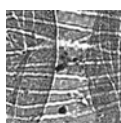


Late Palaeozoic palynomorph assemblages from the Karoo Supergroup and their potential for biostratigraphic correlation, Kalahari Karoo Basin, Botswana

BENSON N. MODIE & ALAIN LE HÉRISSE



Late Carboniferous to Permian core samples from two borehole sections, STRAT 1 and CKP 6, that penetrate the glacial to postglacial and coal-bearing Lower Karoo sequence, Kalahari Karoo Basin, Botswana, contain well preserved pollen and spore palynomorphs. The palynomorph assemblages comprise 165 species of spores and pollen, and few acritarchs and chlorophycean algae. This paper presents a local biozonation of three succeeding assemblage zones, recognisable in each borehole section. The assemblage zones are named: the *Hamiapollenites bullaeformis* Biozone, the *Cyclogranisporites gondwanensis* Biozone and the *Platysaccus papilionis*–*Striatopodocarpites fusus* Biozone, in ascending order of stratigraphy. Assemblages are compared and correlated with assemblages described from other Gondwana areas of Africa, Australia, Arabia, South America and Antarctica. A general analysis of taxa from the Kalahari Karoo Basin indicates a distinct similarity with assemblages from the Paraná Basin of South America. The *Hamiapollenites bullaeformis* Biozone is comparable with the *Vittatina costabilis* Interval Zone of the Paraná Basin. Assemblages from the *Cyclogranisporites gondwanensis* and the *Platysaccus papilionis*–*Striatopodocarpites fusus* zones are comparable with the *Lueckisporites virkkiae* Interval Zone. Age determination for the assemblages in the Kalahari Karoo Basin is inferred from comparison with similar assemblages from previous Gondwana studies, and ranges from the Late Carboniferous (Kasimovian–Gzhelian) to latest Early or possibly earliest Middle Permian (Late Cisularian to Early Guadalupian). • Key words: Kalahari Karoo Basin, Late Carboniferous–Permian, pollen, spores, assemblage zones.

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Although the coal-bearing Karoo Supergroup sequence of the Kalahari Karoo Basin (Fig. 1) is known to be extensive in Botswana (*e.g.* Smith 1984), geological insight into stratigraphic correlation remains minimal. This is greatly compounded by the lack of surface exposure for outcrop analysis and correlation due to extensive cover by a thin veneer of Cainozoic superficial deposits of the Kalahari Desert environment (Thomas & Shaw 1991, Carney *et al.* 1994). The heavy reliance on the traditional method of stratigraphic subdivision, based only on lithological similarities, to correlate widely spaced borehole sections in the Kalahari Karoo Basin is not unequivocal. For example, studies of sedimentary environments and facies distributions have shown that similar units can be deposited at different times, in different areas and with no

physical connection to each other (Reading 1986, Mial 1990). The lack of extensive surface exposure in the Kalahari Karoo Basin and few macrofossils, leaves palynology as the most effective method of dating and correlating the subsurface sequences. Evidence from previous palynological studies (*e.g.*, MacRae 1978, Dolby 1990, ECL 1990, Cadman 1995, Key *et al.* 1995, Stephenson & McClean 1999) indicates that the Lower Karoo sequence contains pollen and spore microfossils suitable for stratigraphic applications. The results of a recent study (*i.e.* Modie 2007), on which this paper is largely based, have also revealed an overwhelming presence of pollen and spore palynomorph assemblages suitable for biostratigraphic analysis. The purpose of this paper, therefore, is to give an account of the nature of palynomorph assem-

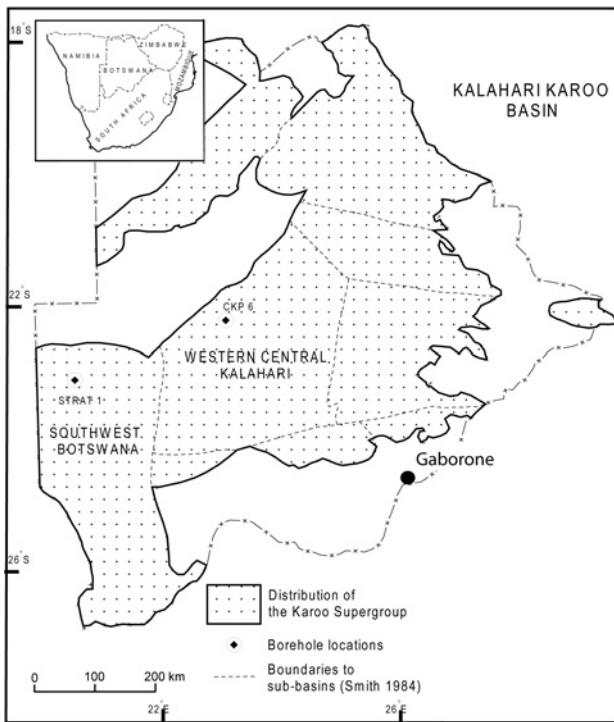


Figure 1. Locality map indicating the position of study boreholes: inset shows the location of Botswana in the region.

blages obtained from the Lower Karoo sequence as well as discuss and highlight their significance to stratigraphic zonation.

Geological setting

The Kalahari Karoo Basin of Botswana is one among several contemporaneous Karoo basins (Smith *et al.* 1993, Johnson *et al.* 1996, ECL 1998) of southwestern Gondwana (*e.g.*, Fig. 2) that became active in the Permo-Carboniferous times, with the earliest deposits laid down during the Late Palaeozoic glacial event. The exact geodynamic setting for the Kalahari Karoo Basin, as well as for the other related Karoo basins, remains little understood. However, several previous workers, amongst them Daly *et al.* (1991), Cox (1992), ECL (1998) and Turner (1999), consider the origin of these basins to be linked to collision induced extensional tectonics related to the Late Palaeozoic to Early Mesozoic Gondwanide Cape orogeny (*e.g.*, Thomas *et al.* 1992). The latter resulted from the subduction of a palaeo-Pacific plate under southern Gondwana, which subsequently led to the development of a retro-arc foreland basin, represented by the Main Karoo Basin in South Africa. The Kalahari Karoo Basin and other subsidiary basins in the north, developed as intracratonic rift basins, in response to the orogenic push from the south (*e.g.*, Daly *et al.* 1991, ECL 1998).

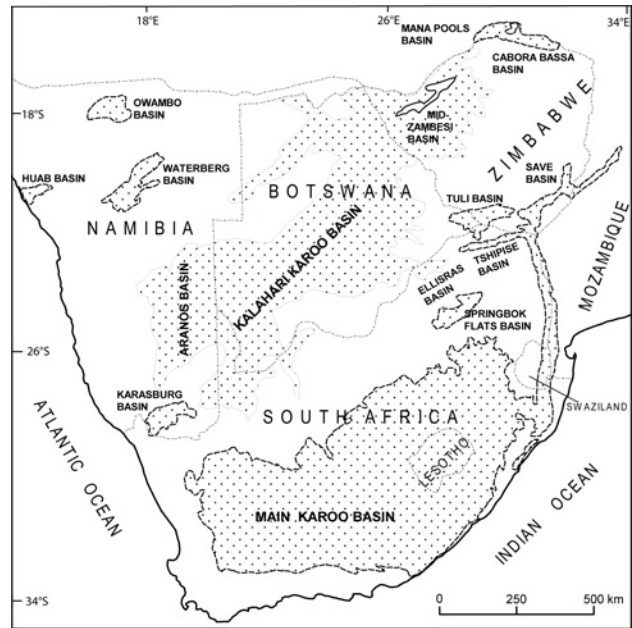


Figure 2. The regional location of the Karoo basins of southern Africa (after Johnson *et al.* 1996).

The sub-surface structural framework of the Kalahari Karoo Basin is little understood due to widespread cover by sediments of the Kalahari Desert environment. Consequently, much of the covered centrally located Kalahari Karoo Basin has hitherto been considered to represent an intracratonic sag basin. Only along the eastern fringe of the basin, where there is limited exposure and near-surface bedrock, has it been possible to demonstrate the occurrence of fault-bounded graben structures (Green *et al.* 1980). In recent times though, the use of geophysical data (*e.g.*, seismic, aeromagnetics *etc.*) to delineate major structural elements, such as faults and lineaments, indicates a rift basin setting for parts of the covered interior of the Kalahari Karoo Basin (Davison & Steenkamp 1995). Generally, both pre- and syn-Karoo fault systems are considered to have had a local influence on the distribution and thickness of the Karoo sequence (ECL 1998).

Stratigraphic sub-division (Fig. 3) of the sequence in the Kalahari Karoo Basin is largely based on lithological comparisons. On a regional scale, the lithostratigraphy is sub-divided into lower and upper sequences based on the location of a major regional mid-Karoo unconformity (ECL 1998). Sequences that belong to the lower Karoo include the Dwyka, Ecca and Beaufort groups, whilst those that belong to the upper Karoo include the Lebung and Stormberg Lava groups. Overall, the entire sequence in the Kalahari Karoo Basin, as in most other Karoo basins in the region, records a transition from a glacial period through fluvio-deltaic and swampy settings and ultimately turning arid before sedimentation came to a halt due to the extrusion of continental flood basalts (Smith 1984, Smith *et al.*

1993, Johnson *et al.* 1996). The Karoo basaltic volcanism, considered to have been initiated by extensional tectonics that marked the beginning of the Gondwana break-up, represents a major regional magmatic event in Karoo geology that occurred between 185–177 Ma ago (Jourdan *et al.* 2005).

Materials and methods

This paper is based on samples sourced from drill-cores provided by the Botswana Department of Geological Survey, as part of a broader project to investigate Karoo basin stratigraphy (Modie 2007). Two well-sampled cored-boreholes, STRAT 1 and CKP 6, provided 120 and 95 samples, respectively, for palynological investigations. STRAT 1 and CKP 6 boreholes are located in separate sub-basins of the Kalahari Karoo Basin *i.e.* Southwest Botswana and Western Central Kalahari sub-basins, respectively (Fig. 1). The stratigraphic range of sampling from STRAT 1 borehole covered the Dwyka and Ecca groups. Sampling from CKP 6 borehole covered the entire Karoo Supergroup clastic sequence *i.e.* from the Dwyka Group to the Lebung Group. All samples were prepared at the Laboratoire de Palaeontologie, Université de Brest, France, where all sample residues, as well as all specimens illustrated in this paper, are presently kept. Samples were processed using standard palynological methods (*e.g.* Wood *et al.* 1996). Palynological slides prepared for each sample were examined using a transmitted-light microscope (*i.e.* Leica DIAPLAN) to perform routine slides analyses for the systematic descriptions of palynomorphs.

Palynomorph content

A total of one hundred and ninety-one productive samples, from both STRAT 1 and CKP 6 boreholes, yielded 165 spore and pollen taxa, and 19 acritarchs and chlorophycean algae, which are listed in Appendix 1. The range of the taxa and proposed biozonation are indicated in Figs 4 and 5. All productive samples are from the Lower Karoo sequence *i.e.* Dwyka, Ecca and Beaufort groups, with the latter, however, only yielding very poorly preserved palynomorphs in the basal sections. Samples from the upper Karoo sequence *i.e.* Lebung Group, which is largely dominated by red beds, are barren. The palynomorphs recovered from the lower Karoo are dominated by pollen and spores (*e.g.*, Figs 4, 5), however a few samples also indicate the rare occurrences of microphytoplanktons (acritarchs and prasinophycean phycomata). There is a visible disparity in the preservation status of palynomorphs from STRAT 1 and CKP 6, which perhaps reflects the palaeo-depositional settings of separate sub-basins where the two boreholes are located.

	AGE STRATIGRAPHY	LITHOLOGY	DEPOSITIONAL ENVIRONMENT
185 Ma	SLG	basalt	Continental flood basalts: extensional tectonics related to on-set of Gondwana break-up
	LEBUNG GROUP	red beds sandstone silt-mudstone sandstone, rare conglomerates	Arid continental palaeo-climate: Aeolian Fluvial Lacustrine
Karoo Supergroup	BG	silt-mud-limestone	Transitional (Lacustrine)
	ECCA GROUP		De-glaciation and amelioration of the climate: Fluvio-deltaic Swamps Lacustrine/marginal marine
	DWYKA G.	mudstone, varvites, siltstone, sandstone, tillites	Glacial palaeo-climate Subglacial Glaciofluvial Glaciolacustrine
Late Carboniferous – Early Jurassic			

Figure 3. Karoo Supergroup lithostratigraphic subdivision and palaeo-environments.

The palynomorph content indicates a strong lithofacies influence, with the sandstone facies producing the poorest yields in comparison with the siltstone and mudstone facies. This observation is considered to reflect preferential sorting with respect to grain-size.

Biozonation

A detailed assessment of the palynomorph content *i.e.* qualitative analysis, revealed the occurrence of taxa suitable for subdividing the Lower Karoo sequence into biostratigraphic units or biozones. Although the range charts could not produce a perfect correlation between STRAT 1 and CKP 6, consideration of the common taxa in terms of the assemblage zones, allowed the strata in both sections to be subdivided into three biozones which are assemblage zones (Figs 4, 5).

Comparison of the data between STRAT 1 and CKP 6 indicates that the base of the sections is characterised by a few common taxa of typically long range nature. There is some disparity in occurrence data between the two sections, which makes the level of comparison in the basal sections rather poorly constrained. The most significant taxon that reflects some degree of correlation between the basal sections is the rare and relatively short to medium range *Punctatisporites ubischii* species. A perhaps significant point to consider with regard to the basal sections is the fact that these marks the junction between older taxa of pre-Karoo strata and those originating in early Karoo times. However, in the case of this study, the youngest pre-Karoo sequence consists of barren earliest Cambrian red beds, which unfortunately are not useful for a stratigraphic review of taxa ranges.

The *Hamiapollenites bullaeformis* Assemblage Zone (Biozone KK 1)

The lower limit of the zone is placed at the lowermost occurrences of taxa *Apiculatisporis parmatus* and *Potonieisporites brasiliensis*. The upper limit of the zone is placed at the last occurrences of taxa *Punctatisporites gracilis*, *Densosporites rotundus*, and *Cristatisporites microvacuolatus*. The zone has been named after the species *Hamiapollenites bullaeformis*, which forms one of the diagnostic taxa, and is restricted to the zone in both STRAT 1 and CKP 6, and occurs in other regionally associated areas.

The diagnostic taxa characteristic of this zone are represented by spores, with the most common being: *Converrucosisporites*, *Cristatisporites*, *Horriditriletes* and *Punctatisporites* spp. The most significant taxa are: *Apiculatisporis unicus*, *Cirrabaculisporites* spp., *Converrucosisporites pseudoreticulatus*, *Converrucosisporites irregularis*, *Cristatisporites inconstans*, *Cristatisporites menendezii*, *Divaricrassus minor*, *Horriditriletes curvibaculosus*, *Lophotriletes rarus*, *Lundbladispota gracila*, *Punctatisporites gretensis*, *Punctatisporites parvus*, *Raistrickia crenata* and *Retusotriletes diversiformis*. The *Vittatina* Bisaccate Group appears in this biozone. It also contains important pollen taxa such as *Caheniasaccites flavatus*, *Cycadopites cymbatus*, *Pakhapites fusus*, *Protohaploxypinus rugatus*, *Potonieisporites congoensis*, *Weylandites lucifer*. The most notable similarity between STRAT 1 and CKP 6, in terms of species range, is a major decrease in diversity indicated by the *Cristatisporites* spp. at the top of the zone. Coincidentally, the top of the zone in both sections also mark a major lithofacies change from a predominantly argillaceous facies, and hence reflecting the possibility of facies-control of the *Cristatisporites* spp. In general, the rest of the zone indicates a close affinity between the

ranges of the taxa and the lithofacies distribution, an observation that may indicate the restriction of ranges due to ecological variations and the geographical isolation of taxa (Miall 1990). Nevertheless, some of the less common but significant and restricted species, such as *Hamiapollenites bullaeformis* and *Raistrickia crenata* appear to have their terminations not closely associated with the top boundary of the zone and hence are probably not related to changes contributing to litho-facies variations. Therefore, the ranges of *Hamiapollenites bullaeformis* and *Raistrickia crenata* are considered to broadly represent time-equivalent events occurring in STRAT 1 and CKP 6. However, in order to improve the confidence level in the reality of this zone, these events require to be verified from other sections as well as searching for other diagnostic taxa in future studies. It should be noted that *Granulatisporites angularis*, present in the biozone, with a long range in the two sections is considered here as a junior synonym of *Granulatisporites austroamericanus* Archangelsky & Gamero, 1979. The latter is also considered a possible junior synonym of *Microbaculispora tentula* Tiwari, 1975, by Playford & Dino (2002). Some specimens referred to in this study as *Converrucosisporites irregularis* (Anderson) comb. nov., are similar to some *Pseudoreticulatispora pseudoreticulata* of Backhouse (1991) which exhibit a large morphological variation. We also put in synonymy with *Converrucosisporites pseudoreticulatus* (Balme & Henelly) comb. nov., *Converrucosisporites confluens* (Archangelsky & Gamero) Playford & Dino, 2002, which is well represented in the biozone. In terms of the lithostratigraphic divisions this zone corresponds to the lowermost Ecca Group (*i.e.* Bori/Kobe formations) and the Dwyka Group. However, the lower boundary of the zone indicates the possibility of diachronosity, with the upper Dwyka section in CKP 6 reflecting time equivalence with the lower Dwyka in STRAT 1.

The *Cyclogranisporites gondwanensis* Assemblage Zone (Biozone KK 2)

This is a rather poorly defined zone (Figs 4, 5), which is characterised largely on long-range and some medium-range taxa. Compared to the *Hamiapollenites bullaeformis* Assemblage Zone, this zone has only a slight dominance of spores over pollen in its list of diagnostic taxa. The most striking characteristic of this zone in both STRAT 1 and CKP 6 is a drop in the consistency of frequency of occurrence of taxa, a feature related to the change in the lithofacies observed at the upper limit of the *Hamiapollenites bullaeformis* Assemblage Zone. As a result, there is a lack of common restricted species to form diagnostic taxa and provide time equivalent events for correlation. The lower limit of this zone is determined by the upper limit of the prece-

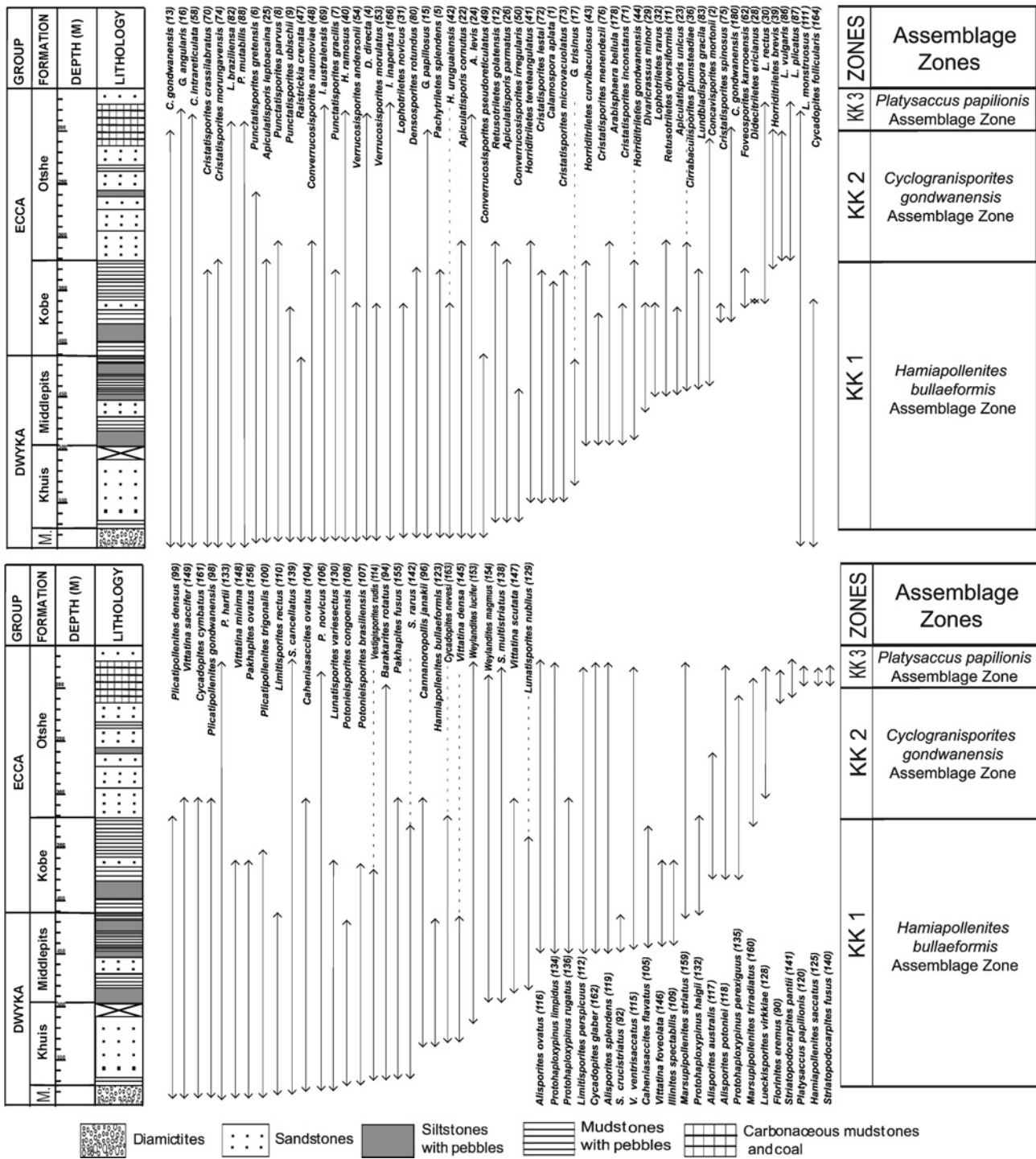


Figure 4. Lithology and range chart of spore and pollen species identified in core samples from STRAT 1 borehole, with inferred palynozonal attributions.

ding zone *i.e.* *Hamiapollenites bullaeformis* Assemblage Zone. The upper limit of the zone is placed at the last occurrence of the taxon *Cyclogranisporites gondwanensis*. The latter has provided a name for the zone because it is the only species that defines the upper limit in both STRAT 1 and CKP 6 borehole sections. The Biozone

KK 2 is also characterized by, amongst others: *Alisporites australis*, *Alisporites ovatus*, *Alisporites potonie*, *Concavisporites mortonii*, *Horriditriletes brevis*, *Laevigatisporites vulgaris*, *Lophotriletes rarus*, *Lueckisporites virkkiae*, *Protohaploxylinus perexiguus* and *Marsupipollenites triradiatus*.

The *Platysaccus papilionis*–*Striatopodocarpites fusus* Assemblage Zone (Biozone KK 3)

This zone (Figs 4, 5) represents a narrow uppermost productive section of the sampled strata, dominated by bisaccate pollen. The lower limit of the zone is placed at the first occurrence of the taxa *Platysaccus papilionis* and *Striatopodocarpites fusus*. The upper limit is not defined due to the non-availability of core material for sampling beyond the topmost sampled level. Consequently, this zone possibly represents a lowermost subzone of a broader zone. The zone is named after these two species because they are the most significant taxa restricted within the zone, as noted in borehole STRAT 1 and CKP 6, as well as in equivalent zones from other previous local studies. The species *Lueckisporites virkkiae* ranges into Biozone KK 3 in STRAT 1, and *Laevigatisporites vulgaris* on the other hand appears in the same range in CKP 6 whereas it disappears in STRAT 1. Other diagnostic short range taxa in the biozone are: *Vestigisporites ventrisaccatus*, common to the two cores and *Florinites eremus*, *Hamiapollenites saccatus*, *Polypodiisporites mutabilis* and *Striatopodocarpites pantii*.

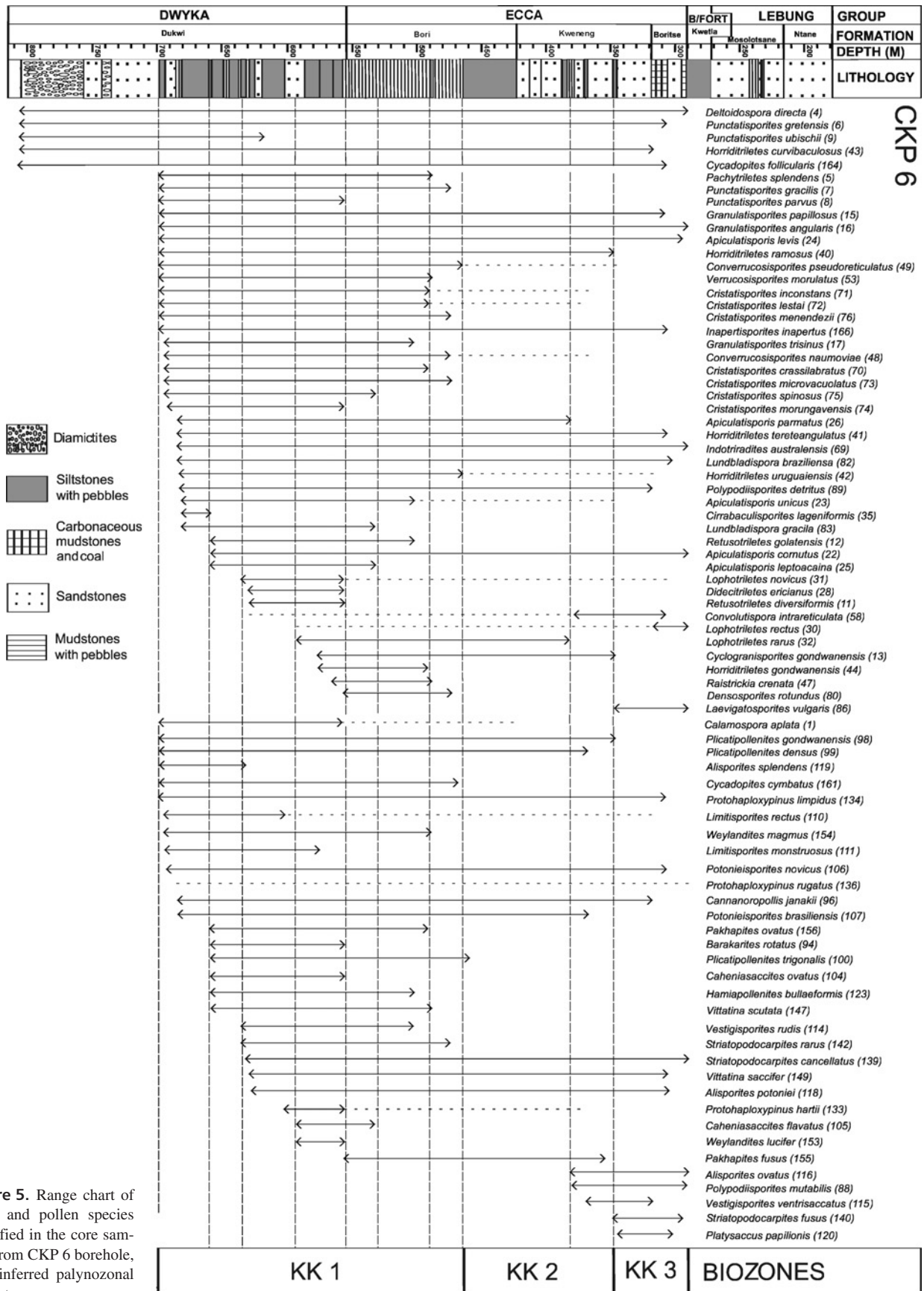
Correlation with previous local studies

Most of the limited palynology studies undertaken from Botswana either present only palynostratigraphic interpretations in terms of biostratigraphic units and their ages or assemblage descriptions without occurrence data (e.g., Dolby 1990, Key *et al.* 1995). This approach presents problems for comparison and correlation due to the unavailability of ranges of taxa, and as a result, only broad comparisons can be considered. A few of the previous studies however (e.g., MacRae 1978, ECL 1990, Stephenson & McClean 1999) do present results that give insight into the vertical characteristics of taxa, which allows for a limited but significant comparison and correlation (e.g., Fig. 6).

Correlation with the zonation scheme of MacRae (1978). – Although displaying some considerable variations in taxonomic terminology, the unpublished work of MacRae (1978) presents the first complete preliminary palynozonation scheme available for correlation. The scheme comprises three concurrent range zones based on the distribution of sixty eight miospore taxa, namely zones I, II, and III, in ascending order of the stratigraphy, and recognised in borehole N1/3 situated in the northeast part of the basin. A broad comparison (Fig. 6) indicates that the section of STRAT 1 that corresponds to Biozone KK 1 can be correlated with MacRae's Biozone 1. Species most significant and common to both sections include: *Vittatina minima*, *Caheniasaccites flavatus*, *Caheniasaccites ovatus*, *Plicatipollenites densus*, *Plicatipollenites gondwanensis*, *Punctatisporites gretensis*

and *Calamospora aplata*. The stratigraphic range of the common taxa indicates a correlation of the middle to upper Dwyka Group (e.g., Khuis and Middlepits formations) and lower Ecca Group (e.g., Kobe Formation) in STRAT 1 with a much condensed similar section of the Karoo Supergroup described in MacRae (1978). The upper section of STRAT 1, which includes biozones KK 2, KK 3, and the topmost section of Biozone KK 1 can be broadly correlated with the section covered by MacRae's concurrent range zones II and III in N1/3. Species common to both sections include: *Alisporites splendens*, *Striatopodocarpites fusus*, *Protohaploxypinus limpidus*, *Alisporites ovatus* and *Laevigatisporites vulgaris*. A comparison of the suprageneric quantitative trends reveals a rise in the relative abundance of bisaccate striate pollen in both sections. Overall, STRAT 1 allows for only a broad and general comparison. As a result there are no visible details that make it possible to comparatively analyse the lithofacies for important factors such as diachronous characteristics.

Correlation with the zonation scheme of ECL (1990). – ECL (1990) erected a regional zonation scheme of five palynozones based on analysis of borehole and field samples from Namibia, Botswana, Zimbabwe, and Zambia. The palynozonation scheme of ECL (1990) is largely based on variations determined by the relative abundance of taxa, which makes it difficult to correlate with the present study in which the zonation is largely based on species' ranges. Nevertheless, few diagnostic taxa allow for a broad comparison and correlation (Fig. 6). The first half of Biozone KK 1 of STRAT 1 can be correlated with Zone I (MZ I) on the basis of common taxa that are dominated by monosaccates and consist of *Plicatipollenites gondwanensis* and relatively diverse *Potoniesporites* spp. Other species of note, albeit in different taxonomic terminology, include *Vestigisporites rudis* and *Cristatisporites morungavensis*. The second half of Biozone KK 1 is correlated with Zone MZ II and the base of Zone MZ III on the basis of the common occurrence of *Cirrabaculisporites plumsteadi*, an increase in non-striate pollen in the upper part of the zones and finally the upper limit of the regular monosaccates *i.e.* *Plicatipollenites* and *Cannanoropollis* species. The KK 2 Biozone is correlated with the upper part of Zone MZ III and Zone MZ IV, based on the occurrence of common significant taxa including *Lueckisporites virkkiae*, *Marsupipollenites triradiatus* and *Laevigatisporites* spp. Other characteristic taxa interesting in terms of correlation include *Protohaploxypinus* spp., *Weylandites lucifer* and *Cycadopites cymbatus*. The uppermost KK 3 Biozone is correlated with Zone MZ V based on a first appearance of *Striatopodocarpites pantii* as well as the following common taxa: *Lueckisporites virkkiae*, *Weylandites lucifer*, *Polypodiisporites mutabilis* and *Laevigatisporites vulgaris*. The base of the zone is generally reflected by a marked increase in the relative abundance of the striate bisaccates.



STRAT 1 BOREHOLE (THIS STUDY)		PAN AFRICAN BASIN STUDY (ECL 1990)	N 1/3 BOREHOLE (MacRae 1978)	MASETLHENG PAN-1 WELL (Dolby 1990)	MORUPULE (Stephenson & McLean 1999)
Lithostratigraphy	Palynostratigraphy				
ECCA GROUP	Otshe Formation	KK 3	MZ V	III	Morupule Section
		KK 2	MZ IV	II	
	Kobe Formation	KK 1	MZ III	I	
			MZ II		
Middlepits Formation	MZ I				
DWYKA GROUP	Khuis Formation			ZONE 2	
	Malogong Formation	∨ ∨ ∨ ∨ ∨ ∨			

Figure 6. Correlation of the zonation scheme from STRAT 1 borehole (core section for reference) with zonation schemes from previous local studies.

Correlation with the work of Stephenson & McLean (1999). – Stephenson & McLean (1999) described an Early Permian palynological assemblage from a Lower Karoo sequence, represented by the Morupule Formation, in the eastern fringe of the Kalahari Karoo Basin. There is remarkable similarity between STRAT 1 and the Morupule section in terms of taxa content, albeit with some variations in taxonomic terminology. However, the majority of the common species depict a long range characteristic in the relatively extensively sampled STRAT 1 section. The Morupule Formation represents a narrow zone in terms of Karoo strata and less than 15 m was sampled by Stephenson & McLean (1999). Consequently, the initiations and terminations of most taxa most likely fall outside the sampled section and hence species ranges remain poorly constrained. Nevertheless, comparison of the common taxa allows only for a broad and general tentative correlation (Fig. 6). The most comparatively significant taxa that correlate STRAT 1 to the Morupule section include *Laevigatosporites vulgaris*, *Alisporites ovatus*, *Alisporites potonieii*, *Florinites eremus*, *Protohaploxypinus limpidus*, *Striatoabieites multistriatus* and *Platysaccus* spp. The ranges of the significant taxa broadly correspond to biozones KK 2 and KK 3 of STRAT 1.

Correlations with regional palynological studies

Palynological studies pertinent to Karoo Supergroup stratigraphy have been undertaken by various workers in several of the contemporary Karoo basins of southwestern Gon-

dwana (e.g. Manum & Duc Tien 1973; Jardiné 1974; Falcon 1975–1978; Utting 1976, Anderson 1977; Wright & Askin 1987; MacRae 1988; Hankel 1992–1993; Aitken 1994; d’Engelbronner 1996; Nyambe & Utting 1997; Kalckreuth *et al.* 1999; Millsted 1994–1999; Semkiwa *et al.* 2003 *etc.*). The results of such studies reveal some important common features that allow for a regional comparison and correlation of the Karoo sequence in the various basins. A selected number of the regional studies are discussed below and compared with the results from STRAT 1 section (e.g., Fig. 7).

South Africa

Correlation with the zonation scheme of MacRae (1988). – MacRae (1988) described palynomorph assemblages from the northern Karoo basins of South Africa and subsequently erected six palynozones *i.e.* A–F, with which a broad correlation with STRAT 1 borehole is possible (Fig. 7). MacRae’s (1988) Biozone A is tentatively correlated with the basal section of STRAT 1 where although no significant taxa exist for direct correlation, common taxa of rather long ranges occur. The top of Biozone B is equated with the upper part of Biozone KK 1 based on the terminations of *Plicatipollenites trigonalis* and *Vestigisporites rudis*, both of which occurs in the two zones. On the other hand, the base of Biozone B favourably equates with the base of Biozone KK 1 as defined on the basis of the initiation of the following species: *Weylandites lucifer*, *Verrucosiporites pseudoreticulatus*, *Horriditriletes tereteangulatus* and

Striatoabieites multistriatus. Biozone C (MacRae 1988), described as the least palynologically productive, favourably equates with the top of Biozone KK 1, characterised by a remarkable decrease in the frequency of occurrence as well as the termination of most species, and the base of Biozone KK 2 of STRAT 1. The top boundary of Biozone KK 2 equates with the top boundary of Biozone D on the basis of the range termination of *Laevigatosporites vulgaris* in STRAT 1, even though the species is known higher up in CKP 6. Biozone KK 3 is correlated with Biozone E, albeit with difficulty, due to the lack of any common significant trends for direct correlation. A perhaps more significant observation is the occurrence of *Platysaccus papilionis* and *Striatopodocarpites fusus*, both of which are restricted to this zone in STRAT 1. The assemblage of common taxa among these zones includes: *Deltoidospora directa*, *Striatoabieites multistriatus*, *Weylandites lucifer*, *Alisporites potonieii*, *Indotriradites australensis*, *Apiculatisporis levis*, *Protohaploxypinus limpidus*, *Protohaploxypinus hartii* and *Striatopodocarpites cancellatus*.

Lithologically, the overall trend deduced from comparative analysis of the palynological assemblages reflects a diachronous Karoo sequence between the north Karoo basins of South Africa (e.g., borehole ET 61 in MacRae 1988) and the sequence at STRAT 1 borehole, especially with regard to the basal successions. MacRae's (1988) biozones A and B which largely fall within the lower Ecca Group succession (i.e. Wellington Formation) but also include a much condensed section of the Dwyka Group, correlate to a large extent with the Dwyka Group (i.e. Malogong, Khuis, and Middlepits formations), as well as a basal section of the Ecca Group (i.e. Kobe Formation) in STRAT 1 borehole. Similarly, Biozone C (MacRae 1988), which represent the lower parts of the middle Ecca succession (i.e. Enkelbult Formation), correlates with the uppermost part of the lower Ecca (i.e. Kobe Formation), but also encroaches into the basal section of the middle Ecca, in STRAT 1 borehole. The uppermost successions, although relatively poorly constrained due to low palynomorph yields, indicate a much closer lithological correlation between the respective successions. The latter reflects the possibility of a shift from a diachronous setting to a near time equivalent deposition during the middle to upper Ecca.

Zimbabwe

Correlation with the scheme of Falcon (1975). – Palynostratigraphic studies from the Mid-Zambezi Karoo Basin in Zimbabwe by Falcon (1975) allow for a broad but limited correlation (Fig. 7), based on rare similarities reflected by qualitative and quantitative analyses. Falcon (1975) erected a zonation scheme that subdivided the Lower Karoo sequence in the Mid-Zambezi Basin into four major assemblage

zones, including eight sub-zones. Biozone KK 1 in STRAT 1 borehole can be equated with Falcon's (1975) Assemblage I. One notable and comparable characteristic are the ranges of *Converrucosisporites pseudoreticulatus* and *Cycadopites cymbatus* species, both considered significant for Assemblage I. However, only *Converrucosisporites pseudoreticulatus* form a significant taxon in the basal section of Biozone KK 1 of STRAT 1. The quantitative analyses also indicate some rare but significant similarities, which include a relatively marked upward increase in the zonolaminatitriletes, as well as an increase in the bisaccates pollen defining the top boundary. A rare direct comparison is reflected by the initiations of *Retusotriletes diversiformis* and *Alisporites ovatus* which both correlate the base of Falcon's (1975) Assemblage Sub-Zone B with the middle part of Biozone KK 1 of STRAT 1. The biozones KK 2 and KK 3 can be equated with Falcon's (1975) Assemblage II, albeit with difficulties. The lower boundary for the correlated zones is placed at the level where there is a marked upward increase in the relative abundances of bisaccates pollen. Taxa of notable and comparable ranges include *Marsupipollenites* spp., *Striatoabieites* spp., *Striatopodocarpites* spp., *Laevigatosporites* spp., *Alisporites splendens* and *Alisporites potonieii*. The introduction of *Laevigatosporites* spp. appears to be the most significant in defining the lower boundary for correlation.

Zambia

Correlation with the zonation scheme of Utting (1976). – Two palynological assemblages described by Utting (1976) from the Lower Karoo Luwumbu Coal Formation of the Luangwa Valley in Zambia broadly compare (Fig. 7) with the assemblages identified in STRAT 1. Based on comparison of limited taxon ranges, the section of borehole STRAT 1 corresponding to Biozone KK 1 can be equated with the older assemblages obtained from the Mukumba Siltstone Member. The few comparable and characteristic taxa, occasionally with variable taxonomic nomenclature, include *Plicatipollenites densus*, *Plicatipollenites trigonalis*, *Converrucosisporites pseudoreticulatus* and *Cristatisporites lestai*. The latter assemblage broadly correlates the Dwyka Group and the Kobe Formation (i.e. lower Ecca Group) of the Kalahari Karoo Basin with the Mukumba Siltstone Member of the Luwumbu Coal Formation in Zambia. The upper section of STRAT 1 corresponding to biozones KK 2 and KK 3, compares favourably with the younger assemblage determined from the Mpwashii Carbonaceous Member. The most significant taxa in terms of comparative analysis of the ranges include *Laevigatosporites* spp., *Alisporites potonieii*, *Protohaploxypinus perexiguus*, *Marsupipollenites striatus*, *Weylandites lucifer* and *Striatoabieites* spp. This assemblage allows for a broad correlation of a section of the Otshe

STRAT 1 BOREHOLE (This Study)	SOUTH AFRICA (MacRae 1988)	ZIMBABWE (Falcon 1975)	ZAMBIA (Utting 1976)	TANZANIA (Semkiwa et al. 2003)	GABON (Jardine 1974)	MADAGASCAR (Wright & Askin 1987)
KK 3	E	II	Mpwashi Carbonaceous Member		PIV	Lower Sakamena
KK 2	D			Scheuringipollenites - Protohaploxypinus Zone	Unfossiliferous	
KK 1	C	I	Mukumba Siltstone Member		PIII	
	B			PII		
No zonation	A			Cannanoropollis - Plicatipollenites Zone		

Figure 7. Correlation of STRAT 1 zonation scheme with a select few zonation schemes from previous regional studies.

Formation which corresponds to the middle Eccla, with the Mpwashi Carbonaceous Member of the Luwumbu Coal Formation in Zambia.

Tanzania

Correlation with the zonation scheme of Semkiwa et al. (2003). – Semkiwa et al. (2003) gave a brief account of palynological analysis from the Lower Karoo sequence of the Songwe-Kiwira Coalfield in Tanzania. A comparison of common taxa reflects the possibility of a broad correlation between STRAT 1 section and the sequence at Songwe-Kiwira Coalfield (Fig. 7). The basal section of Biozone KK 1 can be equated with the *Cannanoropollis*–*Plicatipollentites* Zone on the basis of the common occurrence of monosaccates, dominated by *Cannanoropollis* spp. and *Plicatipollenites* spp. There is also a notable similarity with regard to the common occurrence of *Cristatisporites* spp. This comparison generally correlates the Dwyka Group with the Idusi Formation at the Kiwira Coal Mine. The upper sections of STRAT 1 reveal a much more evident similarity as reflected by the occurrence of several species of comparable ranges. The most significant taxa include *Alisporites ovatus*, *Alisporites potonieii*, *Laevigatosporites* spp., *Marsupipollenites striatus*, *Protohaploxypi-*

nus limpidus, *Protohaploxypinus rugatus*, *Vittatina scutata* and *Weylandites lucifer*. This assemblage allows for a correlation of the section corresponding to the upper half of Biozone KK 1 and Biozone KK 2 with the *Scheuringipollenites*–*Protohaploxypinus* Zone (e.g., Semkiwa et al. 2003). This consequently equates a section of the uppermost Dwyka, as well as the Kobe Formation and much of the Otshe Formation with the Mchuchuma Formation of the Songwe-Kiwira Coalfield in Tanzania.

Kenya

Correlation with the zonation scheme of Henkel (1992). – Henkel (1992) documented Late Permian to Early Triassic assemblages from the Karoo Sequence of the Mombasa Basin in Kenya. Sampling for this work covered a very narrow section of the Maji ya Chumvi Formation, which makes correlation very poor and largely inconclusive. Of the two assemblages described, only the older assemblage, which unfortunately is limited to one sampling level, can be loosely equated with biozones KK 2 and KK 3. Taxa considered for comparative analysis include: *Lueckisporites virkkiae*, *Weylandites* spp., *Plicatipollenites* spp., *Platysaccus* spp., *Striatopodocarpites* spp. and *Protohaploxypinus* spp.

Gabon

Correlation with the scheme of Jardiné (1974). – Palynological studies by Jardiné (1974) on Karoo equivalent sequences revealed three palynological assemblages from the “Série de l’Agoula”, which overlies glacial deposits. The lowermost assemblage P II can be equated (*e.g.*, Fig. 7) with lower part of Biozone KK 1 in STRAT 1 on the basis of common characteristic taxa such as *Pakhapites fusus*, *Pakhapites ovatus*, *Caheniasaccites ovatus* and *Striomonosaccites* spp. The succeeding assemblage P III is loosely correlated with upper part of Biozone KK 1 based on the significant common occurrence of *Protohaploxylinus* spp. and *Striatoabieites* spp. In addition, the latter zone is, in the “Série de l’Agoula”, immediately succeeded by a non-productive interval, which compares well with the interval corresponding to the topmost section of Biozone KK 1, and to Biozone KK 2. Lastly, the uppermost assemblage P IV of the “Série de l’Agoula” can be correlated with Biozone KK 3 based on the common occurrence of *Lueckisporites virkkiae* and *Platysaccus papilionis*, which are characteristic species in both of the sections.

Madagascar

Palynological assemblages described by Wright & Askin (1987) from Karoo sequences of the Morondava Basin in Madagascar indicate some comparable characteristics with the sequence at STRAT 1 borehole. The assemblage that characterizes the Lower Sakamena section of the Madagascar stratigraphy compares favourably with the assemblages at the top of Biozone KK 1, and in biozones KK 2 and KK 3 (Fig. 7). Taxa with closely comparable ranges of occurrence include *Lueckisporites virkkiae*, *Striatopodocarpites pantii*, *Alisporites ovatus*, *Plicatipollenites gondwanensis*, *Protohaploxylinus limpidus*, *Platysaccus* spp. and *Weylandites* spp.

Correlation with other Gondwana regions

Although long-distance (*e.g.*, between continents) palynostratigraphic correlation is a common practice among biostratigraphers, there is always a great deal of uncertainty associated with the frequency of distribution and the palaeogeography of the respective palynomorphs. Firstly, the frequency distribution of taxa, even on a local scale, is greatly skewed such that there are major disparities between different sections under investigation (Agterberg & Gradstein 1999), which ultimately gives rise to imprecise correlations. The extrapolation of such inherent problems to a large-scale or long-distance correlation is likely to result in exaggeration and mis-correlations. A common problem observed in the present study, but also reported by

other workers (*e.g.*, Souza 2006, Stephenson 2008), involves the realization that certain short-range taxa occur as long-range taxa in other regions, making correlation impractical. Secondly, studies have revealed that global floras progressively became palaeogeographically restricted, particularly during the latest Carboniferous to Permian, a phenomenon that has greatly reduced the efficacy of long-distance palynostratigraphic correlation (Playford & Dino 2005). The above observations call for a concerted effort to upgrade and refine palynological data at the local level before attempting to erect long-distance correlation schemes. Therefore, with the above limitations in mind, the results from the present study will be compared and correlated with only a few selected Gondwana regions (*e.g.*, Fig. 8).

South America

Correlation with the zonation scheme of Souza & Marques-Toigo (2003, 2005), and Souza (2006). – Palynological assemblages described by Souza and Marques-Toigo (2003, 2005) and Souza (2006), from the Brazilian Paraná Basin, indicate a remarkable similarity with the assemblages obtained from the Kalahari Karoo Basin in Botswana. Consequently, the palynozones erected for the sequence at STRAT 1 borehole can, to a certain degree, be compared and correlated (Fig. 8). The lowermost basal section of STRAT 1 (*e.g.*, below Biozone KK 1) is poorly constrained but can be loosely correlated with the *Crucisaccites monoletus* Interval Zone on the basis of the common occurrence of monosaccates such as *Cannanoropollis* spp., *Plicatipollenites* spp., *Potoniesporites* spp., and *Caheniasaccites* spp. In addition, both azonotriletes spores (*i.e.* laevigate and apiculate), comprising *Punctatisporites gretensis*, *Horriditriletes* spp. etc., and zonolaminatitriletes (*e.g.*, *Cristatisporites* spp. and *Vallatisporites* spp.) form significant constituents. The section of STRAT 1 borehole confined between the base of Biozone KK 1 and the lower section of Biozone KK 2 can be equated with the *Vittatina costabilis* Interval Zone on the basis of a significant incoming of several *Vittatina* species. In addition, the species after which the zone was named (*e.g.*, Souza & Marques-Toigo 2005, fig. 2f) also form a significant species in STRAT 1 (described as *Vittatina* sp. in this study). The top of Biozone KK 1 in STRAT 1 can be directly correlated with the top of the *Protohaploxylinus goraiensis* Subzone on the basis of the terminations of *Plicatipollenites trigonalis* and *Potoniesporites congoensis*. The upper sections of STRAT 1 borehole, stretching from the upper part of Biozone KK 2 up to and including Biozone KK 3, compares favourably with the *Lueckisporites virkkiae* Interval Zone. Taxa considered pertinent in recognizing the basal sections of the zones of correlation comprise *Lueckisporites virkkiae* and *Laevigatosporites* spp. However, there are several other taxa characteristic of these zones, the most notable being:

Marsupipollenites striatus, *Striatopodocarpites fusus*, *Striatopodocarpites pantii* and *Weylandites lucifer*.

Australia

Correlation with the zonation scheme of Backhouse (1991). – Backhouse (1991) established the most widely compared palynostratigraphic scheme from the Gondwana Permian sequences of the Collie Basin of Australia. There are however some difficulties in correlating the zonation scheme established here with that of Backhouse (1991) for the Collie Basin. The most important limitation is due to the fact that between the two areas certain key species reveal variable ranges and abundances, an observation also recognized by Backhouse (1991) when comparing the assemblages from the Collie Basin with other Australian basins. Due to the difficulties outlined above, only a broad correlation (Fig. 10), based on general similarities in the ranges of common taxa is considered here. The most closely comparable assemblages indicate a probable correlation of biozones KK 2 and KK 3 of STRAT 1 borehole with the *Striatopodocarpites fusus* Zone of the Collie Basin. The most significant taxa pertinent to this correlation comprise *Florinites eremus*, *Horriditriletes tereteangulatus*, *Laevigatosporites vulgaris* forma *colliensis*, *Cycadopites cymbatus* which disappears in KK 2, and *Striatopodocarpites fusus*, all of which are initiated at the same level in the Collie Basin. Other significant species that indicate a comparable range with *Striatopodocarpites fusus* in the Collie Basin, and also form characteristic taxa in the correlatable section of STRAT 1 borehole includes: *Cymatiosphaera gondwanensis*, *Weylandites lucifer*, *Marsupipollenites triradiatus*, *Marsupipollenites striatus*, *Alisporites ovatus*, *Alisporites potonieii*, *Striatoabieites multistriatus* and *Protohaploxypinus limpidus*. Based on the range of a few selected taxa, the lower part of the two cores, STRAT 1 and CKP 6, corresponding to KK 1 Biozone and the interval below, compares favourably with the section at Collie Basin that precedes the *Striatopodocarpites fusus* Zone, and includes the *Pseudoreticulatispora pseudoreticulata* Zone, the *Pseudoreticulatispora confluens* Zone and the top of Stage 2. The assemblage pertinent to this correlation includes: *Plicatipollenites* spp., *Convrrucosisporites naumoviae*, *Puncatisporites gretensis*, *Cycadopites cymbatus*, *Verrucosisporites andersonii* and *Cristatisporites* spp.

Antarctica

Palynological studies undertaken by various workers in Antarctica reveal the occurrence of assemblages with common and comparable taxa to those recognized in this study. As a result, the sequence at STRAT 1 can be generally compared

and broadly correlated with stratigraphic sections from Antarctica (Fig. 8). Permian assemblages described by Farabee *et al.* (1991), from the Buckley Formation of the central Transantarctic Mountains, closely compares with assemblages from the upper sections of STRAT 1 borehole, which comprises the upper part of Biozone KK 1, and biozones KK 2 and KK 3. The most characteristic taxa pertinent to this correlation include: *Marsupipollenites triradiatus*, *Marsupipollenites striatus*, *Protohaploxypinus limpidus* and *Laevigatosporites* spp. Lindström (1995a, b) also described some palynomorph assemblages from Antarctica which compare favourably with those recognized in the Karoo supergroup. The assemblages recognized from the Vestfjella mountain-range (*e.g.*, Lindström 1995a) compare favourably with those obtained from the interval comprised of the upper part of Biozone KK 1 as well as biozones KK 2 and KK 3, as was the case with the Buckley Formation above (*e.g.*, Farabee *et al.* 1991). The most significant taxa for comparison with the sequence at the Vestfjella mountain-range include: *Alisporites ovatus*, *Alisporites potonieii*, *Cymatiosphaera gondwanensis*, *Florinites eremus*, *Laevigatosporites vulgaris*, *Lueckisporites* spp., *Marsupipollenites striatus*, *Marsupipollenites triradiatus*, *Striatopodocarpites fusus*, *Striatoabieites multistriatus*, *Weylandites lucifer* and *Weylandites magmus*.

A comparison of the assemblages from STRAT 1 with those described by Lindström (1995b) from the Heimfrontfjella mountain-range reveals the occurrence of two groups of correlatable taxa. Firstly, an older assemblage characterized by *Cahenniasaccites ovatus*, *Cycadopites nevsi*, *Limitisporites rectus* and *Verrucosisporites andersonii*, which broadly correlates the lower section of STRAT 1, *i.e.* the basal section of Biozone KK 1, with the lower half of Locality A. Secondly, a younger assemblage that correlates the upper part of Biozone KK 1 and biozones KK 2 and KK 3, with the upper half of Locality A (Lindström 1995b) is comprised of typical taxa as observed in the earlier sections above. Such taxa include: *Alisporites ovatus*, *Alisporites potonieii*, *Laevigatosporites vulgaris*, *Protohaploxypinus limpidus*, *Striatopodocarpites fusus*, *Striatoabieites multistriatus* and *Weylandites magmus*.

Oman and Saudi Arabia

Palynological studies from Oman and Saudi Arabia (*e.g.*, Besems & Schuurman 1987; Love 1994; Penney *et al.* 2008; Stephenson & Osterloff 2002; Stephenson *et al.* 2003; Stephenson 2004, 2008) present an opportunity to compare and correlate the sequence in the Kalahari Karoo Basin with the Late Palaeozoic Gondwana sequence of the Arabian Peninsula. However, there is a lack of any significant similarities between taxa from either area, and hence only a limited comparative analysis that allows for only a broad and general correlation is possible.

raphic studies involve quantitative analyses at the genus level and describe assemblages that are confined to and based on the litho-stratigraphic subdivision, making it difficult to compare and correlate in terms of species ranges. In addition, there is some noticeable degree of variation in taxonomical nomenclature, which also contributes to the difficulties of correlation. Tiwari & Tripathi (1992) compiled a species-determined composite palynozonation scheme based on stratigraphic distribution data obtained from previous studies undertaken in the Damodar Graben and several other pertinent basins of India. This work (*i.e.* Tiwari & Tripathi 1992) allows for a limited but important comparative analysis of the assemblages from India and those recognized from the Kalahari Karoo Basin, as is described below.

A review of the ranges of common taxa reveals two groups of assemblages that broadly correlate the sequence at STRAT 1 borehole with the sequences in the Damodar-Rajmahal basins of India. The first group, comprising an older assemblage, is characterized by: *Caheniasaccites ovatus*, *Cannanoropollis* spp. (as *Parasaccites*), *Plicatipollenites* spp. (*i.e.* *P. gondwanensis*, *P. densus*, and *P. trigonalis*), and *Potonieisporites* spp., which closely correlates Biozone KK 1 with Tiwari & Tripathi's (1992) assemblage zones I–III. This comparison broadly equates the Dwyka Group and the lowermost Ecca Group in STRAT 1 with the Talchir Formation of India.

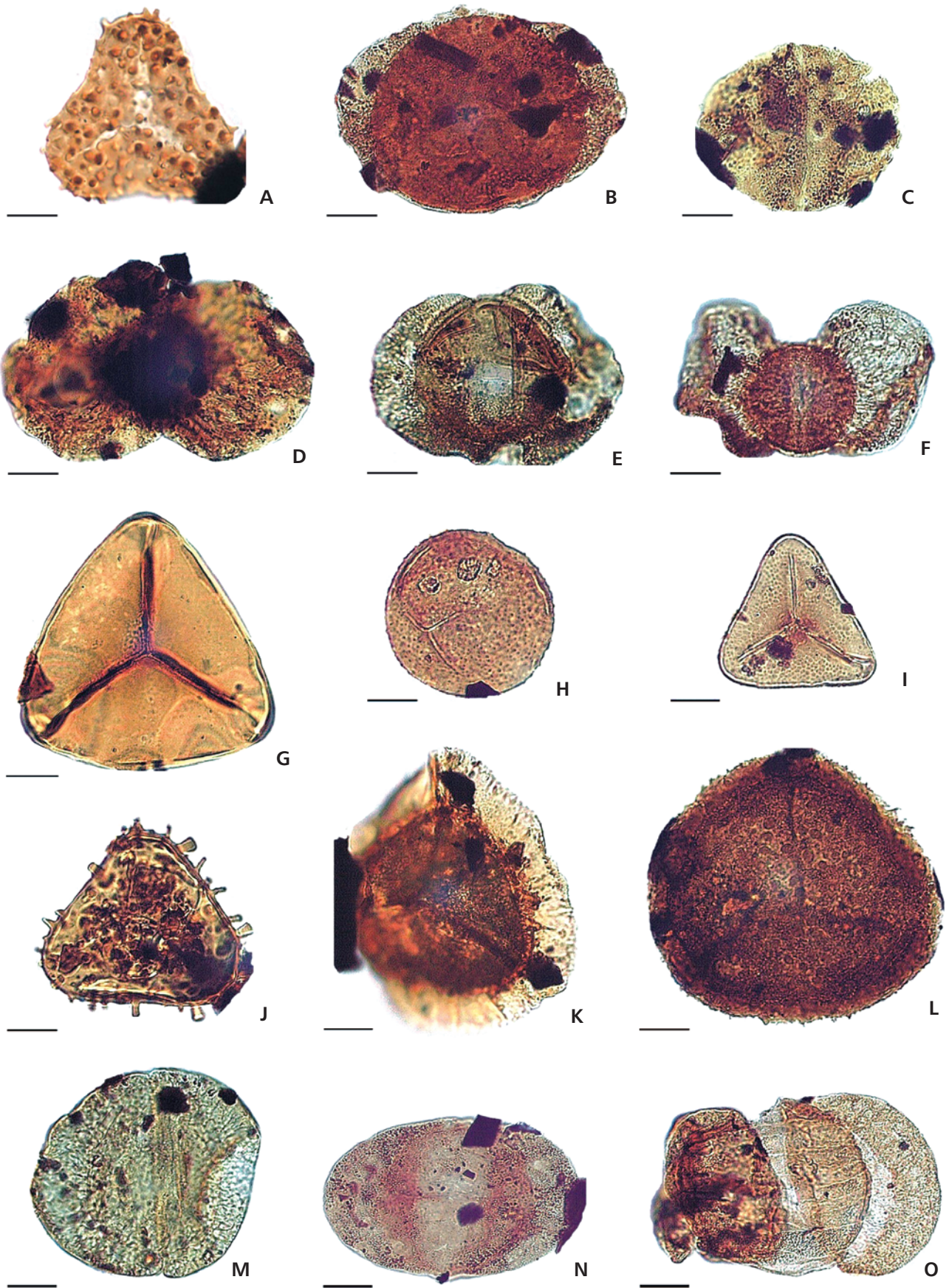
The second group, which forms a younger assemblage and is relatively more diverse, is characterized by the following taxa: *Alisporites ovatus* (as *Scheuringipollenites ovatus*), *Alisporites potoniei* (as *S. maximus*), *Laevigatosporites* spp., *Lophotriletes rectus*, *Marsupipollenites triradiatus*, *Marsupipollenites striatus*, *Protohaploxylinus limpidus* (as *Faunipollenites varius*), *Protohaploxylinus perexiguus* (as *F. perexiguus*), and *Weylandites lucifer*. The latter assemblage favourably compares biozones KK 2 and KK 3, with Tiwari & Tripathi's (1992) assemblage zones III–VIII. Such a comparison broadly correlates much of the Ecca Group in STRAT 1 section, with the Karharbari, Barakar and Kulti formations, as well as basal sections of the Raniganj Formation.

Age deductions

The subject of age determination on the basis of biostratigraphic character requires data of high density and quality the nature of which is beyond the scope of this study. Nevertheless, some general inferences can be made to give insight into chronostratigraphic relations. Age determination for biostratigraphic units depend on reliable correlation with marine sequences containing age-definitive faunas from which internationally agreed reference sections or stratotypes have been developed (Dunn 2001, Playford & Dino 2005, Stephenson 2008). Most of the early reference sections used to erect international standard stages, with respect to the relative geological time-scale, developed in Europe, are largely based on the distribution of ammonoids, conodonts, and foraminifers (Christopher & Goodman 1996). For most Gondwana sequences, where there is a general lack of marine fossils, zonation schemes are mainly based on terrestrial stratigraphic intervals, and precise dating and correlation remains uncertain. This is compounded by the geographic restriction of most Permian assemblages, which resulted from the existence of distinct palaeoclimatic zones with associated floral provinces (ECL 1990, Playford & Dino 2005). In addition, radiometric age determination for Upper Palaeozoic strata of Gondwana, some of them for the South African Karoo Basin (*e.g.* Bangert *et al.* 1999), remain limited, and hence age control for the diagnostic assemblages remains equivocal. Consequently, age control for assemblages, and hence the zonation scheme, from the present study is inferred from comparison with other Gondwana palynofloras, and as a result remains tentative.

Comparison of the palynological assemblages from the poorly constrained basal sections of the Karoo sequence considered in this study, with other previous works (*e.g.*, MacRae 1988, Dolby 1990, Souza 2006), indicate Late Carboniferous ages (*i.e.* Kasimovian–Gzhelian). The latter is seemingly typified, in Gondwana sequences, by the common dominance of monosaccates and trilete spores when compared with the dominance of bisaccate pollen (*e.g.*, MacRae 1988, Souza 2006). Late Carboniferous ages have also been suggested from equivalent lithofacies (*e.g.*,

Figure 9. (Figs 9–11: Representative palynomorphs from the Lower Karoo sequence in STRAT 1 borehole. Slides are kept at the Laboratoire de Paléontologie, Université de Bretagne Occidentale, in Brest, France. Palynomorph locations on slides are recorded as *England Finder* (EF) coordinates.) Pollen and spores of the *Platysaccus papilionis* (A–F) and the *Cyclogranisporites gondwanensis* assemblage zones (G–O). • A – *Lophotriletes rectus* Bharadwaj & Salujha, 1964 (slide: 1383, EF: J34). • B – *Vestigisporites ventrisaccatus* Anderson, 1977 (slide: 1556, EF: W42.2). • C – *Alisporites ovatus* (Balme & Hennelly) Jansonius, 1962 (slide: 1551, EF: O32.4). • D – *Platysaccus papilionis* Potonié & Klaus, 1954 (slide: 1554, EF: E47). • E – *Lueckisporites virkkiae* Potonié & Klaus, 1954 (slide: 1555, EF: E21). • F – *Striatopodocarpites fusus* (Balme & Hennelly) Potonié, 1958 (slide: 1579, EF: V17.4). • G – *Deltoidospora directa* (Balme & Hennelly) Norris, 1965 (slide: 1562, EF: C19.4). • H – *Cyclogranisporites gondwanensis* Bharadwaj & Salujha, 1964 (slide: 1599, EF: P39.3). • I – *Granulatisporites papillosus* Hart, 1965 (slide: 1600, EF: U22.1). • J – *Horriditriletes ramosus* (Balme & Hennelly) Bharadwaj & Salujha, 1964 (slide: 1608, EF: T30.4). • K – *Indotriradites australensis* (Hart) Millstead, 1999 (slide: 1578, EF: P24.2). • L – *Lundbladisporea braziliensis* (Pant & Srivastava) emend. Marques-Toigo & Picarelli, 1984 (slide: 1599, EF: K42). • M – *Alisporites potoniei* (Lakhanpal, Sah & Dube) Somers, 1968 (slide: 1551, EF: O32.4). • N – *Protohaploxylinus limpidus* (Balme & Hennelly) Balme & Playford, 1967 (slide: 1562, EF: P24.4). • O – *Striatopodocarpites cancellatus* (Balme & Hennelly) Hart, 1963 (slide: 1578, EF: Q22). Scale bar corresponds to 10 µm.



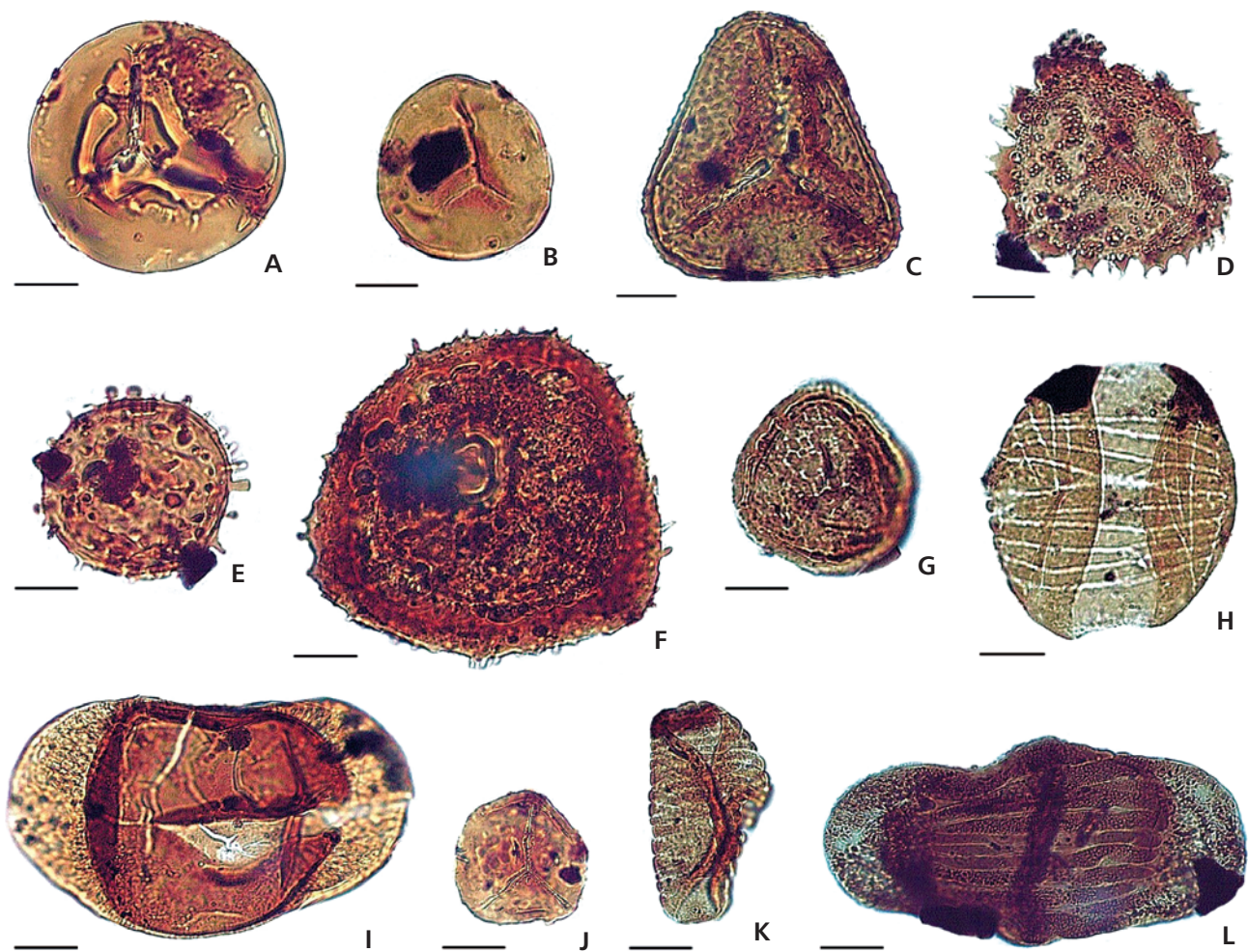


Figure 10. Pollen and spores of the *Hamiapollenites bullaeformis* Assemblage Zone. • A – *Punctatisporites gracilis* Anderson, 1977 (slide: 1602, EF: H47.1). • B – *Retusotriletes diversiformis* (Balme & Hennelly) Balme & Playford, 1967 (slide: 1603, EF: S20.1). • C – *Lophotriletes rarus* Bharadwaj & Salujha, 1964 (slide: 1619, EF: F37). • D – *Cristatisporites microvacuolatus* (Dias-Fabricao) emend. Picarelli & Dias-Fabricao, 1990 (slide: 1598, EF: D39.3). • E – *Raistrickia crenata* Foster, 1979 (slide: 1627, EF: N37.4). • F – *Cristatisporites morungavensis* (Dias-Fabricao) emend. Picarelli & Dias-Fabricao, 1990 (slide: 1622, EF: J31.2). • G – *Densosporites rotundus* Falcon, 1978 (slide: 1581, EF: R21.4). • H – *Weylandites magnus* (Bose & Kar) Backhouse, 1991 (slide: 1563, EF: V30.3). • I – *Limitisporites rectus* Leschik, 1956 (slide: 1571, EF: T24). • J – *Apiculatisporis parmatus* (Balme & Hennelly) comb. nov. (slide: 1603, EF: V49.3). • K – *Vittatina scutata* (Balme & Hennelly) Bharadwaj, 1962 (slide: 1565, EF: Q23). • L – *Hamiapollenites bullaeformis* (Samoilovich) Jansonius, 1962 (slide: 1623, EF: T35.4). Scale bar corresponds to 10 μ m.

Dwyka Group), by Key *et al.* (1995) based on studies from southwest Botswana, as well as Visser (1990) who studied glaciogene deposits from southern Africa. Souza (2006) gives a brief account of limited radiometric ages from the Dwyka Group, which also indicates late Carboniferous stages.

Preliminary correlation of the biozones from STRAT 1 and CKP 6 with other relevant palynological studies from Gondwana sequences (*e.g.*, Wright & Askin 1987; ECL 1990; Hankel 1992; Farabee *et al.* 1991; Lindström 1995a, b; Souza 2006) generally reveal an Early Permian age for Biozone KK 1, whereas the biozones KK 2 and KK 3 are of late early Permian to early Middle Permian age. There are, however, difficulties in defining stage boundaries, which requires more refined data to allow direct correlation at short stratigraphic intervals. Nevertheless, tentative age in-

ferences for the present zonation scheme from the Kalahari Karoo Basin are made based on comparison with the zonation schemes for the Paraná Basin of Brazil in South America (*e.g.*, Di Pasquo *et al.* 2003a, b; Souza & Marques-Toigo 2003, 2005; Souza 2006), and their calibration by radiometric dates (Santos *et al.* 2006, Stephenson 2008). It is also worth noting that the similarities indicated by the assemblage taxa from the Kalahari Karoo Basin and the Paraná Basin are also corroborated by the palaeogeographic similarities of the two basins as reflected by several illustrations of their Late Palaeozoic reconstruction (*e.g.*, Kalkreuth *et al.* 1999, Turner 1999, Wopfner 1999, Golonka & Ford 2000 *etc.*).

As described earlier, the KK 1 Biozone globally correlates with the *Vittatina costabilis* Interval Zone (Souza

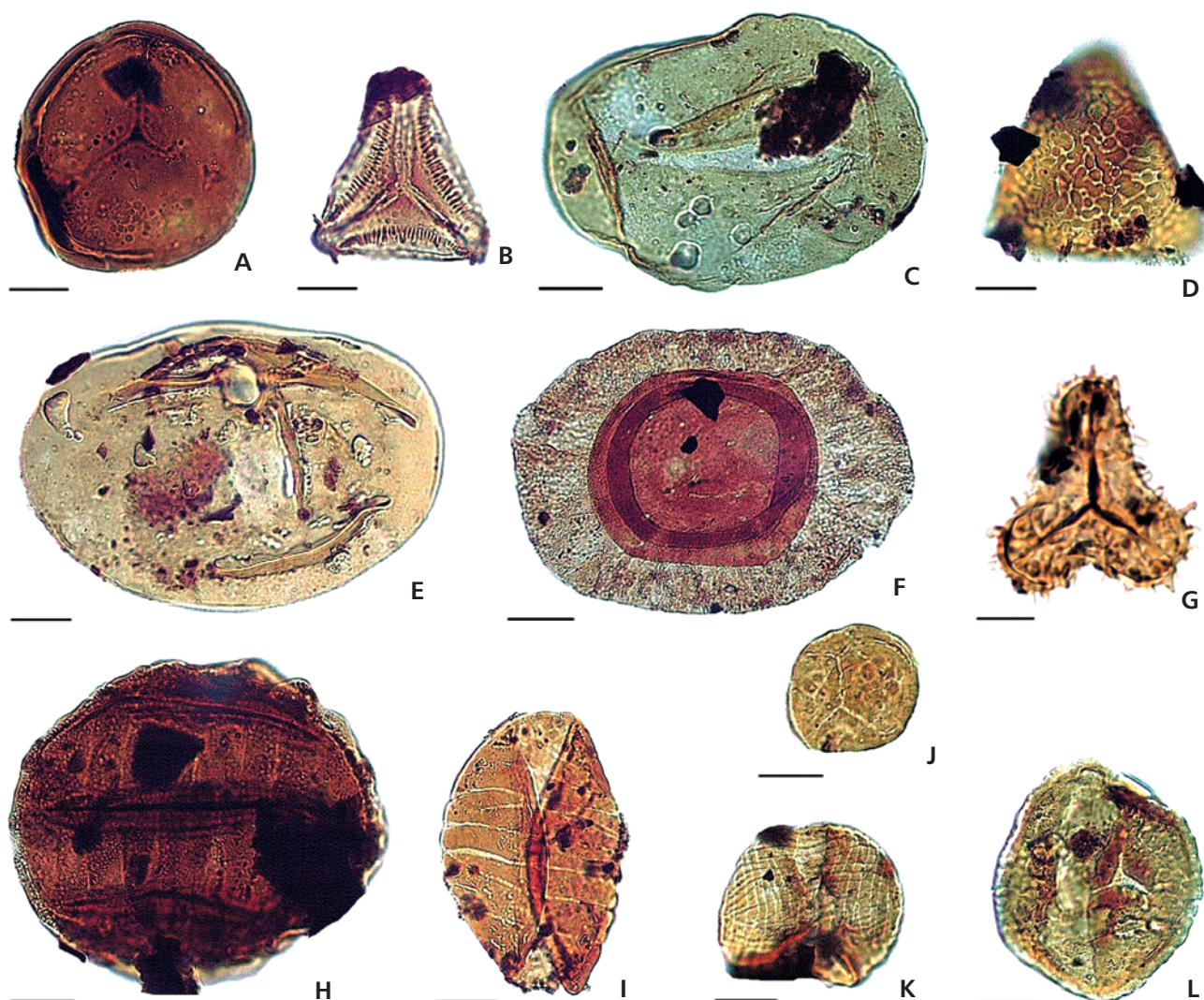


Figure 11. A selected few significant pollen and spores used to determine the range zones for STRAT 1 and CKP6 boreholes. • A – *Punctatisporites ubischii* Foster, 1979 comb. nov. (slide: 1571, EF: T47.4). • B – *Cirrabaculisporites lageniformis* (Anderson) comb. nov. (slide: 1564, EF: K38.3). • C – *Laevigatosporites vulgaris* (Ibrahim) Ibrahim, 1933 (slide: 1580, EF: G33). • D – *Converrucosisporites irregularis* (Anderson) comb. nov. (slide: 1643, EF: U43.3). • E – *Laevigatosporites plicatus* Kar, 1968 (slide: 1561, EF: T30.3). • F – *Potonieisporites congoensis* Bose & Maheshwari, 1968 (slide: 1629, EF: K17.2). • G – *Horriditriteles gondwanensis* (Tiwari & Moiz) Foster, 1975 (1580, EF: E19). • H – *Vittatina* sp. (slide: 1621, EF: Y26.2). • I – *Pakhapites fusus* (Bose & Kar) Menéndez, 1971 (slide: 1613, EF: W37.1). • J – *Divaricrassus minor* (Anderson) Millstead, 1999 (slide: 1599, EF: R22.4). • K – *Weylandites lucifer* (Bharadwaj & Salujha) Foster, 1975 (slide: 1558, EF: O37.1). • L – *Marsupipollenites triradiatus* Balme & Hennelly, 1956 (slide: 1559, EF: M44.1). Scale bar corresponds to 10 µm (except for Fig. 11F where the scale bar represents 20 µm).

2006). From the latter correlation, Early Permian age ranging from the Asselian stage to the Artinskian stage are deduced. The upper part of KK 1 Biozone plus KK 2 and KK 3 biozones generally correlate with the *Lueckisporites virkkiae* Interval Zone (Souza 2006), and in the Parana Basin, Shrimp U-Pb zircon dating of the Irati Formation revealed an age of 278.4 Ma (Artinskian; Gradstein *et al.* 2004) for the base of the *Lueckisporites virkkiae* Zone (Santos *et al.* 2006). Consequently, a tentative late Early Permian to earliest Middle Permian age range is proposed for the upper biozones KK 2 and KK 3. A rare absolute age of 270 Ma reported from the Collingham Formation of

South Africa (*e.g.*, Turner 1999), which overlies the Whitehill Formation, supports a late Early Permian age (*i.e.* Kungurian) for the uppermost part of Biozone KK 2. The latter represent a lithofacies section indicated in Johnson *et al.* (1996) to immediately overlie the Whitehill Formation in the Kalahari Karoo Basin and, hence probably equates with the Collingham Formation. Comparisons of the assemblage characteristic of Biozone KK 3 with several regional and Gondwana-wide studies indicates Middle Permian (Guadalupian) ages (*e.g.*, Wright & Askin 1987, Farabee *et al.* 1991, Hankel 1992, Lindström 1995a). As discussed above, the top of Biozone KK 2, is considered to

represent late Early Permian age, therefore, the succeeding Biozone KK 3 is considered to represent early Middle Permian ages (*i.e.* Roadian). Consequently, the base of Biozone KK 3 is tentatively equated with the boundary between Early and Middle Permian for the sequence at STRAT 1 borehole in the Kalahari Karoo Basin.

Conclusions

The Lower Karoo sequence of the Karoo Supergroup in the Kalahari Karoo Basin contains relatively well preserved pollen and spore palynomorphs suitable for biostratigraphic classifications. Taxa range analysis, determined on the basis of first and last occurrences datum, revealed the occurrence of long, medium, and short range species, which allowed for the subsequent erection of biostratigraphic units or biozones. Three assemblage zones have been erected for each of the study sections *i.e.* STRAT 1 and CKP 6 boreholes. Although there appears to be considerable variation in taxa ranges between the sections considered, the frequent occurrence of common events nevertheless highlights great potential for palynological comparisons. A preliminary direct correlation between STRAT 1 and CKP 6 borehole sections is attainable on the basis of the three assemblage zones which are common to both sections. The assemblage zones erected are comprised of, in ascending order of stratigraphy, the *Hamiapollenites bullaeformis* Assemblage Zone (Biozone KK 1), the *Cyclogranisporites gondwanensis* Assemblage Zone (Biozone KK 2), and the *Platysaccus papilionis*–*Striatopodocarpites fusus* Assemblage Zone (Biozone KK 3). Only limited comparisons and broad correlations with other local previous palynology studies have been established, owing to the non-availability of taxa range data in most such studies. Comparison and tentative correlation of the zones with similar zones erected in the region, as well as Gondwana-wide, have been established, albeit cautiously, in recognition of several limiting factors that commonly hamper long-distance correlations. Amongst the notable limiting factors is the disparity in the frequency distribution of taxa between sections, also relatively common in local correlations, as well as factors of global scale such as palaeogeographic restriction of flora or provincialism, which is considered to have been well established during the latest Carboniferous to Permian times. Generally, there appears to be a closer degree of similarity between assemblages from the Paraná Basin of South America and those from the Kalahari Karoo Basin. Age control for the zonation schemes erected in this study is inferred from comparison with similar assemblages from previous Gondwana studies, and hence remains tentative. The overall age range is from the Late Carboniferous (Kasimovian–Gzhelian) to the latest Early or possibly earliest Middle Permian (Late Cisularian to Early Guadalupian).

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APPENDIX I – SPECIES INDEX, SPORES, POLLEN, ACRITARCHS AND CHLOROPHYCEAN ALGAE IDENTIFIED IN THIS STUDY

1. *Calamospora aplata* Bharadwaj & Salujha, 1964
2. *Concavisporites mortonii* (de Jersey) de Jersey, 1962
3. *Concavisporites* sp.
4. *Deltoidospora directa* (Balme & Hennelly) Norris, 1965
5. *Pachytriletes splendens* (Saksena) Millstead, 1999
6. *Punctatisporites gretensis* Balme & Hennelly 1956
7. *Punctatisporites gracilis* Anderson, 1977
8. *Punctatisporites parvus* Anderson, 1977
9. *Punctatisporites ubischii* Foster 1979 comb. nov.
10. *Punctatisporites* sp.
11. *Retusotriletes diversiformis* (Balme & Hennelly) Balme & Playford, 1967
12. *Retusotriletes golatensis* Staplin, 1960
13. *Cyclogranisporites gondwanensis* Bharadwaj & Salujha, 1964
14. *Cyclogranisporites* sp.
15. *Granulatisporites papillosus* Hart, 1965
16. *Granulatisporites angularis* (Staplin) Ybert, 1975
17. *Granulatisporites trisinus* Balme & Hennelly, 1956
18. *Granulatisporites* sp.
19. *Granulatisporites* sp. A
20. *Anacanthotriletes* sp.
21. *Anacanthotriletes* sp. A
22. *Apiculatisporis cornutus* (Balme & Hennelly) Høeg & Bose, 1960
23. *Apiculatisporis unicus* (Tiwari) Bharadwaj & Srivastava comb. nov.
24. *Apiculatisporis levis* (Balme & Hennelly) Segroves, 1970
25. *Apiculatisporis leptocaina* (Jones & Truswell) comb. nov.
26. *Apiculatisporis parmatus* (Balme & Hennelly) comb. nov.
27. *Didecitriletes eoericiana* (Anderson) Millstead, 1999
28. *Didecitriletes ericianus* (Venkatachala & Kar, 1965)
29. *Divaricrassus minor* (Anderson) Millstead, 1999
30. *Lophotriletes rectus* Bharadwaj & Salujha, 1964
31. *Lophotriletes novicus* Singh, 1964
32. *Lophotriletes rarus* Bharadwaj & Salujha, 1964
33. *Lophotriletes* sp.
34. *Lophotriletes* sp. A
35. *Cirrabaculisporites lageniformis* (Anderson) comb. nov.
36. *Cirrabaculisporites plumsteadi* (Hart) Anderson comb. nov.
37. *Cirrabaculisporites ramosus* Maheshwari & Bose, 1969
38. *Cirrabaculisporites* sp.
39. *Horriditriletes brevis* Bharadwaj & Salujah, 1964
40. *Horriditriletes ramosus* (Balme & Hennelly) Bharadwaj & Salujha, 1964
41. *Horriditriletes tereteangulatus* (Balme & Hennelly) Backhouse, 1991
42. *Horriditriletes uruguaiensis* (Marques-Toigo) Archangelsky & Gamero, 1979
43. *Horriditriletes curvibaculosus* Bharadwaj & Salujha, 1964
44. *Horriditriletes gondwanensis* (Tiwari & Moiz) Foster, 1975
45. *Horriditriletes* sp.
46. *Horriditriletes* sp. A
47. *Raistrickia crenata* Foster, 1979
48. *Convverrucosisporites naumoviae* (Hart) Backhouse, 1991
49. *Convverrucosisporites pseudoreticulatus* (Balme & Hennelly) comb. nov.
50. *Convverrucosisporites irregularis* (Anderson) comb. nov.
51. *Convverrucosisporites* sp.
52. *Convverrucosisporites* sp. A
53. *Verrucosisporites morulatus* (Knox) emend. Smith & Butterworth, 1967
54. *Verrucosisporites andersonii* (Anderson) Backhouse, 1988
55. *Verrucosisporites trisecatus* Balme & Hennelly, 1956
56. *Verrucosisporites* sp.
57. *Verrucosisporites* sp. A
58. *Convolutispora intrareticulata* (Anderson) comb. nov.
59. *Convolutispora* sp.
60. *Convolutispora* sp. A
61. *Convolutispora* sp. B
62. *Foveosporites karrooensis* Anderson comb. nov.
63. *Foveosporites* sp.
64. *Foveosporites* sp. A
65. *Foveosporites* sp. B
66. *Microreticulatisporites* sp.
67. *Microreticulatisporites* sp. A
68. *Clavatisporites* sp.
69. *Indotriradites australensis* (Hart) Millstead, 1999
70. *Cristatisporites crassilabratus* Archangelsky & Gamero, 1979
71. *Cristatisporites inconstans* Archangelsky & Gamero, 1979
72. *Cristatisporites lestai* Archangelsky & Gamero, 1979
73. *Cristatisporites microvacuolatus* (Dias-Fabricao) emend. Picarelli & Dias-Fabricao, 1990
74. *Cristatisporites morungavensis* (Dias-Fabricao) emend. Picarelli & Dias-Fabricao, 1990
75. *Cristatisporites spinosus* (Menendez & Azcuy) Playford, 1978
76. *Cristatisporites menendezii* Playford, 1978
77. *Cristatisporites* sp.
78. *Cristatisporites* sp. A
79. *Densosporites* sp.
80. *Densosporites rotundus* Falcon, 1978
81. *Densosporites* sp.

82. *Lundbladispora braziliensa* (Pant & Srivastava) emend. Marques-Toigo & Picarelli, 1984
83. *Lundbladispora gracila* Stephenson & Osterloff, 2002
84. *Vallatisporites* sp.
85. *Vallatisporites* sp. A
86. *Laevigatosporites vulgaris* (Ibrahim) Ibrahim, 1933
87. *Laevigatosporites plicatus* Kar, 1968
88. *Polypodiisporites mutabilis* Balme, 1970
89. *Polypodiisporites detritus* (Leschik) Anderson, 1977
90. *Florinites eremus* Balme & Hennelly, 1955
91. *Striomonosaccites brevis* Bose & Kar, 1966
92. *Striomonosaccites crucistriatus* Ybert, 1975
93. *Striomonosaccites* sp.
94. *Barakarites rotatus* (Balme & Hennelly) Bharadwaj & Tiwari, 1964
95. *Bascanisporites undosus* Balme & Hennelly, 1956
96. *Cannanoropollis janakii* Potonie & Sah, 1960
97. *Cannanoropollis* sp.
98. *Plicatipollenites gondwanensis* (Balme & Hennelly) Lele, 1964
99. *Plicatipollenites densus* Srivastava, 1970
100. *Plicatipollenites trigonalis* Lele, 1964
101. *Plicatipollenites* sp.
102. *Plicatipollenites* sp. A
103. *Plicatipollenites* sp. B
104. *Caheniasaccites ovatus* Bose & Kar, 1966
105. *Caheniasaccites flavatus* Bose & Kar, 1966
106. *Potonieisporites novicus* Bhardwaj, 1954
107. *Potonieisporites brasiliensis* (Nahuys, Alpern & Ybert) Archangelsky & Gamero, 1979
108. *Potonieisporites congoensis* Bose & Maheshwari, 1968
109. *Illinites spectabilis* (Leschik) comb. nov.
110. *Limitisporites rectus* Leschik, 1956
111. *Limitisporites monstruosus* (Luber in Luber & Waltz) Hart, 1965
112. *Limitisporites perspicuous* (Leschik) comb. nov.
113. *Limitisporites* sp.
114. *Vestigisporites rudis* Balme & Hennelly, 1955
115. *Vestigisporites ventrisaccatus* Anderson, 1977
116. *Alisporites ovatus* (Balme & Hennelly) Jansonius, 1962
117. *Alisporites australis* de Jersey, 1962
118. *Alisporites potonie* (Lakhanpal, Sah & Dube) Somers, 1968
119. *Alisporites splendens* (Leschik) Foster, 1979
120. *Platysaccus papilionis* Potonié & Klaus, 1954
121. *Platysaccus* sp.
122. *Pteruchipollenites* sp.
123. *Hamiapollenites bullaeformis* (Samoilovich) Jansonius, 1962
124. *Hamiapollenites fusiformis* (Marques-Toigo) emend. Archangelsky & Gamero, 1979
125. *Hamiapollenites saccatus* Wilson, 1962
126. *Hamiapollenites tractiferinus* (Samoilovich) Jansonius, 1962
127. *Hamiapollenites* sp.
128. *Lueckisporites virkkiae* Potonié & Klaus, 1954
129. *Lunatisporites nubilus* (Leschik) comb. nov.
130. *Lunatisporites variesectus* Archangelsky & Gamero, 1979
131. *Lunatisporites* sp.
132. *Protohaploxypinus haijii* Foster, 1979
133. *Protohaploxypinus hartii* Foster, 1979
134. *Protohaploxypinus limpidus* (Balme & Hennelly) Balme & Playford, 1967
135. *Protohaploxypinus perexiguus* (Bharadwaj & Salujha) Foster, 1979
136. *Protohaploxypinus rugatus* Segroves, 1969
137. *Protohaploxypinus* sp.
138. *Striatoabieites multistriatus* (Balme & Hennelly) Hart, 1964
139. *Striatopodocarpites cancellatus* (Balme & Hennelly) Hart, 1963
140. *Striatopodocarpites fusus* (Balme & Hennelly) Potonié, 1958
141. *Striatopodocarpites pantii* (Jansonius) Balme, 1970
142. *Striatopodocarpites rarus* (Bharadwaj & Salujha) Balme, 1970
143. *Ephedripites* sp.
144. *Ephedripites* sp. A
145. *Vittatina densa* Anderson, 1977
146. *Vittatina foveolata* Tschudy & Kosanke, 1966
147. *Vittatina scutata* (Balme & Hennelly) Bharadwaj, 1962
148. *Vittatina minima* Jansonius, 1962
149. *Vittatina saccifer* Jansonius, 1962
150. *Vittatina subsaccata* Samoilovich, 1953
151. *Vittatina* sp.
152. *Vittatina* sp. A
153. *Weylandites lucifer* (Bharadwaj & Salujha) Foster, 1975
154. *Weylandites magmus* (Bose & Kar) Backhouse, 1991
155. *Pakhapites fusus* (Bose & Kar) Menéndez, 1971
156. *Pakhapites ovatus* (Bose & Kar) Menéndez, 1971
157. *Gnetaceapollenites* sp.
158. *Pretricolpipollenites* sp.
159. *Marsupipollenites striatus* (Balme & Hennelly) Foster, 1975
160. *Marsupipollenites triradiatus* Balme & Hennelly, 1956
161. *Cycadopites cymbatus* (Balme & Hennelly) Hart, 1965
162. *Cycadopites glaber* (Luber & Waltz) Hart, 1965
163. *Cycadopites nevesi* (Hart) Hart, 1965
164. *Cycadopites follicularis* Wilson & Webster, 1946
165. *Cycadopites* sp.
166. *Inapertisporites inapertus* (Anderson) Falcon, 1978
167. *Micrhystridium* sp.
168. *Tetraporina* sp.
169. *Veryhachium* sp. A
170. *Veryhachium* sp. B
171. *Veryhachium* sp. C
172. Species A
173. Species B
174. Species C
175. Species D
176. Species E
177. *Botryococcus* sp. cf. *B. braunii*
178. *Arabisphaera bellula* Hemer & Nygreen, 1967
179. *Arabisphaera* sp.
180. *Cymatiosphaera gondwanensis* (Tiwari) Backhouse, 1991
181. *Cymatiosphaera* sp. A
182. *Cymatiosphaera* sp. B
183. *Maculatasporites* sp.
184. *Tasmanites* sp.