/16/198a, 198f, 198h (all Graspan), 333, 349 (both Mahura Muthla)
<i>Figures</i>	10a to d

Description

The piece of wood is small, brown, well-rounded pebble, less than 4 cm long. Growth rings are distinct but spring wood has been distorted. Tracheids are square to rectangular, thin-walled, and arranged in regular radial rows with 1 to 5 to 9 tracheid rows between the dark rays (Figure 10a). Early-wood mean tangential diameter is 62µm (range 50 to 72µm) and mean radial diameter is 62µm (range 43 to 77µm). Parenchyma, traumatic ducts and resin are absent. Bordered pitting on the radial walls of the tracheids (Figure 10b) is of the mixed type with uniseriate and contiguous to slightly compressed pits (araucarian), and uniseriate, round and contiguous or separate pits (abietinian). In a few instances the pits are biseriata and opposite to sub-opposite. The average pit diameter is 13 to 15µm. Cross-fields are filled with 4 to 6 narrowly bordered, round to oval pits (taxodioid or araucarioid) 10 x 7µm in size (Figure 10c). Rays are uniseriate and 2 to 10 to 15 cells high (average 85 to 575µm) with very

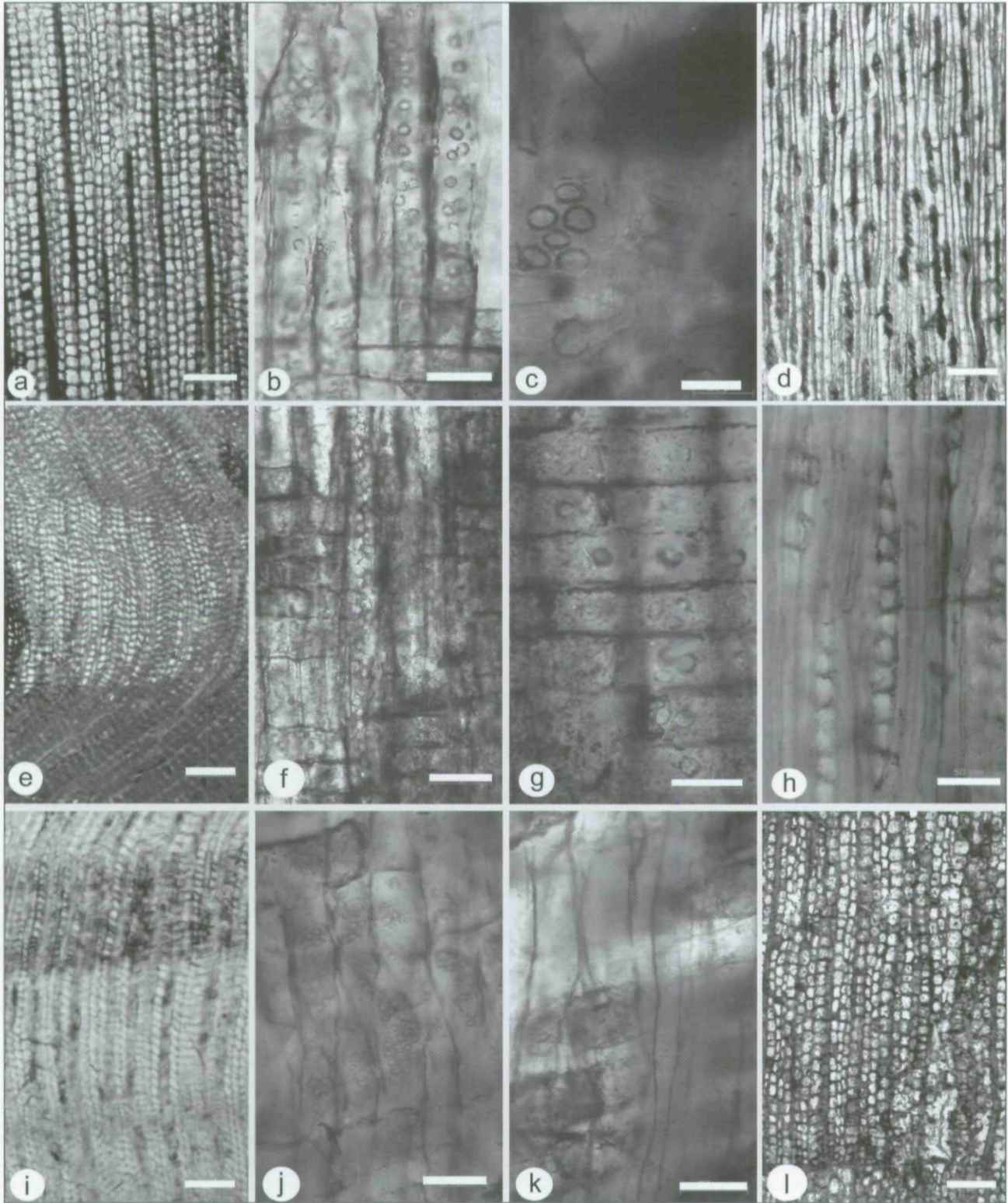


Figure 10. Plates of transverse, radial longitudinal and tangential sections of fossil wood, *Brachyoxylon* (a to d), *Agathoxylon africanum* (e to h), *Agathoxylon karooensis* (i to k) and *Agathoxylon* sp. (l)

rare, low, biseriate portions (Figure 10d). Ray frequency is 6 per mm. Rays consist only of parenchyma cells with smooth walls.

Identification and Comparison

With the mixed tracheid pitting and araucarioid cross-fields this wood is typical of the tracheidoxyl (Creber 1972) genus *Brachyoxylo*. There are numerous species widely distributed in Jurassic and Lower Cretaceous deposits (Philippe 1995) especially in the northern hemisphere and this is the first recorded occurrence from southern Africa (Phillippe et al. 2004).

Agathoxylo Hartig, Agathoxylo africanum (Araucarioxylo africanum Bamford, 1999) Bamford and Philippe (2001)

<i>Specimen</i>	BP/16/206
<i>Collector</i>	J.D. Ward
<i>Locality</i>	Mahura Muthla 198, Visser Dump, sample no: CKO 036
<i>Other specimens</i>	BP/16/207 (Mahura Muthla)
<i>Figures</i>	10e to h

Description

This brown and beige, smooth, rolled pebble is 5.5 x 2.5 x 1.0 cm and has distinct growth rings but the bands of thinner-walled cells are distorted (Figure 10e). The less distorted tracheids have a mean tangential diameter of 27 μ m (range 19 to 34 μ m) and mean radial diameter of 34 μ m (range 22 to 37 μ m) with a square to rectangular outline. Bordered pitting on the radial walls is mostly biseriate, alternate and slightly compressed, rarely uniseriate (Figure 10f). Pits are 10 to 12 μ m and seldom seen in the sections as the wood is so distorted. Axial parenchyma, canals and ducts are absent. Cross-fields contain 2 to 3 to 4 narrowly bordered, oval pits (taxodioid; Figure 10g), 8 μ m wide. Ray cell walls are thin and smooth. Rays are uniseriate with very rare paired cells, 4 to 8 to 13 cells high, and 8 rays per mm (Figure 10h).

Identification and Comparison

The alternate, crowded tracheid pitting and taxodioid cross-field pitting is characteristic of the genus *Agathoxylo* which is the valid name for *Dadoxylo* and *Araucarioxylo* fossil wood types. This large, cosmopolitan group ranges from the Upper Carboniferous to the Tertiary but the species tend to have a much more restricted temporal and geographical distribution. The morphogenus represents a number of different plant groups, for example conifers, cycads, glossopterids etc. The species *A. africanum* has been recorded from a number of sites in the Karoo Basin, from the Upper Permian, Triassic (Bamford, 1999), Jurassic (Bamford, 2000) and Lower Cretaceous (Philippe et al., 2004). It is more common in the older deposits.

Agathoxylo karoensis (Araucarioxylo karoensis Bamford, 1999) Bamford and Philippe (2001)

<i>Specimen</i>	BP/16/336
<i>Collector</i>	M.C.J. de Wit
<i>Locality</i>	Mahura Muthla
<i>Other samples</i>	none
<i>Figures</i>	10i to k

Description

The black to brown fossil log is 10 x 4 x 4 cm. The outline of the tracheids in transverse section is square to rectangular with thin walls which have been distorted in some patches (Figure 10j). Tracheid pitting occurs on the radial walls only and is alternate, 2 to 3 seriate, mostly contiguous, slightly compressed to hexagonal (Figure 10j). Bordered pits have a diameter of 7 to 12 μ m with small apertures. Early-wood tangential diameters range from 36 to 75 μ m with an average of 66 μ m, and mean radial diameter is 58 μ m (range 38 to 72 μ m). Axial parenchyma, canals and resin were not observed. Cross-fields have 6 to 9 taxodioid pits, 5 μ m in diameter (Figure 10k). Ray cell walls are thin and smooth. Rays are relatively high ranging from 3 to 30 cells with an average of 20 cells.

Identification and comparison

This species has also been recorded from the Karoo Basin in South Africa but has a more restricted temporal distribution. As far as is known it is confined to the Upper Permian (*Dicynodon* Assemblage zone). It is similar to the previous species but differs in having the triseriate tracheid pits.

Agathoxylo sp.

<i>Specimens</i>	BP/16/330, 335, 343, 344, 345, 346, 347, 348.
<i>Locality</i>	Mahura Muthla
<i>Collector</i>	M.C.J. de Wit
<i>Figure</i>	10l

Description

The first two specimens are listed as logs and the rest as rounded pebbles (Table 3). All these woods have the typical araucarian features: squarish outline of tracheids in transverse section with relatively thin walls, no axial parenchyma or canals, indistinct growth rings, 1 to 2 seriate tracheid bordered pits which are contiguous and slightly compressed. Rays are uniseriate and 2 to 10 to 18 cells high with thin and smooth walls. Cross-field pits are araucarioid, 3 to 5 pits per field and 4 to 7 μ m in diameter (Figure 10l). As the woods are poorly preserved with distorted growth rings and missing some of the above features, i.e. not preserved, they have not been assigned to a species. They probably belong to one or other of the species described here but without well preserved tracheid pitting it is not possible to distinguish them.

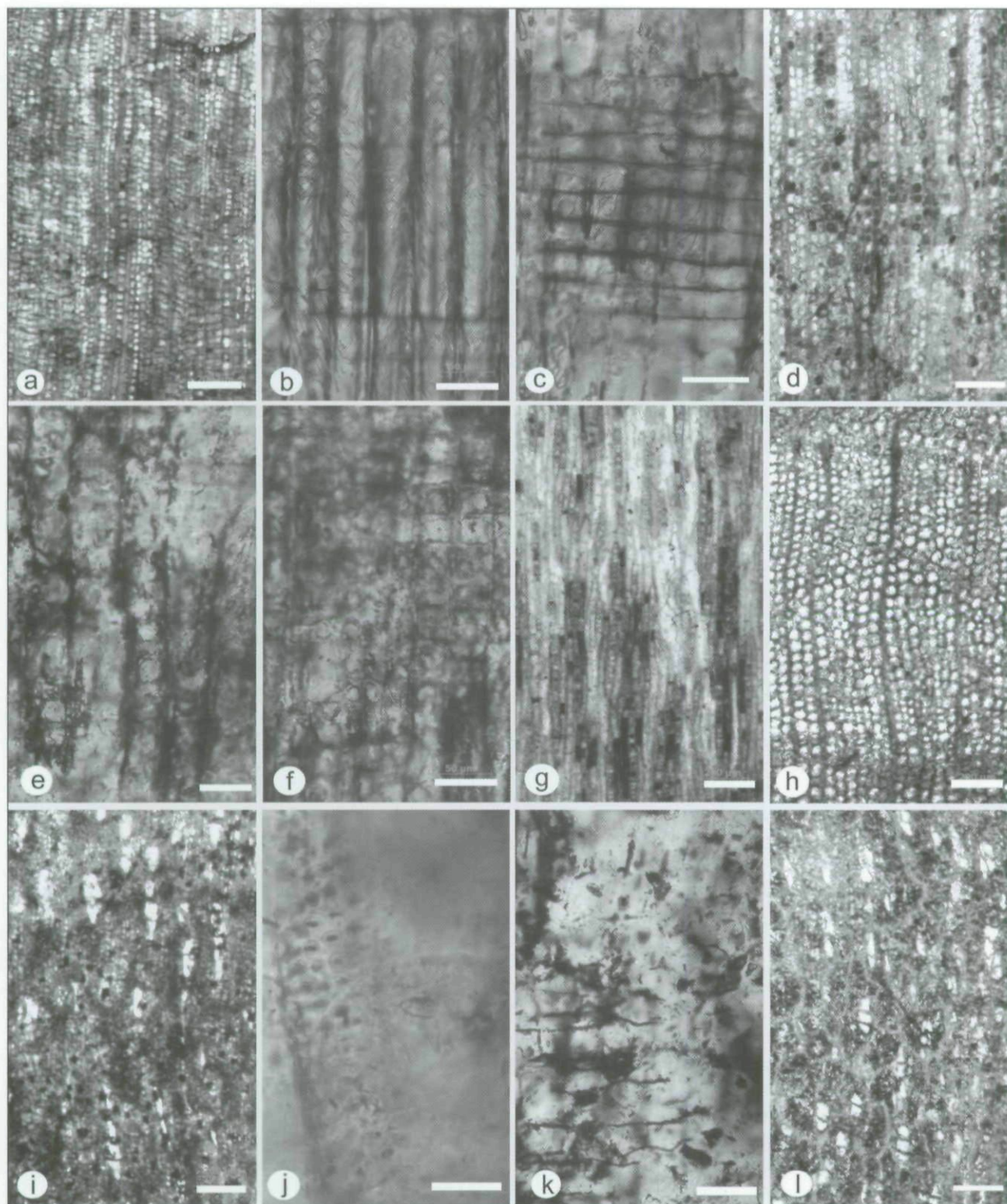


Figure 11. Plates of transverse, radial longitudinal and tangential sections of fossil wood, *Podocarpoxyylon mababalei* (a to c), *Podocarpoxyylon umzambense* (d to g), *Podocarpoxyylon* sp. (h) and dicotyledonous wood (unidentified) (I to L).

**Podocarpaceae, *Podocarpoxyton* Gothan (1905),
Podocarpoxyton mababalei Agashe (1968)**

Specimen BP/16/340
Locality Mahura Muthla
Other samples BP/16/339
Figures 11a to c

Description

The log with a dark centre and light crust measures 11 x 9 x 2.5 cm but from the curvature of the growth rings the tree must have been at least 70 cm in diameter. The specimen is brown in colour, silicified and well preserved. In transverse section the tracheids are rounded to oval with thicker walls than those of the species of *Agatboxyton*. Tracheids are regularly arranged (Figure 11a). Resin (dark substance) is present in some tracheids and ray cells but with no distinct pattern of distribution. Growth rings are 4 to 5 mm wide and indistinct with only 1 to 2 rows of latewood cells which are only slightly narrower than the early-wood cells. The early-wood mean tangential diameter is 41 µm (range 29 to 55 µm) and the mean radial diameter is 45 µm (range 24 to 53 µm). The late-wood mean tangential diameter is 44 µm (range 24 to 53 µm) and mean radial diameter is 18 µm (range 12 to 26 µm). Bordered pitting on the radial walls of the tracheids is uniseriate, separate or contiguous but never compressed, pits 20 µm in diameter (Figure 11b). Axial parenchyma was not observed. Ray height ranges from 5 to 36 cells with an average of 17 cells (height range 300 to 750 µm; width 40 µm). Ray cell walls are thin and smooth. There is one round to oval, narrowly bordered taxodioid pit per cross-field, 13 µm in diameter (Figure 11c). The apertures are obliquely oriented. Checking (oblique lines across the cells) of the tracheid and ray cell walls is prominent and in some regions it obscures the true shape of the cross-field pits and makes them appear long and narrow.

Identification and Comparison

The tracheid and cross-field pits, and the thin and smooth ray cell walls are typical of the Podocarpaceae. Woods of this family first appeared in the Upper Triassic (Selmeier and Vogellehner, 1968) and there are about 80 modern species whose woods are mostly similar to each other and difficult to distinguish. Based on the size and numbers of pits this specimen is mostly similar to *Podocarpoxyton mababalei* (Agashe, 1968) from the Cuddalore Series in India, with putative age of Upper-Miocene to Pliocene. The Indian specimen has uniseriate contiguous and separate tracheid pits, 20 µm wide and uniseriate rays 1 to 11 to 30 cells high with rare biseriate portions. Cross-field pits are taxodioid with oblique apertures and 15 to 20 µm in size which is a little bigger than the South African specimen. Podocarpaceous woods of fossil and modern species are all similar and not easy to distinguish so the date should be treated with caution.

***Podocarpoxyton umzambense* Schultze-Motel
(1966)**

Specimen BP/16/197b
Locality Graspan, sample no BPX 443, GP733.
Other specimens BP/16/197c (Graspan), BP/16/327 (Mahura Muthla)

Figures 11d to g

Description

The log is 8.5 x 4.5 x 3.5 cm, blacks and browns in colour. In transverse section the tracheids are roundish with fairly thick walls and very regularly arranged. The distribution of resin in the wood is distinctive with the dark resin-filled ray cells and adjacent tracheids frequently resin-filled (Figure 11d). Growth rings are indistinct, 2 to 3 mm wide, with latewood cells only slightly narrower than the early-wood cells.

Early-wood tracheid mean tangential diameter is 50 µm (range 38 to 62 µm) and mean radial diameter is 53 µm (range 48 to 62 µm). The late-wood tracheid mean tangential diameter is impossible to measure because of distortion and dark cell contents. Bordered pits are mostly uniseriate, rarely biseriate and opposite, 25 µm wide, and separate or contiguous but never compressed (Figure 11e). Axial parenchyma was not seen but resin is common in ray parenchyma cells and tracheids. Cross-field pits are solitary, with a very narrow border, 10 to 15 µm wide (Figure 11f). Ray cell walls are thin and smooth. Rays are uniseriate and 7 to 32 cells high, and frequently a resiniferous deposit in the adjacent tracheids is associated with the rays (Figure 11g).

Identification and comparison

The wood is undoubtedly podocarpaceous. The abundance and distribution of resin in the rays and tracheids is distinctive and this specimen is very similar to the ones described from the Umzamba Beds in Pondoland, South Africa, which are Upper Cretaceous in age (Schultze-Motel, 1966). The species has also been recorded from the offshore Namaqualand Shelf of South Africa (Bamford and Corbett, 1994), in Coniacian deposits from the same area (Bamford and Stevenson, 2002) and West Coast onshore deposits (Bamford and Corbett, 1995). The latter woods have been tentatively dated as Lower Cretaceous based on the association of other woods in the assemblage.

Podocarpaceae – *Podocarpoxyton* sp.

Specimens BP/16/106, 205, 326, 328, 329, 331, 334, 337, 338, 341, 342.
Locality Mahura Muthla.
Figure 11h

Description

These fossils have not been given a species designation because some of the important features for identification are missing, most commonly the cross-field pitting.

In general these woods are typical of the Podocarpaceae with indistinct growth rings, a small proportion of resiniferous tracheids, separate or contiguous but uncompressed uniseriate bordered pitting on the radial walls of the tracheids, uniseriate rays with cells that have thin and smooth walls and the absence of ray tracheids and resin canals. Rarely poor solitary cross-field pits can be seen but the size of the aperture and walls are indeterminate.

Angiospermae- Dicotyledonae

<i>Specimen</i>	BP/16/204
<i>Locality</i>	Mahura Muthla, sample no CKO 034
<i>Other specimen</i>	BP/16/197a (Graspan), sample no BPX 443/GP773
<i>Figures</i>	11i to l

Description

The piece of wood is 20 x 9 x 6 cm. It is diffuse porous and no clear growth rings were seen. Vessels are arranged in low radial multiples with 1 to 2 to 3 to (4) vessel elements, 50 to 60µm in diameter but as they are radially compressed and distorted their maximum diameter is probably greater (Figure 11i). Perforation plates are scalariform with ten or more bars. Inter-vessel pits are opposite and 5 to 7.5µm (Figure 11j). There are 35 pores per mm² and parenchyma is rare to absent with only a few cells associated with the vessel groups. Fairly thick-walled fibres, also compressed, form the ground tissue. Rays are 2 to 3 cells wide and heterocellular with procumbent and upright cells. Average ray height is 555µm (range 425 to 650µm) but they are poorly preserved so it is not possible to determine presence or the number of marginal cells (Figure 11k). The second specimen of this wood type is very similar (Figure 11l).

Identification and comparison

There are no distinguishing characters for this wood so it is not possible to identify it. From the fossil record angiosperm woods occur from the Upper Cretaceous to the Present but the arrangement of vessels in radial lines of four or more elements is absent in Cretaceous woods and very rare in Paleocene woods and gradually increases in abundance (Wheeler and Baas, 1991). The angiosperm wood is therefore most likely to be of Tertiary age. This example is the first record in southern Africa of scalariform perforation plates, a feature that is more common in temperate woods and even today is very rare in the modern flora of southern Africa.

Fossil wood summary

In addition to the ages that can be ascribed to the various pieces of wood there are several observations that can be made from the fossil material:

1. Fossil woods are representative of at least four periods: Upper Karoo (post-Permian), Early Cretaceous, Late Cretaceous and Tertiary. The evidence for this is:

- 1a. One well preserved log of *Agathoxylon karoensis*, with little sign of transport, is of Permian age. The rest are pebbles of *A. africanum* or *A.sp.* and these range throughout the Karoo.
- 1b. *Brachyoxylon* is restricted to the Late Jurassic and Early Cretaceous.
- 1c. *Podocarpoxyylon umzambense* is typical of the Late Cretaceous and has been recorded from well dated Coniacian and Upper Senonian deposits, but has also been recorded from Lower Cretaceous sediments.
- 1d. The angiosperm woods are Tertiary in age but the age cannot be refined further.
2. Based on the palaeoflora the climate of the Cretaceous has fluctuated. There was a wet phase during the Early Cretaceous in the coastal areas based on the Aptian-Albian Kirkwood Formation woods of the South Coast (de Klerk and Bamford, 2002) and woods from the West Coast (Bamford and Corbett, 1994; 1995). The middle Cretaceous was drier in the interior based on crater-lake deposits at Orapa (Bamford, 1990, Rayner et al., 1997), but the Upper Cretaceous (Senonian) southern climate was much wetter, with forests of *Podocarpoxyylon umbzambense* implying high rainfall in Pondoland (Schultze-Motel, 1966) and on the West Coast (Bamford and Stevenson, 2002), with forested environments and fairly high, non-seasonal rainfall (Alvin, 1982). The interior during the latest Cretaceous was fairly wet where crater lake facies have preserved the pollen record at Banke (71 to 64 Ma; Scholtz, 1985) and Stompoor (Smith, 1986; Scholtz 1987; Trueb et al., 2005).
3. Little is known from the Early Tertiary for the interior, but in the later Tertiary there were great fluctuations in the climate and vegetation along the West Coast. The angiosperm woods preserved at Graspan 773 have not been transported very far. These woods are probably later Tertiary in age and their anatomy is typical of more xeric trees.

Chemistry and provenance of kimberlitic heavy minerals

Kimberlite-derived heavy minerals, pyrope (Mg-Al) garnet and micro-ilmenite (Mg-rich), are present in the matrix of the basal gravel units. Both mineral species have been extracted out of samples taken from concentrates which the diggers produced from the gravels. Since ilmenites are particularly useful in provenance studies, the focus in this study has been to compare the major element chemistry of ilmenites from Mahura Muthla to those from known primary sources to the north-west, south-west and south-east in order to establish the source area for these grains.

The ilmenite plots used in this study are Al₂O₃ versus Cr₂O₃ and Cr₂O₃ vs. MgO (Figures 12A to L). And although only 58 ilmenites were available for this study from Mahura Muthla some important conclusions are nevertheless drawn from this comparison particularly in terms of its proposed sources.

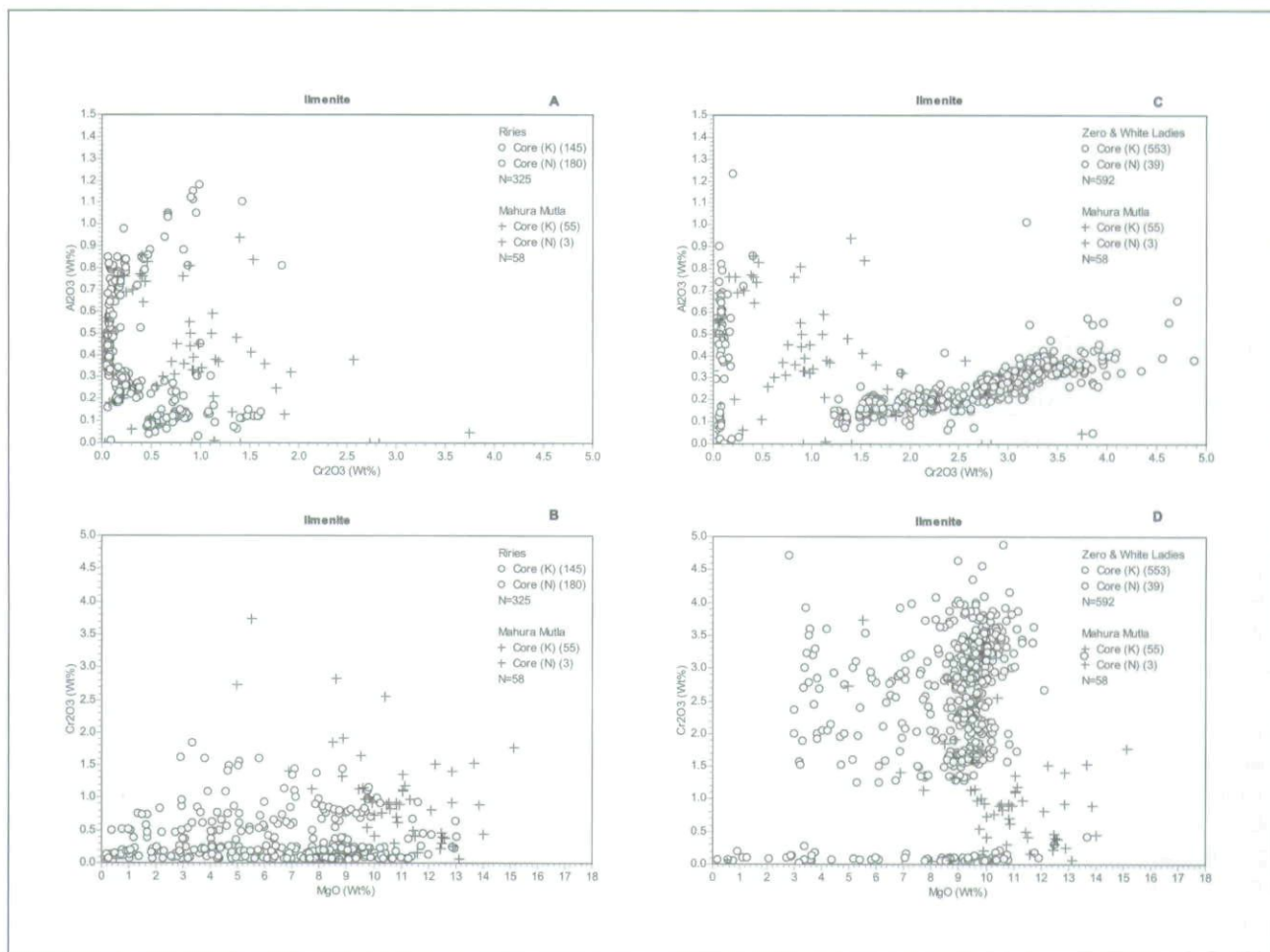


Figure 12. Mineral chemistry plots of Al_2O_3 versus Cr_2O_3 and Cr_2O_3 versus MgO of ilmenites from Riries (A and B), Zero and White Ladies (C and D), Darlestone (E and F), X154 (G and H), Bull Hill (I and J), Mayeng (K and L), compared to those from Mahura Muthla.

Primary sources

The following seven primary sources within a radius of 120 km of Mahura Muthla were used in the ilmenite study: the Zero and White Ladies kimberlites to the north-west; the Riries lamprophyre to the west; the Darlestone Group kimberlites to the southwest; and X154 (Bellsbank North), Bull Hill and Mayeng 02 kimberlites to the south-southeast (Table 4).

Although Group 2 kimberlites, historically referred to as the micaceous group of kimberlites, are generally devoid or at least poor producers of ilmenite, most generally do contain at least some. And a sufficient

number of ilmenites have been recovered from X 154 and the Darlestone Group 2 occurrences to be included in this study.

The Zero and White Ladies form part of the Kuruman kimberlite province and occur 30 to 40 km westnorth-west of Mahura Muthla. Both are Group 1 kimberlites and have been dated using U-Pb of the perovskites at 1147 and 1607 Ma respectively (Donnelly et al., 2008). The Riries intrusion has abundant ilmenite and is not classified as a true kimberlite but rather as a lamprophyre (Donnelly et al., 2008) and has been dated at 1674 Ma by Rb-Sr of mica (Shee et al. 1989). However,

Table 4 Kimberlites and associated rock used in the provenance study. Occurrence, type and age information based on Apter et al. (1984), Donnelly et al. (2008), Shee et al. (1989) and Smith et al. (1985).

Occurrence Name	Occurrence type	Distance to Mahura Muthla	Kimberlite Type	Age Ma	Number of ilmenites
Zero	Pipe	42 km northwest	Group 1	1147] 592
White Ladies	Pipe	30 km west-northwest	Group 1	1607	
Riries	Dyke	102 km west	Lamprophyre	1674	325
Darlestone	Pipe	90 km south-southwest	Group 2	126	25
X 154	Pipe	80 km south-southeast	Group 2	119	113
Bull Hill	Pipe	102 km south-southeast	Group 1		198
Mayeng 02	Sill	108 km south-southeast	Group 1	117	352

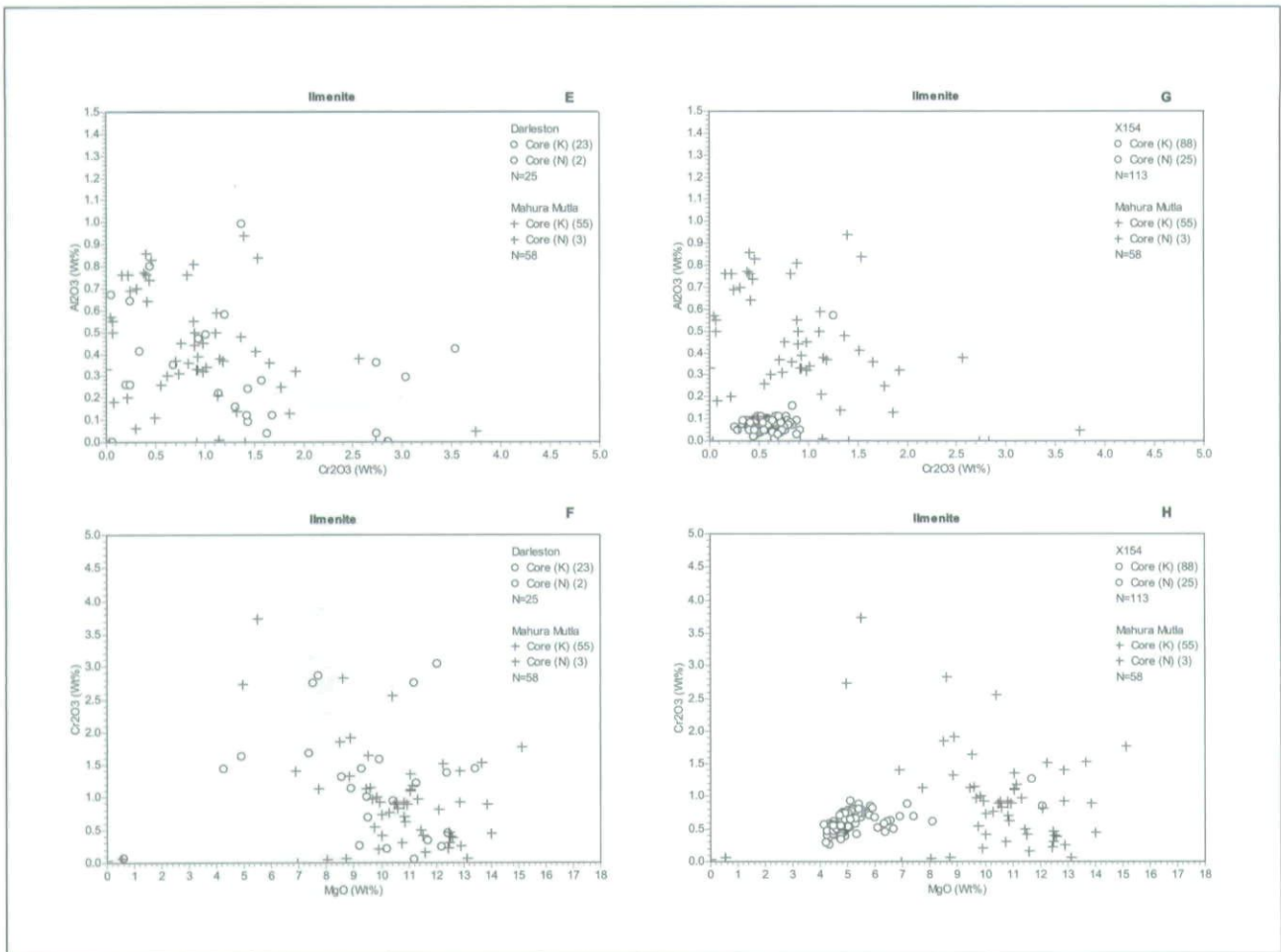


Figure 12. (E to H) continued

as a source of Mg-rich ilmenite it is just as useful as a kimberlite in this provenance study particularly because its ilmenite chemical signature is very distinctive.

The Darlestone Group 2 kimberlite occurs some 90 km south-south-west of Mahura Muthla and 25 km north-east of Danielskuil and is close to X007, also classified as Group 2 and dated at 126 Ma (Donnelly et al., 2008). Due to its proximity and similar petrography it seems reasonable to suggest that X007 is part of the Darlestone cluster, and hence a similar age for all the occurrences in this cluster has been assumed.

The Mayeng kimberlites are a series of sills linked to a narrow surface fissure. These are aphanitic kimberlites classified as hypabyssal, ilmenite-rich, phlogopite kimberlite tentatively dated at 117 Ma (Apter et al., 1984). These sills are probably better referred to as transitional kimberlites, somewhere between a Group 1 and 2, much like the Frank Smith occurrence (EMWS Skinner, personal communication, 2009). Although there is no date for Bull Hill it is likely to be late Cretaceous in age, being a Group 1 type. The Bellsbank occurrences, of which X154 is part, have been classified as Group 2 kimberlites and have been dated using Rb-Sr phlogopite age determination at 119 Ma (Smith et al., 1985).

Ilmenite mineral chemistry

The ilmenites from the Zero and White Ladies occurrences show much higher Cr₂O₃ and lower MgO values than the Mahura Muthla data (Figures 12c to d). Interestingly there are clearly two compositional populations which occur on either side of the Mahura Muthla field and are clearly very different data sets. The mineral chemistry data for the Proterozoic age Ruries lamprophyre is also substantially different to that of Mahura Muthla, with the Ruries grains being low in MgO and distinctly lower in Cr₂O₃ (Figures 12 A and B).

Only 25 grains were available from Darlestone Group 2 kimberlite and although there is good overlap there is a sense that the Cr₂O₃ values are slightly higher, and the MgO tails run at slightly lower levels compared to the Mahura Muthla grains. The fields therefore generally overlap fairly well with the Mahura Muthla field (Figures 12E and F).

The chemistry of the ilmenites from X154 (Bellsbank North) are very clustered at low Al₂O₃ and relatively low MgO levels compared to those from Mahura Muthla, and there is very little overlap between the two (Figures 12G and H).

The Bull Hill and to some extent the Mayeng kimberlites compare provide perhaps more closely in

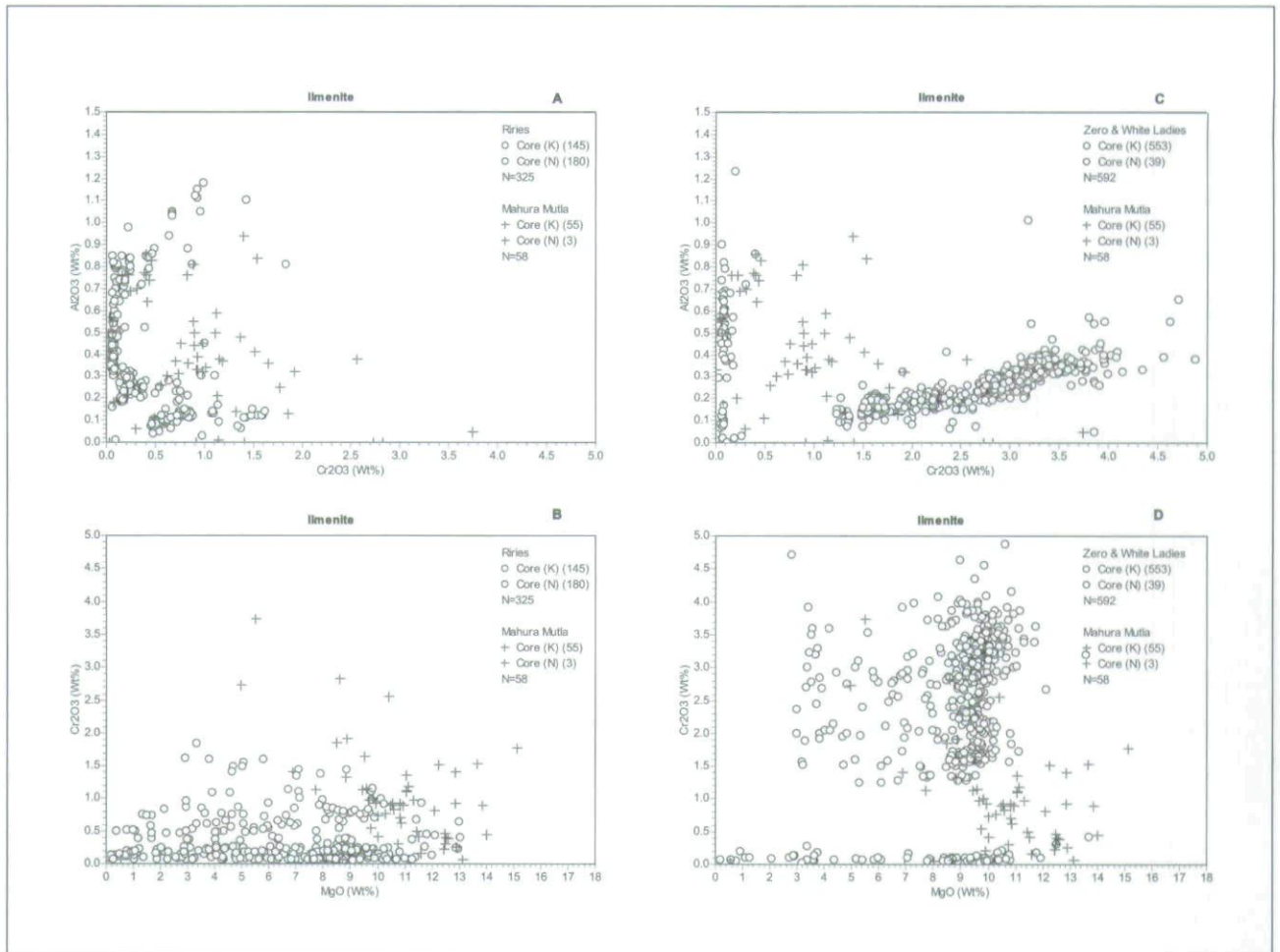


Figure 12. (I to L) continued

terms of ilmenite mineral chemistry for both the Al₂O₃ versus Cr₂O₃ and the Cr₂O₃ versus MgO fields. Although the Mayeng data set is much tighter (Figure 12K and L), the Bull Hill grains have a very similar spread to Mahura Muthla and probably provide the best match (Figures 12I and J).

Source area

The ilmenite mineral chemistry clearly indicates that the source area for the ilmenites is not to the north or north-west of Mahura Muthla. The ilmenite population from Zero, White Ladies and Ruries are significantly different to discard these areas as having supplied material to Mahura Muthla.

The ilmenites from X154 show sufficient differences to downgrade a positive link to the ilmenites that have come out of the gravels. The most convincing overlap of ilmenite chemistry with those from Mahura Muthla comes from Bull Hill, Darlestone and Mayeng (Figures 12E and F, I to L). Despite representing different kimberlite groups the chemical signatures of these three occurrences are surprisingly similar possibly representing the same mantle domain. It is therefore highly likely that the ilmenites in the Mahura Muthla gravels have come from an area to the south-southwest and south-southeast.

Although it is not certain whether the kimberlitic minerals and the diamonds would have been derived from the same source it is reasonable to assume that the two would have been derived from the same region. Although both Bull Hill and Mayeng are devoid of any mining activity and are presumed barren, other occurrences in the area such as Bellsbank and to a lesser extent X 154, Darlestone, and Duivelskop have produced diamonds.

There are therefore two important conclusions that can be drawn from the kimberlite derived heavy minerals. Firstly, based on the ilmenite mineral chemistry the source area of the Mahura Muthla channel was somewhere between the south-southwest and the south-southeast and hence the palaeo-flow direction was towards the north-west, and secondly that the diamonds from the Mahura Muthla gravels have most likely been sourced from the same area making Bellsbank and X154 the most likely candidates with perhaps minor input from Darlestone and Duivelskop. However an undiscovered source in that general area cannot be excluded.

Discussion and conclusions

The palaeo-flow direction of the Mahura Muthla channel was from south to north based on the following evidence:

1. Comparing the mineral chemistry of kimberlitic minerals ilmenites from the gravels and several primary sources within a 120 km radius of Mahura Muthla indicate that its source(s) is to the south.
2. The Kanguru member, the source rocks for the ironstone and jasper cobbles and pebbles within the gravel, crop outs directly south of the channel indicating that these clasts have travelled in a northerly direction.
3. The size of the agates, the fossilised wood and the Kanguru ironstone and jasper cobbles and pebbles decrease in size northwards from Graspan 773 to Mooifontein 640. In addition, the degree of rounding and the intensity of percussion scars, particularly on the ironstones and red chert clasts, increases in the same direction.
4. The limited numbers of imbrication measurements indicate that the flow was from the south and finally the Laurika palaeo-tributary joins the Mahura Muthla palaeo-trunk stream from the south-west suggesting it was flowing northwards.

The age of the filling of this channel has been constrained by the presence of relatively abundant fossil wood particularly at Graspan 773 and Mahura Muthla 198. Four periods of tree growth have been recognised from the palaeo-wood studies. The oldest are Karoo age woods which are preserved as rolled and abraded clasts suggesting that these have been reworked out of the post-Permian Karoo sediments (Beaufort age) which must have covered most of the Ghaap Plateau. The presence of both Lower and Upper Cretaceous woods, mainly in the form of logs, indicate that the drainage was active over most of the Cretaceous period, incising into Karoo basalt and sediments, incorporating post-Permian Karoo wood, and exhuming the Ghaap plateau. Eastward retreat of the Karoo escarpment in Lower Cretaceous times by westward flowing rivers removed the flood basalts between 130 and 100 Ma under fairly high and possibly non-seasonal rainfall. Whilst the flat lying Karoo volcanics, intruded by Group 2 kimberlites, were being removed so agate was the main contributor to the 'raisin-loaf' gravel with some weathered basalt clasts and diamond, a rare but important component in this Cretaceous drainage. In Upper Cretaceous times Beaufort sandstone was the only protection left of the underlying pre-Karoo geology. The climate during this period was one with high rainfall and followed the drier Mid Cretaceous period.

The final entrenchment of the Mahura Muthla channel occurred at the end of the Cretaceous or Early Tertiary times adding ironstone and red chert from the Kanguru layer and locally derived dolomite clasts to the gravels. Like the agates that were derived from the Drakensberg Group basalts, so the diamonds were derived from a Group 2 kimberlite already emplaced around 120Ma and eroded by Upper and Lower Cretaceous rivers. The palaeo-channel was therefore

mainly active during the wetter periods of the Lower and Upper Cretaceous, generally eroding Karoo basalt during the former and removing Beaufort sediments during the latter. The Middle Cretaceous was drier and probably less effective eroding the Karoo.

Based on preserved Upper Cretaceous crater-lake deposits in the Northern Cape and Namaqualand, erosion in the Tertiary was minimal, particularly where Karoo cover had been stripped, and the Mahura Muthla channel must have been close to its present level by then.

The Mahura Muthla channel was part of a north-westerly drainage, incising into the flood basalt and the underlying Beaufort sandstones respectively, and feeding off the easterly retreating basalt palaeo-escarpment (Figure 13A). This system was part of the Kalahari River drainage basin covering southern Botswana and the northern part of the Northern Cape which ultimately exited via the lower Orange River into the Atlantic Ocean approximately in the same area of the present Orange River mouth (De Wit, 1999). Whilst the channel was fed by an eastward retreating flood basalt escarpment in Lower Cretaceous times, the Mahura Muthla drainage became localised to the Ghaap by Late Cretaceous to Early Tertiary times, and subsequently became fossil and calcretised during the development of the African Surface.

At the same time the Cretaceous Karoo River, further south, was cutting into the same Karoo flood basalt from the south-west working its way up into pre-Karoo valleys like the Harts (Figure 13A; De Wit, 1999). Aggressive erosion by the upper Karoo River during the Cretaceous would have isolated the Ghaap from the Kimberley area around 85 Ma (Figure 13B) and diamonds derived from the Group 1 kimberlites around Kimberley where finding their way towards the south-west via the Karoo River until the end of the Cretaceous (De Wit, 2004). The exit of this Karoo River coincided with the present course of the Krom River (De Wit, 1993; Kounov et al., 2008). Phillips and Harris (2008) suggest, based on dating of diamond inclusions, that the palaeo-Karoo River was the transport system for the detrital diamonds in Namaqualand, which were initially derived from the older Group 2 kimberlites. By the close of the Cretaceous period the Kalahari River had captured the Upper Karoo River establishing the main components of the modern Orange/Vaal system (Figure 13B).

Finally the diamonds within the channel have most likely been derived from one or some of the Group 2 kimberlites situated towards the south. So most likely candidate is the Bellsbank Group with possible input from the Darlestone and Duivelskop occurrences but an undiscovered source cannot be excluded. During the Upper Cretaceous or early Tertiary the more southerly kimberlites such as the Bellsbank Group, Bull Hill and Mayeng were located within the Vaal drainage.

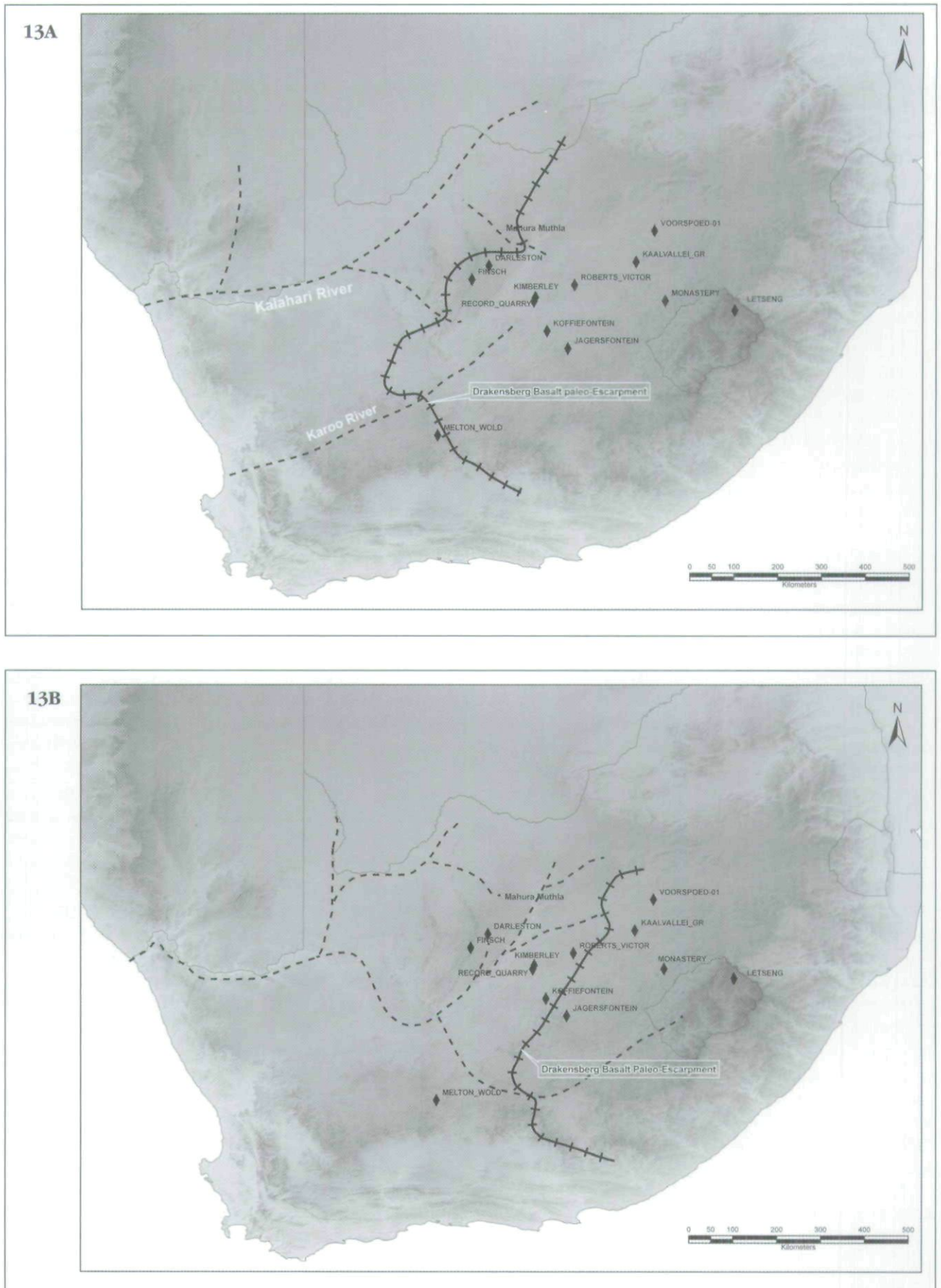


Figure 13. Palaeo-drainage reconstruction of the Early (A) and Late (B) Cretaceous periods showing the eastward retreat of the Drakensberg Basalt escarpment and the emplacement of selected Group 1 and Group 2 kimberlites respectively.

Acknowledgements

Richard Lewis, formerly BPI Palaeontology, is thanked for making the petrographic thin sections of the very hard fossil wood samples. De Beers Consolidated Mines Limited is acknowledged for providing the ilmenite mineral chemistry for the various kimberlites, as is Lindsay Urban for preparing the maps and diagrams. We also thank Tim Partridge for constructive discussions on site. Finally reviews by Brian Bluck and Craig Smith have significantly improved the content of this paper.

References

- Agashe, S.N. (1968). Studies on the gymnosperms of India – Part I. A new species of *Mesembryoxylon*, *M. mahabalei* sp. nov. *The Palaeobotanist*, **17**, 312–316.
- Alvin, A.L. (1982). Cheirolepidiaceae: biology, structure and palaeoecology. *Review of Palaeobotany and Palynology*, **37**, 71–98.
- Apter, D.B., Harper, F.J., Wyatt, B.A. and Smith, B.H.S. (1984). The geology of the Mayeng kimberlite sill complex, South Africa. In: Kimberlites II – the mantle and crust – mantle relationships, *Proceedings, 3rd International Kimberlite Conference*, **1**, 43–58.
- Bamford, M.K. (1990). The angiosperm palaeoflora from the Orapa Pipe, Botswana. *Unpublished PhD thesis, University of the Witwatersrand, South Africa*. 230pp.
- Bamford, M.K. (1999). Permo-Triassic fossil woods from the South African Karoo Basin. *Palaeontologia africana*, **35**, 25–40.
- Bamford, M.K. (2000). Fossil woods of Karoo aged deposits in South Africa and Namibia as an aid to biostratigraphic correlation. *Journal of African Earth Sciences*, **31**, 119–132.
- Bamford, M.K. and Corbett, I.B. (1994). Fossil wood of Cretaceous age from the Namaqualand continental shelf, South Africa. *Palaeontologia africana*, **31**, 83–95.
- Bamford, M.K. and Corbett, I.B. (1995). More fossil wood from the Namaqualand coast, South Africa; onshore material. *Palaeontologia africana*, **32**, 67–74.
- Bamford, M.K. and Philippe, M. (2001). Jurassic – Early Cretaceous Gondwanan homoxyloous woods: a nomenclatural revision of the genera with taxonomic notes. *Review of Palaeobotany and Palynology*, **113**: 287–297.
- Bamford, M.K. and Stevenson, I.R. (2002). A submerged Late Cretaceous podocarpaceous forest, west coast, South Africa. *South African Journal of Science*, **98**, 181–185.
- Beukes, N.J. (1980). Stratigrafie en litofasies van die Campbellrand-subgroep van die Proterofitiese Ghaap-Groep, Noord-Kaapland. *Transactions of the Geological Society of Africa*, **83**, 141–170.
- Beukes, N.J. (1983). Palaeoenvironmental setting of Iron-Formations in the depositional basins of the Transvaal Supergroup, South Africa. In: Trendall A.F. and Morris R.C. (editors), Iron-Formation: facts and problems, *Developments in Pre-Cambrian Geology*, **6**, 131–210.
- Blatt, H., Middleton, G.V. and Murray, R.C. (1980). Origin of Sedimentary Rocks, 2nd Edition, *Prentice-Hall, New Jersey, United States of America*, 634pp.
- Creber, J. (1972). Gymnospermous wood from the Kimmeridgian of East Sutherland and from Sandringham Sands of Norfolk. *Palaeontology*, **15**, 655–661.
- de Klerk, W.J. and Bamford, M.K. (2002). The Early Cretaceous (135Ma) Algoa, and Gamtoos Basins in the Port Elizabeth area of southern Africa. *Field guide for the pre-Symposium field trip 15-19 July 2002, 8th International Symposium on Mesozoic Terrestrial Ecosystems*, 1–30pp.
- de Wit, M.C.J. (1993). Cretaceous evolution of drainage systems in the north-western Cape. *Unpublished PhD thesis, University of Cape Town, South Africa*, 371pp.
- de Wit, M.C.J. (1999). Post-Gondwana drainage and the development of diamond placers in western South Africa. *Economic Geology*, **94**, 721–740.
- de Wit, M.C.J. (2004). The diamondiferous sediments on the farm Nooigedacht (66), Kimberley, South Africa. *South African Journal of Geology*, **107**, 477–488.
- de Wit, M.C.J. and Bamford, M.K. (1993). Fossilwood from the Brandvlei area, Bushmanland as an indicator of palaeoenvironmental changes during the Cretaceous. *Palaeontologia africana*, **30**, 81–89.
- Donnelly, C.L., O'Reilly, S.Y. and Griffen, W.L. (2008). The Kimberlites and related rocks of the Kuruman Kimberlite Province, Kaapvaal Craton, South Africa. *9th International Kimberlite Conference. Extended Abstracts no. 9IKC-A-00125*.
- Eriksson, P.G., Altermann, W. and Hartzler, F.J. (2006). The Transvaal Supergroup and its precursors. In: Johnson M.R., Anhaeusser C.R. and Thomas R.J. (Editors), *The Geology of South Africa, Council for Geoscience of South Africa-Geological Survey of South Africa*, 237–260.
- Hanson, E.K. (2007). Estimated erosion of Cretaceous-aged kimberlites in the Republic of South Africa through the examination of upper-crustal xenoliths. *Unpublished M.Sc. thesis, Rhodes University, South Africa*, 138pp.
- Hawthorne, J.B. (1959). Report on geological investigation of the Mahura Muthla area. *Internal De Beers Consolidated Mines Limited report (unpublished)*, 2pp.
- Hawthorne, J.B. (1975). Model of a kimberlite pipe. *Physics and Chemistry of the Earth*, **9**, 1–15.
- Kounov, A., Viola G., de Wit M.J. and Andreoli M. (2008). A Mid Cretaceous paleo-Karoo River valley across the Knersvlakte plain (northwestern coast of South Africa): Evidence from apatite fission-track analysis. *South African Journal of Geology*, **111**, 409–420.
- Netterberg F. (1980). Geology of southern African calcretes: 1. Terminology, description, macrofeatures and classification. *Transactions of the Geological Society of South Africa*, **83**, 255–283.
- Partridge, T.C. (1990). Palaeodrainage and erosion surface along the southern margin of the Basin: evidence from the Ghaap Plateau. *Symposium on the Geomorphology and Management of Semi-Arid lands, University of Bophuthatswana, June 1990*.
- Partridge, T.C. (1998). Of diamonds, dinosaurs and diastrophism: 150 million years of landscape evolution in southern Africa. *South African Journal of Geology*, **101**, 167–184.
- Partridge, T.C. and Maud, R.R. (1987). Geomorphic evolution of southern Africa since the Mesozoic. *South African Journal of Geology*, **90**, 179–208.
- Philippe, M. (1995). Bois fossiles du Jurassique de Franche-Comté (northeast France). *Palaeontographica, Abteilung B*, **236**, 45–105.
- Philippe, M., Bamford, M., McLoughlin, S., Da Rosa Alves, L.S., Falcon-Lang, H., Gnaedinger S., Ottone, D., Pole, M., Rajanikanth, A., Shoemaker, R.E., Torres, T. and Zamuner, A. (2004). Biogeographic analysis of Jurassic-Early Cretaceous wood assemblages from Gondwana. *Review of Palaeobotany and Palynology*, **129**, 141–173.
- Phillips, D. and Harris, J.W. (2008). Headless placers and the search for buried bodies. *9th International Kimberlite Conference, Frankfurt, Extended Abstract No. 9IKC-A-00018*, 3pp.
- Rayner, R.J., Bamford, M.K., Brothers, D.J., Dippenaar-Schoeman, A.S., McKay, I.J., Oberprieler, R.G. and Waters, S.B. (1997). Cretaceous fossils from Orapa diamond pipe. *Palaeontologia africana*, **33**, 55–65.
- Rogers, A. W., Hall, A.L., Wagner, P.A. and Haughton, S.H. (1929). The Union of South Africa, *Handbuch der Regionalen Geologie, Band VII, Abteilung 7a. Carl Winters Universitätsbuchhandlung*.
- Scholtz, A. (1985). The palynology of the Upper Lacustrine sediments of the Arnot Pipe, Banke, Namaqualand. *Annals of the South African Museum*, **95**, 1–109.
- Scholtz, A. (1987). Interim report on the Stompoor Project. *Unpublished report from the Palynological Laboratory, Department of Archaeology, University of Stellenbosch*, 1–36.
- Schultze-Motel, J. (1966). Gymnosperm-holzer aus den oberkretazischen Umzamba-Schichten von Ost Pondoland (Suid-Afrika). *Senckenbergia lethaea*, **47**, 279–337.
- Selmeier, A. and Vogellehner, D. (1968). *Podocarpoxylon triassicum* n. sp. ein phylogenetisch bedeutsames 'modernes' Sekundärholz aus dem Keuper von Franken. *Neues Jahrbuch Geologisch und Paläontologie Abhandlungen*, **132**, 70–86.
- Shee, S.R., Bristow, J.W., Bell, D.R., Smith, C.B., Allsopp, H.L. and Shee, P.B. (1989). The petrology of kimberlites, related rocks and associated mantle xenoliths from the Kuruman Province, South Africa. In: J. Ross, A.L. Jaques, S.Y. O'Reilly, D.V. Danchin and A.J.A. Janse (Editors), *Proceedings of the 4th International Kimberlite Conference, Kimberlites and Related rocks, Blackwell Carlton, United Kingdom*, 60–82.
- Smith, C.B. (1983). Pb, Sr, and Nb isotopic evidence for sources of southern African Cretaceous kimberlites. *Nature*, **304**, 51–54.

- Smith, C.B., Allsopp, H.L., Krames, J.D., Hutchinson, G. and Roddick, J.C. (1985). Emplacement ages of Jurassic-Cretaceous South African kimberlites by the Rb-Sr method on phlogopite and whole rock samples. *Transactions of the Geological Society of South Africa*, **88**, 249-266.
- Smith, R.M.H. (1986). Sedimentation and palaeoenvironments of Late Cretaceous crater-lake deposits in Bushmanland, South Africa. *Sedimentology*, **33**, 369-386.
- Stratten, T. (1971). Paleocurrent results from the gravels of the Mahura Muthla area. *Internal De Beers Consolidated Mines Limited report (unpublished)*, 19pp.
- Trueb, L., Ross, C.F. and Smith, R. (2005). A new pipoid anuran from the Late Cretaceous of South Africa. *Journal of Vertebrate Palaeontology*, **25**, 533-547.
- Visser, J.N.J. (1972). Sedimentêre insluitels van Karoo-ouderdom in kimberliet van die Finsch-diamantmyn. *Tydskrif vir Natuurwetenskappe*, 32-36.
- Visser, J.N.J., Lowe D.R. and Beukes N.J. (1986). A Permo-Carboniferous glacial pavement and related Karoo rocks along the Ghaap Escarpment near Boetsap, Northern Cape Province. *Transactions of the Geological Society of South Africa*, **89**, 385-388.
- Ward, J.D. (1992). Mahura Muthla gravel deposits. Reivilo area, Vryburg District. *Internal De Beers Consolidated Mines Limited report (unpublished)*, 19pp.
- Wagner, P. A. (1914). The Diamond Fields of Southern Africa. *Struik (Pty) Limited Cape Town, 2nd Impression 1971*, 355pp.

Editorial handling: J. M. Barton

Copyright of South African Journal of Geology is the property of Geological Society of South Africa and its content may not be copied or emailed to multiple sites or posted to a listserv without the copyright holder's express written permission. However, users may print, download, or email articles for individual use.