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PALYNOLOGY OF A COAL SEAM IN KAROO DEPOSITS OF BOTSWANA AND CORRELATION WITH SOUTHERN AFRICAN COAL-BEARING STRATA

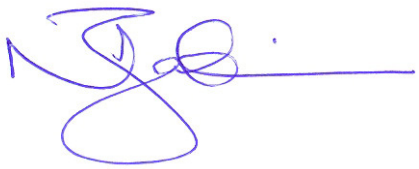
Natasha Barbolini B.Sc. (Hons.) Witwatersrand

Dissertation submitted to the Faculty of Science at the University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Master of Science.

Johannesburg, June 2010

DECLARATION

I hereby certify that this dissertation is completely my own unaided work, and has not been submitted before for any degree or examination at any other University.



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Natasha Barbolini

25 June 2010

ABSTRACT

A significant amount of palynological work has been done on southern African coal seams in the Ecca Group, but as yet there is little consensus on how these areas relate to each other. This study investigated the palynology of a coal seam from Mmamantswe (Mmamabula area), Botswana, approximately 70 km north-east of Gaborone. A total of 124 samples were taken from two borehole cores and subjected to acid preparation, oxidation and acetolysis. Coal samples were found to be barren of palynomorphs. Fifty carbonaceous mudstones and siltstone samples yielded twenty-two productive samples. A thermal alteration index of 3.0-3.5 was assigned for the sediments. Palynomorph diversity was high, with 64 genera and 90 species present, dominated by trilete and alete spores. This indicates a parent flora of mostly lower order lycopods, sphenophytes and ferns. Non-taeniate bisaccate and monosaccate pollens were scarce, and striates extremely rare (only two species), suggesting an autochthonous origin for the coal swamp. The Mmamantswe core was sub-divided into five microfloral assemblage zones. A transition from monosaccate dominance in the lower part of the core, to equal numbers of monosaccates and non-taeniate bisaccates in the upper part of the core, was seen. As the Mmamantswe palynoflora possesses elements of both the Late Carboniferous glacial floras and the mid-Permian coal floras, it is thought to represent a cross-over assemblage dating to soon after the Permo-Carboniferous boundary (Sakmarian and Early Artinskian). The Mmamantswe assemblage can be correlated with Assemblage Zones II and III of Falcon (1975a); Biozones B and C of MacRae (1988); and Zones 1, 2 and 3 of Anderson (1977) but does not fit well into any existing biozonation. The Mmamantswe palynoflora was most similar to that of Milorgfjella, Dronning Maud Land, Antarctica (Larrson *et al*. 1990) and the No. 2 Seam, Witbank, South Africa (Falcon 1989). Taphonomic controls on palynomorph preservation suggest that future studies should also attempt to focus on Permian sediments not containing coal, as microfloral assemblages from coal seams tend to be autochthonous, and subject to local climatic influences. Accordingly they are not as useful for inter-basinal correlation across Gondwana.

Key words: palynology, coal, Karoo, stratigraphy, Botswana, Gondwana, Permian

ACKNOWLEDGMENTS

The following work would not exist without the expert help and guidance of my supervisor, Professor Marion Bamford. I am deeply grateful for her constant support over the past two years. Thanks to Michael Cronwright and Aviva Corporation for providing the samples and geological log. Samples were prepared by Petrus Chakane. Thanks to Dr. Frank Neumann for explaining the Tilia™ program, and to Dr. Michael Stephenson for sending reprints of important papers that could not be obtained otherwise.

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This dissertation is dedicated to my parents, Mario and Annalie, for all their love and support, and for the enthusiasm they have always shown for my studies.

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CHAPTER ONE – INTRODUCTION AND LITERATURE REVIEW

1.1 GENERAL INTRODUCTION

1.1.1 Palaeopalynology

Palaeopalynology (hereafter referred to as palynology) is the study of organic-walled microfossils, particularly fossilized pollen grains and spores (Traverse, 2007). Other microfossils such as acritarchs, dinoflagellates and foraminifera also fall within the scope of palynology, but are limited to marine sediments and shall not be examined here. Continuous pollen sequences in terrestrial sediments of southern Africa are rare, due to the general aridity that prevented permanent lakes or swamps from forming (Scott, 2000; Scott & Woodborne, 2007). Additionally, Karoo intrusives have destroyed some of the existing sequences by heat and devolatization (Falcon, 1975b; Anderson, 1977). Nevertheless, palynomorphs are relatively abundant in many different lithologies of southern Africa, including the Karoo Supergroup sediments. However, palynological records for southern Africa are insufficient, and there is little consensus on how areas relate to each other. This is unfortunate, because palynology is highly useful in vegetation and palaeoenvironment reconstruction (Scott & Woodborne, 2007), stratigraphy, and dating (Scott, 1982).

1.1.2 Applications of palynology

Palynology is very useful in biostratigraphic correlation, correlating lithological units from different areas and often, quite variable lithologies. This is particularly important in areas where faulting impairs lithostratigraphic correlations (Falcon, 1975b). Consequently, palynology has importance for coal (Falcon, 1975b; Millsteed, 1994), fossil fuel (McLachlan & Pieterse, 1978; Batten, 1999; Al-Ameri & Batten, 1997), and diamond exploration (Scholtz, 1985, de Villiers & Cadman, 2001).

Macrofossils are comparatively rare in the rock record and so it is not practical to rely solely on them for dating and correlation. Palynomorphs, by contrast, are often abundantly preserved in ancient sediments, due to their being produced in large numbers for wind pollination. They are made up of sporopollenin, one of the most inert

or stable molecules known. This explains the often excellent preservation of palynomorphs hundreds of millions of years old (Traverse, 2007).

Pollen and spores are small (roughly the same size as silt or very fine sand grains), easily transported, distinctive, and evolve rapidly (Falcon, 1975b). These characteristics are advantageous for the following reasons:

- palynomorphs recovered will represent the general flora of the region because wind-borne pollen grains travel some distance
- spores and pollen are produced by the lower and higher plants respectively and so recovered palynomorphs represent a large proportion of terrestrial plants
- they are useful for dating because they are easy to identify
- they tend to evolve more rapidly than other structures of plants (such as leaves or wood), therefore they are very diverse and indicative of specific taxa

1.1.3 Limitations of palynology

Palynomorphs are usually absent in coarse-grained sandstones, clays, and metamorphosed rocks. Although resistant to all acids, they do not tend to preserve in oxidising environments e.g. “Red Beds”. Volcanic sediments will not yield palynomorphs because temperatures above 200 °C cause carbonisation of the pollen and spores. Metamorphism also destroys palynomorphs. Thus, low-volatile bituminous and anthracitic coals are barren of palynomorphs, while high-volatile bituminous coal from the same stratigraphic horizon is usually rich in pollen (Traverse, 2007).

1.2 OBJECTIVES

This study investigated the palynology of a coal seam in Botswana. Objectives were to:

1. Record all identifiable pollen and spore taxa
2. Predict the quantity and quality of coal present by comparing the Botswana palynoflora with cores from South Africa that have a proven quality and quantity, thus aiding directly in mining operations.
3. Correlate the seam with other coalfields in southern Africa and Gondwana

4. Determine the age and thermal maturity of the coal seam
5. Reconstruct the palaeoenvironment of the peat swamp using both palynological and lithological data

1.3 LITERATURE REVIEW

1.3.1 Karoo biostratigraphy

Palynological analyses are biostratigraphic in nature and combine geological information with the microfossils present in the sediments. All the economically important coal deposits in south-central Africa are found in rocks of the Karoo Supergroup, therefore the geology of the Karoo will be discussed here in detail.

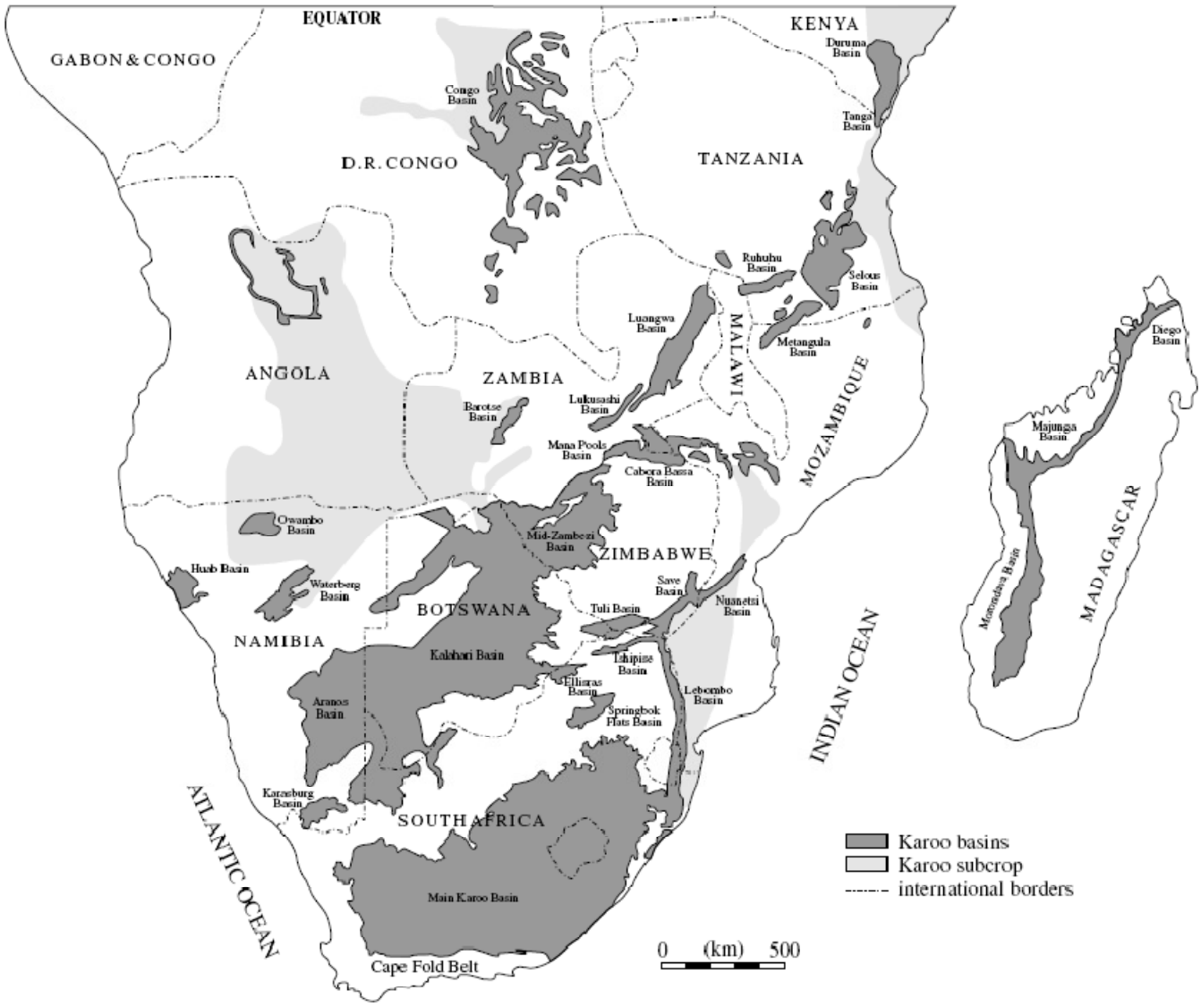


Figure 1.1 **Karoo basins of southern and central Africa. Outcropping basins are shown in dark grey, while basin subcrops beneath unconsolidated sands are marked in light grey (from Catuneanu *et al.*, 2005).**

The Karoo sequence records a period of 100 million years of almost continuous sedimentation, from the Late Carboniferous until mid-Jurassic times (Smith, 1990). Karoo basins cover a massive area of southern and central Africa (Figure 1.1). At their greatest areal extent during the Early Permian, they covered some 4.5 million km^2 (Smith *et al*., 1993). Sedimentation was primarily controlled by two factors: tectonics and climate change arising from continental drift. Tectonics stemmed from the subduction of the palaeo-Pacific plate beneath the Gondwana plate (Catuneanu *et al*., 1998), with at least eight tectonic events from the Late Palaeozoic to the Early Mesozoic. Drift through various latitudes resulted in glaciation during the Late Carboniferous / Early Permian, a fluvio-deltaic regime with progressive aridification from the Middle Permian through the Triassic, to aeolian conditions in the Early Jurassic (Smith, 1990; Catuneanu *et al*., 2005). Karoo sedimentation was terminated by the outpouring of the Drakensberg Lavas in the Middle Jurassic.

The stratigraphic divisions of the Karoo Supergroup in South Africa are the Dwyka, Ecca, Beaufort, and the "Stormberg" Groups (Figure 1.2). The Stormberg is currently an informal unit consisting of the Molteno, Elliot and Clarens Formations, but may be formally reinstated in the future (SACS, 1980). Other south-central African countries have their own terminology for Karoo sediments, but it is mostly easy to correlate these lithologies with those of South Africa (Catuneanu *et al*., 2005).

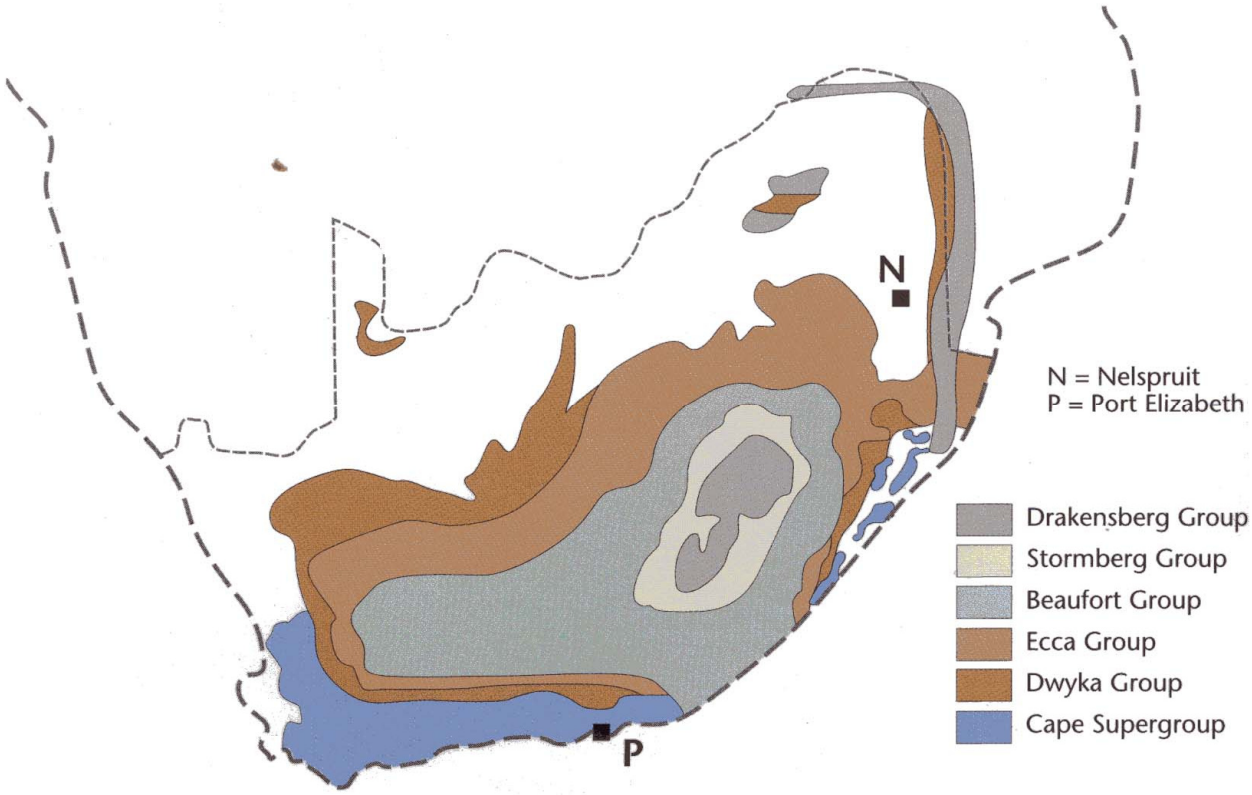


Figure 1.2 **Lithological groups of the Karoo Supergroup in South Africa, with the underlying Cape Supergroup shown in blue (from McCarthy & Rubidge, 2005).**

Deposition of Karoo sediments began with the Dwyka Group tillites in the Late Carboniferous, when Laurasia and Gondwana were joined in the supercontinent of Pangaea. The African plate was positioned over the South Pole, resulting in glaciation of the northern highlands and a southern floating ice sheet to the south (Smith, 1990). The glacial climate was not conducive to a high plant biomass or diversity (Bamford, 2004). Glaciation extended northwards in a convex arch as far as the Gulf of Guinea on the west, to Qatar on the eastern side (Wopfner, 1991). At this time, subduction of the palaeo-Pacific plate to the south led to the formation of the Pan-Gondwanan fold-thrust belt (Catuneanu *et al*., 2005). This orogen provided the supercrustal load for the development of the compressive Karoo retroarc foreland system (Catuneanu *et al*., 1998), which extended throughout the Main Karoo Basin and subsidiary basins, past Mmamantswe (the study site) and as far north as the Tuli Basin (Catuneanu *et al*., 2005).

As the African plate drifted away from the South Pole during the Early Permian, ice covering the basin retreated towards the north. The climate became warmer and more humid, coupled with a sea level rise (Smith, 1990). Glacial meltwater maintained a high water table, creating a shallow inland sea known as the Ecca Sea (Visser & Loock, 1978; Smith, 1990). Marine clays and muds accumulated in this cool climate to form the Lower Ecca Group (Smith *et al*., 1993). Sediments from the Cargonian Highlands, to the north of the sea, were deposited as submarine fan systems in the south, and large deltas prograding into the Ecca Sea in the north (McCarthy & Rubidge, 2005). These deposits form the Upper Ecca, which was deposited in a cool and humid climate. The climate encouraged thick accumulations of peat on the fluvial and delta plains (Smith *et al*., 1993), which today form the coal reserves.

Aridification encouraged recession of the Ecca Sea, and termination of the coal deposits. The prograding deltas merged to fill a large part of the basin, creating the fluvio-lacustrine environment of the Beaufort Group (Smith, 1993). The climate was semi-arid with highly seasonal rainfall (Smith *et al*., 1993). Cape Fold Belt activity shifted northwards, causing the southern mountains to migrate closer to the basin. The Permo-Triassic Beaufort Group records the largest marine and terrestrial extinction in Earth's history, occurring at the P-Tr boundary.

The African plate continued its drift northwards as the siltstones and mudstones of the Molteno Formation, the first in the "Stormberg" Group, were laid down in the Middle Triassic (Smith *et al*., 1993). A flora rich in *Dicroidium* ferns, and annual wood growth rings in *Dadoxylon* wood, indicate a cool-temperate and wet climate (Anderson, 1976). Phases of fault-controlled uplift related to continental dispersal and opening of the South Atlantic influenced deposition of the Molteno (Turner, 1986). Peat accumulated during periods of non-deposition on the braided plains, forming thin coal seams that are not economically exploited (Smith *et al*., 1993). As they are of Triassic and not Permian age, they will not be discussed further.

A first order unloading event from the Late Triassic to the Middle Jurassic halted the flexural tectonism of the foreland system, resulting in proximal sector uplift, coupled with reworking of the foredeep sediments into the distal sector (Catuneanu *et al*., 1998). These sediments are preserved as the red-beds of the Elliot Formation. Climatic conditions gradually progressed from a cool and humid fluvio-lacustrine environment

through to a warm and semi-arid aeolian landscape, with ephemeral streams and playa lakes (Kitching & Raath, 1984).

Aeolian influence continued to dominate during deposition of the Clarens Formation in the Late Triassic to Early Jurassic. Biostratigraphic correlation of the Clarens Formation in the Main Karoo Basin with other basins is difficult due to uncertainties over when exactly volcanism overtook Clarens sedimentation (Smith *et al*., 1993). However, it is known that equivalent lithofacies of the Clarens are present in the Lebombo belt in the northern Transvaal (Bushveld sandstone), Zimbabwe (Forest sandstone), Botswana (Bodibeng sandstone) and Namibia (Etjo sandstone) (Smith *et al*., 1993).

Above the Clarens Formation lie the lava flows of the Mid-Jurassic Drakensberg Group. Volcanism was related to the gradual break-up of Gondwana, which began in the Late Triassic and continued through to the Cretaceous. Violent outpourings infilled the Karoo basins with basaltic lava flows and terminated deposition of Karoo sediments (Smith, 1993).

The above descriptions of palaeoclimate, tectonic controls and continental drift during Karoo sedimentation are valid for the subsidiary as well as the Main Karoo basins, and importantly, agree with the postulated environmental settings for Botswana by Smith (1984) and others.

1.3.2 Geology of Botswana

Botswana has a central intracratonic rift basin infilled with Karoo sediments, but 80% of the bedrock in Botswana is covered by Tertiary to Recent Kalahari sediments, which range from a few metres to a few hundred metres in thickness (Hutchins & Reeves, 1980). Accordingly, most of the geological information on the Karoo Basin outcrops in Botswana has been obtained through boreholes. These data support the wide distribution of Karoo rocks in Botswana (Green, 1966). Regional geophysical studies are also useful for geological mapping of the area (Hutchins & Reeves, 1980).

The primary reference on the Karoo sediments in Botswana is that of Smith (1984). The same lithostratigraphical groups as in South Africa are found in Botswana: the basal

Dwyka Group, comprising glacial diamictites and tillites, the Ecca Group in which the coal deposits are present, the Beaufort Group, and the uppermost "Stormberg" Group, after which Karoo deposition was terminated by the outpouring of flood basalts.

Although the Botswana sediments are equivalent to Karoo rocks, the lithostratigraphical names are different, as in other Karoo basins of Africa (Cairncross, 2001). This can become quite confusing, depending in which area of Botswana one is working (see Figure 1.3 & Table 1.1). For clarity, in the Mmamabula and Mmamantswe areas, the most basal Karoo unit is the Dukwi Formation (part of the Dwyka Group), which unconformably overlies Precambrian rocks equivalent to the fluvial lithologies of the Waterberg Group (South Africa). Above the Dukwi Formation are the Permian coal-bearing units, the Mmamabula Formation, corresponding to the Vryheid Formation (middle Ecca) and the Korotlo Formation, comprising carbonaceous mudstones interbedded with thin coal seams, siltstones and sandstones (Smith, 1984). The Korotlo Formation is equivalent to the Grootegeluk / Volksrust Formations of the Upper Ecca. The Ecca Group equivalents were deposited during a time of regional sag, and occupy an enormous area in southwestern Botswana (Key & Ayres, 2000). These formations are succeeded by the non-carbonaceous shales of the Tlhabala Formation (comparable to the Beaufort Group). Regional uplift within the Kalahari Basin caused major unconformities at the base and top of the Beaufort Group equivalents in Botswana (Key & Ayres, 2000). Above this are the lower Mosolotsane and upper Ntane Formations, sandstone "red-beds" that together form the Lebung Group (equivalent to the Elliot Formation). Correlations of Karoo sediments to Botswana lithologies in other areas are also presented in Table 1.1.

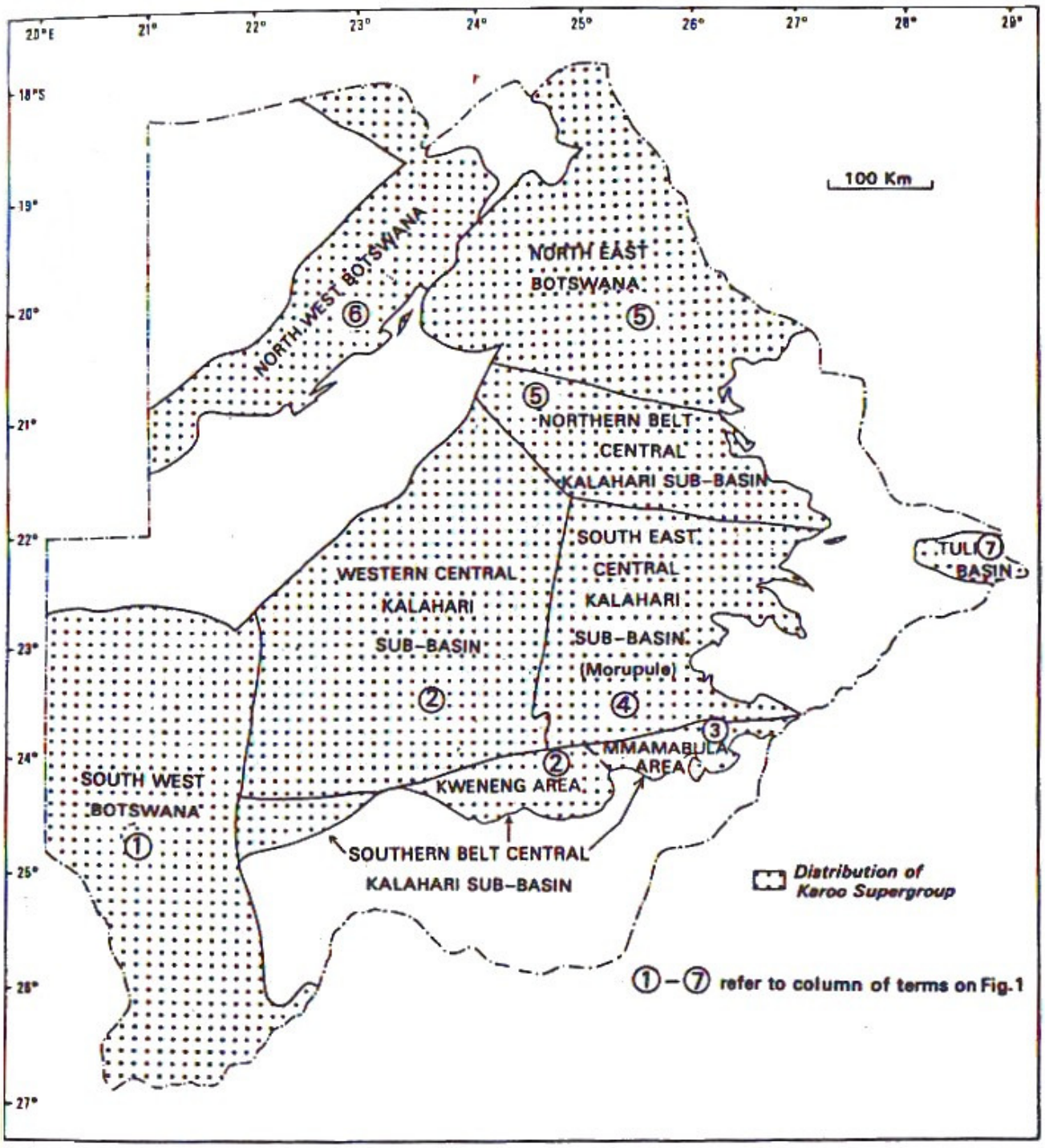


Figure 1. 3 **Discrete areas of Karoo outcrops in Botswana, with numbers referred to in Table 1 (from Smith, 1984).**

Table 1.1 **Correlation of formations in the Karoo Supergroup of Botswana, with area numbers illustrated in Figure 1.3 (after Smith, 1984).**

<table>
<tr><th rowspan="2">GROUPS</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th></tr>
<tr><th>South-west Botswana</th><th>Kweneng and Western Central Kalahari</th><th>Mmamabula</th><th>Morupule and S.E. Kalahari</th><th>North East Botswana and Northern Belt</th><th>North West Botswana</th><th>Tuli Basin Botswana</th></tr>
<tr><td>Stormberg Lava (~U, Stormberg Series)</td><td colspan="5">Stormberg Lava Group (undivided)</td><td>Bobonong Lava Fm</td></tr>
<tr><td rowspan="2">Lebung (~L, Stormberg Series)</td><td>Nakalatlou Sandstone</td><td colspan="4">Ntane Sandstone Fm</td><td rowspan="2">Bodibeng Sandstone Fm</td><td>Tsheung Sandstone Fm</td></tr>
<tr><td rowspan="2">Dondong Fm</td><td colspan="3" rowspan="2">Mosolotsane Fm</td><td>(north east only) Nowasha Fm</td><td rowspan="2">Savuti Fm</td><td rowspan="2">Korebo Fm</td></tr>
<tr><td>Thune Fm</td><td>Pandamatenga Fm</td></tr>
<tr><td>Beds equivalent to Beaufort Group</td><td>Kule Fm</td><td>Kwetla Fm</td><td>Lekotsana Fm</td><td colspan="2" rowspan="2">Tlhabala Fm</td><td rowspan="4">?
Marakwena Fm
Tale Fm
?</td><td rowspan="4">Seswe Fm</td></tr>
<tr><td rowspan="3">Ecca (~Ecca Series)</td><td rowspan="2">Otshe Fm</td><td rowspan="2">Boritse Fm</td><td>Korotlo Fm</td><td>Serowe Fm</td><td rowspan="2">Tlapana Fm</td></tr>
<tr><td>Dibete Fm</td><td rowspan="2">Morupule Fm</td></tr>
<tr><td></td><td>Mmamabula Fm</td></tr>
<tr><td>Kweneng Fm</td><td>Mosomane Fm</td><td>Kamotaka Fm</td><td>Mea Arkose Fm</td></tr>
<tr><td></td><td>Kobe Fm</td><td>Bori Fm</td><td>Bori Fm</td><td>Makoro Fm</td><td>Tswane Fm</td><td>?</td><td>Mofdiahogolo Fm</td></tr>
<tr><td rowspan="3">Dwyka (~Dwyka Series)</td><td>Middlepits Fm</td><td colspan="4" rowspan="3">Dukwi Fm</td><td rowspan="3">?</td><td rowspan="3">?</td></tr>
<tr><td>Khuis Fm</td></tr>
<tr><td>Malogong Fm</td></tr>
</table>

As one of the primary objectives of this work is to correlate the Botswana coal seam under study with those of other southern African coal-bearing strata, Karoo terminology will be used (where possible) throughout this work. This is to avoid confusion and facilitate comparison between the lithologies. It is possible to do this because lithostratigraphical groups in Botswana and South Africa were deposited contemporaneously according to chronological studies (Key *et al*., 1998).

Tectonism does not seem to have played the same role in Karoo deposition in Botswana as it did in South Africa (Hutchins & Reeves, 1980). The Botswana Karoo rocks are extensively faulted, but most of the faults have small vertical and horizontal offsets, not impacting on the ability to correlate the formations. Excluding the reactivation of the Zoetfontein fault and the Kalahari line, results of geophysical studies suggests that Karoo sedimentation was not dictated by movements on major fault-lines. Rift-type faulting, such as that found in the Okavango, seems to be a relatively recent development (Hutchins & Reeves, 1980). This is fortunate as tectonic activity not only affects the deposition of coals, but also renders it more difficult to correlate them with surrounding lithologies.

1.3.3 Coal deposits in southern Africa

All of south-central Africa's bituminous, anthracite and coking coal reserves date from the Early Permian to the Triassic, with economically exploitable coal seams all contained in the Ecca Group (Cairncross, 1990). Outcrops of Permian strata in each country are illustrated below (Figure 1.4).

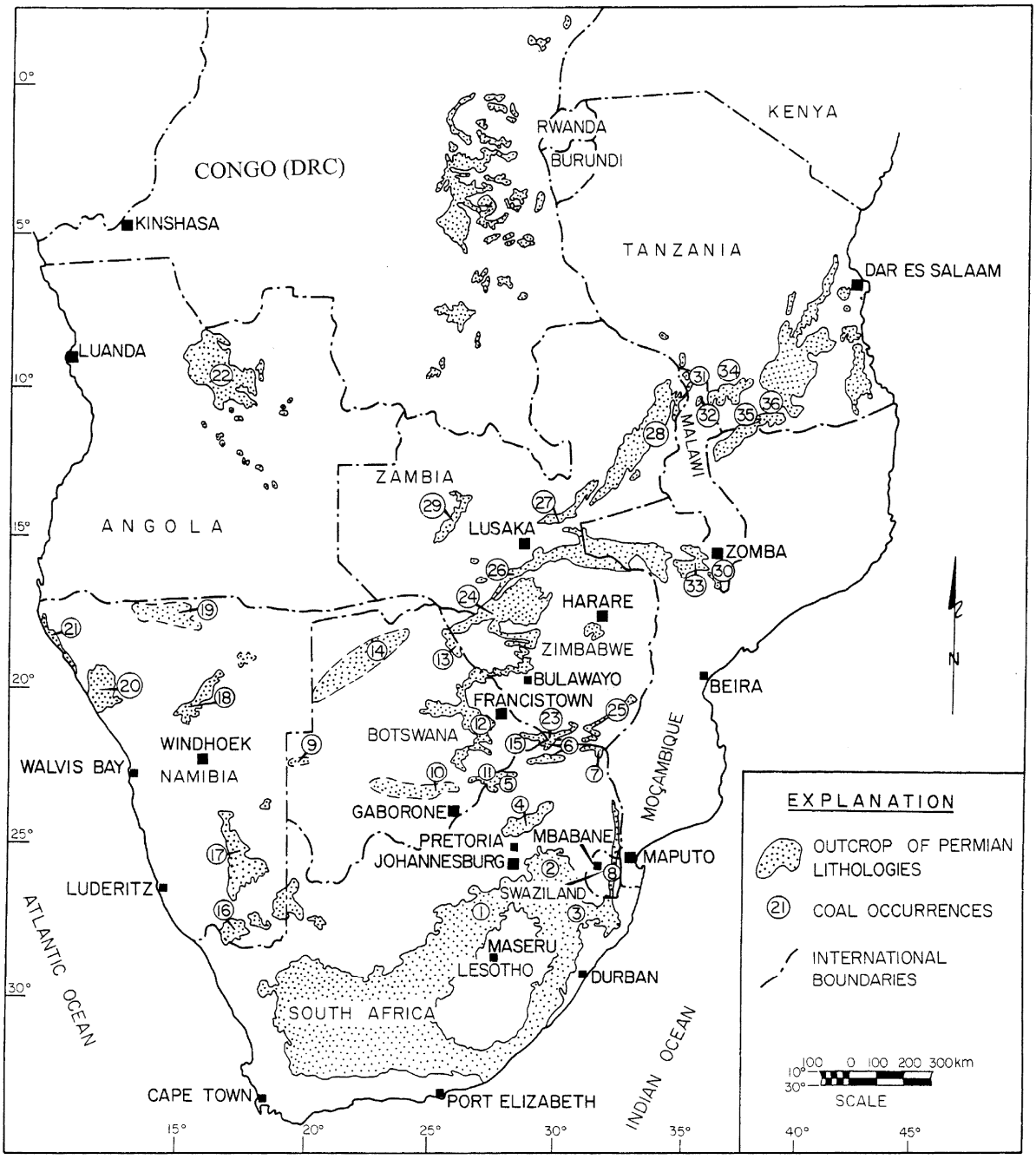


Figure 1.4 **Outcrops of Permian strata in south-central Africa (grey stippling), and associated coal outcrops marked with encircled numbers. Coal localities are listed in Appendix A (from Cairncross, 2001).**

Southern African coals were deposited in three kinds of tectonic basins: foreland (e.g. Karoo basin of South Africa), intercratonic (e.g. Livingstonia, Malawi), and intracratonic (e.g. Waterberg Coalfield of South Africa) (Cairncross, 2001). Karoo coal deposits reach as far north as the Congo Basin, central Tanzania and central Madagascar

(Catuneanu *et al*., 2005) (Figure 4). The South African Karoo basin is considered to be the type-locality for the southern African coals (Cadle *et al*., 1993).

Karoo coals, and those of Gondwana as a whole, are generally rich in minerals and variable in organic matter content / type (Cadle *et al*., 1993). They are very unlike Laurasian coals in grade, rank and type, as they formed in different palaeoenvironments (Falcon, 1986). The northern Carboniferous deposits arose from peat deposition in humid, tropical swamps (Stach *et al*., 1982), while the southern Permian coals were deposited in post-glacial, temperate conditions (Tankard *et al*., 1982). Numerous factors influenced the deposition and thickness of coal in the southern hemisphere, including climate, topography of basement rocks, and degree of tectonic activity (Cadle *et al*., 1993).

Glacial conditions immediately prior to coal deposition were especially influential. Ice movement of glaciers caused various striations and grooves in the pavement rock. When the ice retreated, many undrained basins remained (Plumstead, 1957). Peat was deposited mainly in these low-lying areas (Falcon, 1989). Moraine deposits also prevented drainage, creating temporary basins where peat could accumulate (Plumstead, 1957). During the cold post-glacial climate in which the oldest coals were deposited, both plant growth and decomposition would have been inhibited (Falcon, 1989). This produced coals with a high inertinite content. Later coals would have been deposited in a temperate setting, where fast-growing vegetation and rapid accumulation of peat resulted in coals rich in vitrinite (Falcon, 1989).

1.3.4 Coalfields of Botswana

Botswana has vast proven reserves of coal, which have remained under-developed until the present. Primary reasons for this lack of exploitation may have been historical absence of a domestic market for the product combined with lack of infrastructure for the cost-efficient export of coal, such as railway lines (Fichani, 2003). No sea ports are nearby. Other contributing factors may have been political instability and South Africa's dominance of the coal market (Fichani, 2003). At the moment Botswana is largely dependent on electricity supply from South Africa, but by exploiting their own reserves of coal they have the potential to become an important coal supplier to other

southern African countries. Botswana coals, like those of in the rest of the southern hemisphere, are predominantly inertinite rather than vitrinite (Cairncross, 2001), and are bituminous to anthracitic in rank (Falcon, 1989).

Coal deposits in the Lower Ecca result from peat swamps preserved on the delta tops especially in the Mmamabula area (Smith, 1984). Upper Ecca coals were deposited in slow-subsidence, fluviatile-dominated deltas in a swampy floodplain environment. Smith (1984) concluded that most coal deposits in Botswana are allochthonous rather than autochthonous, because plant remains within the coals are not well preserved, with many unidentifiable fragments. This suggests peat undergoing prolonged transport onto floodplains and not accumulation *in situ*. Inconsistent subsidence during peat accumulation would have caused desiccation and oxidation of plant matter, producing coals with a high micrinite (inertinite) content, and destroying microflora (Falcon, 1975b). This does not mean that these sediments contain no microflora at all, indeed, the Vryheid Formation coals in South Africa also have a very high inertinite content (Cadle *et al*., 1993) yet several successful microfloral studies have been achieved working on these coals (e.g. Falcon *et al*., 1984; Aitken, 1993, 1998; Millsteed, 1994). It simply means that some horizons would be non-productive. Additionally, inertinite content is affected by many different factors, including the origin of plant material, climatic fluctuations (Cairncross, 2001), and tectonic setting (Hunt & Smyth, 1989).

Coal deposition in Botswana is complex, with probably many time periods of deposition and localized faulting. This is reflected by the number of sub-basins into which the coalfields have been divided (Cairncross, 2001). Significant coal outcrops in Botswana include Morupule-Moijabana, Bobonong-Foley-Dukwe-Pandamatenga, Dutlwe, Letlhakeng, Ncojane, and Mmamabula-Mmamantswe (Figure 1.5).

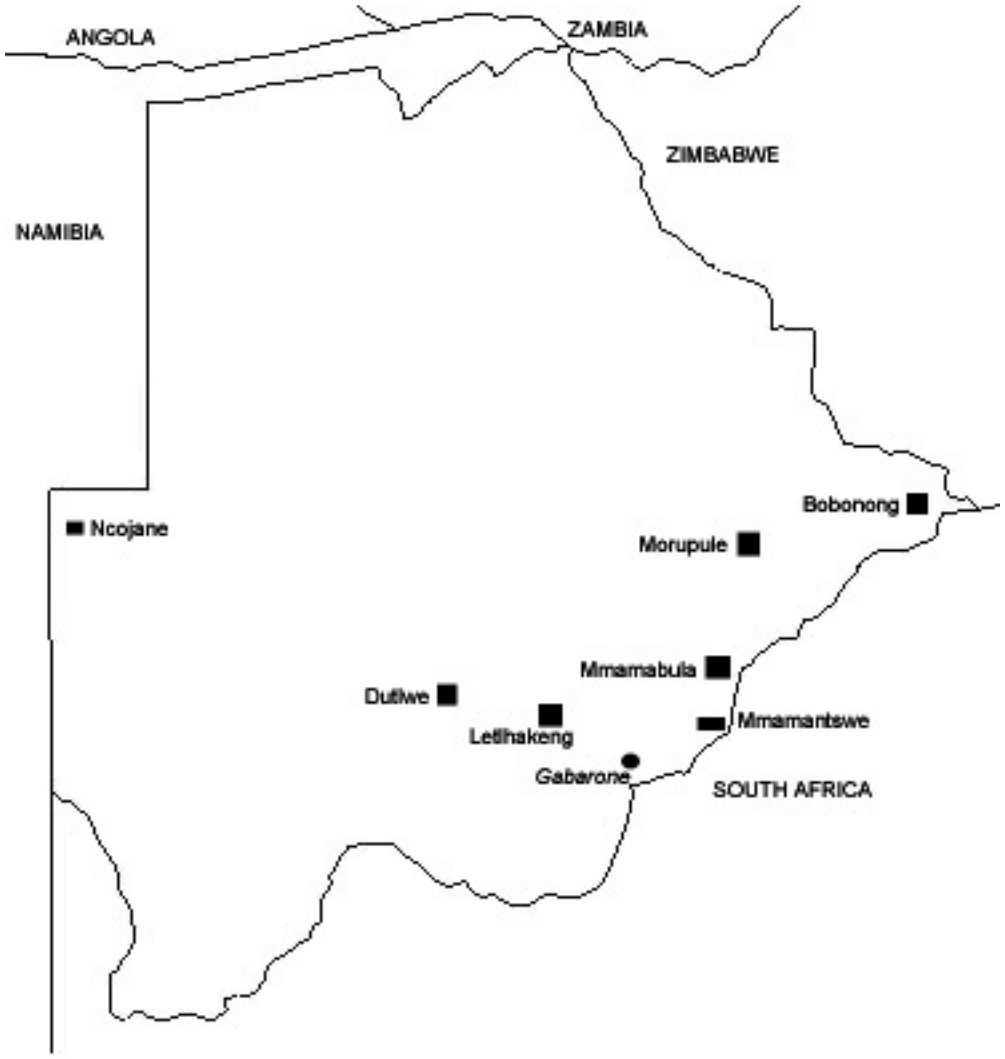


Figure 1.5 **Coalfields of Botswana. The Mmamabula-Mmamantswe coalfields are to the southeast (compiled from Green, 1973 and Cairncross, 2001).**

The economically important Morupule and Moijabana coalfields are located in the east of Botswana, with an Aktastinian (Upper Artinskian) palynological age (Stephenson & McLean, 1999). They are found in the Ecca-equivalent Morupule and Serowe Formations (Cairncross, 2001). The Letlhakeng coalfield is west of Mmamabula, with coal primarily in the upper Ecca deposits (Cairncross, 2001). The Dutlwe coalfield is west of Letlhakeng, with the Ecca-equivalent deposits containing some economically important seams (Cairncross, 2001). The Serule coalfield is north of Morupule and contains coking coal within the Dwyka and Ecca Groups (Cairncross, 2001). The Foley-Dukwe-Pandamatenga-Bobonong coalfields are found to the east of Botswana. Foley is

suitable for power generation, Dukwe is possibly of reasonable quality, Pandamatenga contains coal but at extreme depths (500 – 700 m), and Bobonong coal is inferior. The Ncojane coalfield is in southwestern Botswana and its economic potential is unclear at this time (Cairncross, 2001).

The only coal seam in Botswana currently being exploited is at Morupule. Mines at Mmamabula and Mmamantswe are in the process of being built, with their northern boundary being demarcated by the Zoetfontein fault (Clark *et al*., 1986). Aviva Corp. Ltd. is the company currently funding the construction of the Mmamantswe coal mine, which is situated 40 km south of Mmamabula (town), and 70km northeast of Gaborone (Figure 1.6). The nearest town is Olifants Drift on the Botswana-South Africa border. At Mmamantswe, the Kalahari sand is about 30m thick, thus drilling was necessary to establish the lithology of the Karoo sediments underneath. There is an estimated total of 1.3 billion tons of coal at Mmamantswe, which is expected to supply a power station on site (Aviva Corp., 2008).

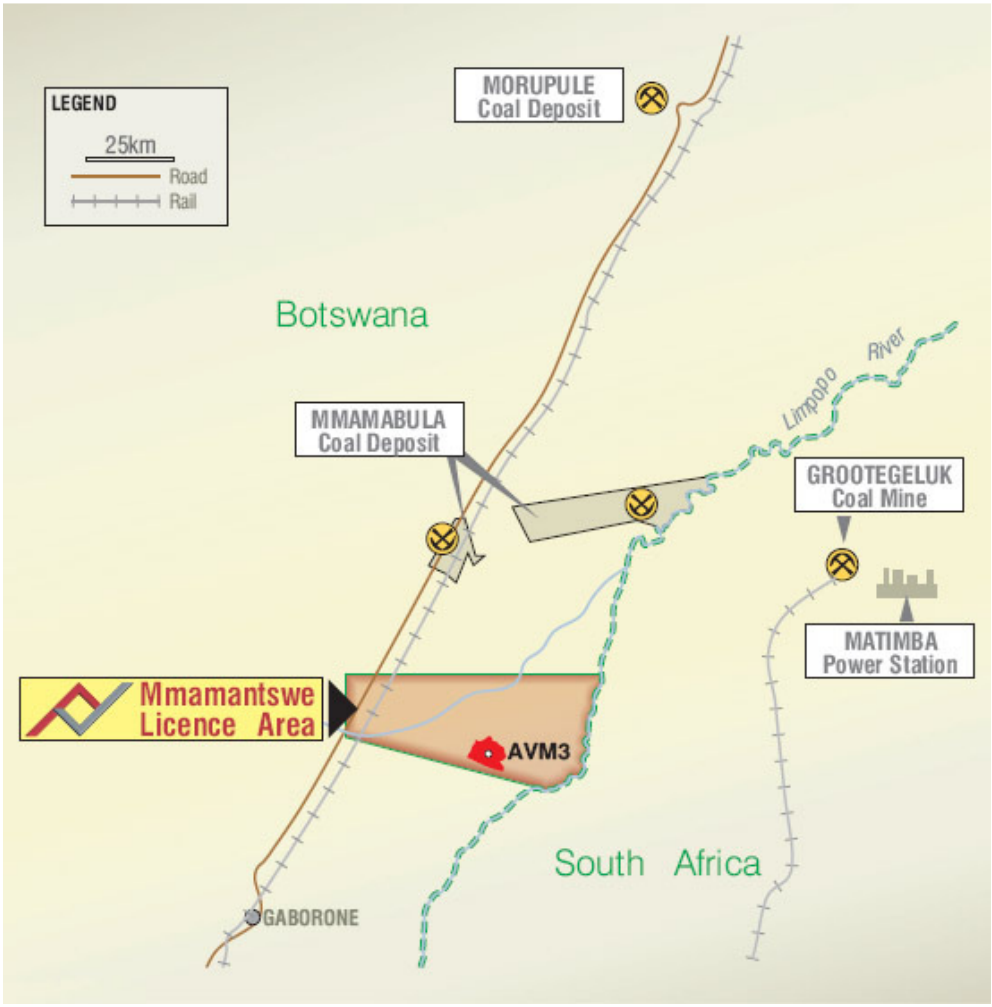


Figure 1.6 **Location of the primary coal deposits in the south-west of Botswana, including Mmamantswe, Mmamabula, Morupule, and Grootegeluk in the Waterberg of South Africa (property of Aviva Corp. Ltd., 2007).**

Green (1973) described the lithology of the Mmamabula and Dibete areas in detail. The Middle Ecca contains yellow and white felspathic sandstones, grits and conglomerates with two coal zones, while the Upper Ecca lithology is black shales and mudstones, with numerous coal seams. Two major seams are present in the Middle Ecca: the Lower Coal (semi-bright banded coal) and the Upper Coal (dull massive type). These are presently referred to as the D1 and M2 seams, of the Dibete and Mmamabula Formations respectively. In some parts, an additional thin seam overlies the Upper Coal, and is known as the Thin Upper Coal (Green, 1961).

Prior to 1983, both BP Coal and JCI drilled in the Mmamantswe area and intercepted what may be the same three coal seams found at Mmamabula, between 30m and 110m depth. These seams had a combined thickness of 23m, with a shallow dip and calorific values of between 15 and 20 MJ/kg. No further investigations have been carried out until the present.

1.3.5 Palynological application in coal mining

The first use of stratigraphic palynology in pre-Pleistocene deposits was the attempted correlation of coal beds, most likely economically motivated. Coal seam correlation can sometimes be problematic due to the flora of coal swamps being highly localized (Traverse, 2007). However, Falcon (1975b) maintains that the physical components of coals indicate the dominant parent floras in the region, as well as depositional environment and levels of water fluctuation. A reasonable degree of coal seam correlation has already been achieved in southern Africa, and will hopefully continue so that coal deposition in the Karoo basin can be understood from a biological as well as a lithological perspective.

The majority of countries in the southern hemisphere depend on fossil fuels, specifically coal, to meet their energy requirements. Most of southern Africa's electricity supply is derived from coal-fired power plants. Thus, existing reserves need to be utilised in the most advantageous manner possible, and new reserves must constantly be sought (Falcon, 1989). Accordingly, it is advantageous to utilise as many stratigraphic tools as possible in mining exploration. Palynology can assist in explaining why a coal has particular chemical and physical properties. Coal-forming floras in different habitats would have varied in chemical composition, influencing their flammability (Falcon, 1975b). Increasing amounts of spores, pollens, cuticles, waxes and resins produce higher-volatility coals. Also, sporopollenin is not present in every species to the same degree, thus the taxa as well as the amounts of palynomorphs present will affect the volatility of the coal (Falcon, 1975b). Conversely, certain types of palynomorphs, waxes and resins can negatively affect the coking potential of some coals (Falcon, 1975b).

As well as the original composition of the coal flora, subsequent thermal influences will affect hydrocarbon potential. Therefore, the thermal maturity of coal-bearing

sedimentary rocks should be established. Methods for determining thermal maturity include optical measurements (vitrinite reflectance, organic matter fluorescence), and physiochemical techniques (determination of T_{max}, conversion of clay minerals from smectite to illite, biomarker isomers) (Pross *et al*., 2007). All of these methods require expensive and advanced analytical testing. However, palynological testing is fairly straightforward and can form part of the greater geological assessment of the mine. As sediments undergo partial degrees of metamorphism, palynomorphs contained within change colour on a sliding scale which can help to determine the thermal maturity of the rock under investigation.

Historically, palynomorph colouration has been judged by eye against a classification scale chart, many of which are available. They include the Staplin (1969, 1982) Thermal Alteration Index (1-5) and the Thermal Alteration Scale of Batten (1980, 1982) (Table 1.2).

Table 1.2 **Spore Colouration Index for determining hydrocarbon maturity (from Batten, 1980).**

Observed colour of palynomorphs	Significance for hydrocarbons
1. colourless, pale yellow, yellowish green	Chemical change negligible; organic matter immature, having no source potential for hydrocarbon
2. yellow	Some chemical change, but organic matter still immature
3. light brownish yellow, yellowish orange	Some chemical change, marginally mature but not likely to have potential as a commercial source
4. light medium brown	Mature, active volatilization, oil generation
5. dark brown	Mature, production of wet gas and condensate, transition to dry gas phase
6. very dark brown-black	Over-mature, source potential for dry gas
7. black (opaque)	Traces of dry gas only

The above classification systems are problematic because one is limited by an integer scale of between 5 and 10 colours (Yule *et al*., 1998). They are fairly subjective as every individual interprets colour slightly differently. Additionally, colour-blind people are prevented from using these systems. More objective assessments are now being used, but are not widespread as yet.

Marshall (1991) estimated thermal maturity by using a microspectrophotometer, a highly accurate method but inaccessible to most on the basis of photometer cost, and the use of complex software. Yule *et al*. (1998) advocated the method of Colour Image Analysis (CIA), which uses the RGB (red, green, blue) intensity of a standard computer display to calculate colour readings of pollen and spores. Microscope images are transmitted to a computer screen and the RGB measurements taken from one spatial point on the image. Background illumination must be standardised. This is currently the most preferable method, being more objective than judging by eye, and using standard equipment without specialised software programs.

A drawback is that palynomorphs having the same thermal history can sometimes vary in colour, for the following reasons. Wall thickness and composition of individual grains can influence colouration (Pross *et al*., 2007), and small temperature increases can cause rapid colour change within a single sample e.g. from yellow to brown (Yule *et al*., 1998).

1.3.6 Taphonomic constraints

Palynomorph data, as with anything else from the fossil record, has taphonomic constraints. This should always be considered when using pollen records for stratigraphy or palaeoenvironment reconstruction. Taxa with a high pollen production, and those that are wind dispersed, tend to be prevalent (Scott & Woodborne, 2007). However, before the Middle Triassic, insect-pollinated plants were rare (Labandeira, 2000, 2002), and so the latter statement is not a concern for palynologists working before this time period. Certain pollen types appear to be over-represented after preparation, due to their robusticity, while others can be under-represented for various reasons e.g. their buoyancy during centrifugation can result in them being discarded along with the supernatant (Traverse, 2007).

Palynomorphs often survive being reworked in sediments, thus giving an incorrect age for that stratigraphic layer. Fossil grains are distinguishable from modern grains as their inner contents have been lost, with only the outer microspore wall being preserved, so while it is simple to recognise if a Mesozoic spore is recycled into modern sediments, it becomes much more difficult when the time periods are close together, for example a Pliocene spore reworked into Pleistocene sediments (Traverse, 2007). Generally, the older palynomorphs are more poorly preserved, with ragged walls and a different colour. Marine palynomorphs in terrestrial sediments can be another clear indication of reworking. Luckily, reworking in peats and coals is "practically non-existent" (Traverse, 2007: p. 574) as virtually all the spores and pollen in coal strata belong to the vegetation that formed the coal.

The problem of not being able to properly correlate the Permian Gondwana macroplants to the pollens found in equivalent sediments also places limitations on palynological interpretations (Anderson, 1977). Although indicator pollens and morphotaxa are well known in their own right, it is important to begin attempting to interpret palynomorphs in the context of which macroplants they indicate. This will assist not only in a better understanding of the palaeoflora, but also the environmental conditions in which they flourished.

1.3.7 Gondwana Permian Floras

The united supercontinent of Gondwana appears to have formed a single plant kingdom (Anderson, 1977). A mixed and diversified *Gangamopteris* and *Glossopteris* macroflora was responsible for coal formation in the southern hemisphere, which included sub-arctic mosses, conifers, lycopods, ferns, seed ferns, cordaitales and early gymnosperms (Figure 1.7).

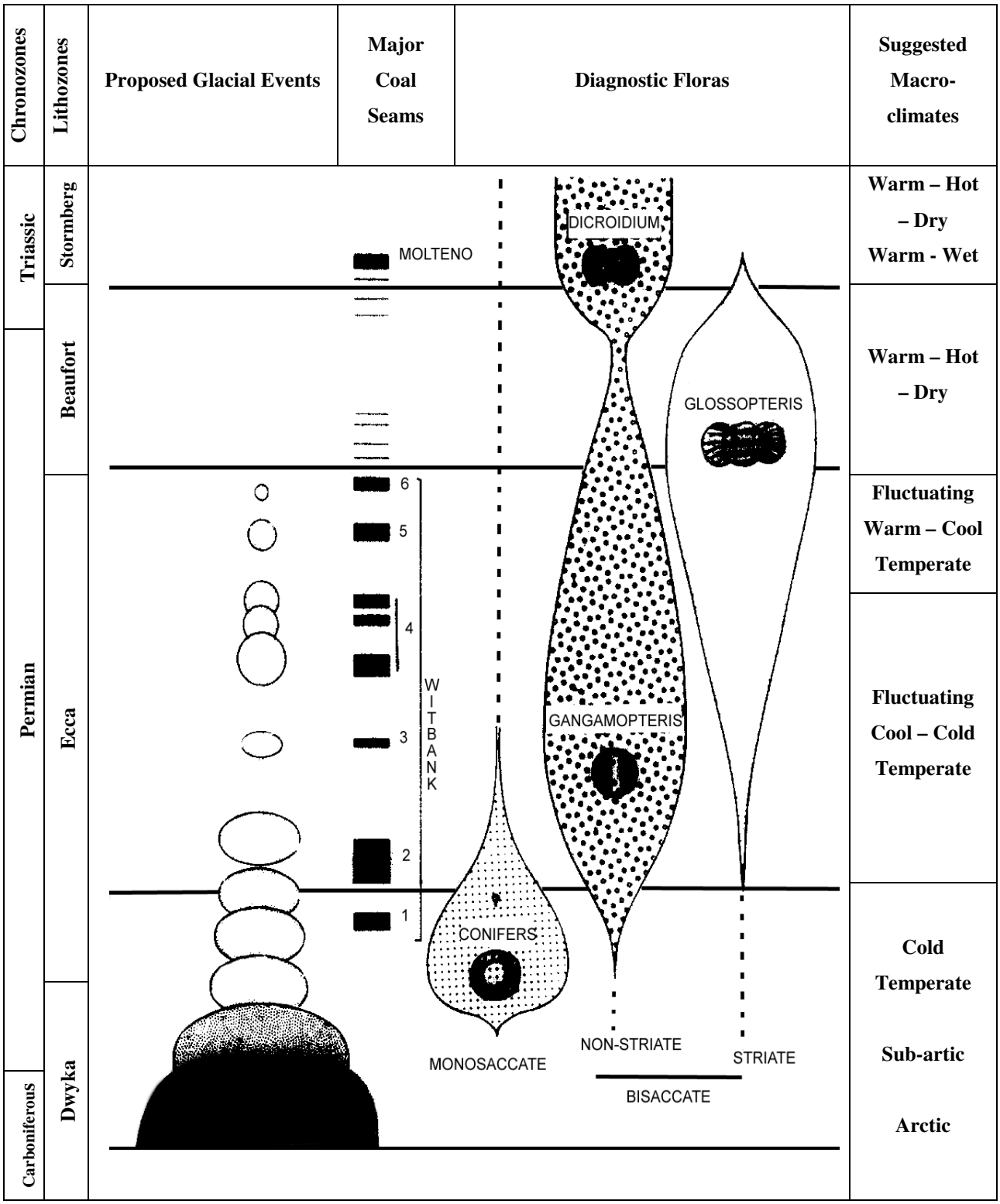


Figure 1.7 **Dominant floras and climatic fluctuations during Karoo deposition (after Falcon, 1986).**

Monosaccate microfloras at the Dwyka-Ecca boundary indicate a proliferation of gymnosperms and lower order, spore-producing plants. This was quickly replaced by a

non-striate, bisaccate-rich microflora (*Sulcatisporites*) during the early Ecca. From the Mid-Ecca a slow change to a striate, bisaccate-rich microflora (*Protohaploxypinus*) took place, which dominated the microfloras of Zimbabwe, Zambia and South Africa during the Permian. *Protohaploxypinus* has been identified as a pollen form genus of the glossopterid plants (Falcon, 1978; Pigg & Trivett, 1994) and is indicative of a continental upland or higher latitude environment. The complete dominance of striate saccate pollens during the Permian indicates that plants were mostly wind-pollinated, with a harsh environment responsible for the protective striations on the outer walls of the pollen grains (Falcon, 1989). Saccate pollens are highly useful in chronostratigraphy as they represent more stable upland parent floras that are less affected by water availability than lower-order spore-producing plants (Falcon, 1989).

1.3.8 Previous palynological work in southern Africa

The palynology of coal-bearing strata in southern Africa has been investigated more than any other local lithology due to its economic importance, especially in South Africa. Data from the rest of southern Africa is scattered and scarce. New sampling along with correlating the work of previous authors will go some way towards rectifying this issue.

1.3.8.1 South Africa

Hart (1964a, b, 1965, 1966, 1969a, b, c, 1970) is responsible for a major contribution to Gondwana Permian palynology. In South Africa, he studied the Dwyka, Ecca and Beaufort Groups in the Cape as well as many boreholes from Transvaal and Orange Free State localities. Hart also worked on many sites in south-central Africa. Due to the exponential increase of papers on Gondwana Permian palynology during the latter part of the twentieth century (see Anderson, 1977), Hart's work has now become somewhat outdated, nevertheless his diagrams of spores and pollen are still useful. Hart also modified Western classification systems to include typically Permian species from Gondwana.

Anderson (1977) subdivided the Dwyka, Ecca and Beaufort Groups of the Northern Karoo into seven zones, according to their palynomorph content (Figure 1.8). Anderson

assumed that the vertebrate biozones of the Karoo should correlate with the microfloral zones, but this hypothesis has not yet been tested. Zone 1 (tillites, grits, siltstones, sandstones) corresponds to the Dwyka Group and is very low in palynomorph quantity. Zone 2 encompasses the Lower Ecca, which is made up of siltstones, sandstones, carbonaceous shales and thin coal seams. Zone 3 (Middle Ecca) has an extremely speciose microflora compared to the Dwyka, but spores are virtually absent. The sampled Middle Ecca lithology comprises sandstones, siltstones, coal seams and carbonaceous shales. Zone 4 corresponds to the Upper Ecca (siltstones), and microfloral diversity declines steadily as one moves into Zones 5, 6, and 7 (*Tapinocephalus*, *Cistecephalus* and *Daptocephalus* Zones respectively) of the Lower Beaufort Group (variously coloured siltstones and sandstones). Reference areas for Zones 2 (Lower Ecca) and 3 (Middle Ecca) contained coal, thus, the palynomorphs contained therein can be considered indicator taxa for coal-bearing strata (Figure 1.8). Zone 4 (Upper Ecca) did not contain coal but this is a reflection of the chosen reference areas. In many parts of South Africa and south-central Africa, coal deposits are contained in Upper Ecca deposits. Thus a tentative connection to coal seams can be made for the palynomorphs contained in Zone 4 (Figure 1.8).

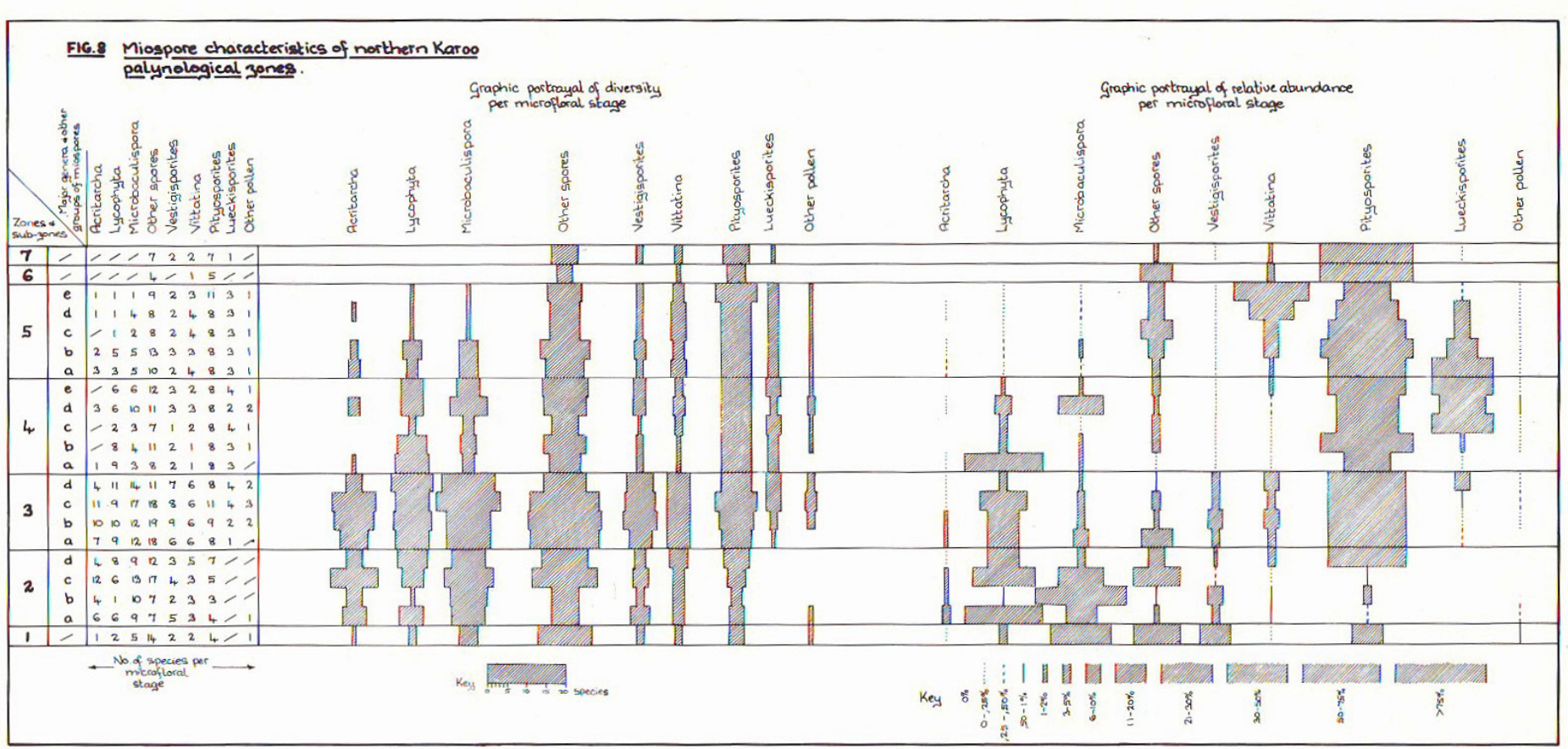


Figure 1.8 **A synthesis of the palynomorphs from the Dwyka, Ecca and Beaufort Groups of the northern Karoo basin (from Anderson, 1977).**

Anderson (1977) also made an attempt to relate the pollen taxa to their parent plant groups, namely Acritarcha; Lycophyta; Sphenophyta + Filicophyta; Glossopteridophyta; and Coniferophyta + Cycadophyta + Ginkgophyta. This information is now outdated, however it represents an important step towards incorporating palynology into a larger assessment of palaeoflora and past biomes.

Anderson (1977) presents various groups of species that are useful in Permian stratigraphic correlation (Table 1.3). Column 1 contains species that have a wide geographic range and occur very commonly in Permian Gondwana. Species in Column 2 are associated with regions of first appearance, the direction and rate of colonisation, and diachronous extinctions from region to region. Column 3 contains species with notable patterns of geographic distribution that colonised wide areas of Gondwana but have specific limits to their ranges.

Table 1.3 **Species groups useful in Permian stratigraphic correlation (compiled from Anderson, 1977).**

~ 1 ~	~ 2 ~	~ 3 ~
Microbaculispora tentula	*Cyclogranisporites bharadwaji*	*Zinjisporites spinosus*
Microbaculispora trisina	*Polypodiisporites detritus*	*Gondisporites braziliensis*
Microbaculispora villosa	*Vittatina multistriata*	*Vittatina simplex*
Microbaculispora ericiana	*Vittatina lucifera*	*Vittatina lucifera*
Microbaculispora pseudoreticulata	*Vittatina fasciolota*	*Vittatina magma*
Punctatisporites gretensis	*Vittatina triradiata*	*Lueckisporites nyakapendensis*
Apiculatisporis levis	*Pityosporites ovatus*	*Lueckisporites welkomensis*
Laevigatosporites vulgaris	*Pityosporites maximus*	*Lueckisporites hannonicus*
Vestigisporites balmei	*Pityosporites fusus*	*Lueckisporites neohannonicus*
Vestigisporites gondwanensis	*Pityosporites cancellatus*	*Dulhuntyispora dulhuntyi*
Vestigisporites rotatus	*Lueckisporites nyakapendensis*	*Dulhuntyispora parvithola*
Vittatina simplex		*Indospora clara*
Vittatina lucifera		*Bascanisporites undosus*
Pityosporites cancellatus		*Densipollenites pullus*
Pityosporites amplus		
Lueckisporites nyakapendensis		
Lueckisporites neohannonicus		
Cycadopites cymbatus		
Gnetaceaepollenites sinuosus		

Unfortunately, Anderson made use of the palaeodeme concept for his biozonation of the Dwyka, Ecca and Beaufort Groups as well as later studies in the Molteno Formation. This involves assessing the variation within a localised assemblage in order to define species present. While this is claimed to reduce the subjectivity involved in making species assignments, it complicates the task of reconstructing the palaeoflora of a large region. Since palaeodemes are by definition confined to a specific area, they retard comparison and correlation between study sites for the purposes of assessing more general patterns of evolutionary diversity. For these reasons, Anderson's work is not particularly suited to comparison with other biozonation schemes across Gondwana. However, it was used in precisely this fashion (e.g. Backhouse, 1991; Cesari, 2007), perhaps for lack of another system that also covers as wide a time frame, but was erected using an accepted taxonomic approach. Such a system was only published by Aitken 21 years after Anderson's work (see below), and accordingly appears to be struggling for international acceptance over the original scheme for the Northern Karoo basin.

Falcon (1988, 1989) examined macro- and micro-factors (including palynology) affecting the quality and distribution of the No. 2 seam, Witbank coalfield. This seam is one of the most economically important in the coalfield. At the time of its deposition, a changeover from Dwyka to Ecca floras was occurring. At the onset of deglaciation at the end of the Dwyka, a distinctive and monosaccate-rich microflora existed, including *Virkkipollenites*, *Barakarites*, *Caheniasaccites*, *Plicatipollenites*, and *Potonieisporites* (Figure 1.9). These are taxa typical of Dwyka floras, with the assemblage being relatively low in diversity. Trilete spores are most common. The Early Ecca assemblage is much more diverse, with the introduction of the bisaccate striate pollens *Striatopodocarpites* and *Striatoabietites*, a new *Protohaploxypinus* species, and a new variety of spore taxa, with Aletes, Plicates and Saccates recurring cyclically. The coal seam is assigned an Early Permian age. The introduction or evolution of new taxa can be seen throughout the accumulation of the No. 2 Seam, suggesting a warming climate.

Genera	A B C D E F G H I J	Species	A B C D E F G H I J
Tetrasporina		*Cycl. parvus*	
Mehlisphaeridium		*Tetr. tetragona*	
Pakhapites		*Mehl. colliensis*	
Cyclogranisporites		*Virk. radius*	
Virkkipollenites		*Cala. plicata*	
Calamospora		*Retu. diversiformis*	
Retusotriletes		*Delt. directa*	
Deltoidospora		*Cycl. verrucosus*	
Microbaculispora		*Micr. tentula*	
Plicatipollenites		*Micr. micronodosa*	
Potonieisporites		*Plic. indicus*	
Illinites		*Poto. thomasi*	
Sulcatisporites		*Poto. novicus*	
Striatoabietites		*Illi. unicus*	
Verrucosisporites		*Sulc. ovatus*	
Granulatasporites		*Stbi. multistriatus* VRI	
Punctatisporites		*Verr. pseudoreticulatus*	
Schizosporis		*Sulc. splendens*	
Cycadopites		*Gran. obscurus*	
Peltacystia		*Verr. parmatus*	
Apiculatisporis		*Punc. intrareticulatus*	
Neoraistrickia		*Schi. scissus*	
Pilasporites		*Cyca. cymbatus*	
Marsupipollenites		*Apic. filiformis*	
Limitisporites		*Neor. congoensis*	
Tugasporites		*Pelt. venosa*	
Alisporites		*Punc. gretensis*	
Lophotriletes		*Apic. levis*	
Vestigisporites		*Neor. ramosa*	
Caheniasaccites		*Pila. calculus*	
Florinites		*Mars. triradiatus*	
Cyclobaculisporites		*Limi. monstruosus*	
Gondisporites		*Tuga. delasaucei*	
Parasaccites		*Alis. plicatus*	
Platysaccus		*Virk. obscurus*	
Protohaploxypinus		*Loph. rarus*	
		Vest. gondwanensis	
		Cahe. ovatus	
		Alis. gracilis	
		Loph. dwykanensis	
		Flor. eremus	
		Cycl. bharadwaji	
		Virk. mehtae	
		Alis. tenuicorpus	
		Punc. gretensis FM	
		Verr. naumovai	
		Gond. salisburyensis	
		Para. diffusis	
		Platy. leschiki	
		Prot. amplus	

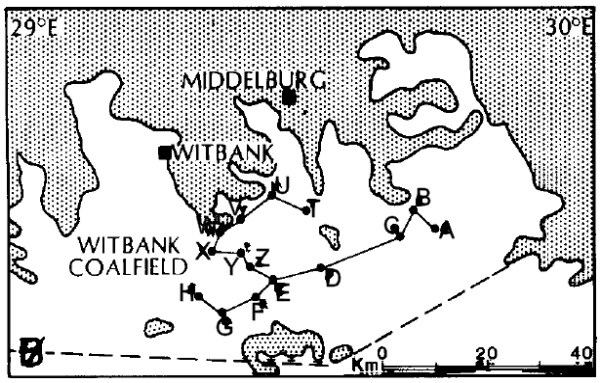


Figure 1.9 **List of palynomorph genera and species in the Witbank No. 2 Seam, with channel-section sites indicated on map (after Falcon, 1988*).**

***It is thought by the author that dashes indicate the species was present but rare, solid lines indicate intermediate abundance, and double dashes indicate excessive abundance of that species. However, no explanation is given in the original source.**

Falcon *et al*. (1984) investigated the palynoflora of the Witbank / Highveld coalfields in South Africa, and erected four Zones and five Sub-zones for the Basin. The No. 1 and No. 2 seams contain similar monosaccate assemblages, formed during the post-glacial regime in the early Ecca. There is a significant increase in the number of pollen taxa from the No. 2 to the No. 4 Seams. However, Falcon *et al*. (1984) only sampled the coal seams and not the interbedded sediments. Accordingly, many taxa could possibly occur earlier than stated (Millsteed, 1994).

Aitken (1993, 1994, 1998) also worked on the Vryheid Formation (Witbank / Highveld coal seams) as well as Lindley in the Orange Free State. He proposed a new microfloral biozonation scheme for the Northern Karoo, with ten zones for the Permian and Lower Triassic (Table 1.4). This incorporates earlier work by MacRae (1988).

Table 1.4 **Biozones and Concurrent Range Zones for the northern Karoo Basin (after Aitken, 1998).**

Lithology		**Biozone**	**Concurrent Range Zone**
Beaufort Group	Estcourt Formation	**X**	*Aratrisporites – Calamospora plicata*
		IX	*Ephidripites – Cycadopites*
		VIII	*Osmundacidites senectus – Alisporites potoniei*
Ecca Group	Volksrust Formation	**VII**	*Protohaploxypinus limpidus – Lunatisporites pellucidus*
		VI	*Guttulapollenites hannonicus – Protohaploxypinus rugatus*
	Vryheid Formation	**V**	*Lueckisporites virkkiae – Corisaccites alutus*
		IVB	*Striatopodocarpites fusus – Weylandites lucifer*
		IVA	*Granulatisporites trisinus* Interval Zone
		III	*Striatopodocarpites cancellatus – Marsupipollenites triraditus*
		II	*Mehlispaheridium colliensis – Alisporites splendens*
Dwyka Group		**I**	*Potonieisporites novicus – Cannanoropollis densus*

Striate bisaccate pollen genera dominate the No. 5 seam assemblage, especially *Protohaploxypinus*, *Striatopodocarpites*, and *Weylandites* (Aitken, 1994). It can be correlated with Zone V, Sub-zone H as erected by Falcon *et al*. (1984), and Biozone F of MacRae (1988) from the Waterberg, to which is it particularly similar. The No. 5 seam assemblage is also broadly comparable to the Striatiti florizone of Hart (1967) and Zone 5 of the northern Karoo Basin (Anderson, 1977). The T.A.I. (thermal alteration index) value of the palynological material is between 3,0 and 3,5 (dark orange to brown colour). The palaeoenvironment of the Witbank / Highveld coalfields is seen as a floodplain dotted with wide shallow pans and peat swamps, intermingled with water-logged mud flats. The No. 5 seam is tentatively suggested as Guadalupian in age.

Millsteed (1994) suggested an Artinskian (Aktastinian to lower Baigendzhinian) age for the Vereeniging area in the Orange Free State Coalfield (Vryheid Formation). Establishing an age relied upon three index species: *Pseudoreticulatispora pseudoreticulata* (Balme & Hennelly) Bharadwaj & Srivastava, 1969, *Granulatisporites trisinus* Balme & Hennelly, 1956, and *Praecolpatites sinuosus* (Balme & Hennelly) Bharadwaj & Srivastava, 1969. These are indices that have also been used to define three palynological stages in Australia (Kemp *et al*., 1977). Millsteed found a sudden increase in the number of pollen taxa between the Middle and the Top Seams, similar to what Falcon *et al*. (1984) observed in the Witbank coalfields. In Vereeniging, *Praecolpatites sinuosus* occurs along with *Weylandites* sp., *Barakarites* sp., *Marsupipollenites striatus*, *Lueckisporites* sp., and *Platysaccus* sp. These taxa have also been found in Witbank / Highveld, thus allowing a correlation of the coal-bearing strata (Millsteed, 1994). The Bottom and Middle Seams in Vereeniging correlate with the No. 2 seam in Witbank, and the Top Seam to the No. 4 Seam. Plant macrofossil evidence from Vereeniging supports this correlation.

Palynology has also been applied to the coal-bearing strata of the Waterberg and Soutpansberg-Pafuri Basins in Limpopo by MacRae (1988). MacRae identified six recognisable biozones in these areas (Table 1.5).

Table 1.5 **Biozones of the Waterberg and Pafuri Basins (after MacRae, 1988).**

Biozone	Name	Indicator palynomorphs	Formations
F	*Striatopodocarpites fusus – Weylandites lucifer*	*Weylandites lucifer* *Gnetaceaepollenites sinuosus* *Striatopodocarpites fusus*	Mikambeni Formation
E	*Kraeuselisporites enormis - Striatopodocarpites cancellatus*	*Cirratriradites africanensis* *Kraeuselisporites enormis* *Alisporites potoniei* *Protohaploxypinus limpidus* *Striatopodocarpites cancellatus*	Grootegeluk Formation
D	*Laevigatosporites vulgaris – Alisporites* sp. 1	*Deltoidospora directa* *Laevigatosporites vulgaris* *Alisporites* sp. 1 *Platysaccus radialis*	Enkelbult Formation
C	*Cyclogranisporites gondwanensis* Interval Zone	No indicator taxa as Biozone C is an informal zone	
B	*Potonieisporites novicus – Cannanoropollis densus*	*Verrucosisporites* sp. *Limitisporites monstruosus* *Cannanoropollis densus* *Potonieisporites novicus* *Caheniasaccites ovatus*	Wellington Formation
A	*Plicatipollenites gondwanensis – Granulatisporites papillosus*	*Granulatisporites papillosus* *Plicatipollenites goraiensis* *Pteruchipollenites gracilis* *Cannanoropollis mehtae* *Cannanoropollis janakii*	Dwyka Formation Basement

MacRae recorded significant floral changes from Biozone A to Biozone B, and accordingly placed the Carboniferous / Permian boundary in this position. Although the debate continues regarding the precise placement of the boundary, as there is no lithological record of it, the latest evidence from Bangert *et al*. (1999) places it at 290 Ma, at the termination of Dwyka Group deposition. This is in conflict with the placement of the Biozone A / B boundary, which falls in the Lowermost / Lower Ecca.

1.3.8.2 Botswana

MacRae (1978) analysed core samples from Lower Karoo sediments near Francistown (north-eastern Botswana). Three concurrent range zones were erected on a palynological basis: Concurrent Range Zone I (rich in monosaccate pollen), Concurrent Range Zone II (bisaccates more abundant than monosaccates), and Concurrent Range Zone III (no monosaccates, bisaccate striate miospores dominant). These zones were correlated with Zones 1-3 of the Dwyka and Ecca Groups in Zimbabwe (Falcon, 1975a), and Zones 1-3 of the Northern Karoo Basin in South Africa (Anderson, 1977). Substantial coal seams in the Francistown area of Botswana were found to be equivalent in age to the Lower and Middle Ecca of the Main Karoo Basin.

Key *et al*. (1998) sampled boreholes from the Tshabong area of south-western Botswana situated in the Kalahari Basin of the Karoo Supergroup. Palynomorphs were Carboniferous and Permian in age (Dwyka and Ecca Groups). While some Dwyka palynomorphs indicated marine incursions (presence of marine acritarchs), Ecca rocks contained only freshwater palynomorphs (i.e. no acritarchs), which is consistent with the presence of the Ecca Sea. Palynomorphs formerly restricted to the Beaufort Group in South Africa were also recovered from the Tshabong sediments. This confirmed the existence of the Beaufort Group in southern Botswana. Another significant finding was that no significant Ecca-age coal seams were found in the south-western area of Botswana. Thus, Key *et al*. (1998) deemed this area unsuitable for prospecting.

The study by Stephenson and McLean (1999) represents the first published work on palynological assemblages from coal-bearing strata in Botswana. This is due to the economic sensitivity of such information. Sediments were from Morupule in the southeast of Botswana, the only operational coal mine in Botswana at present. Forty-five species of pollen, spores and acritarchs were recorded (Figure 1.10). Stratigraphically important taxa include *Verrucosisporites pseudoreticulatus*, *Procoronaspora spinosa*, *Laevigatosporites colliensis*, *Striatocarpidites cancellatus*, and *Microbaculispora micronodosa*. Palynology and lithology appear to be strongly linked. Small trilete miospores dominate coals, while carbonaceous mudstones are dominated by gymnospermous bisaccate pollen.

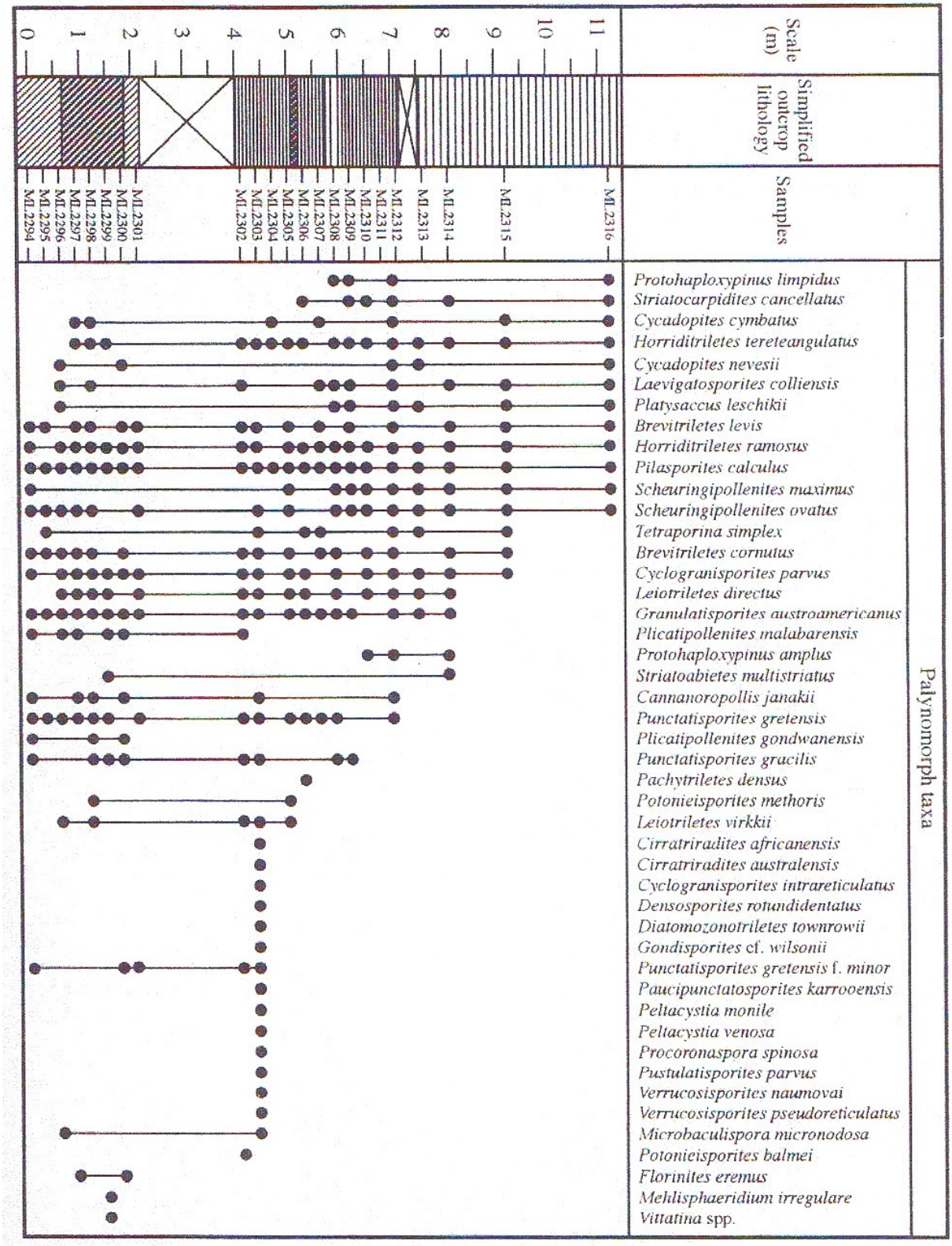


Figure 1.10 **Stratigraphic distribution of palynomorphs from Morupule, Botswana (from Stephenson & McLean, 1999).**

The Morupule deposits have been correlated with palynological biozones erected by earlier authors (Figure 1.11). These include the 3a Microfloral Biozone of the northern Karoo (Anderson, 1977), Sub-Biozone F of the northern Karoo and Mid-Zambezi Basins (Falcon *et al*., 1984), the upper section of Biozone B in the Waterberg (MacRae, 1988), and the upper section of the LM Biozone in Zambia (Utting, 1978). An Aktastinian age (early Artinskian) for the Morupule sediments is proposed due to correlation with Australian Permian strata.

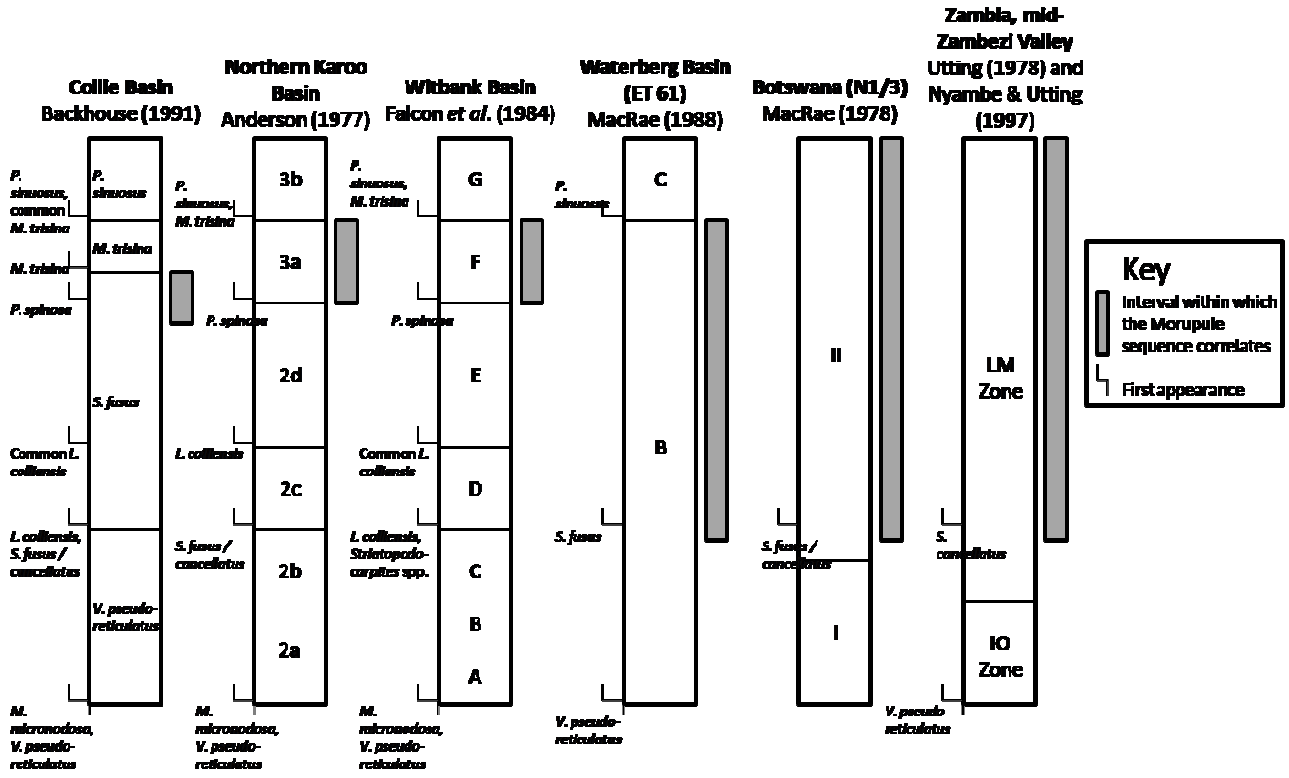


Figure 1.11 **Stratigraphic correlation of Morupule sediments to biozonation schemes for southern Africa and the Collie Basin, Australia (after Stephenson & McLean, 1999).**

Some important notes regarding the preparation of coaly material are included in Stephenson and McLean (1999), which were taken under consideration when preparing sediments for this study. Use of Schulze's solution on coaly residues produced considerable amounts of unoxidised humic material along with suitably oxidised palynomorphs. Residues could not be oxidised further as this damaged or destroyed specimens, particularly the genera *Protohaploxypinus* and *Striatopodocarpites*. Pollen counts of two assemblages from the same sample after 5 minutes and 20 minutes

oxidation time revealed a 12% reduction in taeniate bisaccate pollen. It was concluded that oxidation should continue for no longer than 10 minutes, to prevent the selective destruction of specimens. Humic material was separated from palynomorphs by density centrifugation, with repeated treatments of increasingly dilute zinc chloride if necessary.

1.3.8.3 Namibia

In Namibia, post-Sakmarian Formations are not present in the Waterberg, Ovambo and Huab basins (Catuneanu *et al*., 2005). As the palynological age for most Permian coal deposits is Artinskian–Kungurian and for younger coals, Ufimian–Kazanian (see Catuneanu *et al*., 2005 & Section 4.9), it is not possible to correlate Namibian coal strata to those in the rest of south-central Africa. Additionally, most of the information on Namibian coals is confined to inaccessible company reports, with little published in the scientific literature (Cairncross, 2001). At present, Namibia is not commercially exploiting coal at all (Cairncross, 2001).

1.3.8.4 Zimbabwe

Falcon (1975a) investigated the palynology of the Mid-Zambezi and Sabi-Limpopo Basins of Zimbabwe, working on the Dwyka, Ecca and Lower Beaufort Groups (Carboniferous and Permian sediments). A major change is evident in the floral communities, from primarily monosaccate pollens and trilete spores during the Carboniferous, to Disaccate-Striatiti dominated pollens in the Permian (Table 1.6). Four assemblage zones were erected: Assemblage Zone I (Dwyka Group + Lower Wankie Sandstone: *Virkkipollenites - Plicatipollenites* Assemblage), Assemblage Zone II (black shales and coals: Transition Zone), Assemblage Zone III (Upper Wankie Sandstone: *Densosporites -Gondispore* assemblage), and Assemblage Zone IV (Madumabisa Mudstone: *Vittatina-Lueckisporites* Assemblage).

Table 1.6 **Palynomorph diagram of the four Assemblage Zones and eight Assemblage Sub-zones of the Permian Matabola Flats borehole in the Mid-Zambezi Basin (after Falcon, 1975a).**

	H	ASSEMBLAGE ZONES Assemblage Zone IV *Vittatina-Lueckisporites* Assemblage **Notable genera***:* *Protohaploxypinus* *Platysaccus* *Striatopodocarpites* *Sulcatisporites*	ASSEMBLAGE SUB-ZONES Assemblage Sub-zone H *Taeniaesporites-Guttulapollenites* Assemblage Striatiti dominant > 50%
Madumabisa Mudstone	G	*Vittatina* *Thymospora* *Hemipollenites* *Marsupipollenites* *Lueckisporites* *Rheinschospora* **Quantitative content**: Disaccites 40-75% Striatiti 25-60% Monosacciti <5% Triletes 0-20% Aletes 0-15%	Assemblage Sub-zone G *Cirratriradites africanensis* Assemblage Introduction of: *Cirratriradites* *Vittatina* *Hamiapollenites* *Lueckisporites*
Upper Wankie Sandstone	F	Assemblage Zone III *Densosporites- Gondispore* assemblage **Introduction of:** *Thymospora* *Rheinschospora* *Verrucosphaera*	Assemblage Sub-zone F **Quantitative content**: Disaccites 20-40% Striatiti 10-20% Monosacciti <5% Triletes >40% Aletes 10-30%
Black Shales & Coals	E	Assemblage Zone II **Transition Zone**: miospores genera and species characteristic of both assemblages	Assemblage Sub-zone E **Introduction of:** *Laevigatosporites* *Lophotriletes*
	D		Assemblage Sub-zone D **Introduction of:** *Striatopodocarpites* *Densipollenites* *Striatoabietites*
Lower Wankie Sandstone	C	Assemblage Zone I *Virkkipollenites-Plicatipollenites* Assemblage **Notable genera**:	Assemblage Sub-zone C *Acanthotriletes* Assemblage Monosaccites notably abundant
Dwyka III	B	*Microbaculispora* *Calamospora* *Granulatisporites* *Cycadopites* *Punctatisporites* *Protohaploxypinus*	Assemblage Sub-zone B *Quadrisporites horridus* Assemblage
Dwyka II			
Dwyka I	A	*Zinjispora* *Apiculatisporis* *Acanthotriletes* *Lophotriletes* *Retusotriletes* *Potonieisporites*	Assemblage Sub-zone A *Granulatisporites-* *Microbaculispora tentula*

Falcon (1978) compared the Permo-Triassic palynofloras from opposing sides of the Rhodesian watershed, namely the Mid-Zambezi and Sabi-Limpopo basins. They were divided into six Concurrent Range Zones and twelve Concurrent Range Sub-zones, with Sub-zones A-H present in the Mid-Zambezi Valley and Sub-zones D-L in the Sabi-Limpopo Valley. Total species diversity increases from the Dwyka, peaks in the Mid-Ecca to Lower Beaufort and then declines again. Subzones D-G (Lower to Upper Ecca) times appear to have been the main coal-forming period. Falcon established that Permian microfloras of Zimbabwe (Rhodesia) were closely related to those of South Africa, Botswana, Zambia, Tanzania, Peninsular India and Western Australia. They were only superficially similar to those of Gabon, Congo, Malagasy, Salt Range, Indian and Eastern Australia.

1.3.8.5 Zambia

Utting (1976) examined pollen and spore assemblages from the Luwumbu Coal Formation (Lower Karroo) of the North Luangwa Valley, Zambia and established an Ecca age for these sediments. The Gwembe Formation is also in the Ecca series, and has a very similar palynology to the Luwumbu Coal Formation. Utting (1978) recorded the palynology of the Siankondobo Coalfield, located in the Gwembe Formation, Kazinze area, Zambia. Monosaccate palynomorphs dominate the basal section of the Siankondobo Sandstone Formation (Zone IO), and the assemblage is very similar to Zone 1, Zimbabwe (Falcon, 1975a). However, Cesari (2007) suggests that due to the presence of *Vittatina* sp. and *Converrucosisporites confluens*, Zone IO is better correlated with Subzone C, Zimbabwe.

Thus, a significant amount of palynological work has been done on southern African coal seams in the Ecca, but as yet there is little consensus on how these areas relate to each other. In-depth correlation of these areas would lead to a greater understanding of coal deposits in southern Africa, and could have potential implications for the associated fauna. Palynological correlations of the stratigraphic layers in the separate basins may also contribute to our understanding of Karoo basinal development.

CHAPTER TWO – MATERIALS AND METHODS

2.1 CORE SAMPLING

Samples were obtained from two boreholes, AVM 67 and AVM 75, in the south-east area of Mmamantswe, Botswana (Figure 2.1). Cores were drilled through the Mmamabula and Korotlo Formations (Cronwright, M., pers. comm.). There are no intrusions in the area, and cores were unweathered, which is important for good preservation of palynomorphs.

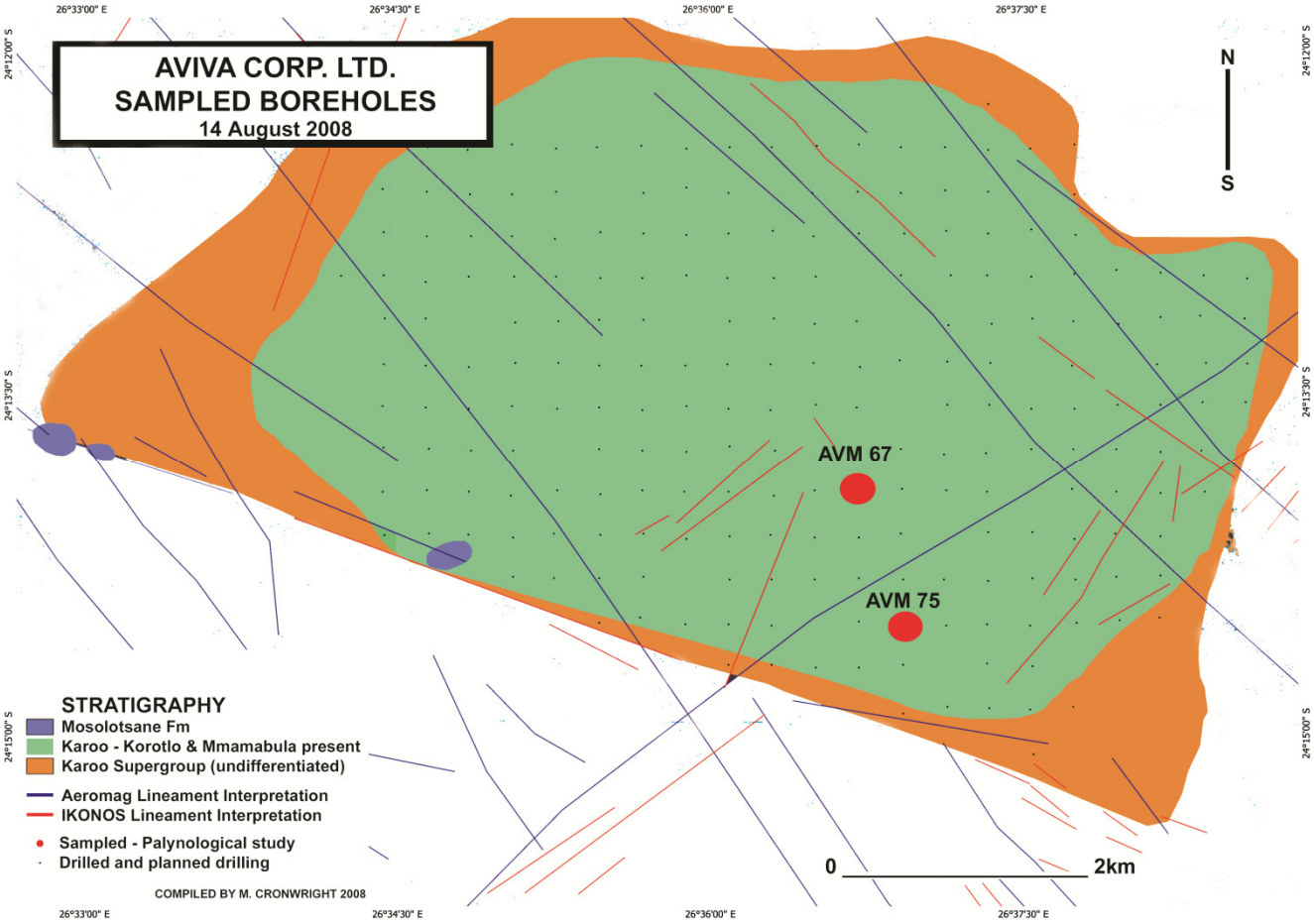


Figure 2.1 **Locations of drilled boreholes AVM 67 and AVM 75 within the Mmamantswe area (property of Aviva Corp. Ltd., 2007).**

Cores were dug very close to one another (less than 1 km apart) and so should reflect a similar lithology. Two cores were chosen because one was not sufficient to provide suitable samples from all the different lithologies represented. In core AVM 67, deposits above 60 m were weathered and crumbly, thus samples were not taken from these "Beaufort Group" equivalents as they would likely have suffered oxidative damage and contamination. However, AVM 67 possessed a more balanced combination of carbonaceous mudstones and coals, rather than predominantly coal deposits. This was desirable as mudstones have a higher probability of containing abundant palynomorphs than coal. 103 samples were taken from Core AVM 67, ranging from 63.565 m – 117.495 m. AVM 75 was also sampled due to it having well preserved diamictites underlying the coal, and relatively unweathered Beaufort Group deposits above the coals. 21 samples were taken from Core AVM 75, from 33.79 m – 60.9 m, and then from 133.53 m – 140.06 m. Sample positions are indicated on the core logs in Chapter 3 (Figures 3.2 and 3.3).

Samples were taken approximately every 50 cm except where a core loss prohibited it, or that particular section of the core was judged unsuitable for palynological analysis i.e. if many cracks ran through the section, or the section had crumbled. In these cases the next suitable piece of core was sampled instead, and sampling then resumed as normal. 124 samples were taken in total from both cores and placed in labelled, new plastic zip-lock bags. Relatively large samples were taken (approx. 500 g each) so that only the innermost section could be used in the analysis, minimising contamination.

2.2 SAMPLE PREPARATION

2.2.1 Summary of techniques

Methods of acid preparation vary considerably among palynologists, although general principles of using hydrochloric acid to dissolve carbonates, hydrofluoric acid to dissolve silicates, and some type of float-sink procedure are by and large adhered to. These general procedures have been in place since the middle of the twentieth century e.g. Norem (1956) developed a similar method to the one used in this study. Ultimately, the specific method of sample preparation must be determined by availability of chemicals and equipment, sediment sample type, and experimentation with different

treatments. Various combinations of treatments were tested on the Mmamantswe sediments and the results are discussed in Chapter 4.

As wind-pollinated palynomorphs are present in the atmosphere in large numbers, they drift down and become incorporated into the sediment. Once sediment is lithified, they are preserved in the rock. In order to study these palynomorphs, they must be extracted from the rock without damage. Acid preparation is useful for this because sporopollenin in the exine of pollen is acid-resistant, whilst most mineral constituents of a rock are not (Traverse, 2007). However, the exact method of acid preparation varies with the type of rock being processed. Samples from core AVM 67 consisted mainly of carbonaceous mudstones interbedded with coal, while core AVM 75 contained glacial diamictites at the base of the core, and "Beaufort" deposits above the coal / mudstone bands. Due to the high content of organic material within the coals and mudstones, they required oxidation treatment in addition to the normal preparation procedures. A summary of preparation methods is given below (Figure 2.2).

All equipment used in the preparation process (beakers, measuring spoon, pestle and mortar, hammer etc.) were thoroughly scrubbed with boiling water and liquid soap before and after each use, and left to stand in 40% nitric acid for approximately 1 hour. Equipment was given a final rinse with distilled water, and when not in use, stored in a dust-proof cupboard.

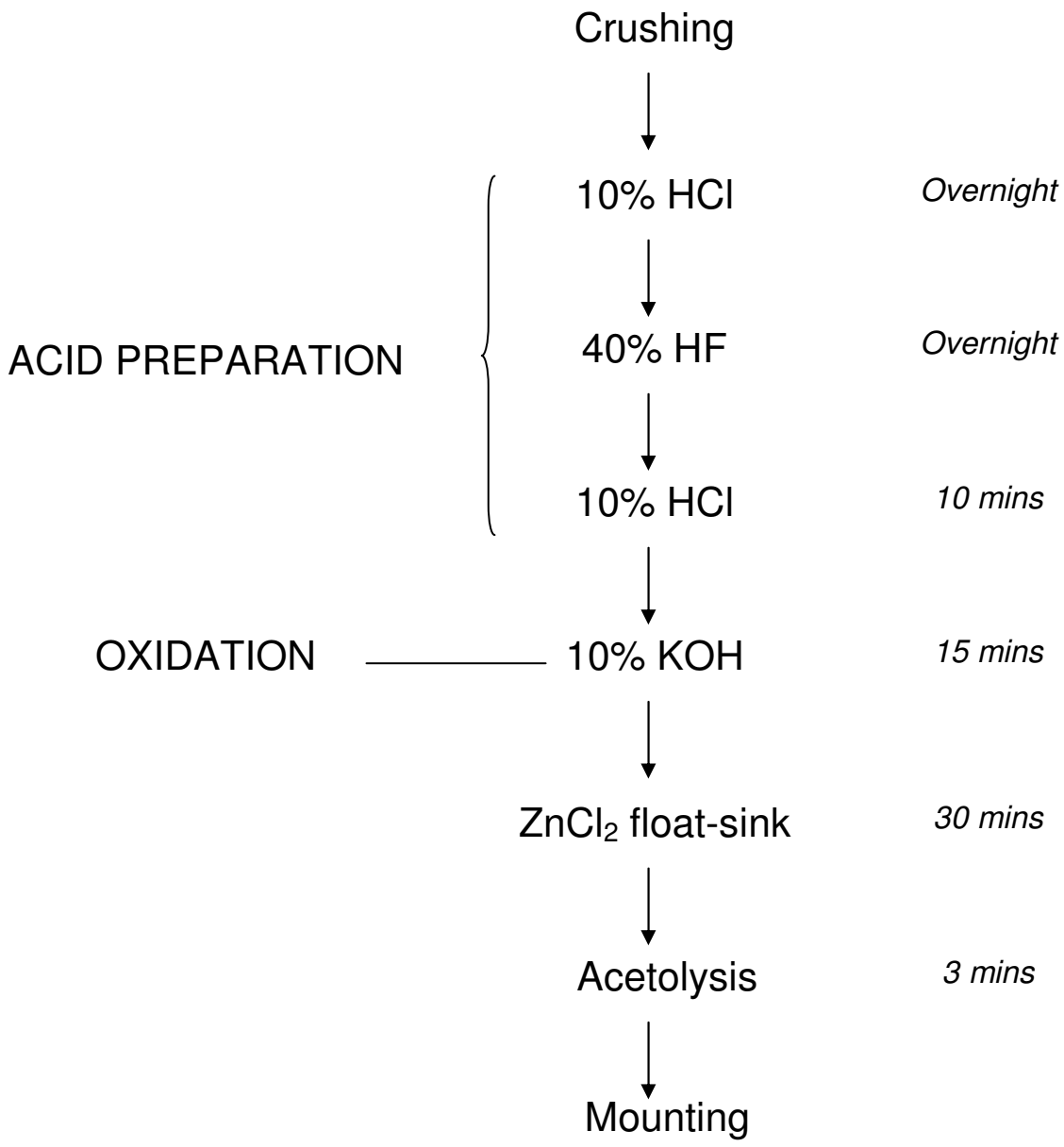


Figure 2.2 **Flowchart of methods used for preparing Mmamantswe sediments.**

2.2.2 Crushing

Rock needs to be crushed into fine particles (less than 1mm diameter) before any acids are added, in order for chemical reactions to proceed as completely as possible. If the Mmamantswe sediments were not crushed to a fine powder at the start of chemical preparation, a significant part of the sediment did not have the clay removed by hydrofluoric acid. After centrifugation, the sample then became a gluey pellet that could not be removed from the tube. Accordingly it was important to crush sediments finely.

Cores were washed with distilled water and soap before crushing, then wrapped in layers of sterile laboratory-issue paper towelling and crushed with a small hammer. A fine powder was achieved by grinding with a pestle and mortar, placed in a labelled polypropylene 100 ml beaker and covered with a lid. Depending on the palynological richness of the sample sediments, between 1g and 100g of material can be processed (Scott, L., pers. comm.). For these samples, an average of 25 g of rock was used and proved to be sufficient. Using larger amounts of rock required the sample to be concentrated, increasing preparation time significantly.

2.2.3 Acid preparation

A number of different acids were added to each sample to break down different mineral constituents of the rock matrix. Samples were left to react with each acid for a specific period of time (Figure 2.2). Between each treatment, residues were transferred to 45 ml centrifuge tubes, distilled water added and centrifuged at 3000 r.p.m. for 5 minutes. The supernatant (containing dissolved minerals) was poured off, with the pellet (containing miospores) remaining behind. Fresh distilled water was added, the sample agitated with a Whirly Mixer, and centrifuged repeatedly until the pH was neutral (two to three washings). All chemical procedures were carried out in a fume cupboard, while the preparator wore a lab coat, eye protection and disposable gloves.

Samples were first treated with 10% hydrochloric acid (HCl) to remove carbonates, and samples left overnight. Degree of effervescence was noted and samples washed and centrifuged.

Next, 40% cold hydrofluoric acid (HF) was added. A lead apron and face shield were employed for this step due to the extremely dangerous nature of HF. No glassware was allowed to come into contact with the acid as it dissolves silicates. Approximately half the samples reacted violently, boiling and smoking, indicating a large proportion of silica in the sample. This was worth noting because HF is not recommended as a standard treatment for coals in many papers or textbooks. The reaction of these sediments highlights that not all coals are similar in chemical make-up. Samples were left for 24 hours in HF to ensure a complete reaction. This posed no danger to the pollen grains – they can be safely left in HF or HCl for days or weeks (Moore *et al*., 1991).

After centrifugation and washing, 10% hydrochloric acid (HCl) treatment was added to dissolve fluoride complexes formed during HF treatment, left for 10 minutes and washed.

Sediments containing a high proportion of organic matter e.g. coals, lignites, peats, and carbonaceous mudstones, require specialized treatment during palynological processing. They must first be oxidised before a heavy mineral separation, also known as a float-sink procedure, can be run. This treatment releases pollen from the matrix and allows it to float into the supernatant because of its low mass. Heavy minerals remain sedimented in a pellet at the bottom of the centrifuge tubes and are discarded. However, all fine organic matter, not only pollen, rises up into the supernatant. If this matter is not removed before heavy mineral separation, the supernatant becomes a thick black syrup with no hope of extracting the pollen grains. Removal of organic matter by oxidation is a precarious process, as fossil palynomorphs can also be adversely affected by the procedure, swelling or rupturing if exposed for too long (Moore *et al*., 1991).

Oxidation consisted of boiling residues in 10% potassium hydroxide solution (KOH) for no longer than 15 minutes, to prevent the outer walls of the pollen grains swelling and rupturing. Organics were liberated into the supernatant (making it dark brown to black), which could be poured off and the pellet washed.

Samples were then ready for a heavy mineral separation with zinc chloride ($ZnCl_2$). A saturated $ZnCl_2$ solution, having a specific gravity of 2, is ideal for separating organic particles like pollen grains (S.G. of 1.4) from heavier mineral such as fluorite (3.2), quartz (2.6), and calcite (2.7) (Funkhouser & Evitt, 1959). Bromoform is often used for the float-sink procedure, however it is an expensive and highly toxic chemical. Zinc chloride is relatively cheap and far less hazardous, thus it is preferred for this procedure. It was made up by adding $ZnCl_2$ powder or pellets to 10% HCl until the solution reached a specific gravity of approximately 2. The resulting syrup was added to each centrifuge tube containing the washed pellet, Whirlymixed, and centrifuged at 3000 r.p.m for 30 minutes.

After mineral separation, two or more distinct layers were observable in each tube, with the sediment at the bottom. For the first time, the supernatant contained the lightweight pollen grains. Using a disposable glass pipette, this layer was extracted and placed in a

small 15 ml centrifuge tube for acetolysis, the final cleaning procedure. Residues were initially submerged in glacial acetic acid, followed by treatment with a fresh mixture of 9 parts acetic anhydride to 1 part sulphuric acid. This removed any remaining amorphous organic matter. Residues were then ready for mounting.

2.2.4 Slide preparation

In all the principal textbooks of pollen analysis (e.g. Faegri & Iversen, 1989; Moore *et al*., 1991; Traverse, 2007), glycerin jelly is recommended as the best mounting medium for pollen slides and is preferable to silicon oil. It dries solid, which is necessary in a warm climate, and grains remain in place so they can be located repeatedly. A disadvantage is that slides have a lifespan of between 15-20 years, as grains slowly swell within the mounting medium as the sporopollenin oxidises (Traverse, 2007). Residues were pipetted onto on 25 x 76 mm glass slides (thickness of 1 mm) with a dab of glycerin jelly, sealed with 22 x 50 mm glass coverslips and dried on a warming plate.

2.2.5 Microscope analysis

Prepared slides were examined with the Olympus BX51m and Zeiss Axioskop 2 light microscopes. Slides were classified as productive (if 250 grains could be counted) or non-productive. However, approximately half of the "non-productive" slides contained some miospores. Where possible, visual counts of 250 grains per sample were made under 400x magnification. If a slide did not quite yield 250 grains, another slide from the same sample was made up and counted until the total reached 250. Counts were presented as a Tilia™ pollen diagram. Raw data is included in Appendix B.

Photographs were taken under 1000x magnification (oil immersion) to show fine detail. A ColorView Soft Imaging System, AxioCam ICc 1 camera, and Analysis™ software were used for digital photography. Palynomorphs were identified and described on the basis of shape, ornamentation, laesura type, colpi or sacci. Figure 2.3 summarises miospore descriptive terminology, ornamentation / sculpture, and dimensions. Descriptions, identifications and illustrations of the palynomorphs as well as their stratigraphic occurrence are given in Chapter 3.

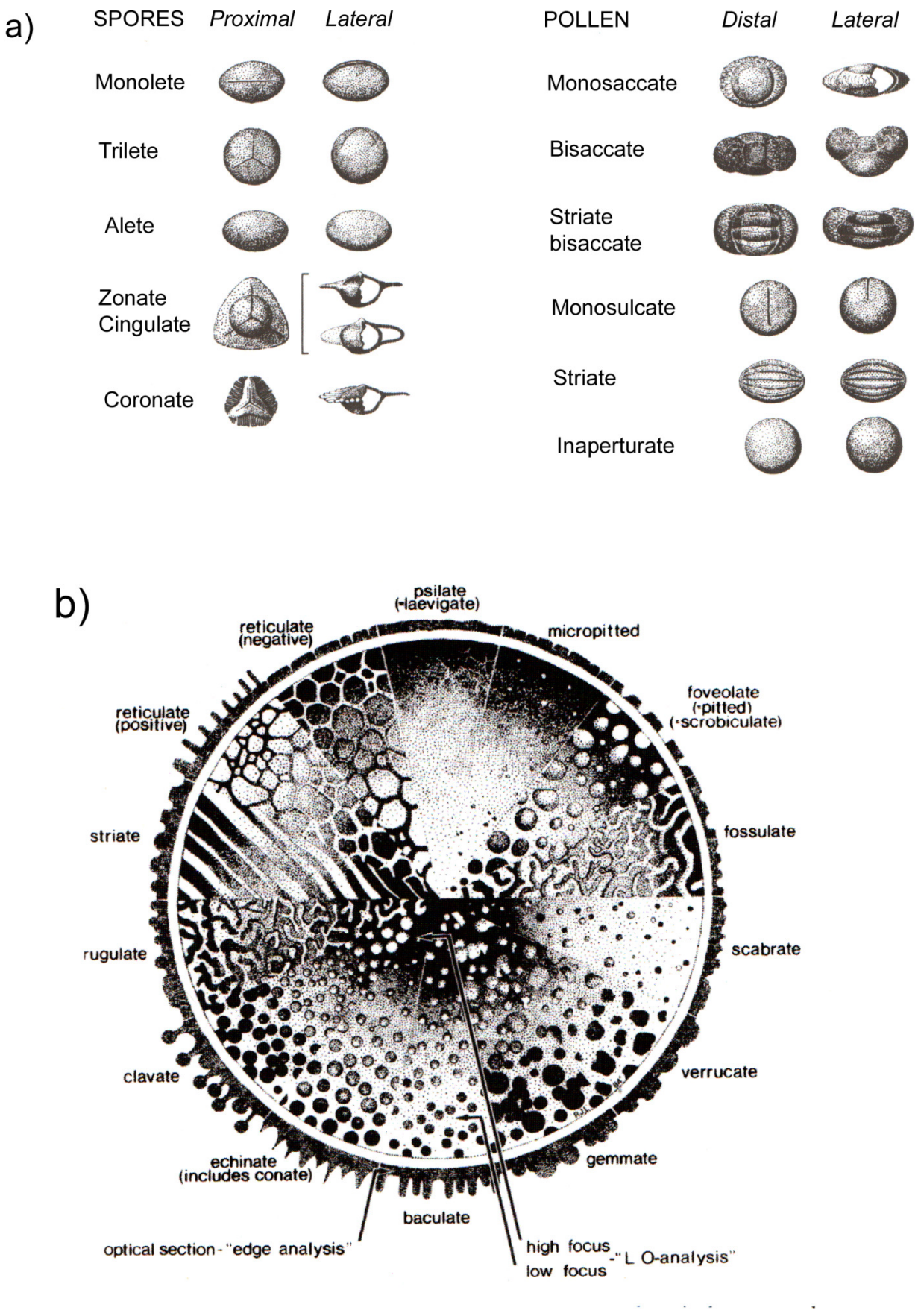


Figure 2.3 **Approach for identifying, classifying and describing spores and pollen from Mmamantswe (modified from Traverse, 2007).**

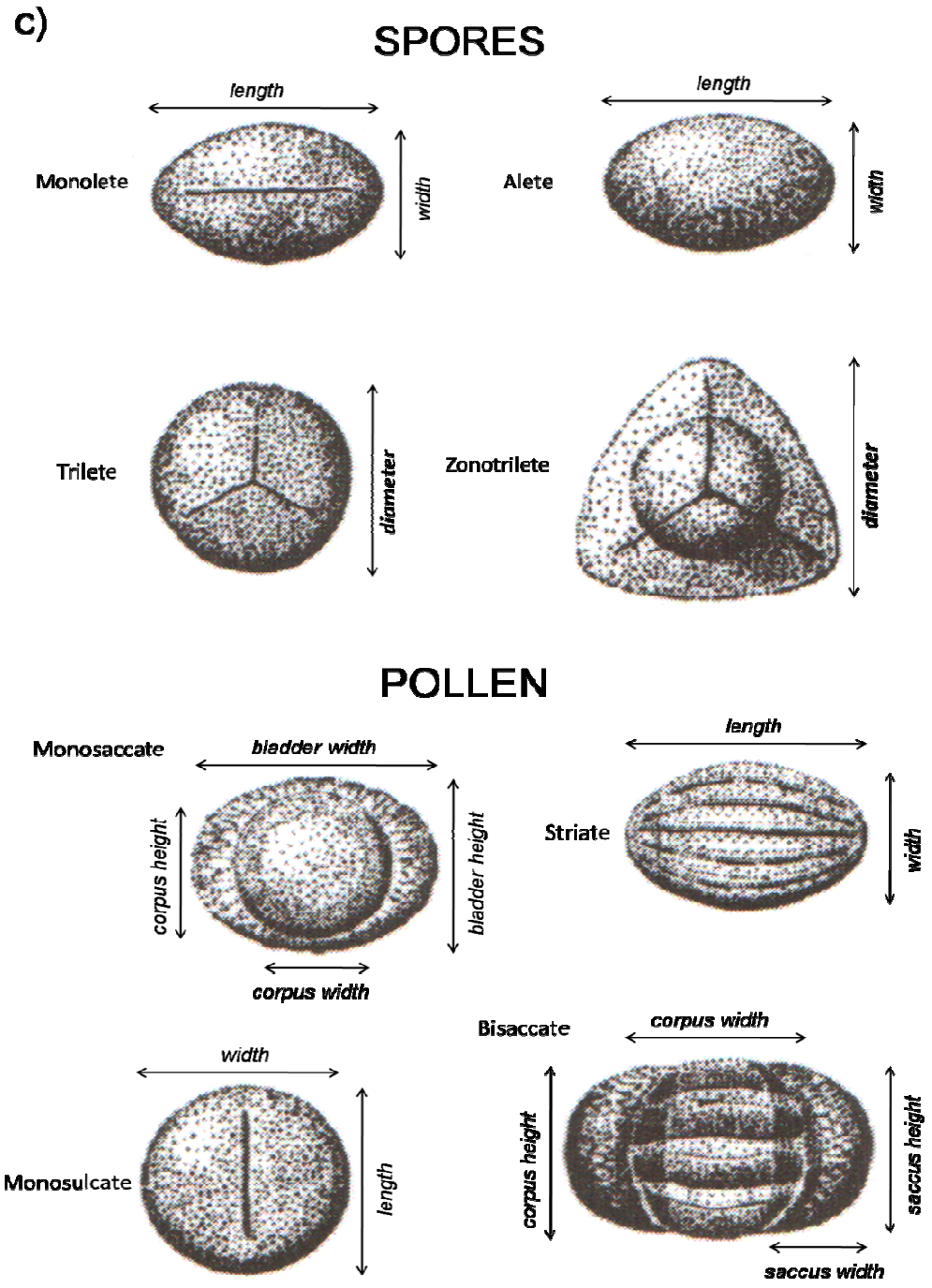


Figure 2.3 **Approach for identifying, classifying and describing spores and pollen from Mmamantswe (modified from Traverse, 2007).**

a) Morphological types of spores and pollen in proximal and lateral orientation.

b) Various types of ornamentation and sculpture of miospores. Low focus is shown to the outside of the grain, and high focus towards the inside (L.O. analysis). Negative and positive elements are shown around the external surface (exine) of the grain (edge analysis).

c) **Dimensions of spores and pollen. In trilete spores, measurements were made by aligning the radius along one arm of the trilete laesura. Ornamental elements were not included in the measurements.**

CHAPTER THREE - RESULTS

3.1 SYSTEMATIC PALYNOLOGY

It is a continuing problem in palynology that a standardized system for identification and classification of miospores is yet to be put in place. There is no single classification system which is protected by the ICBN, and accordingly, different systems abound within the literature, and variations of one system or a combination of two or more are used on sole discretion of the author. It is repeatedly emphasised how problematic this is (e.g. Traverse, 2007, p. 174), however it does not seem that anything is going to be done about it. Therefore, palynologists need to make calculated decisions about which system to use, considering such factors as ease of comprehension and suitability to sample composition and time period.

Gondwanan palynologists have additional problems in that not nearly as much work has been done here as in the northern hemisphere, with most of the existing studies using varying classification systems as well. It is also felt by many (e.g. Hart, 1965; Anderson, 1977; Falcon, 1978a) that the proliferation of genera and species in the literature, especially from Gondwana, is due to duplication in naming and does not reflect actual taxonomy. Accordingly, it becomes a dilemma to choose which authors and classification systems one is to follow.

The system most widely used by Western palynologists is that of Potonié (1956 - 1970); the turmal classification of anteturmas Sporites and Pollenites, with further subdivisions under these two main units. Other systems for classifying Palaeozoic and Mesozoic miospores are variations of Potonié's original classification. For example, Hart (1965) incorporates certain modifications for species that are typically Permian in occurrence. It is more or less this system which has been used by MacRae (1978, 1988) and Aitken (1998) and which is retained here. Thus meaningful comparisons can be made instead of restricting one's conclusions to a specific area, which does not contribute much to an understanding of evolutionary patterns.

Although the system of Potonié is used worldwide for the Carboniferous and Permian, there are some problems with the classification. Firstly it is artificial in nature, due to the fact that one is classifying fossils solely on morphological characteristics, with

mostly no knowledge of the parent plants that produced them. Accordingly, it is unlikely that most miospore morphotypes reflect real-world species (Traverse, 2007). Another problem is that the difference between the anteturmas Sporites and Pollenites is functional, not morphological, creating problems for identification (Traverse, 2007). However, the system is not likely to go out of use as it does work, and so these problems must simply be worked around. Completely different methods of classification such as the palaeodeme concept used by Anderson (1977) are not nearly as practical and have not been adopted by other authors.

Micrographs of the various palynomorph types found in the Mmamantswe sediments are arranged below and classified using the turmal system. Approximately 25% of the miospores could not be matched with known types in the literature, however most of the unknowns were rare to very rare in the sample. It is possible that these specimens were orientated differently, making identification difficult. For this reason, they have not been formally named as new species at this point. High resolution *colour* photographs are included in plates. The orientation and size of images has not been changed, in order to facilitate comparison between the morphotypes. A CD with high resolution images has been included that allows for further magnification and manipulation of images as required. A problem specific to Gondwana and particularly southern African palynology is that micrographs in past publications are black and white (which tend not to print well), and that only pictures of selected morphotypes are included. There is no database of high resolution images of all southern African palynomorphs to date, inhibiting the growth of the field and its incorporation into the larger framework of Gondwanan palynology.

The suggestion of Traverse (2007) that a table be included when using the turmal system, which illustrates exactly which variation is being used, is an excellent one, and if all palynologists did this, it would go a long way towards ease of comprehension, and making meaningful comparisons between studies. Tables for the anteturmas Sporites (Table 3.1) and Pollenites (Table 3.2) are presented below. As the turmal system is only useful for categorising pre-Cenozoic floras (Traverse, 2007), the vast variety of angiospermous pollen types had not yet evolved. It is for this reason that there are fewer categories for the Anteturma Pollenites than for Sporites. As the individual turmal units are not validly published names subject to priority, author citations and dates should not

used alongside such units (Traverse, 2007), as seen in previous publications (e.g. MacRae, 1978; Aitken, 1994).

Table 3.1 **Turmal classification for the spores from Mmamantswe. Table format is derived from Traverse (2007). Some groups are not represented in the Mmamantswe sediments. However, they are retained in this table for clarification of the turmal scheme, and to aid comparison with other sites, where they are present. Absent groups are marked with a star.**

Diagnostic feature	**SPORITES**												**Anteturma**
Aperture	**TRILETES**						**MONOLETES**			**ALETES**	**HILATES**		**Turma**
Stratification	ACAVATITRILETES		LAMINATI-TRILETES		PSEUDO-SACCITRILETES*	PERINO-TRILETES*	ACAVATO-MONOLETES		CAVATO-MONOLETES*		ACAVATI-HILATES	CAVATI-HILATES	**Supra-subturma**
Equatorial features	AZONOTRILETES	ZONOTRILETES	AZONOLAMINATITRILETES*	ZONOLAMINATITRILETES		AZONOPEROTRILETES ZONOPEROTRILETES	AZONOMONOLETES	ZONOMONOLETES*				AZONOCAVATIHILATES	ZONOCAVATIHILATES	**Subturma**
Sculpture	LAEVIGATI APICULATI MURORNATI	AURICULATI TRICRASSATI* CINGULATI*			MONOPSEUDOSACCITI POLYPSEUDOSACCITI		LAEVIGATOMONOLETI SCULPTATOMONOLETI					EPITYGMATI OPERCULATI		**Infraturma**

Table 3.2 **Turmal classification for the pollens from Mmamantswe. Table format is derived from Traverse (2007). As in Table 3.2, absent groups are marked with a star.**

POLLENITES					**Anteturma**
SACCITES		PLICATES			**Turma**
MONOSACCITES (MONOSACCATES)	DISACCITES (BISACCATES)	PRAECOLPATES*	MONOCOLPATES (MONOSULCATES)	POLYPLICATES*	**Subturma**
TRILETESACCITI VESICULOMONORADITES CAHENIASACCITI* ALETESACCITI STRIASACCITI*	DISACCITRILETI* DISACCIATRILETI STRIATITI				**Infraturma**

Palynomorphs from Mmamantswe are described below and grouped according to the turmal groups tabulated above. Descriptions are presented in a table format, including species name, reference if available, morphology, size of the photographed specimen, stratigraphic range through the two cores, total abundance and any comments. The plate reference for each specimen is noted below the species name, and plates are distributed intermittently between descriptions. Micrographs of all described specimens were taken at 1000X magnification except where stated. Scale bars in the lower right hand corner represent 10 µm (1000X) and 20 µm (400X).

ANTETURMA SPORITES

TURMA TRILETES

SUPRASUBTURMA ACAVATITRILETES

SUBTURMA AZONOTRILETES

Infraturma Laevigati

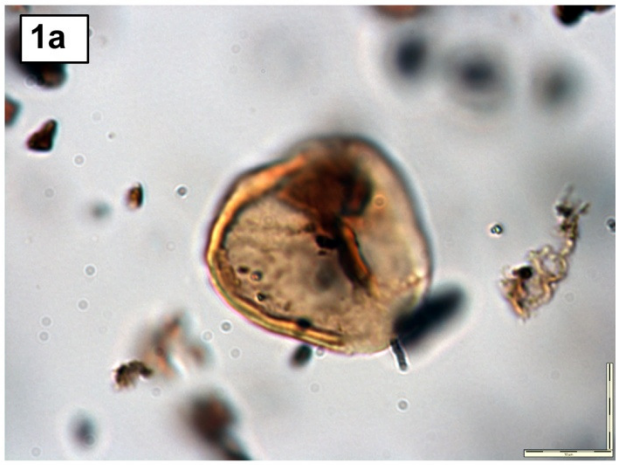
Deltoidospora magna (de Jersey) Norris 1965 Plate 1 (1a & 1b)	
REFERENCE	Raine *et al*., 2008
JUNIOR SYNONYMS	*Leiotriletes magna* (de Jersey) Norris 1965
DESCRIPTION	Amb triangular, apices broadly rounded, inter-apical region straight to slightly concave. Trilete laesura distinct and thickened when seen, bordered by folded labra. Laesura not apparent in some specimens as it is obscured by folds. Exine approx. 1-2 µm thick and laevigate.
SIZE	25 µm
DISCUSSION	Raine *et al*. (2008) uses the name *Leiotriletes magna* (de Jersey) Norris 1965 for this morphotype, however it has been determined that *Leiotriletes* is most likely a junior synonym of *Deltoidospora* (Balme, 1995). Accordingly, the latter genus is used here.
STRATIGRAPHIC RANGE AT MMAMANTSWE	65.44 m – 69.9 m (AVM 67)
TOTAL ABUNDANCE	169 specimens

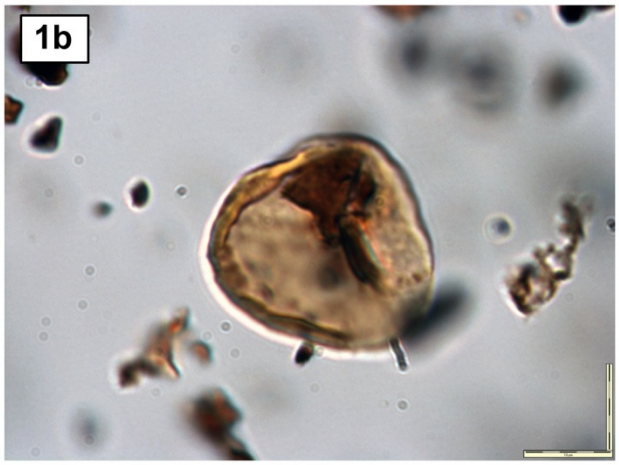
Cf. *Deltoidospora magna* (de Jersey) Norris Plate 1 (2)	
REFERENCE	Raine *et al*., 2008
JUNIOR SYNONYMS	*Leiotriletes* (de Jersey) Norris 1965

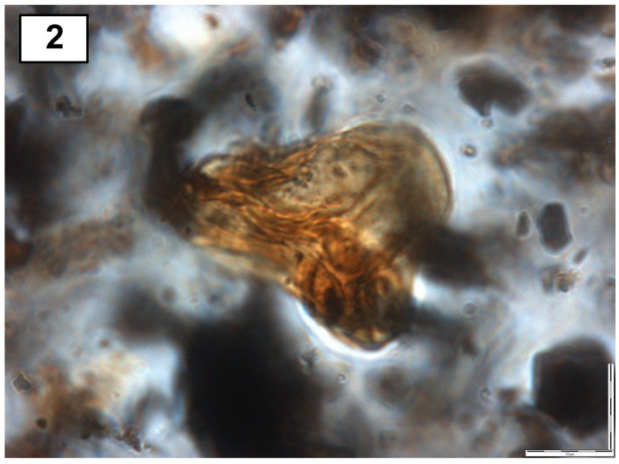
DESCRIPTION	Amb triangular, apices rounded, inter-apical region slightly concave. Trilete laesura with strongly folded labra. Radii extend almost to spore periphery. Exine of medium thickness, laevigate and strongly folded. Circular thickening in one corner with smaller repeated trilete mark – may be due to folding.
SIZE	29 µm
DISCUSSION	Unusual specimen that may have suffered post-depositional compression.
STRATIGRAPHIC RANGE AT MMAMANTSWE	ǀ 98.85 m ǀ (AVM 67)
TOTAL ABUNDANCE	1 specimen

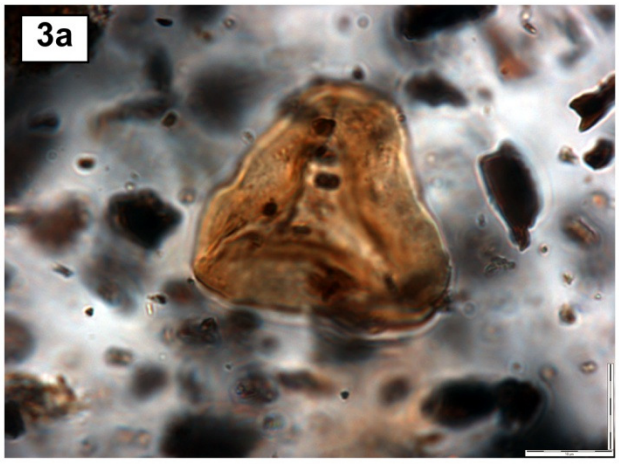
Deltoidospora directa (Balme & Hennelly) Hart 1965 Plate 1 (3a, 3b, 3c)	
REFERENCE	Manum & Tien, 1973: p. 218, Plate I (4)
JUNIOR SYNONYMS	*Leiotriletes directus* Balme & Hennelly 1956
DESCRIPTION	Amb triangular, apices rounded, inter-apical region straight to slightly concave. Trilete laesura with radii distinct, may sometimes be obscured by folding. Exine thin, laevigate, often folded.
SIZE	26 µm
DISCUSSION	Specimens often seen from an oblique angle instead of in polar view.
STRATIGRAPHIC RANGE AT MMAMANTSWE	64.45 m – 117.495 m (AVM 67)
TOTAL ABUNDANCE	67 specimens

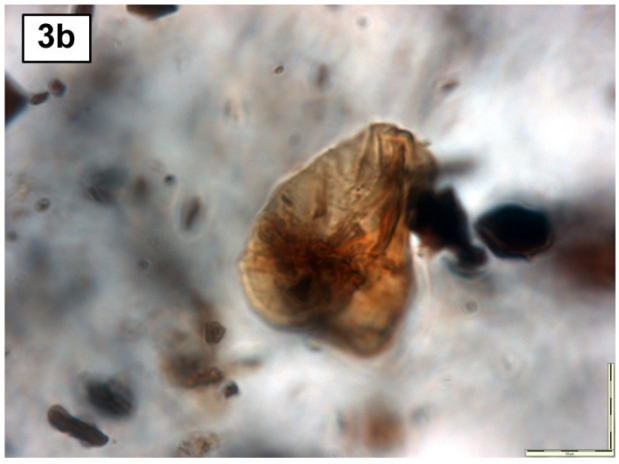
Plate 1













Deltoidospora lukagaensis (Kar & Bose) Falcon 1975 Plate 2 (1)	
REFERENCE	MacRae, 1978: p. 21, Plate 1 (2-3)
DESCRIPTION	Amb triangular, apices sharp with rounded points, cheilocardioid. Trilete laesura distinct with thin radii. Exine thin, laevigate, often folded.
SIZE	22 µm
DISCUSSION	Seen in a variety of orientations, consequently the trilete laesura is not always apparent. MacRae (1988) gives *D. lukagaensis* as a junior synonym of *Concavisporites mortonii*, however *D. lukagaensis* is distinctly cheilocardioid without a torus, while *C. mortonii* has a distinct torus and is not cheilocardioid. Therefore the two species are kept separate here.
STRATIGRAPHIC RANGE AT MMAMANTSWE	63.565 m – 137.95 m (AVM 67 and AVM 75)
TOTAL ABUNDANCE	802 specimens

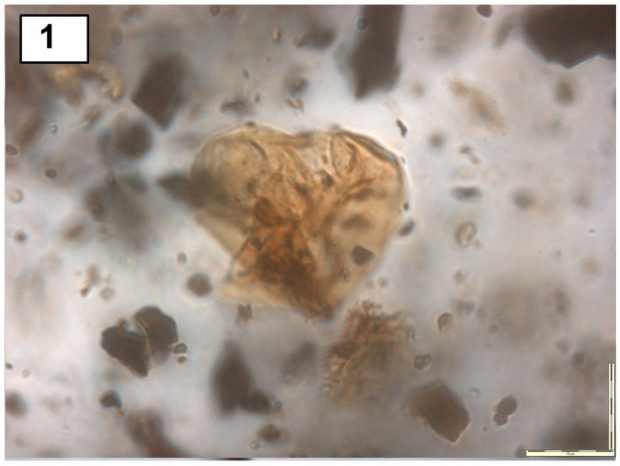
Concavisporites mortonii (de Jersey) de Jersey 1962 Plate 2 (2)	
REFERENCE	MacRae, 1988: p. 23, Plate 3 (4-6)
DESCRIPTION	Amb triangular, apices rounded, inter-apical region straight to slightly concave. Trilete laesura with radii distinct, may sometimes be obscured by folding, laesura bordered by torus (kyrtome). Exine approx. 1 µm thick and laevigate.
SIZE	28 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	63.565 m – 80.735 m (AVM 67)
TOTAL ABUNDANCE	6 specimens

Punctatisporites cf. *minutus* Kosanke 1950 Plate 2 (3a, 3b)	
REFERENCE	Kremp & Ames, 1959 (Vol. 5): p. 5-8
DESCRIPTION	Amb triangular, apices rounded, inter-apical region strongly convex. Trilete laesura distinct, radii thin with lips slightly developed, and extend almost to spore periphery. Exine 1-2 µm thick and laevigate.
SIZE	20 µm
DISCUSSION	There are many species of *Punctatisporites* that all appear similar to *P. gretensis* but differ in size. MacRae (1988) & Aitken (1994) have placed all specimens, no matter their size, into *P. gretensis*. In this study, specimens fell into one of two distinct size ranges, accordingly larger specimens were placed into *P. gretensis* and smaller specimens into *P. minutus*.
STRATIGRAPHIC RANGE AT MMAMANTSWE	65.44 m – 137.95 m (AVM 67 and AVM 75)
TOTAL ABUNDANCE	64 specimens

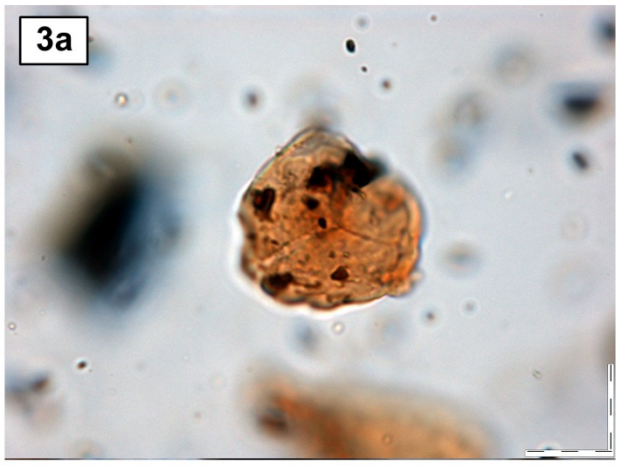
Punctatisporites gretensis Balme & Hennelly 1956 Plate 2 (4) (400X)	
REFERENCE	MacRae 1988: p. 22, Plate 1 & 2
DESCRIPTION	Amb triangular, apices rounded, inter-apical region convex. Trilete laesura distinct, radii thin, curved and extend two thirds of spore. Characteristic splitting of the spore along one radius. Exine thick, approx. 6 µm and laevigate.
SIZE	90 µm
DISCUSSION	Unusually large specimens for the Mmamantswe assemblage
STRATIGRAPHIC RANGE AT MMAMANTSWE	64.45 m – 137.95 m (AVM 67 and AVM 75)
TOTAL ABUNDANCE	38 specimens

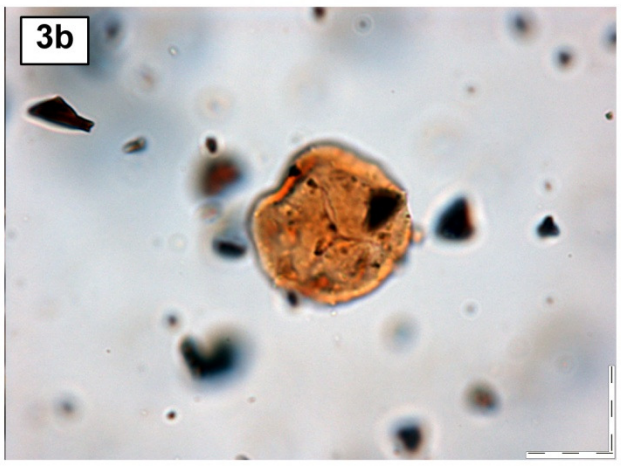
Laevigatisporites minimalis forma *pulla* Dybová & Jachowicz 1957 Plate 2 (5)	
REFERENCE	Kremp & Ames, 1962 (Vol. 18): p. 18-44
DESCRIPTION	Amb triangular, apices rounded, inter-apical region convex. Trilete laesura indistinct (due to oblique angle). Radii extremely thickened and elliptical. Exine thin and laevigate to microgranulate.
SIZE	30 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	65.44 m – 80.735 m (AVM 67)
TOTAL ABUNDANCE	13 specimens

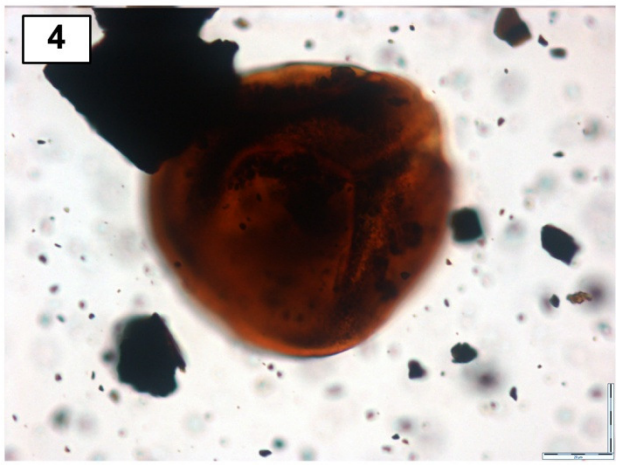
PLATE 2

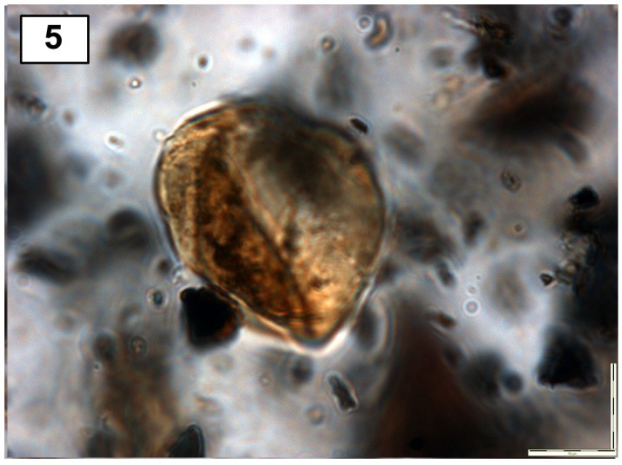












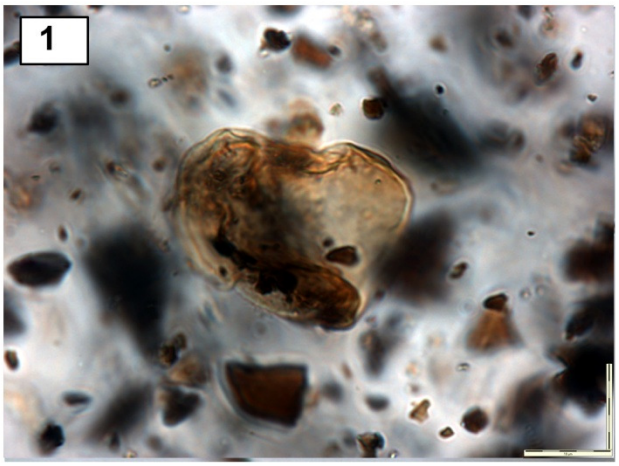
Laevigatisporites sp. Ibrahim 1933 Plate 3 (1)	
REFERENCE	Kremp & Ames, 1962 (Vol. 18): p. 18-44
DESCRIPTION	Amb triangular (specimen folded), apices rounded, inter-apical region concave. Trilete laesura indistinct, when apparent, radii thin. Exine approx. 1µm thick and laevigate.
SIZE	28 µm
DISCUSSION	These specimens possess all of the diagnostic characters of the genus *Laevigatisporites* but cannot be matched with an existing species.
STRATIGRAPHIC RANGE AT MMAMANTSWE	63.565 m – 137.95 m (AVM 67 and AVM 75)
TOTAL ABUNDANCE	271 specimens

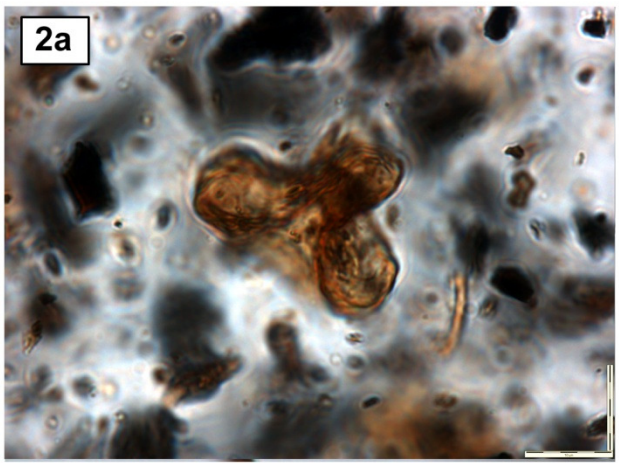
Cf. *Acanthotriletes gracilus* (Kara-Murza) Chalishev & Varyukhina Plate 3 (2a, 2b, 2c)	
REFERENCE	Hart, 1970: p. 118, Fig. 26 (76)
DESCRIPTION	Amb triangular, apices rounded, inter-apical region concave. Trilete laesura indistinct. Exine thin and laevigate (*A. gracilus* has echinate ornamentation). Edges strongly folded and curl distinctively.
SIZE	19 µm
DISCUSSION	Orientation of spores complicates identification
STRATIGRAPHIC RANGE AT MMAMANTSWE	65.44 m - 117.495 m (AVM 67)
TOTAL ABUNDANCE	81 specimens

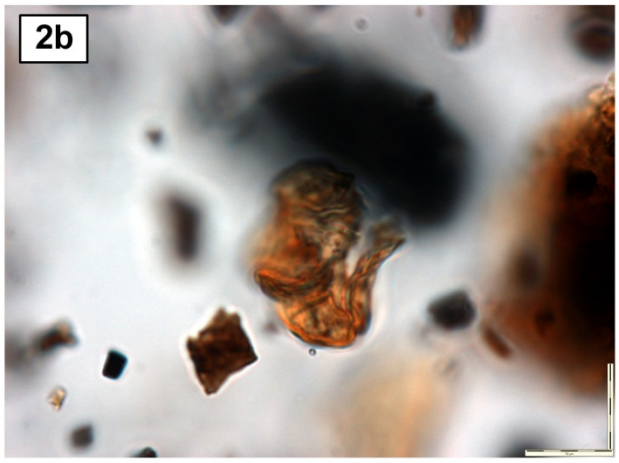
Trilete laevigate sp. 1 Plate 3 (3)	
DESCRIPTION	Amb circular. Trilete laesura distinct, radii sinuous (split open along upper arm). Radii extend to spore periphery. Exine thin, laevigate.
SIZE	20 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	ǀ 65.44 m ǀ (AVM 67)
TOTAL ABUNDANCE	1 specimen

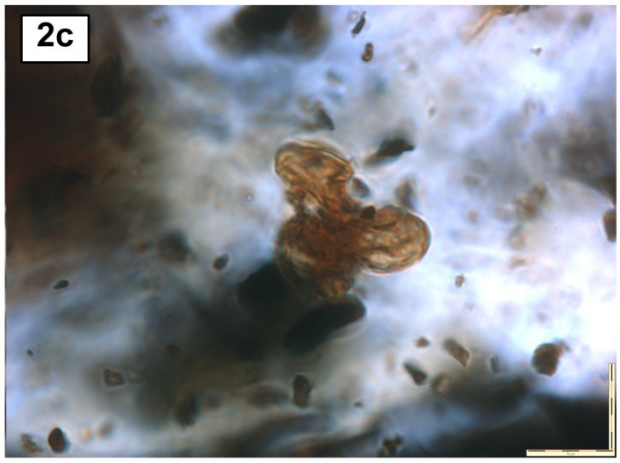
Trilete laevigate sp. 2 Plate 3 (4)	
DESCRIPTION	Amb triangular, apices sharp, inter-apical region straight to slightly convex. Trilete laesura distinct, radii sinuous and slightly thickened. Radii extend to spore periphery. Exine thin and laevigate.
SIZE	21 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	ǀ 65.44 m ǀ (AVM 67)
TOTAL ABUNDANCE	1 specimen

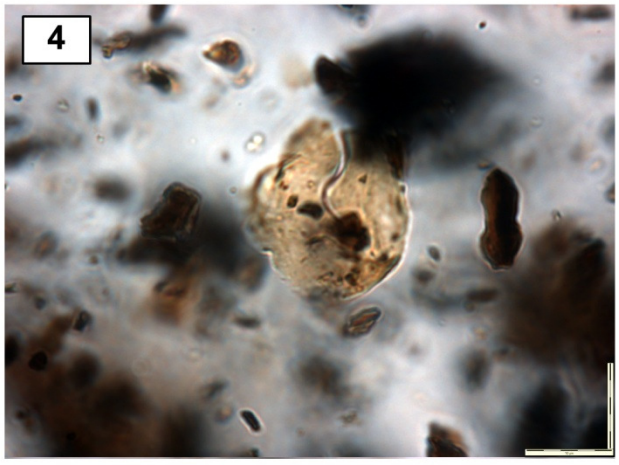
Plate 3

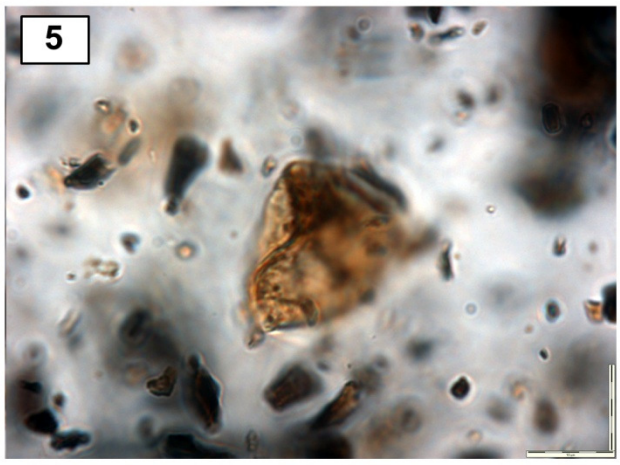












Trilete laevigate sp. 3 Plate 4 (1a, 1b)	
DESCRIPTION	Amb triangular, apices sharp, inter-apical region straight to slightly convex. Trilete laesura indistinct. Exine thin and laevigate with random folds.
SIZE	20 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	64.45 m – 69.9 m (AVM 67)
TOTAL ABUNDANCE	11 specimens

Trilete laevigate sp. 4 Plate 4 (2)	
DESCRIPTION	Amb triangular, apices rounded, inter-apical region straight. Trilete laesura indistinct. Exine thin and laevigate with two longitudinal folds, one on each side down length of grain.
SIZE	30 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	| 117.495 m | (AVM 67)
TOTAL ABUNDANCE	4 specimens

Infraturma Apiculati

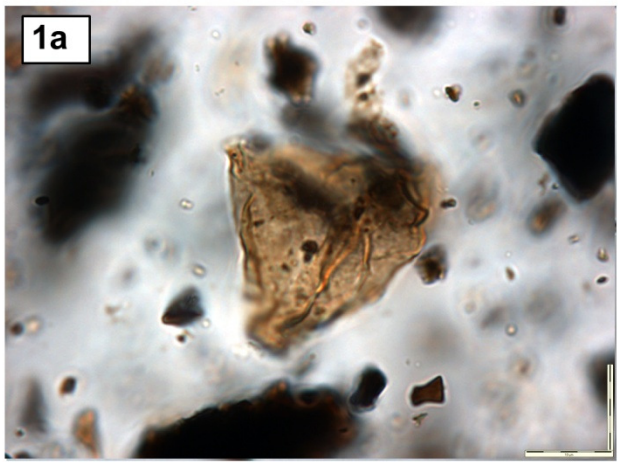
Subinfraturma Baculati

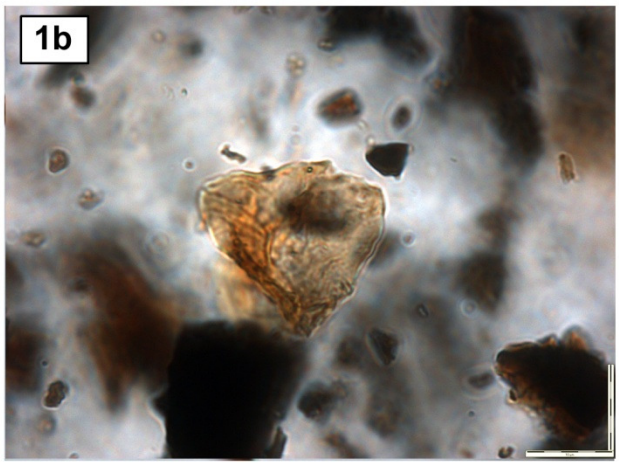
Horriditriletes tereteangulatus (Balme & Hennelly) Backhouse 1991 Plate 4 (3a, 3b)	
REFERENCE	Prevec *et al*., 2009: p. 479, Plate IX (4)
JUNIOR SYNONYMS	*Acanthotriletes tereteangulatus* Balme & Hennelly 1956

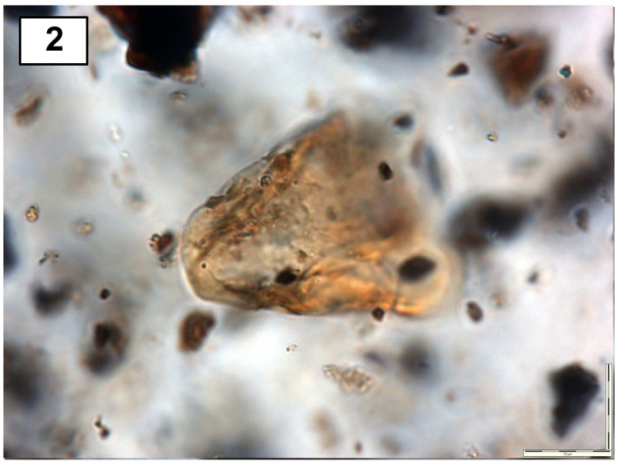
DESCRIPTION	Amb triangular, apices rounded, inter-apical region concave. Trilete laesura distinct and thin, no labra present. Radii taper towards tips and extend to spore periphery. Exine approx. 1µm thick with baculate ornamentation. Baculi elongate and thin.
SIZE	22 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	63.565 m – 117.495 m (AVM 67)
TOTAL ABUNDANCE	150 specimens

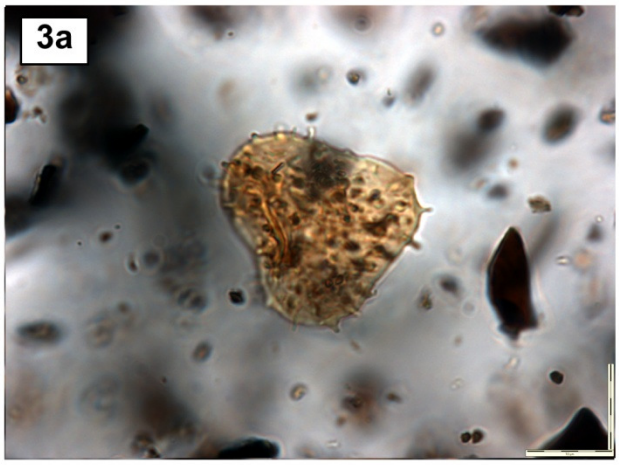
Horriditriletes tereteangulatus forma *convexus* (Balme & Hennelly) Backhouse 1991 Plate 4 (4)	
REFERENCE	Backhouse, 1991: p. 260, Plate II (6-9)
JUNIOR SYNONYMS	*Acanthotriletes tereteangulatus* Balme & Hennelly 1956
DESCRIPTION	Amb triangular, apices rounded, inter-apical region convex. Trilete laesura distinct and thin, no labra present. Radii taper towards tips and extend to spore periphery. Exine approx. 1 µm thick with baculate ornamentation. Baculi elongate and thin.
SIZE	20 µm
DISCUSSION	These specimens have a convex inter-apical region, while the taxon above has a concave inter-apical region. According to Aitken (1994), *H. tereteangulatus* is normally concave but occasionally convex. However, in this study the two forms are kept separate as it is felt that differences in the inter-apical region are significant.
STRATIGRAPHIC RANGE AT MMAMANTSWE	65.44 m – 117.495 m (AVM 67)
TOTAL ABUNDANCE	11 specimens

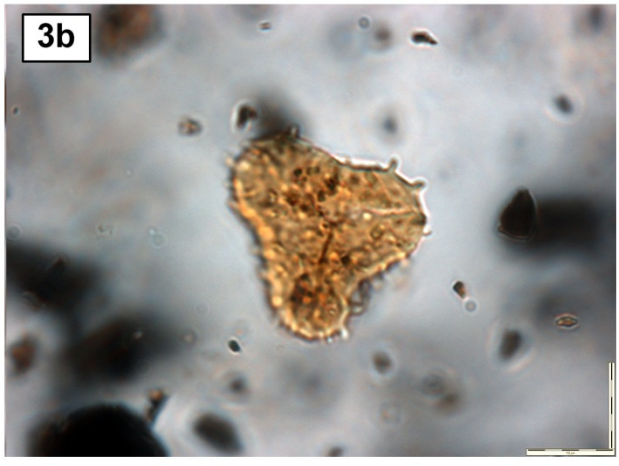
PLATE 4

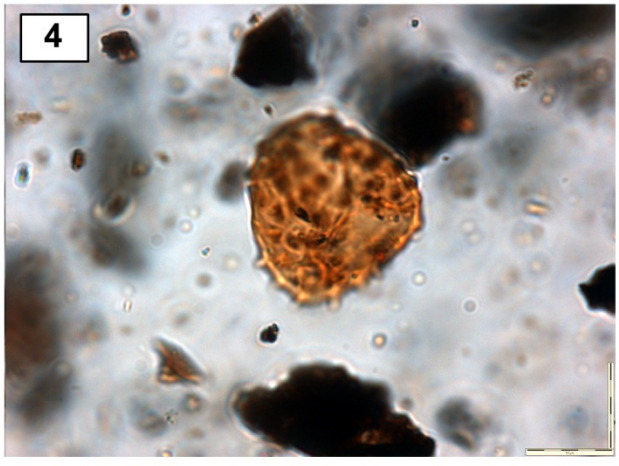












Horriditriletes ramosus (Balme & Hennelly) Bharadwaj & Salujha 1964 Plate 5 (1)	
REFERENCE	MacRae, 1988: p. 29, Plate 6 (17-23)
JUNIOR SYNONYMS	*Neoraistrickia ramosa* (Balme & Hennelly) Hart 1960
DESCRIPTION	Amb triangular, apices broadly rounded, inter-apical region straight to slightly convex. Trilete laesura indistinct due to ornamentation. Exine thin with baculate ornamentation. Baculi thick and blunt-tipped.
SIZE	35 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	65.94 m – 137.95 m (AVM 67 and AVM 75)
TOTAL ABUNDANCE	41 specimens

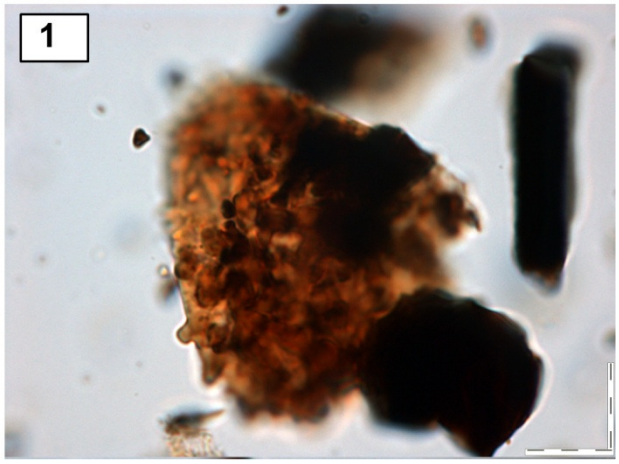
Horriditriletes sp. (Balme & Hennelly) Bharadwaj & Salujha 1964 Plate 5 (2a, 2b)	
REFERENCE	Bharadwaj & Salujha, 1964: p. 193
DESCRIPTION	Amb triangular, apices sharply rounded, inter-apical region strongly convex. Trilete aperture distinct, radii very short. Folds positioned randomly on exine. Light baculate ornamentation on distal face, baculi small and thin.
SIZE	17 µm
DISCUSSION	These specimens possess all of the diagnostic characters of the genus *Horriditriletes* but cannot be matched with an existing species.
STRATIGRAPHIC RANGE AT MMAMANTSWE	63.565 m – 117.495 m (AVM 67)
TOTAL ABUNDANCE	108 specimens

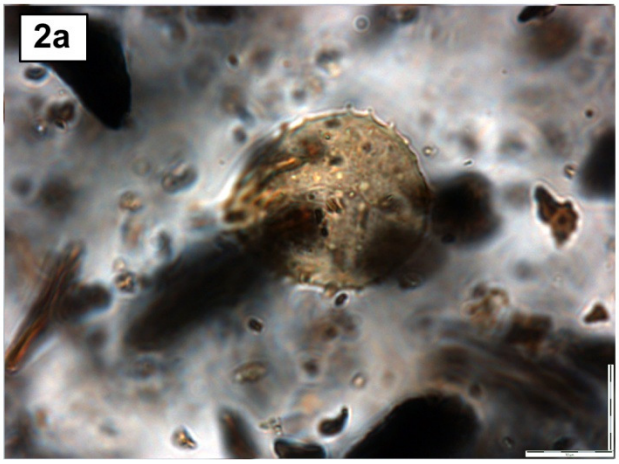
Neoraistrickia pilata Singh 1964 Plate 5 (3)	
REFERENCE	Kremp & Ames, 1962 (Vol. 35): p. 35-233, Fig. 28
DESCRIPTION	Amb triangular, apices rounded, cheilocardioid. Trilete laesura distinct, radii thin and extend one half to three quarters of spore. Exine approx. 1µm thick, with baculate ornamentation. Baculi vary in shape and tend to cluster around the apices.
SIZE	17 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	65.44 m - 117.495 m (AVM 67)
TOTAL ABUNDANCE	31 specimens

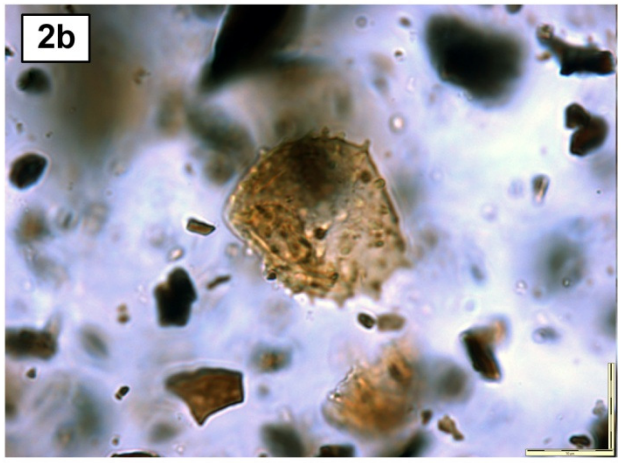
Lobatisporites sp. Tiwari & Moiz 1971 Plate 5 (4a, 4b)	
REFERENCE	Jansonius & Hills, 1976: Card 1500
JUNIOR SYNONYMS	MacRae (1988) & Aitken (1994) give *Lobatisporites* as a junior synonym of *Horriditriletes*, however Jansonius & Hills (1976) highlight differences between the two genera. *Horriditriletes* does not possess the strongly concave sides of *Lobatisporites* and thus the two genera are kept separate here.
DESCRIPTION	Amb triangular, apices rounded, inter-apical region concave. Trilete laesura distinct, radii thin and extend almost to spore periphery. Exine thin and heavily baculate, baculi of medium length and thick.
SIZE	20 µm
DISCUSSION	These specimens possess all of the diagnostic characters of the genus *Lobatisporites* but cannot be matched with an existing species.
STRATIGRAPHIC RANGE AT MMAMANTSWE	65.44 m – 117.495 m (AVM 67)

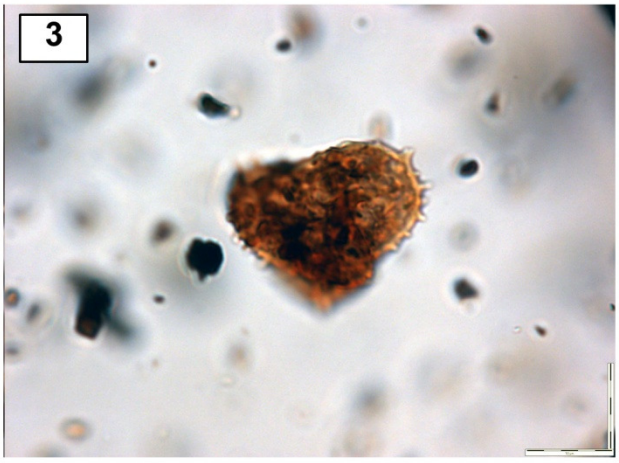
TOTAL ABUNDANCE	69 specimens

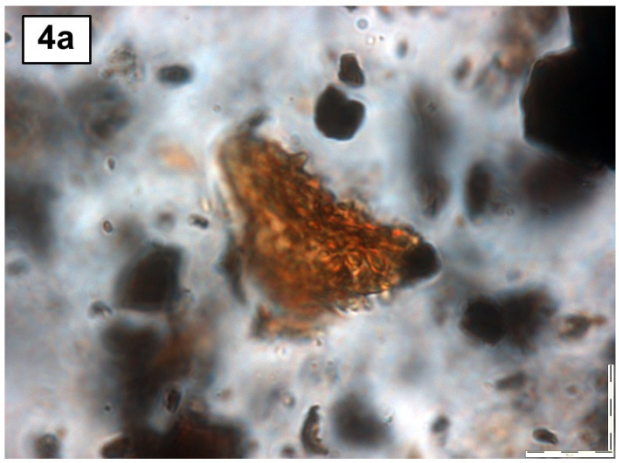
Plate 5

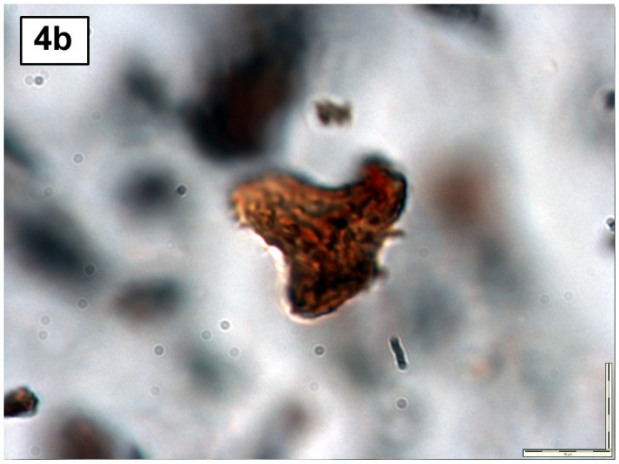












Mehlisphaeridium regulare Anderson 1977 Plate 6 (1)	
REFERENCE	Anderson, 1977: p. 2 , Plate 1 (11-20)
DESCRIPTION	Amb triangular, apices rounded, inter-apical region straight to slightly concave. Trilete laesura indistinct due to unusual exine. Baculi visible with LO analysis but appear to blend into each other on spore surface.
SIZE	19 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	ǀ 69.9 m ǀ (AVM 67)
TOTAL ABUNDANCE	1 specimen

Cf. *Raistrickia pallida* Dybová & Jachowicz 1957 Plate 6 (2)	
REFERENCE	Kremp & Ames, 1962 (Vol. 18): p. 18-47
DESCRIPTION	Amb triangular, apices rounded, inter-apical region strongly concave. Trilete laesura indistinct (possibly due to oblique view or heavy ornamentation). Exine approx. 1µm thick, ornamentation heavily baculate. Baculi thick and rounded at tips.
SIZE	35 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	64.45 m - 70.885 m (AVM 67)
TOTAL ABUNDANCE	11 specimens

Cf. *Azonotriletes spinosellus* Luber & Waltz 1941 Plate 6 (3)	
REFERENCE	Kremp & Ames, 1962 (Vol. 17): p. 17-47
DESCRIPTION	Amb triangular to ellipsoidal, trilete laesura distinct. Radii

	thickened, taper towards tips and extend to spore periphery. Exine thin with sparse baculate ornamentation on distal face.
SIZE	20 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	ǀ 65.44 m ǀ (AVM 67)
TOTAL ABUNDANCE	1 specimen

Subinfraturma Nodati

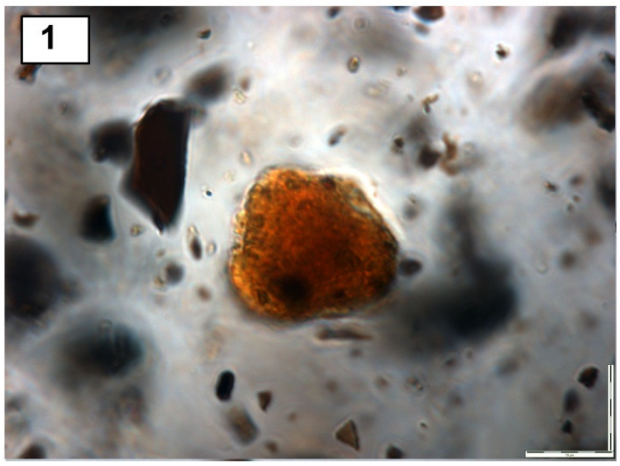
Granulatisporites spinosus Kosanke 1950 Plate 6 (4)	
REFERENCE	Kremp & Ames, 1959 (Vol. 5): p. 5-30
DESCRIPTION	Amb triangular, apices rounded, inter-apical region convex. Trilete laesura indistinct, when seen extends to spore periphery. Exine thin with echinate ornamentation. Echinae are long and cone-shaped.
SIZE	26 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	64.45 m – 117.495 m (AVM 67)
TOTAL ABUNDANCE	24 specimens

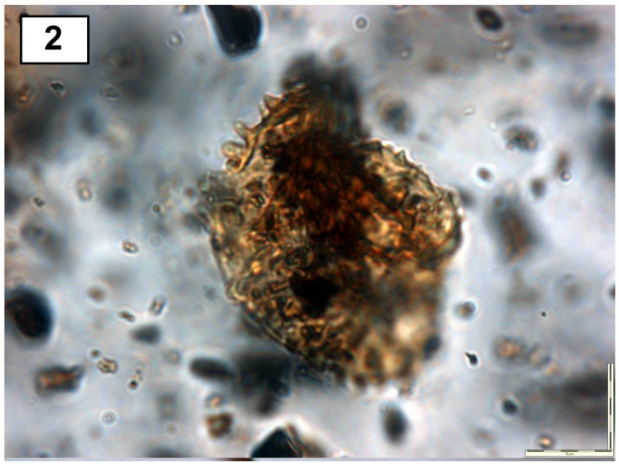
Apiculatisporis cornutus (Balme & Hennelly) Høeg & Bose 1960 Plate 6 (5)	
REFERENCE	MacRae, 1988: p. 28, Plate 6 (11-12)
DESCRIPTION	Amb triangular, apices broadly rounded, inter-apical region convex. Trilete laesura distinct., radii thin with no labra. Exine approx. 1-2 thick with echinate ornamentation on distal face. Echinae are short with a wide base (coni).
SIZE	37 µm

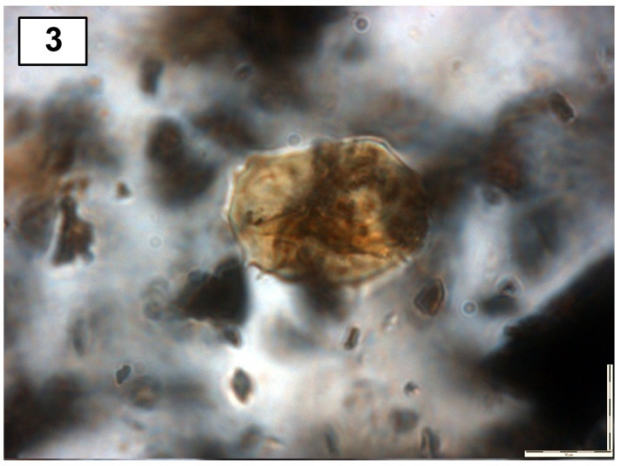
STRATIGRAPHIC RANGE AT MMAMANTSWE	63.565 m – 137.95 m (AVM 67 and AVM 75)
TOTAL ABUNDANCE	91 specimens

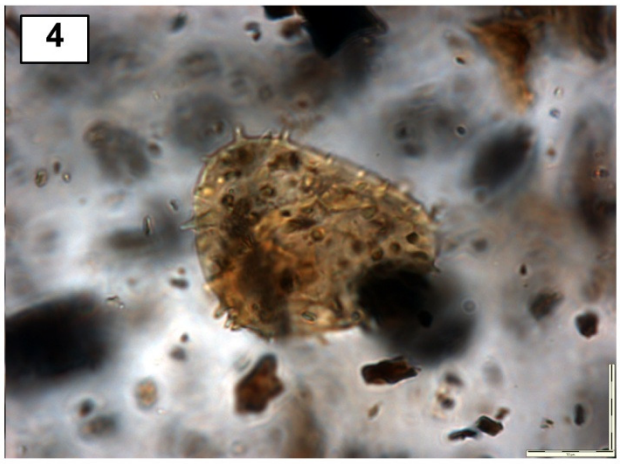
Apiculatisporis communis Potonié & Kremp 1956 Plate 6 (6)	
REFERENCE	Jansonius & Hills, 1976 – Card 4074
SYNONYMS	*Brevitriletes communis* Bharadwaj & Srivastava 1969
DESCRIPTION	Amb triangular, apices broadly rounded, inter-apical region convex. Trilete laesura usually distinct (above specimen folded). Exine approx. 1 µm thick with echinate ornamentation. Echinae long and recurved, with distinctive appendages at tips that may detach during preparation.
SIZE	18 µm
DISCUSSION	Due to folding of all specimens, a clear photograph in polar view could not be obtained.
STRATIGRAPHIC RANGE AT MMAMANTSWE	ǀ 115.36 m ǀ (AVM 67)
TOTAL ABUNDANCE	3 specimens

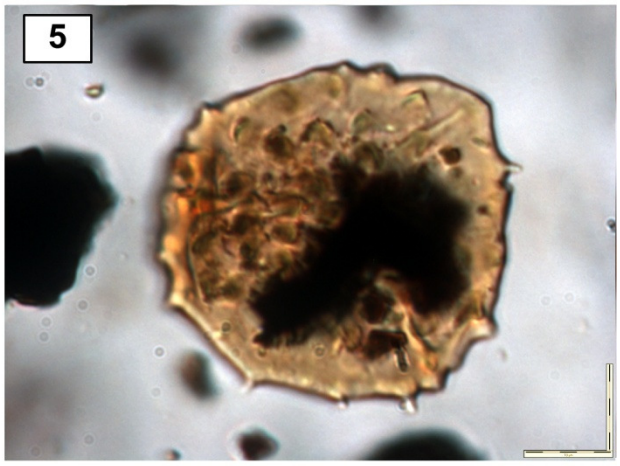
Plate 6

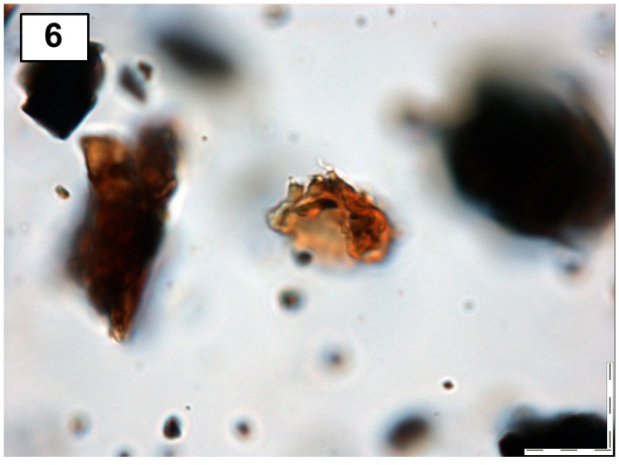












Lophotriletes scotinus Segroves 1970 Plate 7 (1a, 1b)	
REFERENCE	MacRae, 1988; p. 27, Plate 6 (2)
DESCRIPTION	Amb triangular, apices rounded, inter-apical region straight to slightly convex. Trilete laesura distinct, radii extend to almost spore periphery, thin with no labra. Exine thin with sparse echinate ornamentation on distal face only. Echinae short and wide (coni).
SIZE	20 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	63.565 m – 117.495 m (AVM 67)
TOTAL ABUNDANCE	60 specimens

Lophotriletes cf. *microsaetosus* (Loose) Potonié & Kremp 1955 Plate 7 (2)	
REFERENCE	MacRae, 1988; p. 27, Plate 6 (7, 24)
DESCRIPTION	Amb triangular, apices rounded, inter-apical region straight to slightly convex. Trilete laesura distinct, radii extend to almost spore periphery, thin with no labra. Exine thin with sparse echinate ornamentation on distal face only. Echinae short and wide (coni).
SIZE	24 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	ǀ 110.86 m ǀ (AVM 67)
TOTAL ABUNDANCE	6 specimens

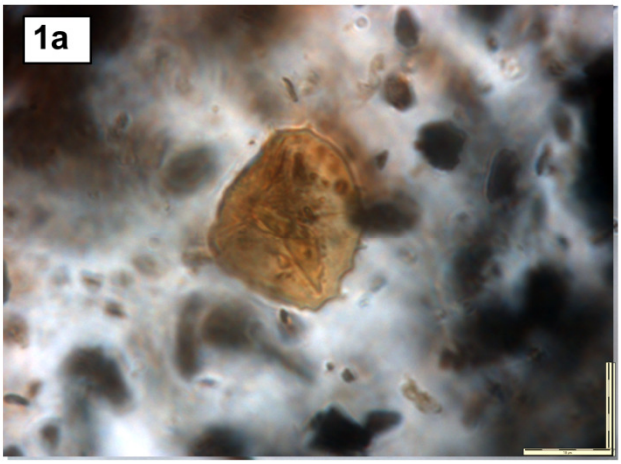
Lophotriletes sp. Naumova *ex* Potonié & Kremp 1954 Plate 7 (3)	
REFERENCE	Aitken, 1994: p. 43, Plate 2 (36)
DESCRIPTION	Amb triangular, apices sharp, inter-apical region straight. Trilete laesura distinct, radii thin and extend one half to three quarters of spore. Exine thin with sparse echinate ornamentation.
SIZE	20 µm
DISCUSSION	These specimens possess all of the diagnostic characters of the genus *Lophotriletes* but cannot be matched with an existing species.
STRATIGRAPHIC RANGE AT MMAMANTSWE	65.44 m – 115.96 m (AVM 67)
TOTAL ABUNDANCE	27 specimens

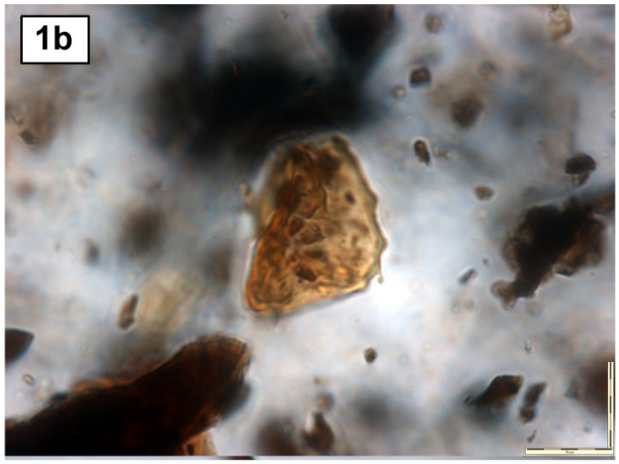
Subinfraturma Verrucati

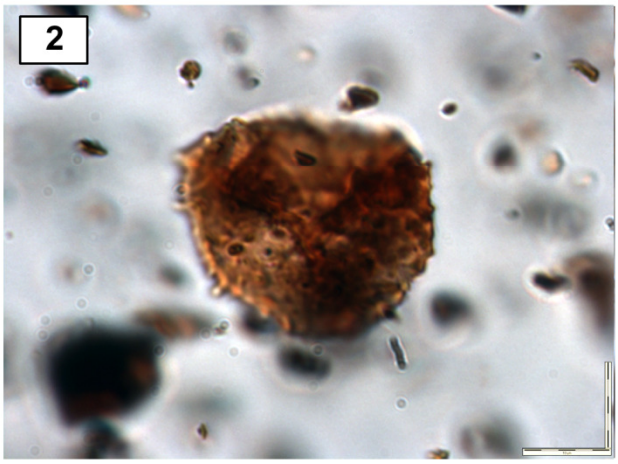
Verrucosisporites naumovae Hart 1963 Plate 7 (4)	
REFERENCE	MacRae, 1988: p. 31, Plate 7 (10-22)
JUNIOR SYNONYMS	*Microbaculispora naumovae* (Hart) Anderson 1977
DESCRIPTION	Amb triangular, apices rounded, inter-apical region straight to slightly convex. Trilete laesura distinct, radii thin and extend to spore periphery. Exine approx. 1-2 µm thick with heavy verrucate ornamentation, verrucae are small and tightly packed.
SIZE	35 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	64.45 m – 137.95 m (AVM 67 and AVM 75)
TOTAL ABUNDANCE	72 specimens

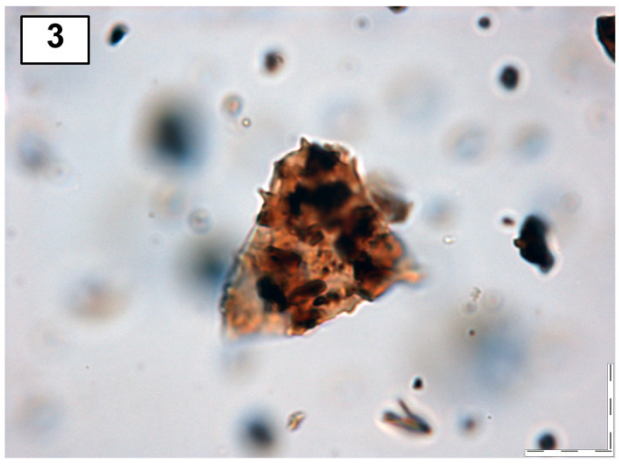
Verrucosisporites sp. (Ibrahim) Smith & Butterworth 1967 Plate 7 (5)	
REFERENCE	MacRae, 1988: p. 31, Plate 7 (10-22)
DESCRIPTION	Amb triangular, apices sharp, cheilocardioid. Trilete laesura indistinct. Exine thin with verrucate ornamentation.
SIZE	17 µm
DISCUSSION	These specimens possess all of the diagnostic characters of the genus *Verrucosisporites* but cannot be matched with an existing species.
STRATIGRAPHIC RANGE AT MMAMANTSWE	79.25 m – 115.36 m (AVM 67)
TOTAL ABUNDANCE	37 specimens

Plate 7

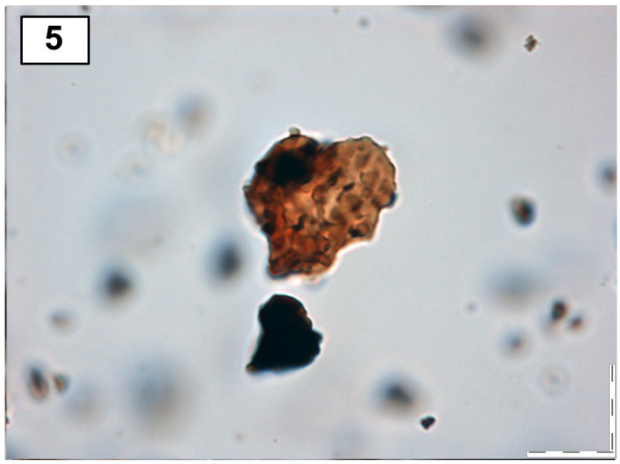












Converrucitriletes verrucosus Dybová & Jachowicz 1957 Plate 8 (1a, 1b)	
REFERENCE	Kremp & Ames, 1962: L.P. Spores 18-24
SYNONYMS	*Verrucosisporites* (Ibrahim) Smith & Butterworth 1967 is considered a senior synonym of the above genus.
DESCRIPTION	Amb triangular, apices rounded, inter-apical region concave. Trilete laesura distinct, bordered by thin dark labra. Radii extend three quarters length of spore. Exine thin with verrucate ornamentation.
SIZE	22 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	65.44 m – 117.495 m (AVM 67)
TOTAL ABUNDANCE	10 specimens

Subinfraturma Granulati

Granulatisporites trisinus Balme & Hennelly 1956 Plate 8 (2)	
REFERENCE	MacRae, 1988: p. 25, Plate 5 (23)
JUNIOR SYNONYMS	*Microbaculispora trisina* (Balme & Hennelly) Anderson 1977
DESCRIPTION	Amb triangular, apices rounded, inter-apical region straight to slightly convex. Trilete laesura distinct and bordered by thin labra, radii extend to periphery of spore. Exine 1-2 µm thick with granulate sculpture.
SIZE	45 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	63.565 m – 137.95 m (AVM 67 and AVM 75)
TOTAL ABUNDANCE	412 specimens

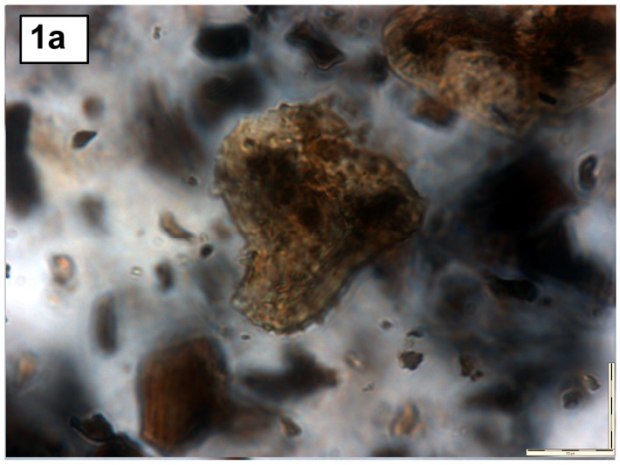
Granulatisporites papillosus Hart 1965 Plate 8 (3)	
REFERENCE	MacRae, 1988: p. 25, Plate 5 (1-22)
DESCRIPTION	Amb triangular, apices sharp, inter-apical region straight. Trilete laesura distinct, radii thin, and extend to spore periphery. Radii bordered by light-coloured labra. Exine thin and granulate.
SIZE	49 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	64.45 m – 115.36 m (AVM 67)
TOTAL ABUNDANCE	17 specimens

Granulatisporites convexus Kosanke 1950 Plate 8 (4) (400X)	
REFERENCE	Kremp & Ames, 1959 (Vol. 5): p. 5-24
DESCRIPTION	Amb triangular, apices broadly rounded, inter-apical region straight to slightly convex. Trilete laesura distinct, radii thin and extend two thirds of spore body. Exine approx. 3-5 µm thick and laevigate, however under SEM the exine is seen to be granulate (hence the genus).
SIZE	55 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	63.565 m - 92.52 m (AVM 67)
TOTAL ABUNDANCE	17 specimens

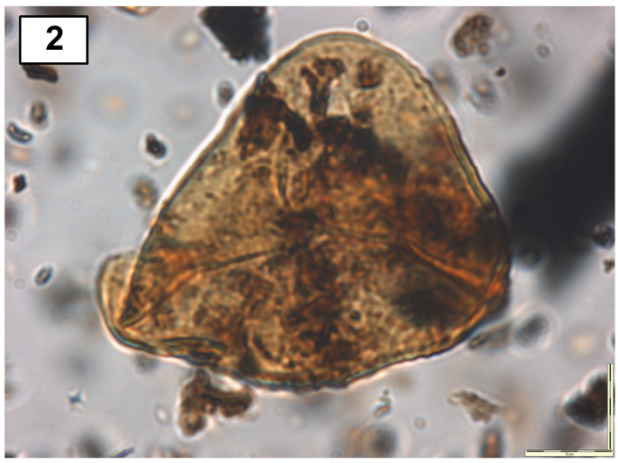
Cyclogranisporites gondwanensis Bharadwaj & Salujha 1964 Plate 8 (5)	
REFERENCE	MacRae, 1988: p. 24, Plate 4 (19-21)
DESCRIPTION	Amb circular to roundly triangular. Trilete laesura distinct

	and thin, radii extend one half to three quarters of spore body. Exine approx. 1 µm thick and granulate.
SIZE	27 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	63.565 m – 101.93 m (AVM 67)
TOTAL ABUNDANCE	67 specimens

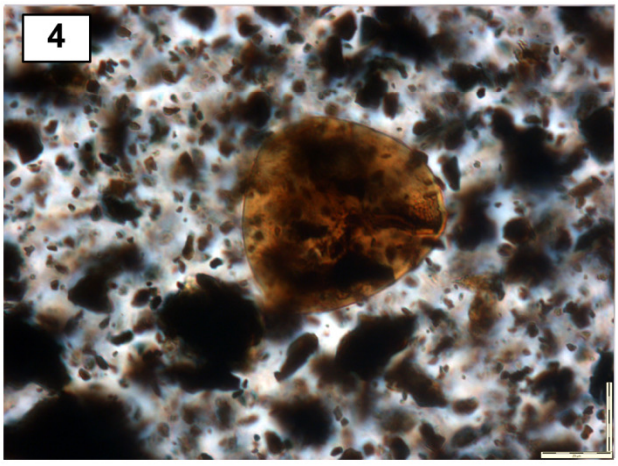
PLATE 8













Cf. *Cyclogranisporites verrucosus* Anderson 1977 Plate 9 (1)	
REFERENCE	MacRae, 1988: p. 24, Plate 4 (13-18)
DESCRIPTION	Amb broadly oval, trilete laesura indistinct. Exine thin and thickly ornamented with small grana and verrucae.
SIZE	28 µm x 23 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	63.565 m – 101.93 m (AVM 67)
TOTAL ABUNDANCE	19 specimens

Subinfraturma Gemmati

Pustulatisporites distinctus Ağrali & Akyol Plate 9 (2a, 2b)	
REFERENCE	Hart, 1970: p. 128, Plate 37 (34)
DESCRIPTION	Amb lenticular. Trilete laesura often indistinct due to ornamentation, radii thin and extend one half to three quarters of spore. Exine thin and distinctly gemmate, forming "pustules". Pustules are usually not visible with LO analysis.
SIZE	25 µm x 20 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	65.44 m – 115.36 m (AVM 67)
TOTAL ABUNDANCE	78 specimens

Gemmate trilete sp. 1 Plate 9 (3)	
DESCRIPTION	Amb triangular, apices broadly rounded, inter-apical region sharply concave. Trilete laesura distinct, thickened, and

	bordered by labra. Radii extend three quarters of spore periphery. Exine thin and heavily covered with gemmate ornamentation.
SIZE	23 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	65.44 m – 115.36 m (AVM 67)
TOTAL ABUNDANCE	5 specimens

Infraturma Muronati

Subinfraturma Reticulati

Punctatisporites pseudofoveosus Azcuy 1975 Plate 9 (4)	
REFERENCE	Papa & Pasquo, 2007: p. 108, Fig. 7 (A)
DESCRIPTION	Amb triangular (folded on right upper side). Apices broadly rounded. Inter-apical region straight to slightly convex. Trilete laesura bordered by dark labra. Radii are thin and distinct, extend one half to three-quarters radius of spore. Exine thin with reticulate sculpture.
SIZE	35 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	65.44m - 115.36m (AVM 67)
TOTAL ABUNDANCE	5 specimens

ANTETURMA SPORITES

TURMA TRILETES

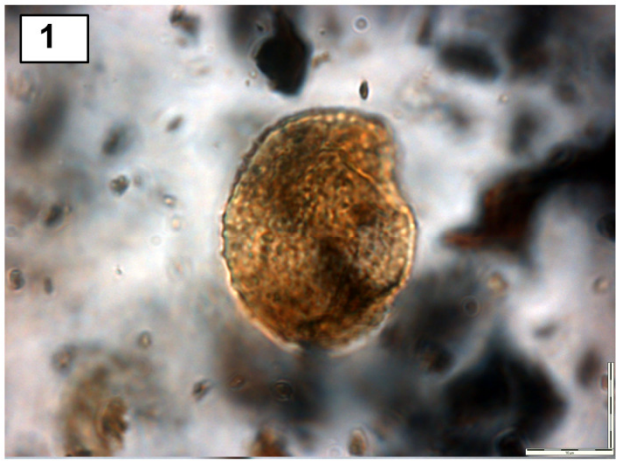
SUPRASUBTURMA ACAVATITRILETES

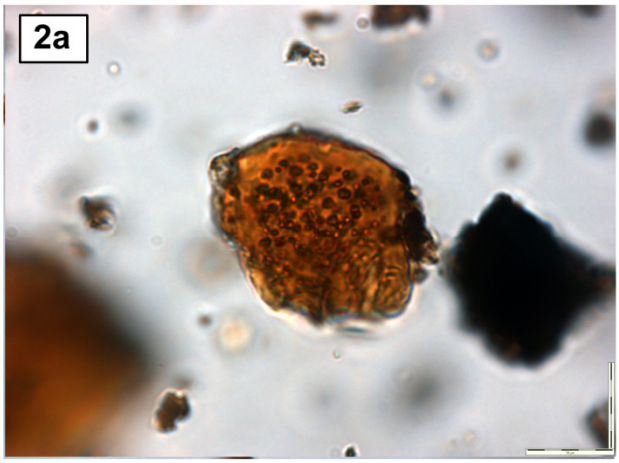
SUBTURMA ZONOTRILETES

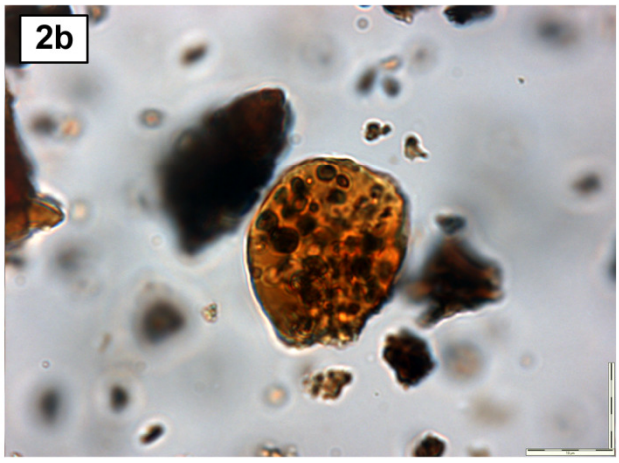
Infraturma Auriculati

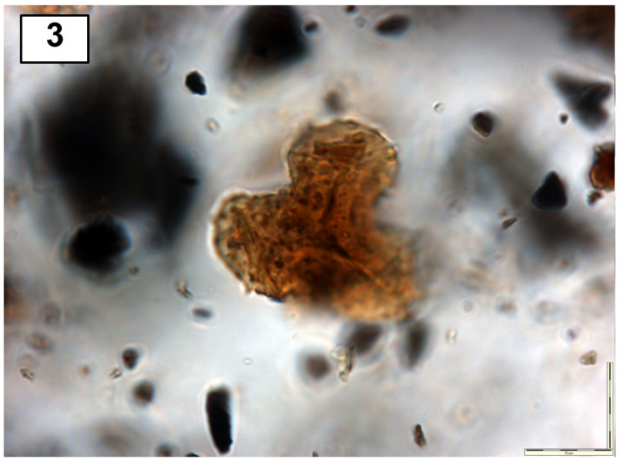
Triquitrites minutus Alpern 1958 Plate 9 (5)	
REFERENCE	Kremp & Ames, 1962 (Vol. 18): p. 18-103
DESCRIPTION	Amb triangular, apices rounded, inter-apical region concave. Trilete laesura distinct and thin. Radii extend almost to periphery of spore. Apices have a thickened spore wall forming a "cap". Exine laevigate and thin.
SIZE	25 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	63.565 m - 65.44 m (AVM 67)
TOTAL ABUNDANCE	10 specimens

Plate 9

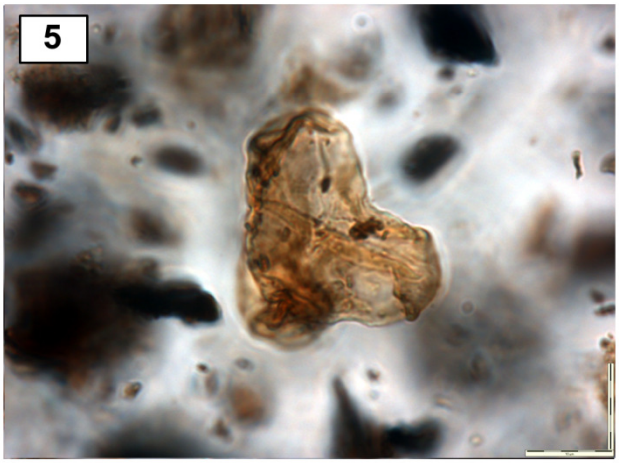












ANTETURMA SPORITES

TURMA TRILETES

SUPRASUBTURMA LAMINATITRILETI

SUBTURMA ZONOLAMINATITRILETES

Infraturmae Crassiti & Cingulicavati

Cristatisporites spinosus (Menéndez & Azcuy) Playford 1978 *emend*. César 1985 Plate 10 (1)	
REFERENCE	Papa & Pasquo, 2007: p. 110, Fig. 8 (E)
JUNIOR SYNONYMS	*Dentatisporites* Kemp 1975 *Zinjisporites spinosus* (Kar & Bose) Anderson 1977 *Z. congoensis* (Maheshwari & Bose) Anderson 1977
DESCRIPTION	Amb triangular, apices broadly rounded, inter-apical region straight to slightly convex. Trilete laesura indistinct, radii slightly thickened and do not extend onto zona. Exine ornamentation of echinae and baculi, both thin and elongated. Echinae are recurved.
SIZE	37 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	93.14 m – 117.495 m (AVM 67)
TOTAL ABUNDANCE	7 specimens

Cristatisporites cf. *inconstans* Archangelsky & Gamerro 1979 Plate 10 (2a, 2b)	
REFERENCE	Papa & Pasquo, 2007: p. 110, Fig. 8 (A)
DESCRIPTION	Trilete zonate spore with subtriangular amb. Apices rounded, inter-apical region strongly convex. Radii distinct and thickened, bordered by thin dark labra. Radii slightly sinuous, extend to spore periphery. Exine approx. 1µm thick, with well-defined echinate ornamentation on both proximal &

	distal face. Echinae are 2-3 µm high and randomly orientated.
SIZE	19 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	64.45m - 98.85m (AVM 67)
TOTAL ABUNDANCE	24 specimens

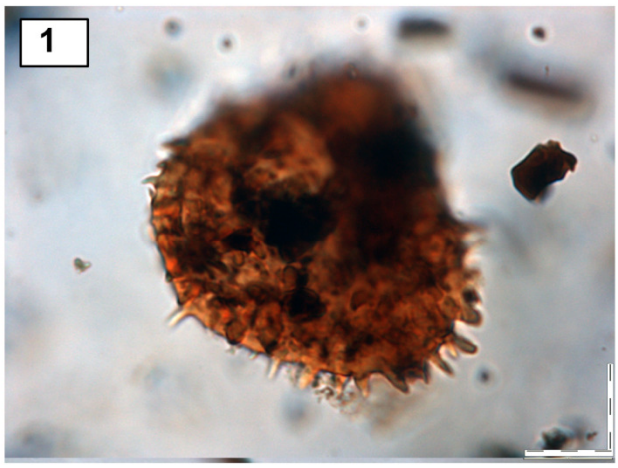
Gondisporites raniganjensis Bharadwaj 1962 Plate 10 (3)	
REFERENCE	Kremp & Ames, 1962 (Vol. 35): p. 35-16
DESCRIPTION	Amb triangular, apices sharp, inter-apical region slightly convex. Trilete laesura distinct, radii slightly thickened, arms extend to spore body margin. Body-exine thin and granulate with sporadic baculi. Thin zona with granulate exine, approx.4-6µm wide, margin undulating to dentate.
SIZE	55 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	63.565 m- 137.95 m (AVM 67 and AVM 75)
TOTAL ABUNDANCE	98 specimens

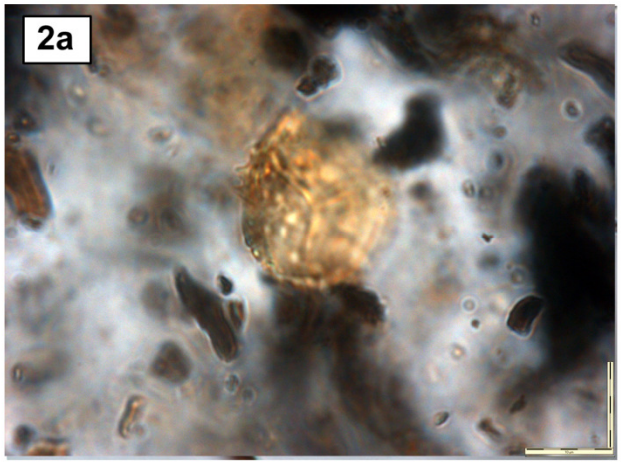
Cirratriradites cf. *africanensis* Hart 1963 Plate 10 (4)	
REFERENCE	MacRae, 1988: p. 34, Plate 10 (18-22)
JUNIOR SYNONYMS	*Indotriradites splendens* (Balme & Hennelly) Foster 1979
DESCRIPTION	Amb circular to sub-circular. Trilete laesura distinct, radii slightly thickened, arms extend to spore body margin. Body-exine thin with ornamentation of small coni / baculi. Thin zona with laevigate exine, approx.5-8µm wide, margin undulating.
SIZE	55 µm
DISCUSSION	The above species is similar to *Gondisporites raniganjensis*

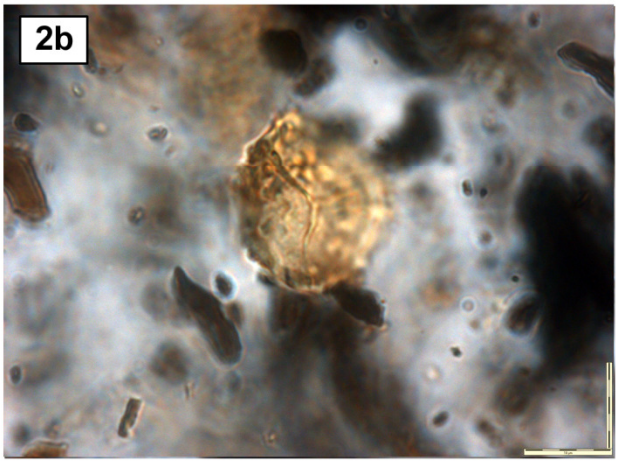
	but has a circular amb and margin is never dentate.
STRATIGRAPHIC RANGE AT MMAMANTSWE	63.565 m - 117.495 m (AVM 67)
TOTAL ABUNDANCE	125 specimens

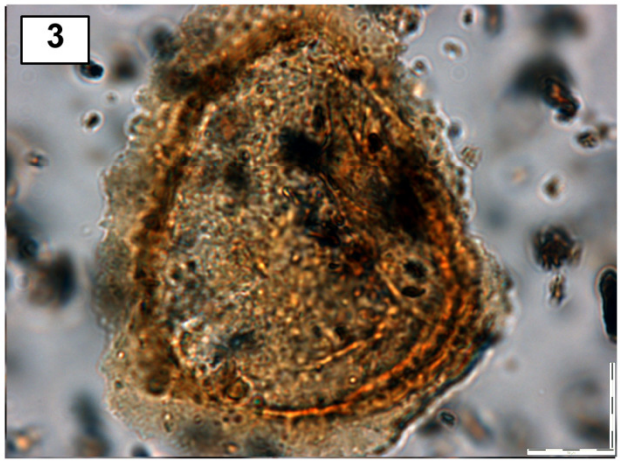
Lycospora cf. *pseudoannulata* Kosanke 1950 Plate 10 (5) (400X)	
REFERENCE	Hart, 1970: p. 126, Fig. 36 (48)
DESCRIPTION	Amb triangular, apices broadly rounded, inter-apical region strongly convex. Trilete laesura, radii distinct, darkened and thickened. Radii extend onto zona and almost to periphery of spore. Exine 1-2µm thick, laevigate.
SIZE	81 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	ǀ 115.36 m ǀ (AVM 67)
TOTAL ABUNDANCE	1 specimen

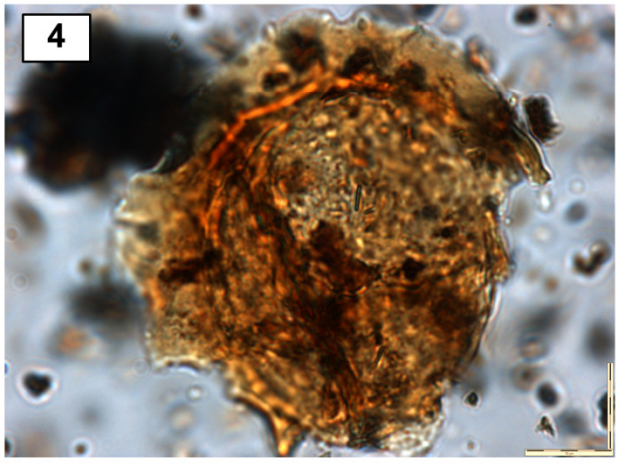
Plate 10

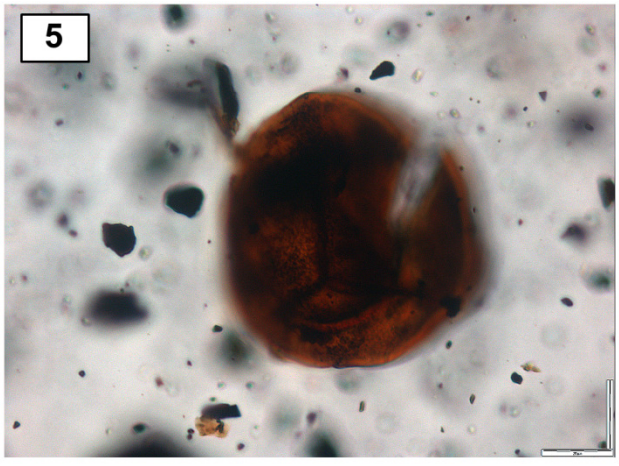












Zonotrilete sp. 1 Plate 11 (1)	
DESCRIPTION	Amb circular. Trilete laesura distinct and widened, radii extend to spore body margin. Spore body distinct. Cingulum reticulate with undulating margin.
SIZE	27 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	65.44 m – 115.36 m (AVM 67)
TOTAL ABUNDANCE	5 specimens

ANTETURMA SPORITES

TURMA MONOLETES

SUPRASUBTURMA ACAVATOMONOLETES

SUBTURMA AZONOMONOLETES

Infraturma Laevigatomonoleti

Laevigatosporites colliensis (Balme and Hennelly) Venkatachala and Kar 1968 Plate 11 (2)	
REFERENCE	Backhouse, 1991: p. 283, Plate XIII (1-4)
DESCRIPTION	Amb reniform, monolete laesura thin and extending full length of spore. Exine 1-2 µm thick and laevigate.
SIZE	36 µm x 25 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	63.565 m – 117.495 m (AVM 67)
TOTAL ABUNDANCE	203 specimens

Laevigatosporites minimus Dybová & Jachowicz 1957 Plate 11 (3)	
REFERENCE	Kremp & Ames, 1962 (Vol. 18): p. 18-46
DESCRIPTION	Amb ellipsoidal, monolete laesura widened and extending full length of spore, forming "I" shape. Exine thin and laevigate.
SIZE	26 µm x 21 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	63.565 m – 115.36 m (AVM 67)
TOTAL ABUNDANCE	38 specimens

Monolete laevigate sp. 1 Plate 11 (4)	
DESCRIPTION	Amb elongately oval, monolete laesura extending full length of spore. Exine thin and laevigate. Darkening around equatorial area.
SIZE	24 µm x 19 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	65.44 m – 80.735 m (AVM 67)
TOTAL ABUNDANCE	10 specimens

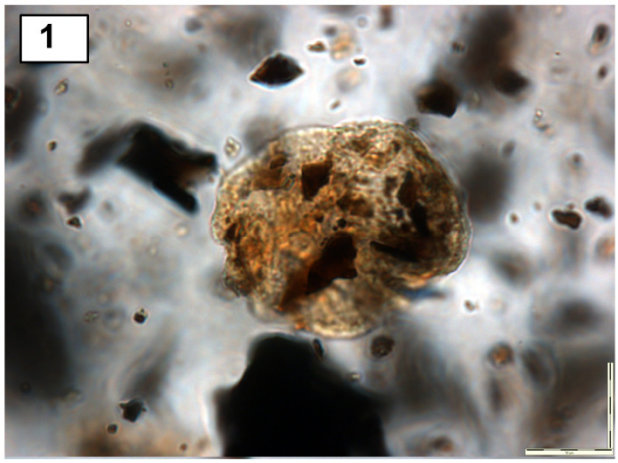
Infraturma Sculptatomonoleti

Tuberculatosporites cf. *aberdarensis* de Jersey 1962 Plate 11 (5)	
REFERENCE	Raine *et al*., 2008
DESCRIPTION	Amb elongately oval. Monolete laesura simple and extending length of spore. Exine thin with echinate ornamentation. Echinae short.

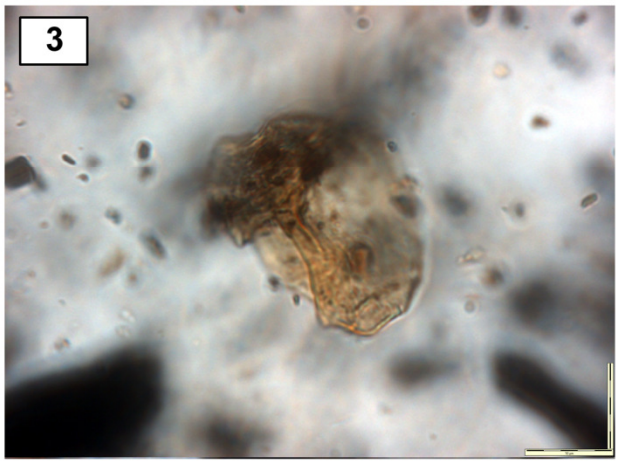
SIZE	23 µm x 16 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	64.45 m – 115.36 m (AVM 67)
TOTAL ABUNDANCE	19 specimens

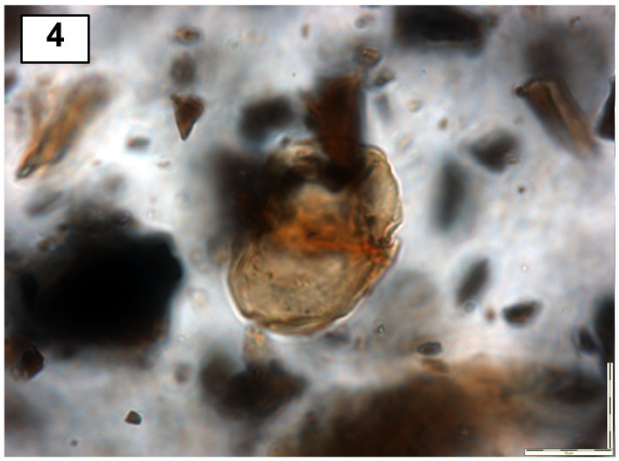
Tuberculatosporites sp. Imgrund ex Potonié & Kremp 1954 Plate 11 (6)	
REFERENCE	Jansonius & Hills, 1976: Card 4564
DESCRIPTION	Amb broadly oval, monolete laesura simple and extending half spore length, often obscured. Exine thin with random folds and regularly spaced echinate ornamentation.
SIZE	24 µm x 18 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	64.45 m – 98.85 m (AVM 67)
TOTAL ABUNDANCE	15 specimens

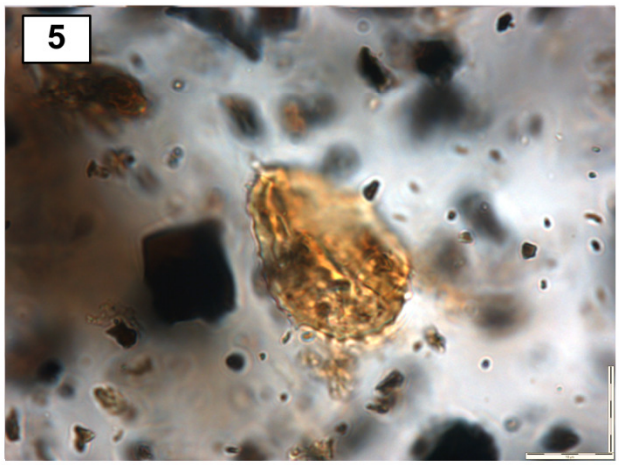
Plate 11

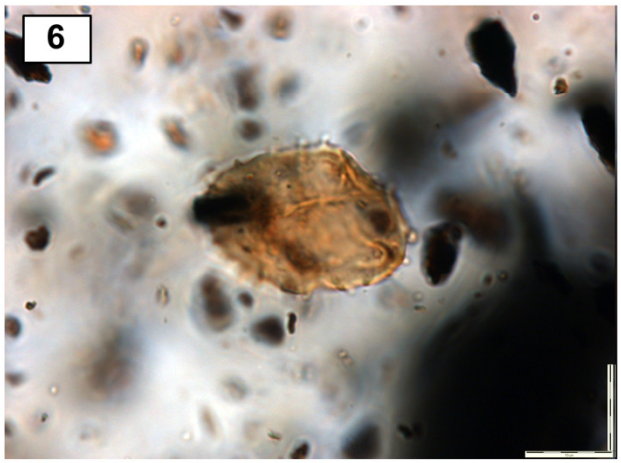












Thymospora opaqua Singh 1964 Plate 12 (1a, 1b)	
REFERENCE	Hart, 1970: p. 128, Fig. 37 (15)
DESCRIPTION	Amb circular-lenticular. Monolete laesura distinct and thin, bordered by thin dark labra. Exine approx. 1µm thick, with baculate ornamentation. Baculi short and thin.
SIZE	24 µm x 21 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	65.44 m – 117.495 m (AVM 67)
TOTAL ABUNDANCE	36 specimens

Thymospora thiessenii (Kosanke) Wilson & Venkatachala 1963 Plate 12 (2)	
REFERENCE	MacRae, 1988: p. 41, Plate 14 (9-12)
JUNIOR SYNONYMS	*Laevigatosporites thiessenii* Kosanke 1943 *Verrucososporites thiessenii* (Kosanke) Bharadwaj 1957
DESCRIPTION	Amb circular to subcircular, monolete laesura obscured by ornamentation. When seen, extends approx. half to three quarter length of spore. Exine approx. 1-2 µm thick, ornamented with verrucae which fuse to form rugulae.
SIZE	36 µm x 32 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	63.565 m – 69.9 m (AVM 67)
TOTAL ABUNDANCE	16 specimens

Thymospora pseudothiessenii (Kosanke) Wilson & Venkatachala 1963 Plate 12 (3)	
REFERENCE	MacRae, 1988: p. 40, Plate 14 (13-22)
JUNIOR SYNONYMS	*Laevigatosporites pseudothiessenii* Kosanke 1950

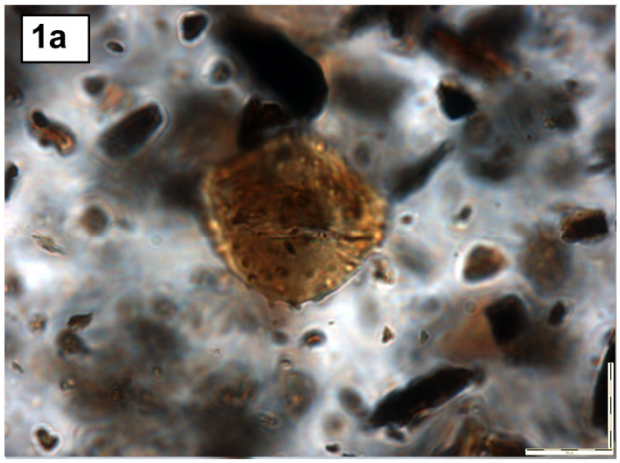
	Verrucososporites ipsviciensis de Jersey 1962
DESCRIPTION	Amb lenticular, monolete laesura often obscured by ornamentation. When seen, extends approx. half to three quarter length of spore. Exine approx. 1µm thick, irregular but heavy verrucate ornamentation.
SIZE	23 µm x 16 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	64.45 m – 117.495 m (AVM 67)
TOTAL ABUNDANCE	24 specimens

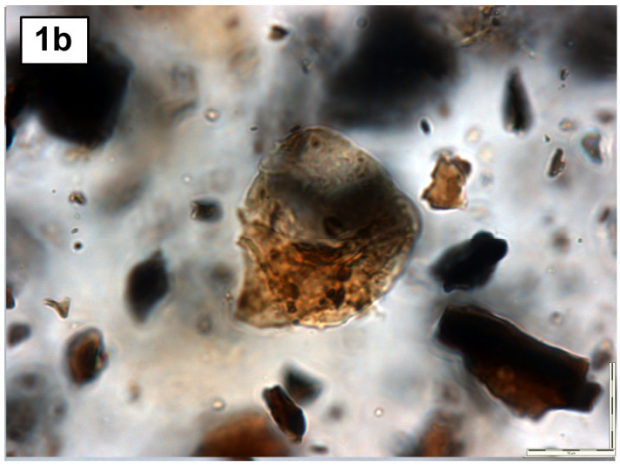
Convolutispora sp. Hoffmeister, Staplin & Malloy 1955 Cf. *Polypodiisporites mutabilis* Balme 1970 Plate 12 (4)	
REFERENCE	Bussert & Schrank, 2007: p. 7, Plate 1 (5) Aitken, 1994: p. 67, Plate 4 (77-84)
DESCRIPTION	Amb broadly oval, monolete laesura simple, extending half to three quarters of spore perimeter. Exine thin with rugulate ornamentation.
SIZE	21 µm x 17 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	68.37 m – 80.735 m (AVM 67)
TOTAL ABUNDANCE	11 specimens

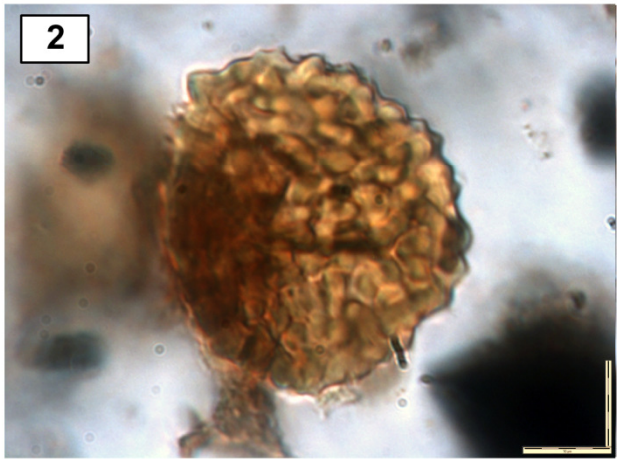
Monolete baculate sp. 1 Plate 12 (5)	
DESCRIPTION	Amb quadrangular, monolete laesura thin and bordered by thin labra, extends half to three quarters length of spore. Exine thin with evenly spaced baculate ornamentation.
SIZE	20 µm x 20 µm
STRATIGRAPHIC RANGE	65.44 m – 115.36 m (AVM 67)

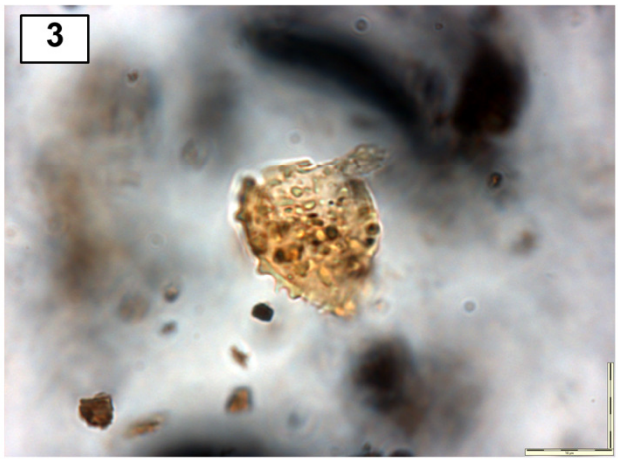
AT MMAMANTSWE	
TOTAL ABUNDANCE	63 specimens

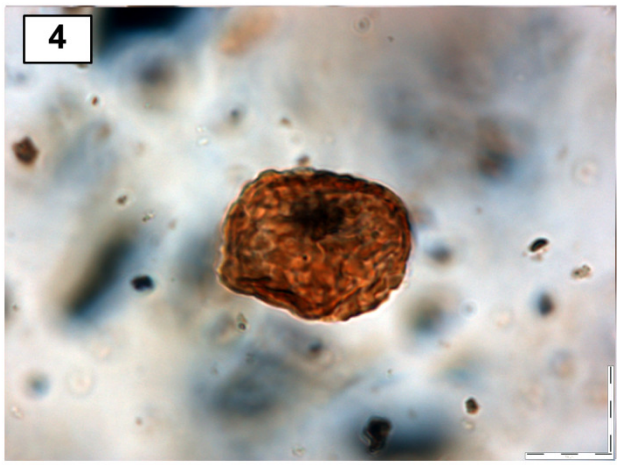
Plate 12

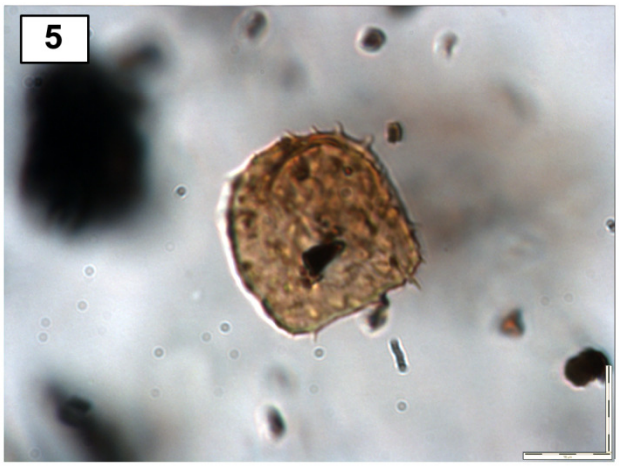












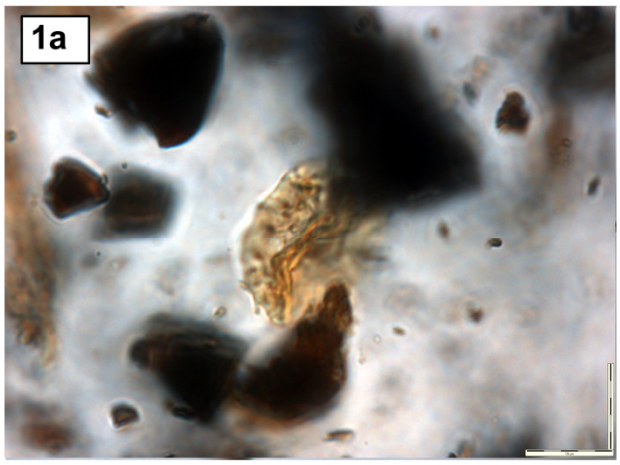
Monolete baculate sp. 2 Plate 13 (1a, 1b)	
DESCRIPTION	Amb ellipsoidal, monolete laesura distinct, extending full length of spore and bordered by folded labra. Exine thin with sparse baculate ornamentation on distal face.
SIZE	22 µm x 14 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	64.45 m – 117.495 m (AVM 67)
TOTAL ABUNDANCE	35 specimens

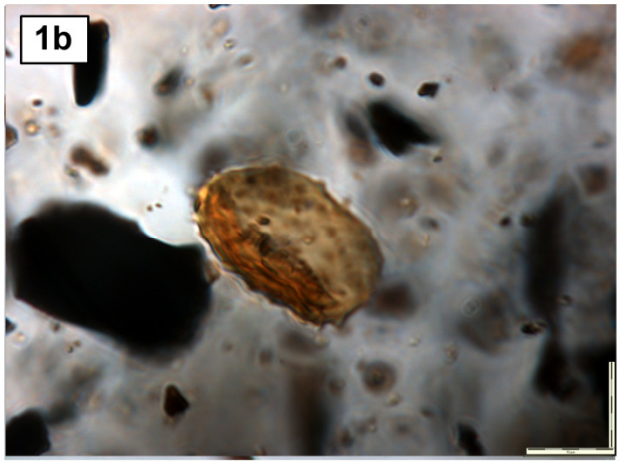
Monolete baculate sp. 3 Plate 13 (2a, 2b)	
DESCRIPTION	Amb circular to sub-circular, monolete laesura distinct and bordered by dark and acutely thickened labra. Exine moderately baculate with baculi irregularly spaced. Baculi of medium height and thin.
SIZE	19 µm x 16 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	65.44 m – 115.96 m (AVM 67)
TOTAL ABUNDANCE	22 specimens

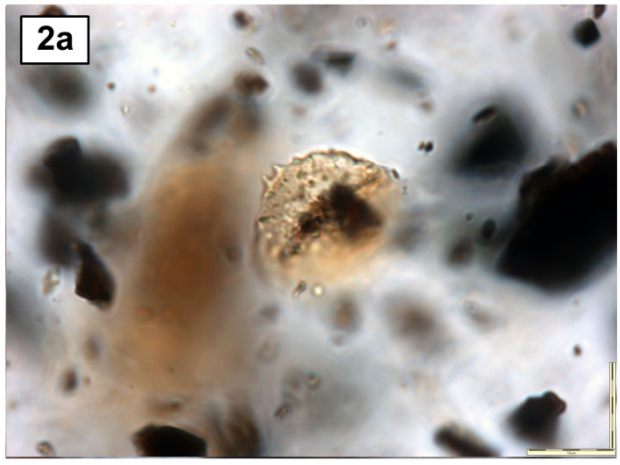
Monolete baculate sp. 4 Plate 13 (3a, 3b)	
DESCRIPTION	Amb circular, monolete laesura simple and widened, extends three quarter length of spore. Exine thin with baculate ornamentation.
SIZE	19 µm x 17 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	65.44 m – 115.36 m (AVM 67)

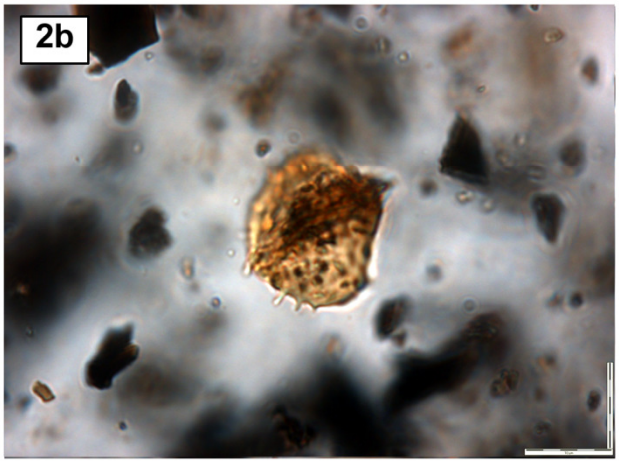
TOTAL ABUNDANCE	63 specimens

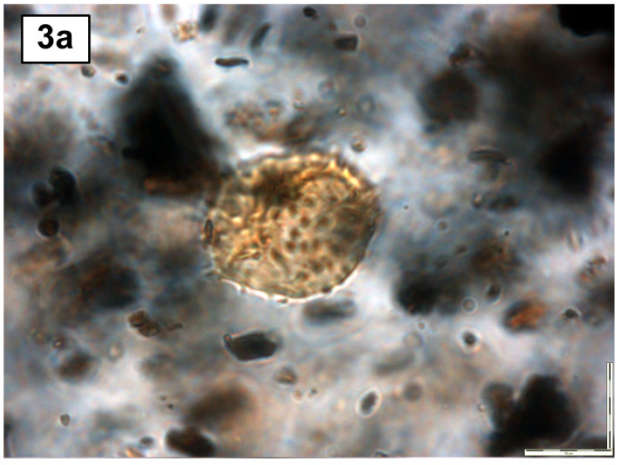
Plate 13













ANTETURMA SPORITES

TURMA HILATES

Hilate sp. 1 Plate 14 (1)	
DESCRIPTION	Amb broadly oval, laesura not present. Defined inner body of teardrop shape, with small dark oval inside inner body. Exine thick with rugulate ornamentation.
SIZE	27 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	65.94 m – 78.32 m (AVM 67)
TOTAL ABUNDANCE	5 specimens

Hilate sp. 2 Plate 14 (2)	
DESCRIPTION	Amb reniform. Dark inner body that follows reniform shape of outer spore margin. Exine thin with regular but widely-spaced thin baculi.
SIZE	24 µm x 14 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	65.44 m – 92.52 m (AVM 67)
TOTAL ABUNDANCE	3 specimens

Hilate sp. 3 Plate 14 (3a, 3b)	
DESCRIPTION	Amb broadly oval, laesura not present. Lighter inner body that follows oval shape of outer spore margin. Exine 2-3 µm thick and laevigate.
SIZE	30 µm x 24 µm

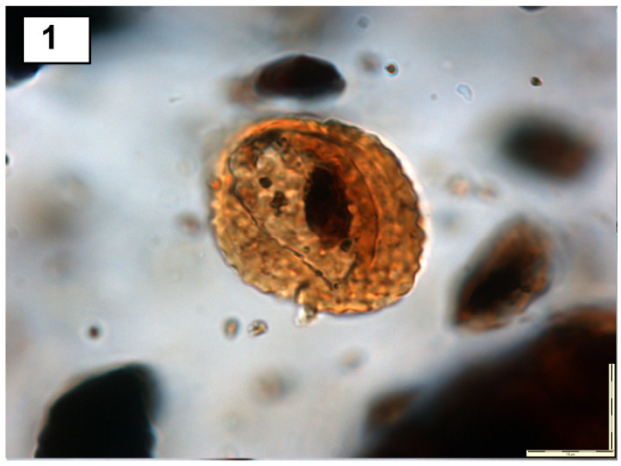
STRATIGRAPHIC RANGE AT MMAMANTSWE	66.91 m – 115.36 m (AVM 67)
TOTAL ABUNDANCE	26 specimens

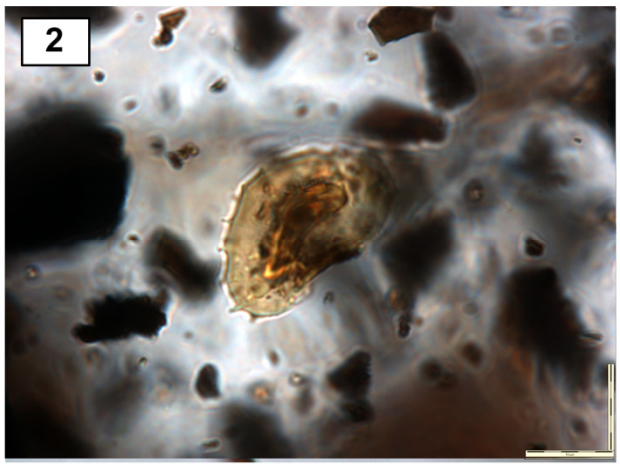
ANTETURMA SPORITES

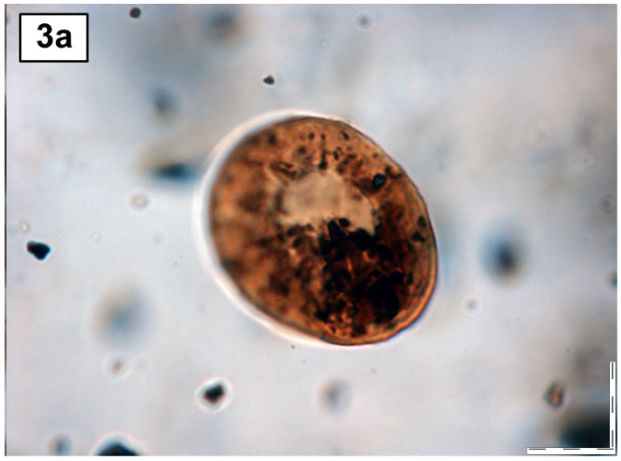
TURMA ALETES

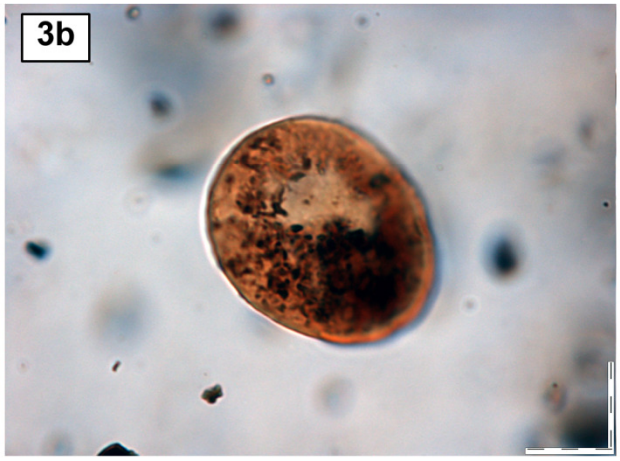
Inaperturopollenites dubius (Potonié & Venitz) Thomson & Pflug 1953 Plate 14 (4a, 4b)	
REFERENCE	Jansonius & Hills, 1976: Card 3985
DESCRIPTION	Amb subcircular to lenticular, inaperturate. Exine very thin and laevigate to microgranulate, heavily folded. Spores have a tendency to split (likely due to very thin exine).
SIZE	27 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	63.565 m – 137.95 m (AVM 67 and AVM 75)
TOTAL ABUNDANCE	252 specimens

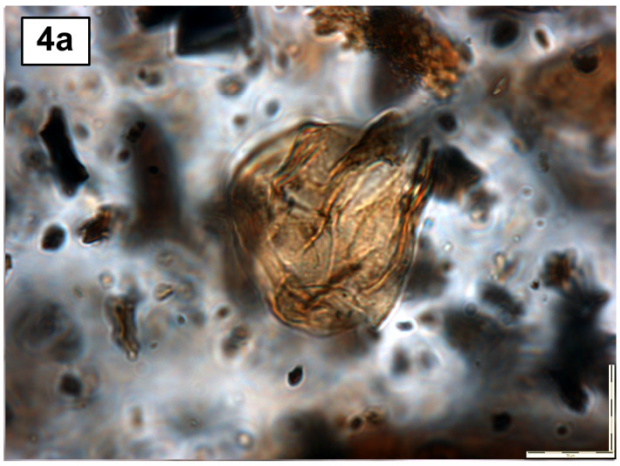
Plate 14

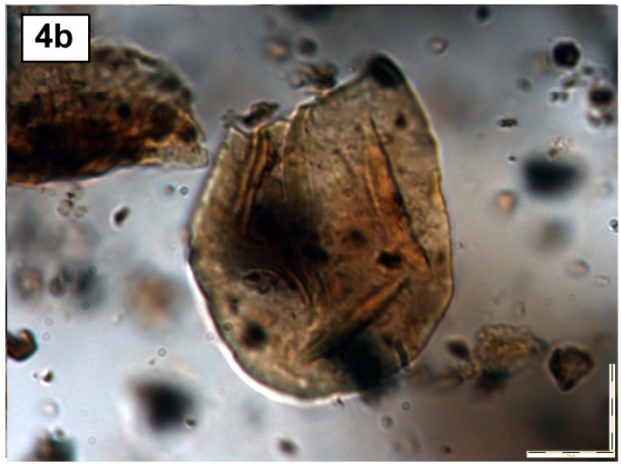












Peltandripites davisii Wodehouse 1933 Plate 15 (1)	
REFERENCE	MacRae, 1988: p. 157, Plate 15 (10)
DESCRIPTION	Amb ellipsoidal, alete. Exine thin with regular echinate ornamentation. Echinae uniformly long (3-4 µm), with some spines recurved.
SIZE	25 µm x 16 µm
DISCUSSION	MacRae (1988) gives the history of the genus along with the fact that it was originally designated for Eocene specimens. Due to the artificial nature of palynological studies, MacRae felt that a geological time difference should not influence the choice of nomenclature. This addresses a much larger problem (see Traverse, 2007) on which there is yet no consensus in the palynological world. Are morphotaxa assigned based solely on morphological characteristics, or does the author attempt to integrate natural botanical affinity and chronology with morphology? As the present study has not attempted taxonomic revision of any kind, the specimens are allocated to *Peltandripites* for the present. However, in the future a new genus may be erected to encompass the material from Mmamantswe and the Waterberg. MacRae (1988) mentions they may be similar to the acritarch *Baltisphaeridium*.
STRATIGRAPHIC RANGE AT MMAMANTSWE	65.44 m – 137.95 m (AVM 67 and AVM 75)
TOTAL ABUNDANCE	111 specimens

Circulisporites parvus (de Jersey) Norris 1965 Plate 15 (2)	
REFERENCE	MacRae, 1988: p. 43, Plate 15 (16-18)
DESCRIPTION	Amb circular, no laesura present. Exine ornamented with

	multiple concentric ribs that resemble tree rings.
SIZE	30 um
STRATIGRAPHIC RANGE AT MMAMANTSWE	ǀ 63.565 m ǀ (AVM 67)
TOTAL ABUNDANCE	4 specimens

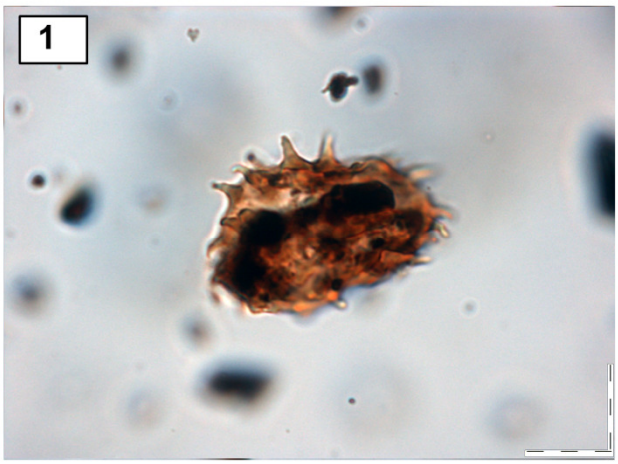
Cf. *Pilasporites calculus* Plate 15 (3)	
REFERENCE	Stephenson & McLean, 1999: p. 8, Fig. 5 (k)
DESCRIPTION	Amb lenticular, spore alete. Distinctive bicolouration that divides spore in half equatorially. Exine thin with sparse scabrate ornamentation.
SIZE	46 µm x 32 µm
DISCUSSION	Algal origin. Extremely abundant throughout the Mmamantswe core. The only spore at Morupule to be common in both mudstones and coals.
STRATIGRAPHIC RANGE AT MMAMANTSWE	63.565 m – 137.95 m (AVM 67 and AVM 75)
TOTAL ABUNDANCE	421 specimens

Pilasporites plurigenus Balme & Hennelly 1956 Plate 15 (4)	
REFERENCE	Utting, 1978: p. 63, Plate 2 (18)
DESCRIPTION	Amb circular. Laesura not apparent. Exine approx. 1-2µm thick and laevigate under LM (likely micropitted under SEM). Small and random folds in exine.
SIZE	30 µm
DISCUSSION	Algal origin. Abundant in the lower part of the core.
STRATIGRAPHIC RANGE AT MMAMANTSWE	63.565 m – 137.95 m (AVM 67 and AVM 75)

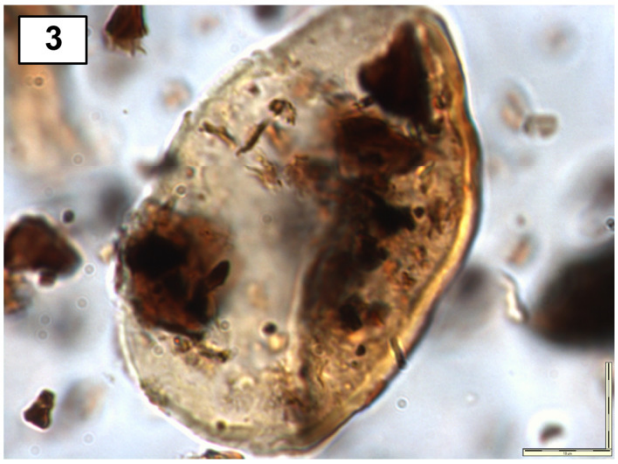
TOTAL ABUNDANCE	344 specimens

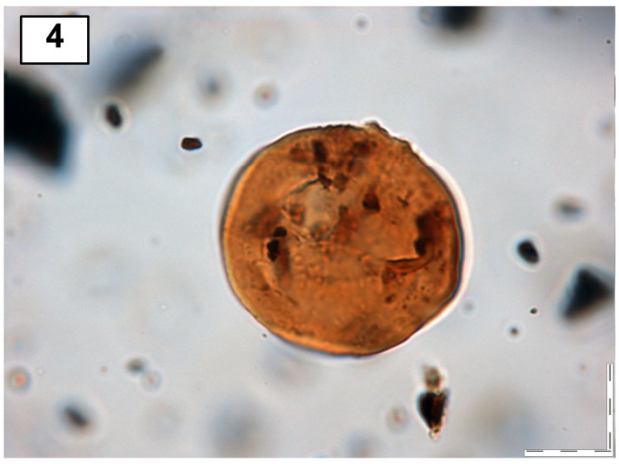
Brazilea scissa (Balme & Hennelly) Foster 1975 Plate 15 (5a, 5b)	
REFERENCE	Papa & Pasquo, 2007: p. 111, Fig. 9 (G)
DESCRIPTION	Amb circular to lenticular, laesura not present. Exine very thin and microgranulate / laevigate. Random folds orientated over surface, exine has a tendency to split open (probably due to its thinness).
SIZE	24 µm x 20 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	63.565 m – 117.495 m (AVM 67)
TOTAL ABUNDANCE	83 specimens

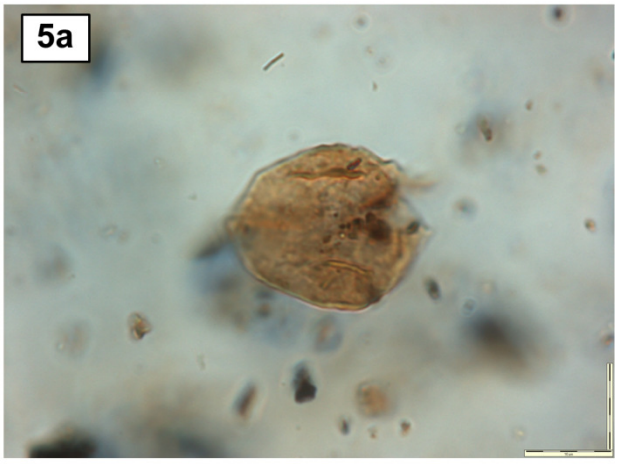
Plate 15

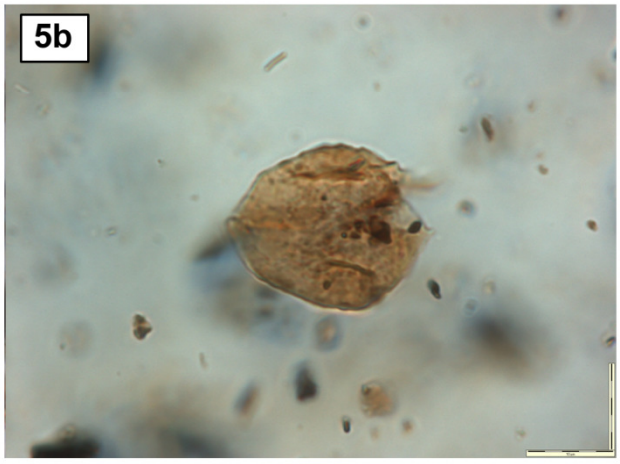












Granulatasporites subreticulatus (Samoilovich) Hart 1965 Plate 16 (1a, 1b)	
REFERENCE	MacRae, 1988, p. 44, Plate 15 (6)
JUNIOR SYNONYMS	*Azonaletes subreticulatus* Samoilovich 1953
DESCRIPTION	Amb quadrate, apices rounded. Trilete laesura absent. Slight depression in centre of spore bounded by two folds. Exine laevigate to granulate.
SIZE	40 µm x 35 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	63.565 m - 137.95 m (AVM 67 and AVM 75)
TOTAL ABUNDANCE	280 specimens

Haplocystia pellucida Segroves 1967 Plate 16 (2)	
REFERENCE	MacRae, 1988, p. 45, Plate 15 (11-14)
DESCRIPTION	Amb circular to sub-circular, alete. Exine is two-layered: outer layer is 3 µm thick with narrow grooves. Inner layer is thin, dark, and laevigate to microgranulate.
SIZE	30 µm x 30 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	70.885 m – 137.95 m (AVM 67 and AVM 75)
TOTAL ABUNDANCE	11 specimens

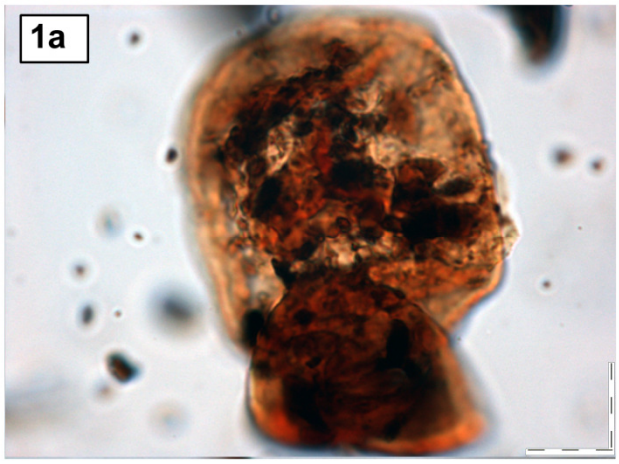
Alete sp. 1 Plate 16 (3)	
DESCRIPTION	Amb quadrate, laesura obscured by ornamentation. Exine thin with baculate ornamentation. Baculi very long and thin.
SIZE	25 µm x 22 µm
STRATIGRAPHIC RANGE	66.91 m – 117.495 m (AVM 67)

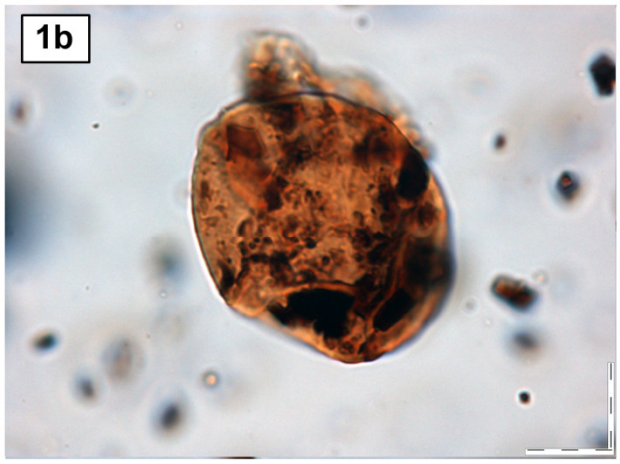
AT MMAMANTSWE	
TOTAL ABUNDANCE	22 specimens

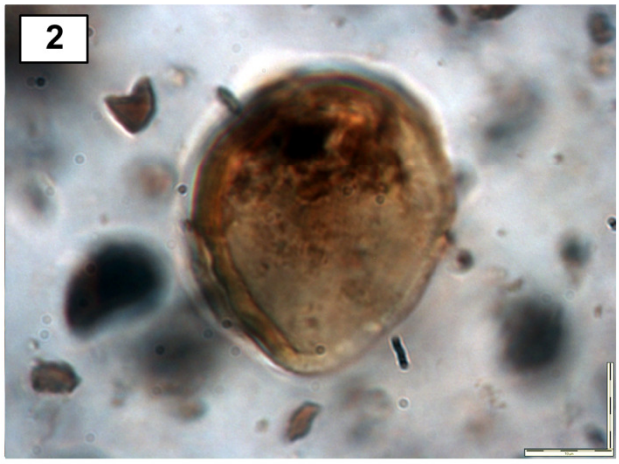
Alete sp. 2 Plate 16 (4)	
DESCRIPTION	Amb elongately oval, laesura not apparent. Exine approx. 1µm thick with echinate ornamentation and random folding. Echinae short and wide.
SIZE	18 µm x 13 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	64.45 m – 115.96 m (AVM 67)
TOTAL ABUNDANCE	58 specimens

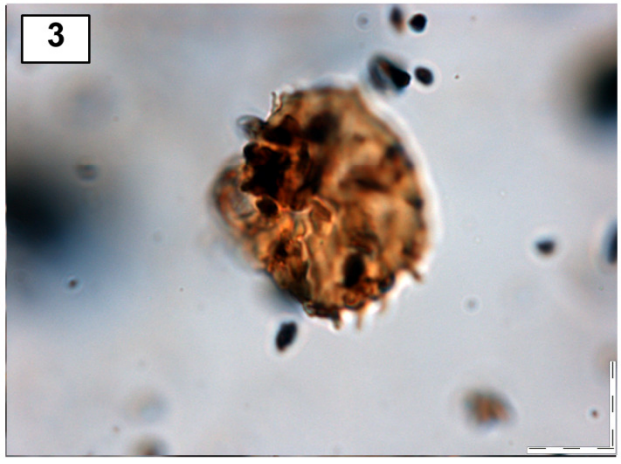
Alete sp. 3 Plate 16 (5)	
DESCRIPTION	Amb quadrate, corners rounded. Laesura not apparent. Exine thin, ornament of irregularly spaced short baculi.
SIZE	27 µm x 20 µm
DISCUSSION	
STRATIGRAPHIC RANGE AT MMAMANTSWE	64.45 m - 117.495 m (AVM 67)
TOTAL ABUNDANCE	40 specimens

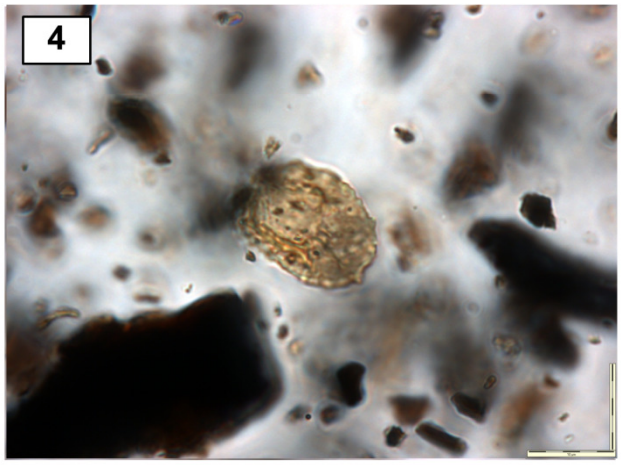
Plate 16

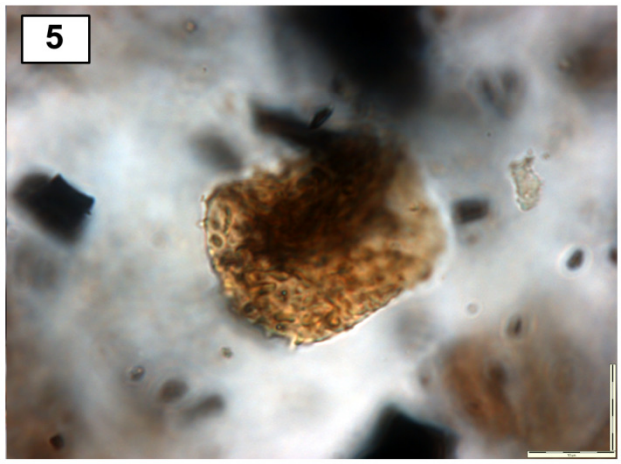












ANTETURMA POLLENITES

TURMA SACCITES

SUBTURMA MONOSACCITES

Infraturma Triletesacciti

Cannanoropollis densus (Lele) Bose & Maheshwari 1968 Plate 17 (1a, 1b) (1b at 400X)	
REFERENCE	MacRae, 1988: p. 74, Plate 34 (1-15)
JUNIOR SYNONYMS	*Vestigisporites gondwanensis* (Balme & Hennelly) Anderson 1977
DESCRIPTION	Amb circular to sub-circular. Corpus distinct, exoexinal expansion surrounds corpus, exinal surface reticulate. Faint trilete aperture visible in some specimens. Bladder exine reticulate, gently undulate margin. Saccus approx. half the width of the corpus radius.
SIZE	60 µm (c-d); 80 µm (b-d)
STRATIGRAPHIC RANGE AT MMAMANTSWE	63.565 m – 137.95 m (AVM 67 and AVM 75)
TOTAL ABUNDANCE	28 specimens

Infraturma Vesiculomonoraditi

Sulcatisporites splendens (Leschik) Bharadwaj 1962 Cf. *Alisporites potoniei* (Lakhanpal, Sah & Dube) Somers 1968 Plate 17 (2)	
REFERENCE	Kremp & Ames, 1962 (Vol. 13): p. 13-112 Aitken, 1994: p. 88, Plate 5 (113)
SYNONYM	*Alisporites* is considered a senior synonym of *Sulcatisporites* by Jansonius (1962). However, *Sulcatisporites splendens* was

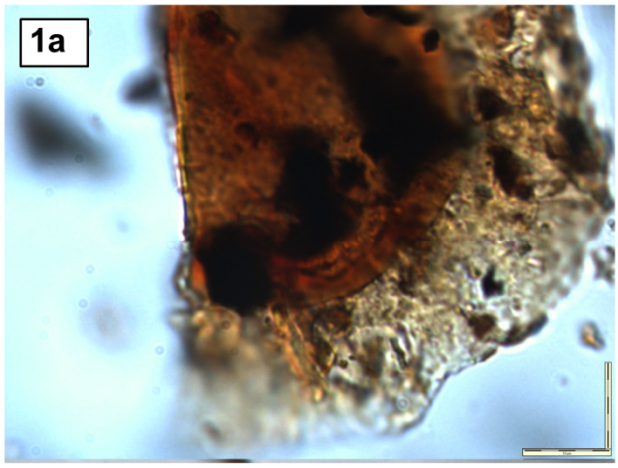
	a closer match for the above material than any species of *Alisporites* and so the former name is retained here.
DESCRIPTION	Amb sub-circular to broadly oval. Corpus distinct and light-coloured, narrowly oval and elongated in the transverse direction. Bladder with reticulate exine.
SIZE	4 µm (c-w); 20 µm (c-h); 32 µm (b-w); 29 µm (b-h)
STRATIGRAPHIC RANGE AT MMAMANTSWE	66.4 m – 69.9 m (AVM 67)
TOTAL ABUNDANCE	12 specimens

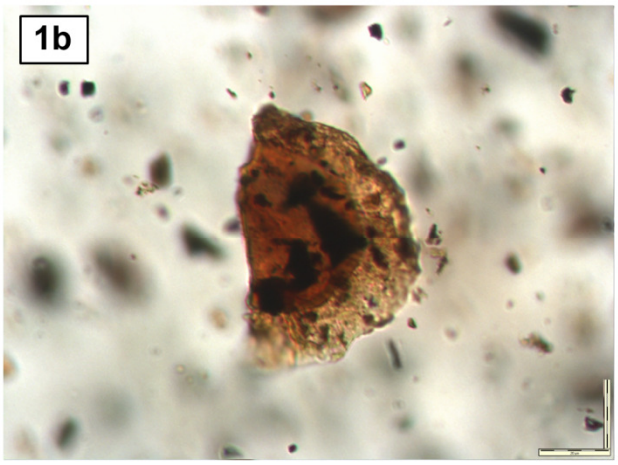
Cf. *Potonieisporites barrelis* Tiwari 1965 Plate 17 (3a, 3b) (3a at 400X)	
REFERENCE	Souza, 2006: p. 20, Plate III (4)
DESCRIPTION	Amb haploxynoid, corpus distinct and blackened, elongately oval with square ends (diamond-like). Bladder exine thin and granulate.
SIZE	(approx.) 24 µm (c-w); 40 µm (c-h); 60 µm (b-w); 60 µm (b-h)
DISCUSSION	All specimens encountered were damaged. Specimens were recognised by the distinct diamond-like shape of the corpus. Two photos are included. Although the most complete specimen (17a) appears to be bisaccate, part of the bladder has broken off at each pole. The other photo shows partial attachment of the monosaccate bladder (17b). However, identification remains tentative until such time as a complete specimen is found.
STRATIGRAPHIC RANGE AT MMAMANTSWE	68.37 m – 98.85 m (AVM 67)
TOTAL ABUNDANCE	3 specimens

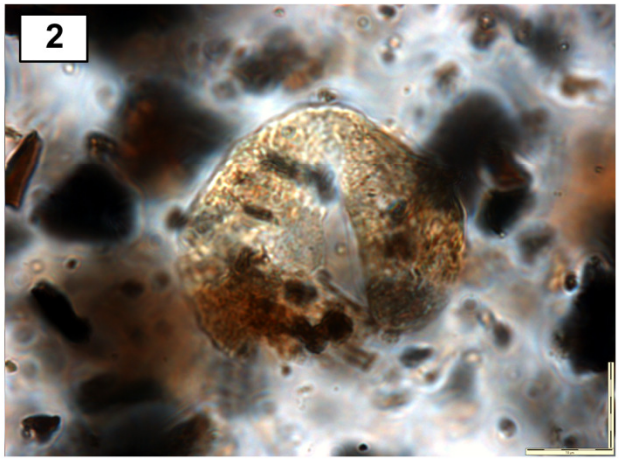
Infraturma Aletesacciti

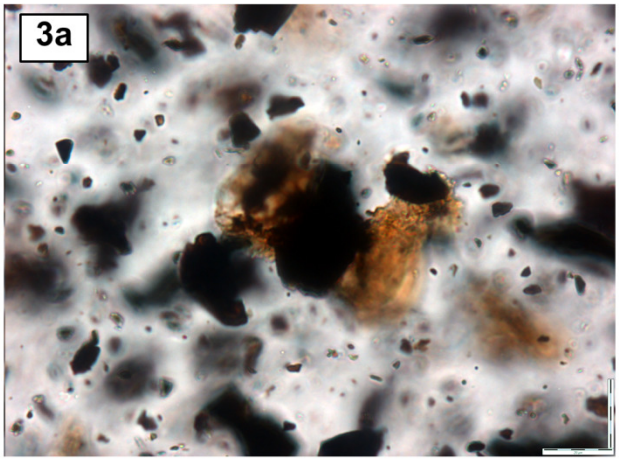
Florinites similis Kosanke 1950 Plate 17 (4)	
REFERENCE	Kremp & Ames, 1959 (Vol. 5): 5-95
DESCRIPTION	Amb elongately oval. Corpus triangular in shape with rounded apices, surrounded by peripheral folds perhaps due to compression. Bladder exine is thin and granulate.
SIZE	30 µm (c-w); 22 µm (c-h); 60 µm (b-w); 32 µm (b-h)
STRATIGRAPHIC RANGE AT MMAMANTSWE	ǀ 65.94 m ǀ (AVM 67)
TOTAL ABUNDANCE	1 specimen

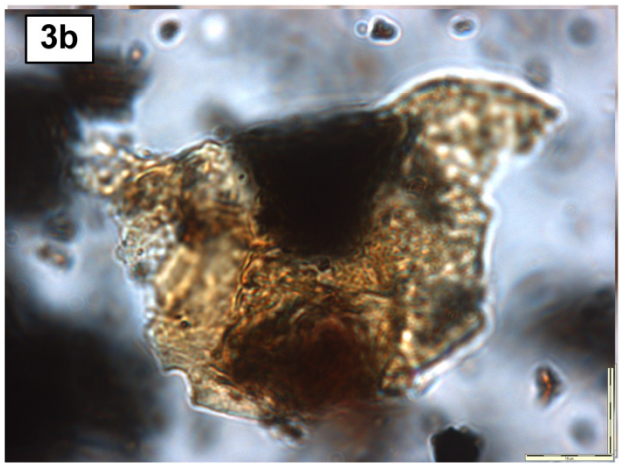
Plate 17













Cordaites rotata (Luber) Chalishev & Varyukhina Plate 18 (1)	
REFERENCE	Hart, 1970: p. 118, Fig. 26 (39)
DESCRIPTION	Amb circular, no surface markings apparent, granulate exine. Thick laevigate bladder encircles pollen body.
SIZE	24 µm (c-d); 28 µm (b-d)
STRATIGRAPHIC RANGE AT MMAMANTSWE	63.565 m – 98.85 m (AVM 67)
TOTAL ABUNDANCE	65 specimens

ANTETURMA POLLENITES

TURMA SACCITES

SUBTURMA DISACCITES

Infraturma Disacciatrileti

Pinuspollenites labdacus Raatz 1938 ex Potonié 1958 Plate 18 (2)	
REFERENCE	Jansonius & Hills, 1976: Card 2012
DESCRIPTION	Amb diploxynoid. Corpus distinct and tetragonal to circular in shape, wider and slightly shorter than sacci. Sacci greater than semi-circular in shape, resemble ears. Exine of corpus and sacci reticulate.
SIZE	24 µm (c-w); 22 µm (c-h); 21 µm (s-w); 22 µm (s-h)
STRATIGRAPHIC RANGE AT MMAMANTSWE	ǀ 66.4 m ǀ (AVM 67)
TOTAL ABUNDANCE	3 specimens

Cf. *Illinites unicus* (Kosanke) Helby 1966 Plate 18 (3)	
REFERENCE	Jerzykiewicz, 1987: p. 123, Plate 3 (5,6)
DESCRIPTION	Amb diploxynoid, corpus distinct and sub-circular in shape, similar height and width to sacci. Sacci quadrate in shape. Exine thin and microgranulate.
SIZE	22 µm (c-w); 23 µm (c-h); 23 µm (s-w); 29 µm (s-h)
STRATIGRAPHIC RANGE AT MMAMANTSWE	64.45 m – 80.735 m (AVM 67)
TOTAL ABUNDANCE	20 specimens

Vestigisporites gondwanensis (Mehta) Hart Plate 18 (4)	
REFERENCE	Hart, 1970: p. 124, Fig. 34 (51)
DESCRIPTION	Amb weakly diploxynoid. Corpus indistinct, subcircular to oval, non-taeniate. Sacci greater than semicircular in shape and reticulate. Corpus narrower in width and shorter in height than sacci.
SIZE	25 µm (c-w); 22 µm (c-h); 27 µm (s-w); 24 µm (s-h)
DISCUSSION	MacRae (1988) discusses the taxonomic history of *V. gondwanensis* under the senior synonym *Plicatipollenites*. There is discrepancy between various authors on whether this genus is for monosaccates or bisaccates. It seems that currently, *Vestigisporites* as *Plicatipollenites* is now considered to be a monosaccate genus, however in the past it was used for bisaccates as well. To complicate matters, Hart (1970) used the name *V. gondwanensis* for a bisaccate, while Anderson, 1977 used the same name for a monosaccate. Accordingly the above species now requires transfer to a suitable bisaccate genus.
STRATIGRAPHIC RANGE AT MMAMANTSWE	64.45 m – 115.96 m (AVM 67)

TOTAL ABUNDANCE	8 specimens

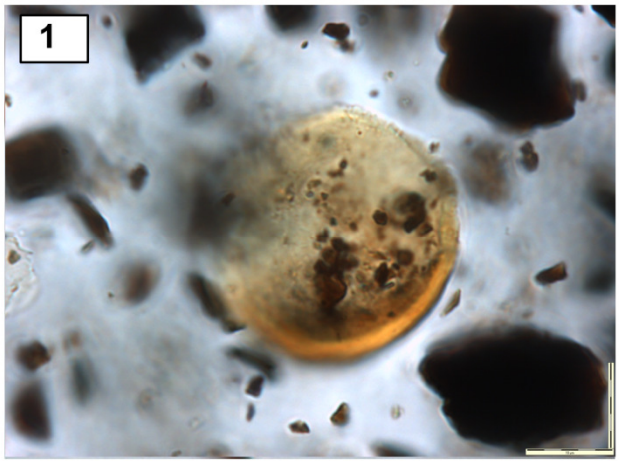
Bisaccate sp. 1 Plate 18 (5)	
DESCRIPTION	Amb diploxynoid, corpus indistinct, circular in shape and shorter in height than sacci. Sacci greater than semi-circular in shape. Exine thin and granulate.
SIZE	42 µm x 31 µm (corpus & sacci not distinct from each other)
DISCUSSION	Only bisaccate specimen to be seen from equatorial view
STRATIGRAPHIC RANGE AT MMAMANTSWE	64.45 m – 80.735 m (AVM 67)
TOTAL ABUNDANCE	8 specimens

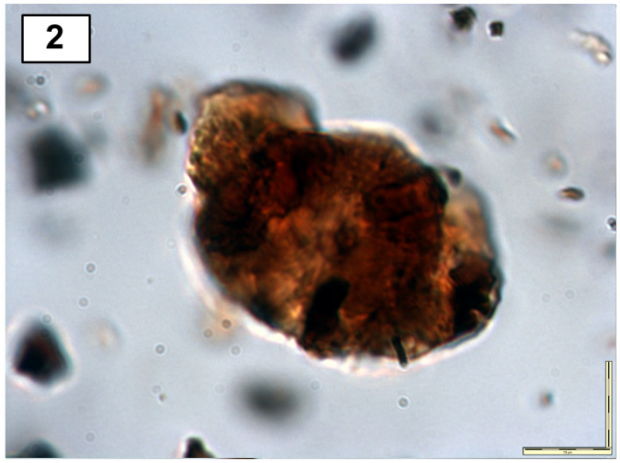
Infraturma Striatiti

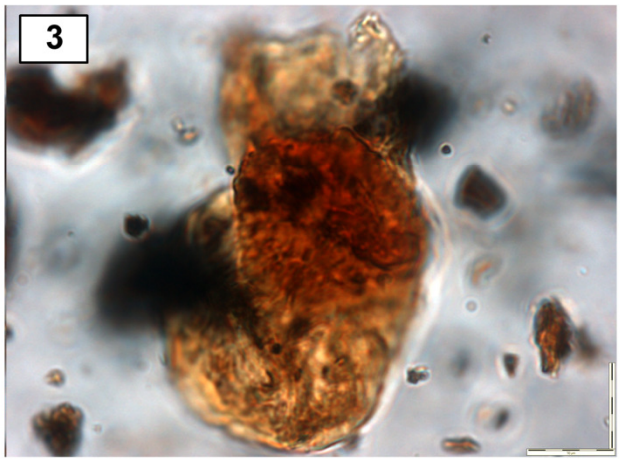
Lueckisporites fusus Balme & Hennelly 1955 Plate 18 (6)	
REFERENCE	Kremp & Ames, 1962 (Vol. 13): p. 13-1
SYNONYMS	*Striatopodocarpites* (Balme & Hennelly) Potonié 1958 is considered a senior synonym of *Lueckisporites* by Foster (1975, 1979).
DESCRIPTION	Amb diploxynoid. Corpus distinct, circular to oval with longitudinal dehiscence slit. Striae present in the genus but not visible in specimens seen. Sacci greater than semi-circular in shape, of similar width to corpus but greater in height. Exine thin and granulate.
SIZE	23 µm (c-w); 30 µm (c-h); 23 µm (s-w); 37 µm (s-h)

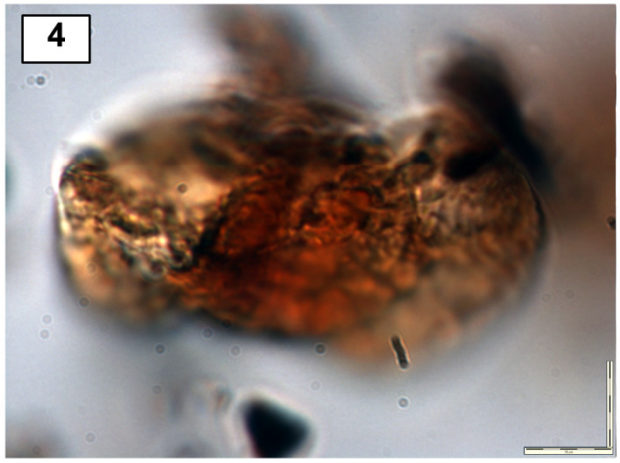
DISCUSSION	In material from Mmamantswe assigned to *Lueckisporites*, striae were **no**t observed on the corpus. Many forms in the literature also did not possess visible striae. Although *Lueckisporites* has since been combined to *Striatopodocarpites*, the above observations may suggest an emendation.
STRATIGRAPHIC RANGE AT MMAMANTSWE	68.37 m – 92.52 m (AVM 67)
TOTAL ABUNDANCE	11 specimens

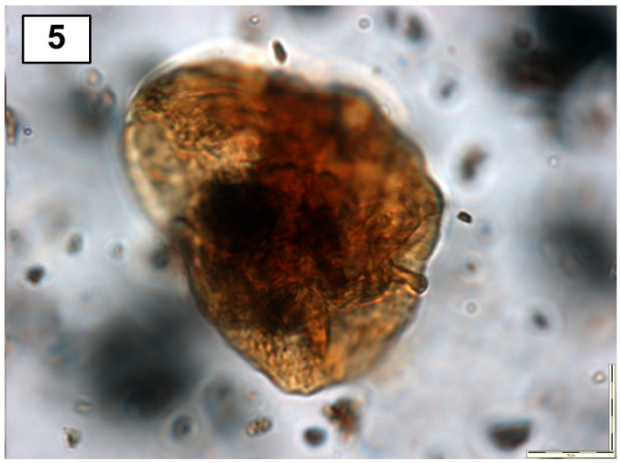
Plate 18

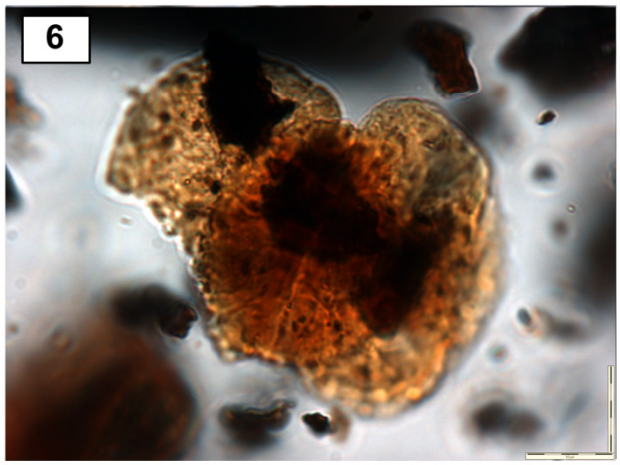












ANTETURMA POLLENITES

TURMA PLICATES

SUBTURMA MONOSULCATES

Entylissa vetus Balme & Hennelly 1956 Plate 19 (1)	
REFERENCE	Kremp & Ames, 1962 (Vol. 13): p. 13-23
DESCRIPTION	Amb broadly oval, length approx. one and a half times width. Sulcus extends full length of grain with narrow cappula at both poles. Exine approx. 1µm thick and laevigate.
SIZE	36 µm (l) x 28 µm (w)
STRATIGRAPHIC RANGE AT MMAMANTSWE	78.32 m – 101.93 m (AVM 67)
TOTAL ABUNDANCE	8 specimens

Cycadopites cymbatus (Balme & Hennelly) Hart 1965 Plate 19 (2)	
REFERENCE	Kremp & Ames, 1962 (Vol. 13): p. 13-24
JUNIOR SYNONYMS	*Entylissa cymbatus* Balme & Hennelly 1956
DESCRIPTION	Amb elongately oval, length approx. twice width. Sulcus extends full length of grain, narrows across the centre and widens out at each pole. Exine thin with microgranulate sculpture.
SIZE	46 µm (l) x 25 µm (w)
STRATIGRAPHIC RANGE AT MMAMANTSWE	64.45 m – 101.93 m (AVM 67)
TOTAL ABUNDANCE	22 specimens

Vittatina scutata (Balme and Hennelly) Bharadwaj 1962 Plate 19 (3)	
REFERENCE	Backhouse, 1991: p. 293, Plate XIX (11-13)
DESCRIPTION	Amb rectangular with slightly convex longitudinal sides. Length approx. two thirds that of width. Sulcus extends full length of grain, narrows near one end of the grain so that sides fold over each other slightly. Sulcus widens out at each pole. Exine ornamented with numerous horizontal taeniae that become rugulae transversely.
SIZE	46 µm (l) x 31 µm (w)
STRATIGRAPHIC RANGE AT MMAMANTSWE	ǀ 64.45 m ǀ (AVM 67)
TOTAL ABUNDANCE	22 specimens

ALGAE

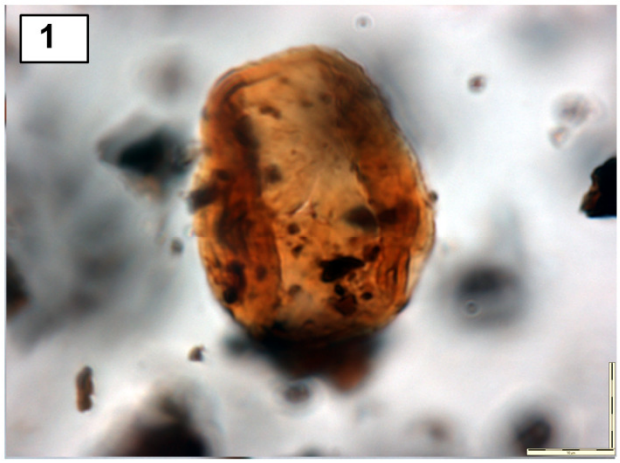
Botryococcus braunii Kutzing 1849 Plate 19 (4)	
REFERENCE	Raine *et al*., 2008
DESCRIPTION	Cluster of freshwater algal cells. Each cell pentadactyl in shape, thin and folded.
SIZE	Variable
DISCUSSION	*Botryococcus* is one of the only genera used for Permian palynomorphs that is not a morphotaxon - it has natural affinity to the modern algal genus *Botryococcus*.
STRATIGRAPHIC RANGE AT MMAMANTSWE	65.44 m – 93.14 m (AVM 67)
TOTAL ABUNDANCE	4 specimens

INCERTAE SEDIS

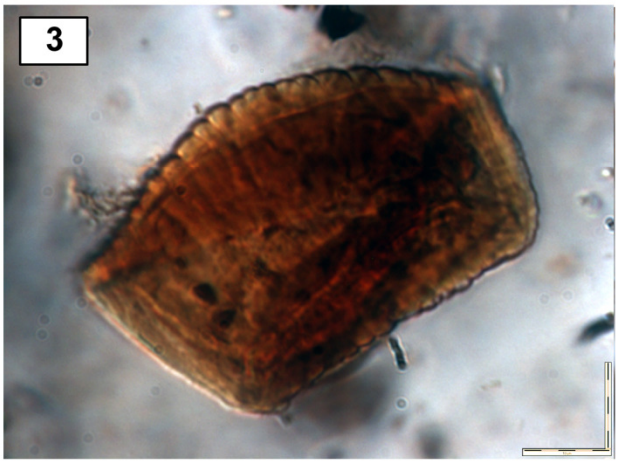
Unknown sp. 1 Plate 19 (5)	
DESCRIPTION	Body of uncertain origin, too small to be a miospore – max. 6 µm diameter. Triangular amb with rounded apices, long filaments attached all over surface of body. All specimens seen were the same shade of bright orange-yellow.
SIZE	4 - 6 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	l 69.9 m l (AVM 67)
TOTAL ABUNDANCE	3 specimens

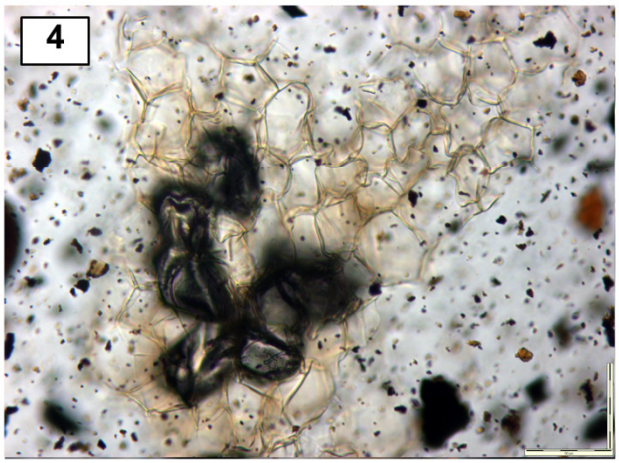
Unknown sp. 2 Plate 19 (6)	
DESCRIPTION	Polyad (two multiples of four?), individual bodies obscured and too small to be identified. May be adherent mass of immature spores. Affinity unknown.
SIZE	19 µm x 16 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	66.4 m – 79.25 m (AVM 67)
TOTAL ABUNDANCE	13 specimens

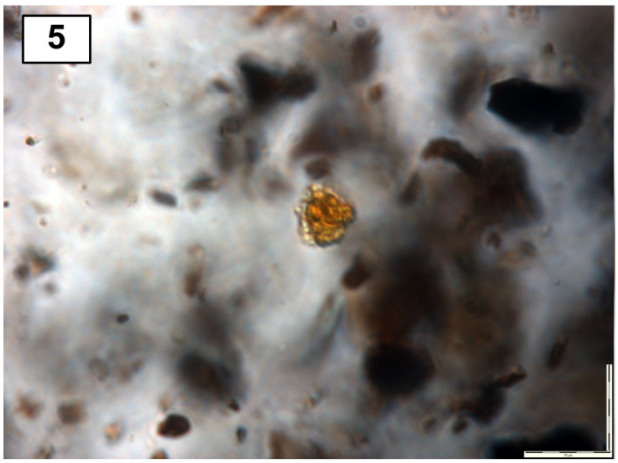
Plate 19

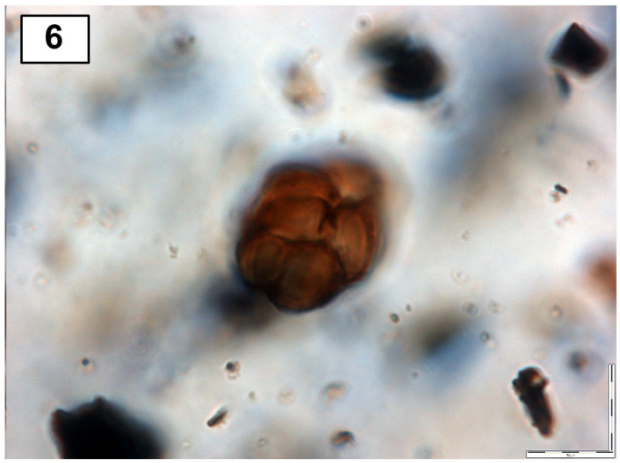






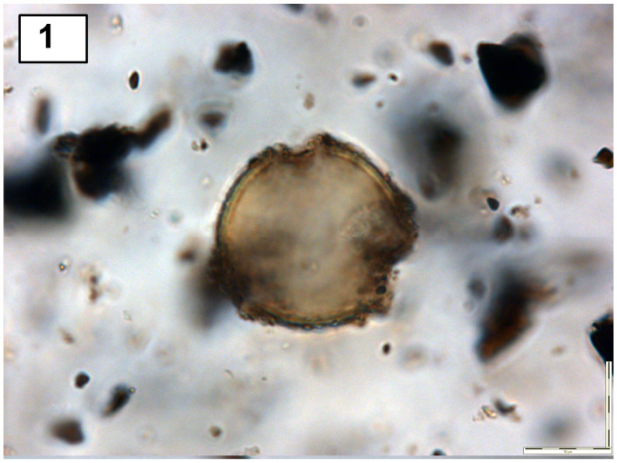






Unknown sp. 3 Plate 20 (1)	
DESCRIPTION	Single tricolporate pollen grain which is almost certainly a laboratory contaminant rather than a reworked specimen, since it is a dark grey and differently coloured to all other grains found (which are varying shades of orange, brown or black depending on thermal maturation).
SIZE	21 µm
STRATIGRAPHIC RANGE AT MMAMANTSWE	ǀ 117.495 m ǀ (AVM 67)
TOTAL ABUNDANCE	1 specimen

Plate 20



3.2 MICROFLORAL COMPOSITION

The microfloral composition at Mmamantswe includes trilete, alete and monolete spores, and monosulcate, monosaccate and bisaccate pollens. The sample also contains a symmetrically tricolporate pollen grain that must either be a reworked specimen or a modern contaminant, as symmetrically tricolporate pollen only appears after the middle of the Cretaceous (Traverse, 2007). Due to the colour of the specimen (dark grey), it is almost certainly a laboratory contaminant as no other specimen (spore, pollen grain or AOM) has this colouration. All other specimens in the sample are varying shades of yellow, orange, brown or black according to their thermal maturation.

3.3 LITHOLOGICAL AND CLIMATIC CONTROLS ON PALYNOMORPH PRESERVATION

In the Witbank / Highveld coalfields (Falcon, 1989; Falcon *et al*., 1984; Aitken, 1994), Vereeniging (Millsteed, 1994), and Morupule, Botswana (Stephenson & McLean, 1999), coals were palynologically productive. In these studies, either coals were medium to high-volatile bituminous in rank, or the rank of coal was not mentioned. Palynological studies in Francistown, Botswana (MacRae, 1978) and the Soutpansberg (MacRae, 1989) did not sample coals for confidentiality purposes.

The Mmamantswe coals are low-volatile bituminous in rank (Cronwright M., pers. comm.). Such coals are supposed to be barren of palynomorphs (Traverse, 2007) and this was indeed the case. At Mmamantswe, lithologies with sufficient palynomorphs were either interbedded coals with carbonaceous mudstones / siltstones, or carbonaceous mudstones only. Samples consisting only of coal were always barren. This is explained by the fact that the Mmamantswe coals (low-volatile bituminous) were subjected to more thermal alteration than most South African coals, which tend to be medium to high-volatile bituminous in rank (although South Africa also has coals that rank as anthracitic). Low volatile bituminous coals tend to contain spores that are very dark brown, having undergone palaeotemperatures of around 170°C (Batten, 1996). The spores contained in the coal layers at Mmamantswe were metamorphosed beyond recognition or destroyed.

Prepared slides of the 'Beaufort' sediments were completely barren of miospores, and covered with red material. This indicates the presence of hematite in this lithology, explaining why there are no spores present – they have been subjected to oxidation and destroyed. All diamictite samples were also barren and for this reason are thought to represent either Late Dwyka glacial lithology or deglaciation at the Dwyka-Ecca boundary, while conditions were still unfavourable for wide-spread plant life.

Due to the above lithologies being barren, Core AVM 75 yielded only one productive sample (137.95 m, AVM 75) from a conglomerate and carbonaceous mudstone layer just above the diamictites. Due to the two cores being dug less than 1 km apart, the productive sample from AVM 75 was included in the pollen diagram and microfloral zonation, and represents the lowermost stratigraphic horizon. All other samples originate from Core AVM 67.

Palynomorph abundance was generally low even in productive slides (totaling 22). Many slides contained some miospores but were classified as non-productive because 250 grains could not be counted. This is unlikely to be a result of preparation as so many treatment methods were experimented with. Rather, it is thought to be due to environmental conditions at the time of coal formation.

Peat swamps were created through by an accumulation of plant matter in near-marine or inland sedimentary basins. To be transformed into coal, organic matter required burial under shallow water, preventing decomposition. The weight of sediment and plant matter caused gradual subsidence of the basin, whereby layers of peat would be compressed at increasing depth, and be transformed into coal by high temperature and pressure. A lowered water level would result in an elevated pH and decay by aerobic bacteria, whilst too high a water table would significantly reduce plant growth and halt peat deposition (Plumstead, 1957; Watson, 1958, 1960; Falcon, 1975b; Cairncross & Cadle, 1988). Accordingly, coal formation is a delicate process that could be easily disrupted by water table fluctuations, resulting in either different grades of coal, or coals interbedded with mudstones or sandstones. It is hypothesised that at Mmamantswe, inconsistent subsidence of the basin resulted in plant matter periodically building up above the water level and being exposed to oxygen. This would have resulted in a high pH, oxidation of plant matter, and an elevated level of microbial activity, forming inertinite (dull) coals and carbonaceous shales (Renton *et al*., 1980; Cairncross & Cadle,

1988). Regular episodes of oxidation would explain why the productive carbonaceous mudstones were generally low in palynomorph abundance.

All productive slides were relatively clear of organic debris, enabling counting. Apart from this, there was no pattern to the surrounding lithological or organic matter among productive or non-productive slides. Bright orange to brown organic matter was seen on several slides, while others had varying amounts of light brown to black carbon chunks (3 µm – 100 µm) interspersed with miospores. This indicates that palynomorph preservation was not facies-controlled.

3.4 PALYNOMORPH SIZES

Some of the miospores from Mmamantswe were unusually small in size (Table 3.3). Initially this created problems with identification. Although morphotypes matched both the description and illustrations for a particular species, they did not fall within the known size range. As this occurred more frequently, it suggested that a particular factor was responsible for reduced palynomorph size, rather than a mass of new species which, apart from their size, appeared remarkably similar to known forms in the literature. Many species did match published size ranges, and a few relatively large spores (> 50µm) were also present. Interestingly, the size ranges at Mmamantswe were relatively narrow compared to published size ranges: between 5 and 10 µm for smaller grains, and 10 – 15 µm for larger spores.

Table 3.3 **Comparison of the size ranges of selected miospore types from Mmamantswe with published size ranges. The miospores included in the table represent forms that could be confidently identified to species level from the literature.**

Genus & species	Morphological type	Size range at Mmamantswe	Published size range
Horriditriletes tereteangulatus	Trilete spore	20 – 25 µm	26 – 41 µm
Neoraistrickia pilata	Trilete spore	17 – 23 µm	40 – 50 µm
Granulatisporites spinosus	Trilete spore	23 – 28 µm	26 – 28 µm
Gondisporites raniganjensis	Zonotrilete spore	51 – 57 µm	90 – 115 µm
Sulcatisporites splendens	Monosaccate	22 – 25 µm (h) x 26 – 32 µm (w)	45 µm (h) x 57 µm (w)
Florinites similis	Monosaccate	37 µm (h) x 56 µm (l)	124 – 142 µm (h) x 88 – 97 µm (l)
Lueckisporites fusus	Bisaccate	45 - 55 µm total bladder span	81 – 146 µm total bladder span

3.5 MICROFLORAL TRENDS

Microfloral trends are illustrated on the following fold-out page, in a Tilia™ pollen diagram (Figure 3.1). The Y-axis is marked with horizon depths and core lithology. All miospore species are listed above. The X-axis records the total abundance of each species. The far right of the diagram shows, in order, abundances of Triletes, Monoletes, Aletes, Zonotriletes, Hilates & other incertae sedis, Monosaccates, Bisaccates and Monosulcates. Assemblage zones are marked across the diagram with double lines, and are distinguished by specific associations of fossil taxa (Hedberg, 1976). Non-productive horizons were not included in the diagram as they created "noise" and made patterns harder to identify. For this reason, a lithological section was

not included in the pollen diagram as all productive horizons originated from carbonaceous mudstone / siltstone horizons. Most of the forms found at Mmamantswe were long-ranging and present throughout the core. Assemblage zones were thus established by morphotype cycles of increase and decrease, or progressive development of certain forms (Figure 3.1). Increases and decreases in the various forms may have been seasonal, caused by floods, drought or climatic fluctuation.

Mmamantswe can be sub-divided into five microfloral assemblage zones:

- Zone 1: 137.95 m -115.36 m (trilete-monosaccate dominant)
- Zone 2: 115.36 m – 101.93 m (monolete-alete spike)
- Zone 3: 101.93 m – 80.735 m (zonotrilete-hilate spike)
- Zone 4: 80.735 m – 70.885 m (increased abundance across all groups)
- Zone 5: 70.885 m – 63.565 m (zonotrilete-bisaccate increase)

Triletes

The number of trilete species present was the highest of all groups. Quantitatively, azonotriletes were generally the most abundant group at Mmamantswe. These spores made up between 31-80 % of the miospore fraction. Triletes decreased progressively through Zone 1.

Aletes

Aletes were the second most abundant group at Mmamantswe, and also plentiful throughout the core. At horizons 63.565 m, 66.4 m, 70.885 m, 80.735 m, 92.52 m, 93.14 m, 110.86 m, and 115.96 m, they take over from triletes as the most abundant group. Aletes made up between 6-48 % of the miospore fraction. They were not as speciose as azonotrilete spores. Aletes increase progressively through Zone 1.

Monoletes

Monoletes were well-represented throughout the core, but not as plentiful as triletes or aletes. Monoletes made up between 1-27 % of the miospore fraction. Monoletes, aletes and triletes also followed similar patterns of increase and decrease throughout the core, except in Zone 1. While triletes decreased progressively, aletes and monoletes increased.

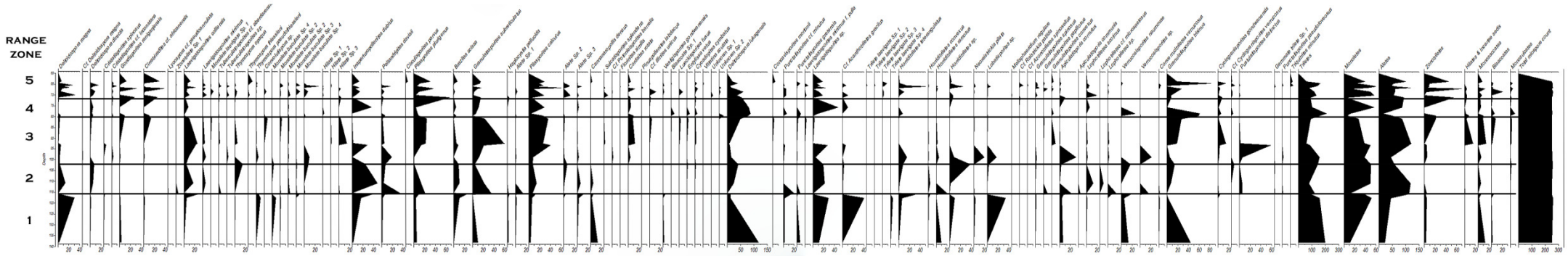


FIGURE 3.1: TILIA POLLEN DIAGRAM ASSIMILATING MIOSPORE COUNTS FROM ALL PRODUCTIVE HORIZONS AT MMAMANTSWE. CORE AVM 67 IS REPRESENTED FROM 63.565 M - 117.495 M, AND THE 137.95 M HORIZON IS DERIVED FROM CORE AVM 75

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Zonotriletes

Zonotriletes are also present throughout the core, however they show a marked increase in Zone 5 (horizons 63.565 m, 66.91m and 70.885 m). In these horizons, they make up between 18-28 % of the miospore fraction.

Hilates

These spores, none of which could be matched with forms in the literature, were rare throughout the core but most plentiful in Zone 3.

Saccates

Saccates comprise a very small quantitative and qualitative proportion of the assemblage.

- Monosaccate pollen abundance and diversity was low. The monosaccate *Cannanoropollis densus* is present in the deepest part of the core, declines sharply at the Zone 1 – Zone 2 boundary, and then increases and decreases cyclically through the rest of the zones. Other monosaccate genera first appear in Zone 3, and increase in species diversity from here on.

- Bisaccate pollen abundance and diversity was extremely low. Although present from Zone 1, (6 specimens), the group only becomes significant in the middle of Zone 3. Horizon 68.37 m, Zone 5, shows the highest proportion of bisaccates, at 8.4 % of the miospore fraction

Monosulcates

Monosulcate pollen abundance and diversity was generally very low. However, monosulcates are not a dominant group in other studies either, therefore this was not considered to be unusual.

Numerous researchers have found the palynomorph abundance and species diversity to be especially high throughout the Ecca and contemporaneous formations around southern Africa (Anderson, 1977; Falcon, 1978; Millsteed, 1994). At Mmamantswe, species diversity increased significantly from the beginning of Zone 2, with many new forms appearing at this horizon. A total of 64 genera and 90 species were present throughout the cores.

3.6 LITHOLOGY OF MMAMANTSWE

Core logs of AVM 67 and AVM 75, Mmamantswe, Botswana are included, courtesy of Rock & Stock Investments and Aviva Corp. Ltd (Figure 3.2 and Figure 3.3). Rock at Mmamantswe is covered by up to 9 m of unconsolidated sand, demonstrating the need for using cores to establish lithology. Weathered sandstones and siltstones are present underneath the loose sand and presumed to be Cenozoic in age. In core AVM 75, fresh siltstone begins at a depth of 32 m and it is from this depth that the barren "Beaufort" sediments were taken.

Interbedded coal and carbonaceous mudstones range from 44 m – 116 m in the AVM 67 core. In AVM 75 there is a predominance of coal over carbonaceous mudstone and it is for this reason that samples from the former core were selected. Many spores of algal origin are present in the mudstones, indicating large bodies of water in the area, as expected for coal sediments. It is likely that these sediments are also freshwater and terrestrial in origin. Current geological evidence suggests that the Karoo basin experienced few marine incursions during the Early to Middle Permian (Cairncross, 2001).

Barren diamictites are present near the base of AVM 75, along with mafic lithology thought to be part of the Waterberg Group. The deepest productive sample (137.95 m, AVM 75) was taken from a well-sorted conglomerate and carbonaceous mudstone layer just above the diamictites. It was also one of the most abundant samples, and is postulated to represent a transition from river systems formed by post-glacial outwash, to the beginning of the peat swamps.

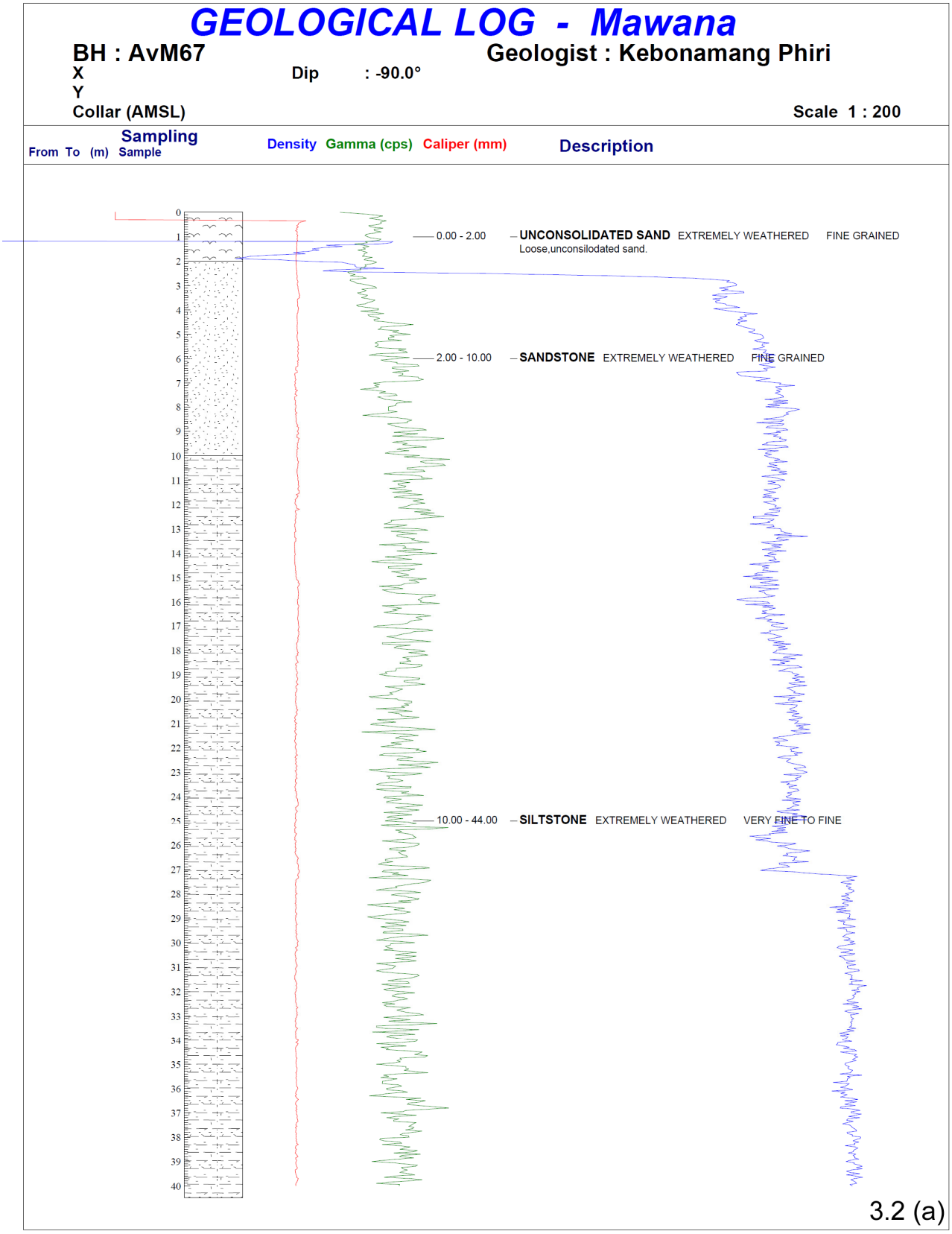


Figure 3.2 **Geological log of Core AVM 67, Mmamantswe, Botswana. Property of Aviva Corp. Ltd. Samples taken are indicated to the left of the stratigraphic column. Non-productive samples are marked with a cross, and productive samples with a tick mark.**

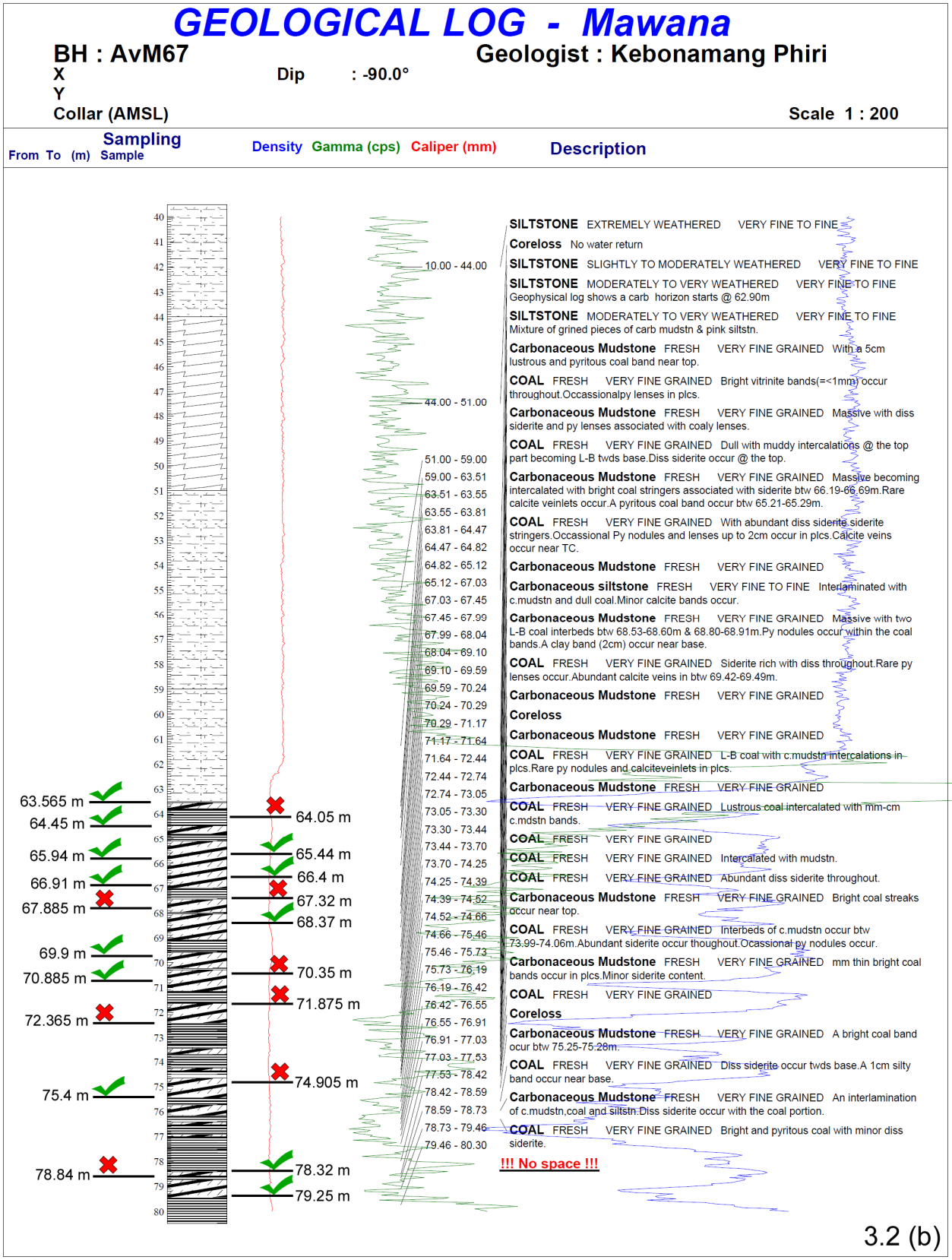


Figure 3.2 **Geological log of Core AVM 67, Mmamantswe, Botswana. Property of Aviva Corp. Ltd. Samples taken are indicated to the left of the stratigraphic column. Non-productive samples are marked with a cross, and productive samples with a tick mark.**

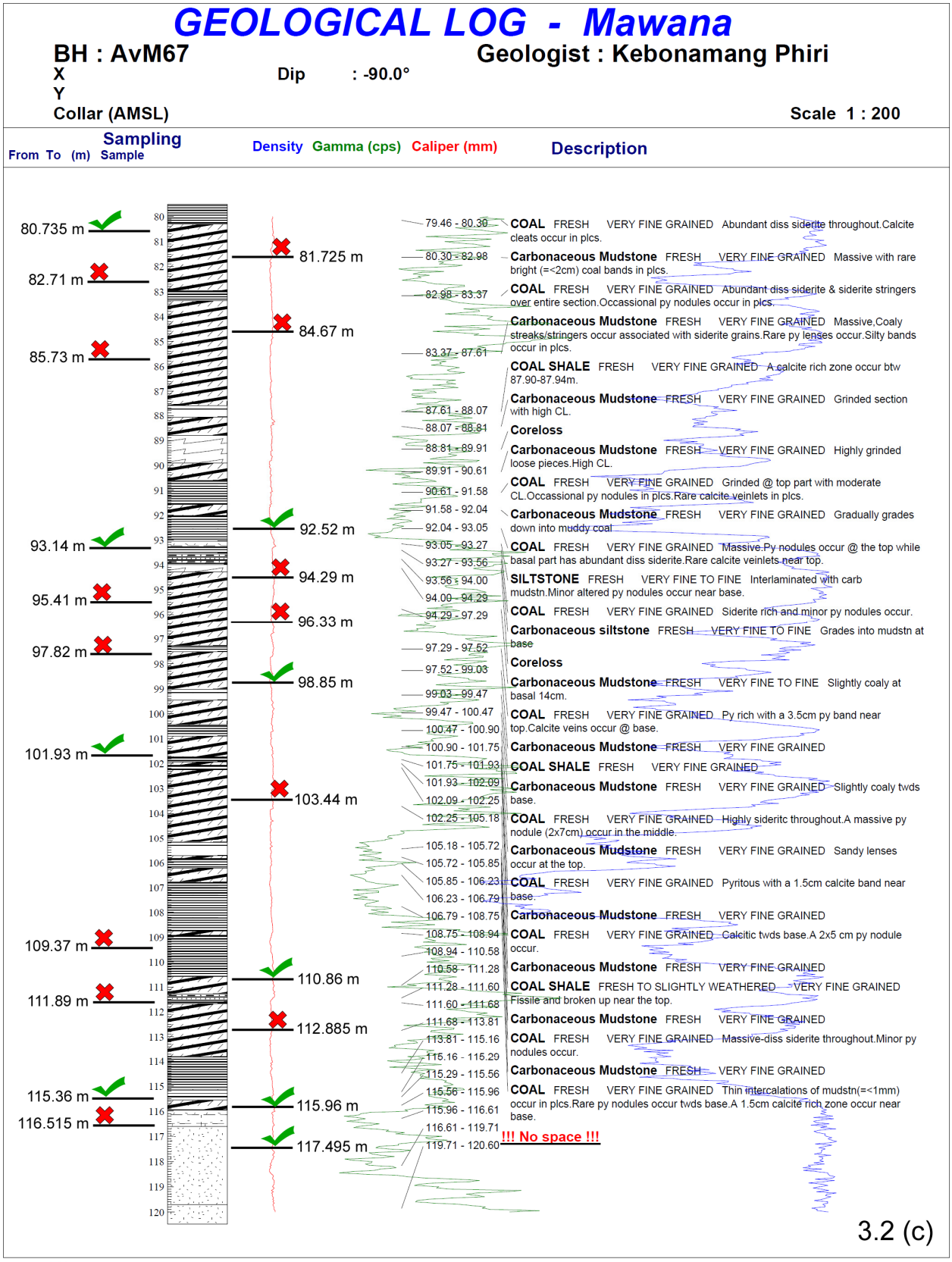


Figure 3.2 **Geological log of Core AVM 67, Mmamantswe, Botswana. Property of Aviva Corp. Ltd. Samples taken are indicated to the left of the stratigraphic column. Non-productive samples are marked with a cross, and productive samples with a tick mark.**

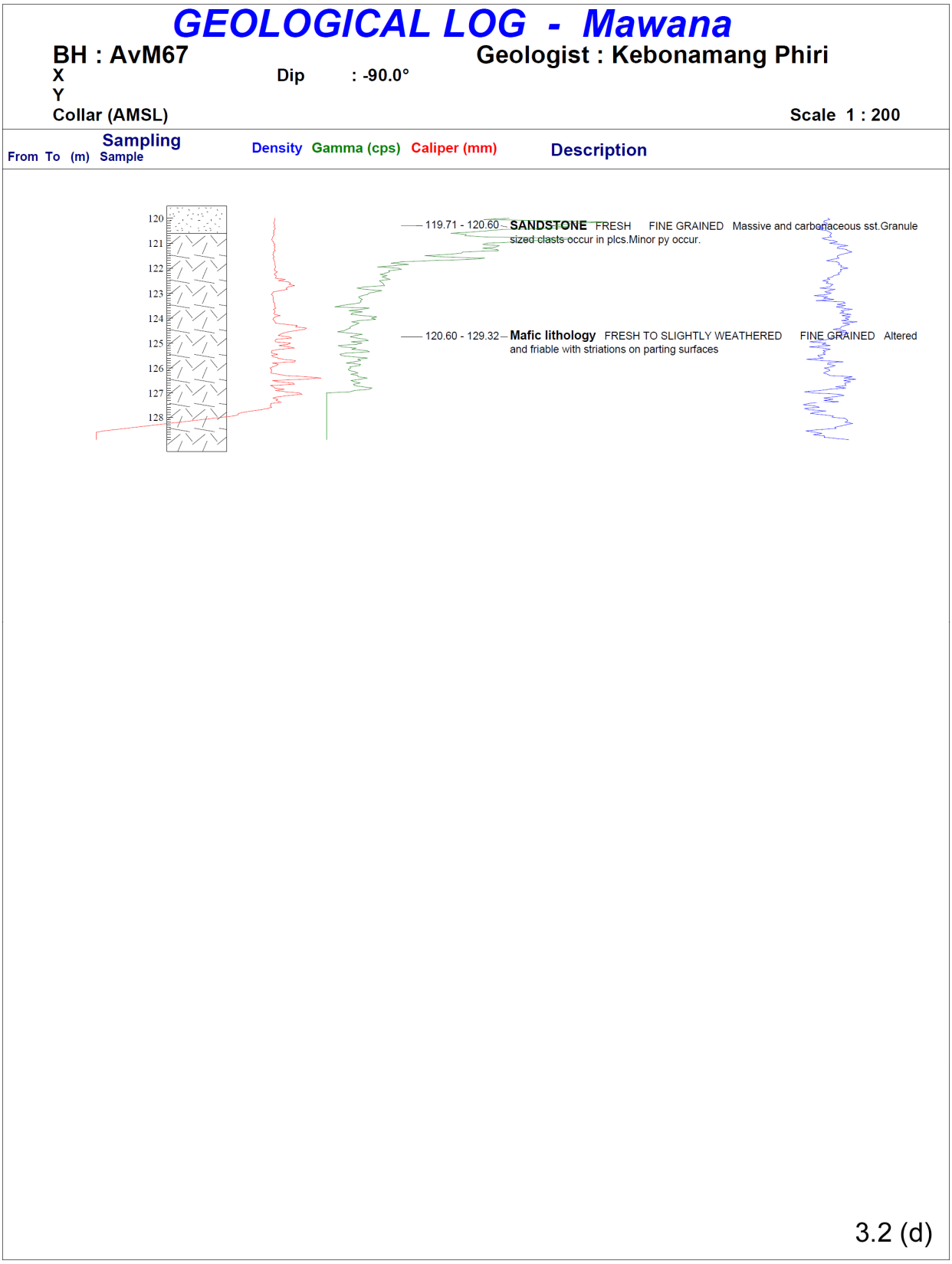


Figure 3.2 **Geological log of Core AVM 67, Mmamantswe, Botswana. Property of Aviva Corp. Ltd. Samples taken are indicated to the left of the stratigraphic column. Non-productive samples are marked with a cross, and productive samples with a tick mark.**

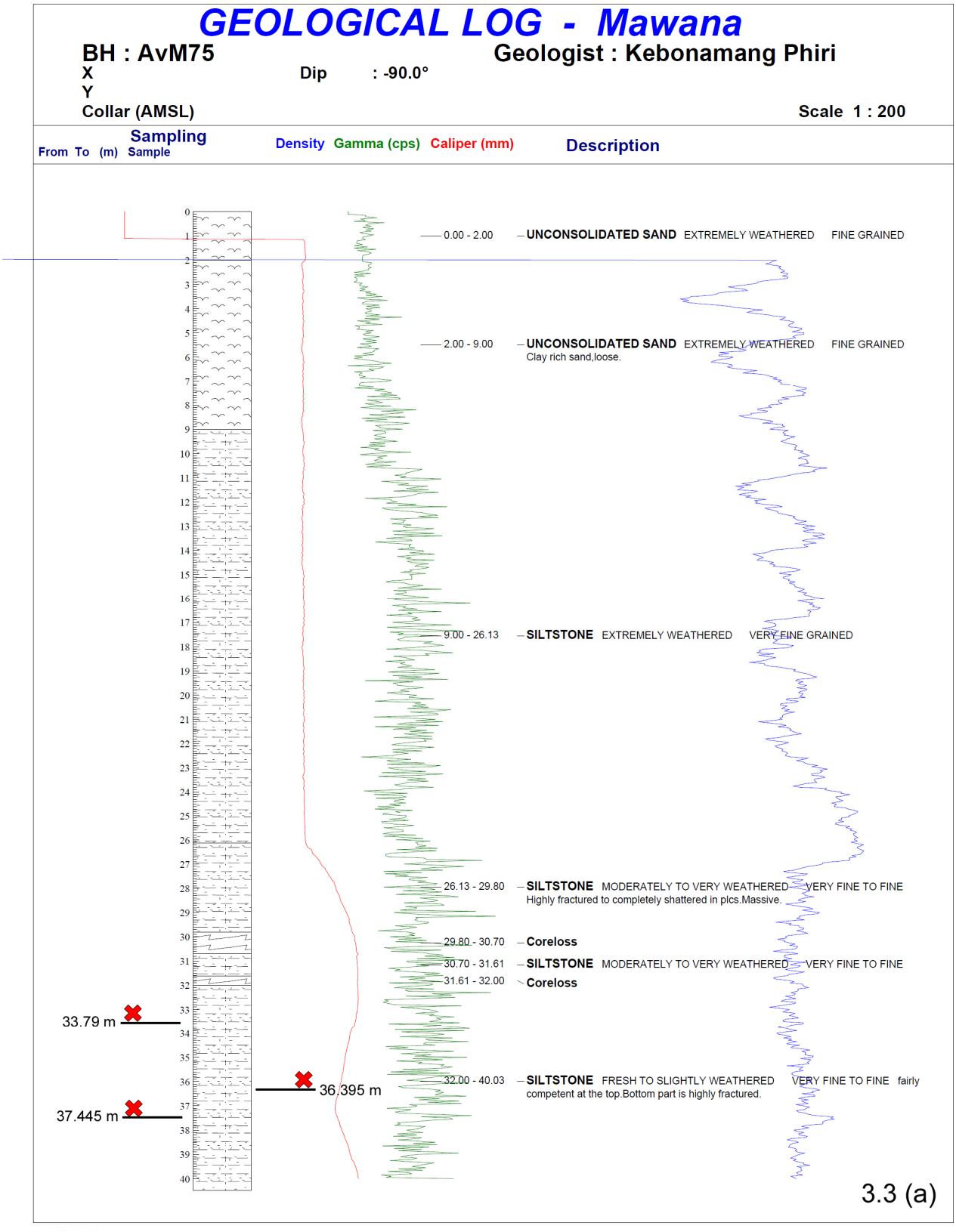


Figure 3.3 **Geological log of Core AVM 75, Mmamantswe, Botswana. Property of Aviva Corp. Ltd. Samples taken are indicated to the left of the stratigraphic column. Non-productive samples are marked with a cross, and productive samples with a tick mark.**

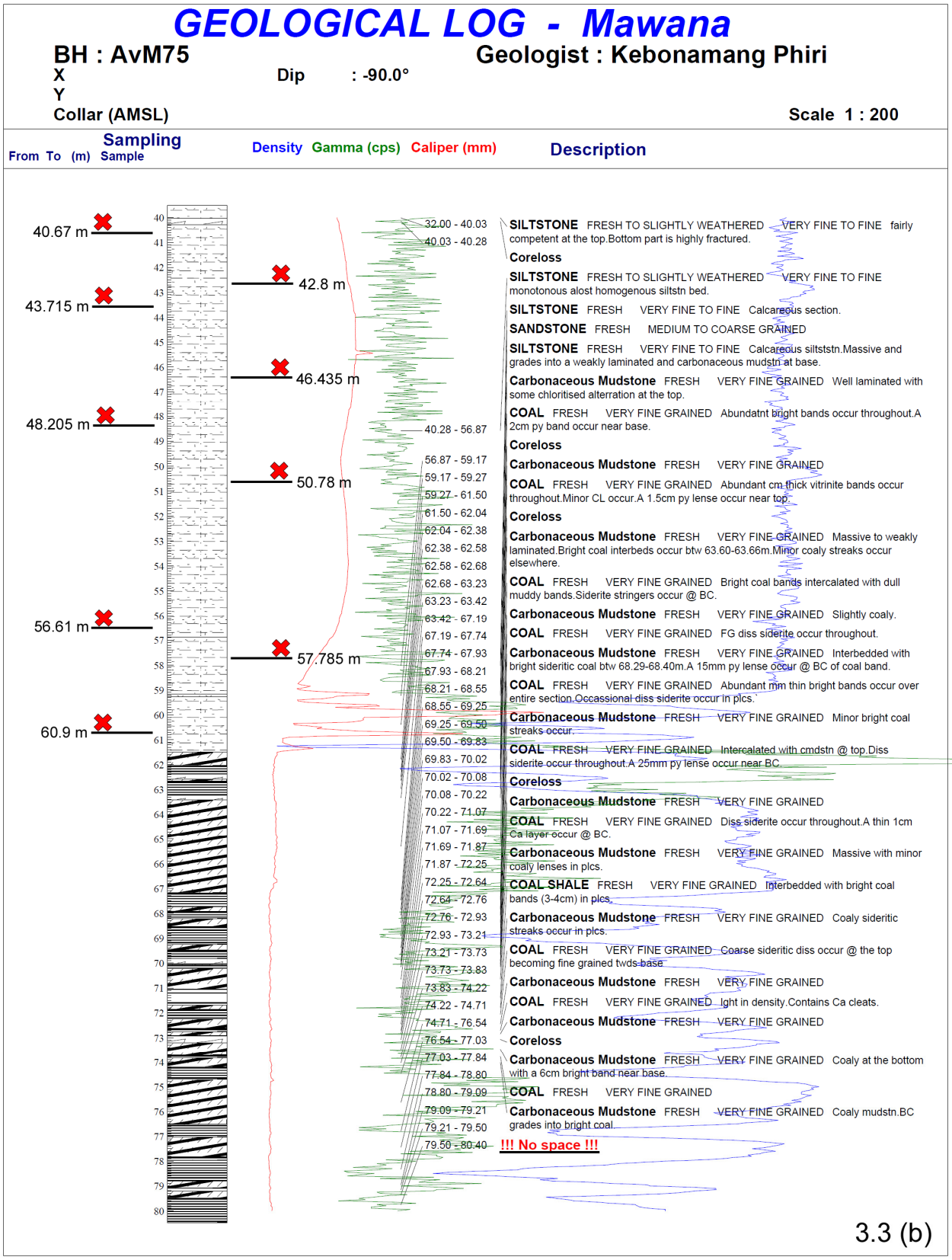


Figure 3.3 **Geological log of Core AVM 75, Mmamantswe, Botswana. Property of Aviva Corp. Ltd. Samples taken are indicated to the left of the stratigraphic column. Non-productive samples are marked with a cross, and productive samples with a tick mark.**

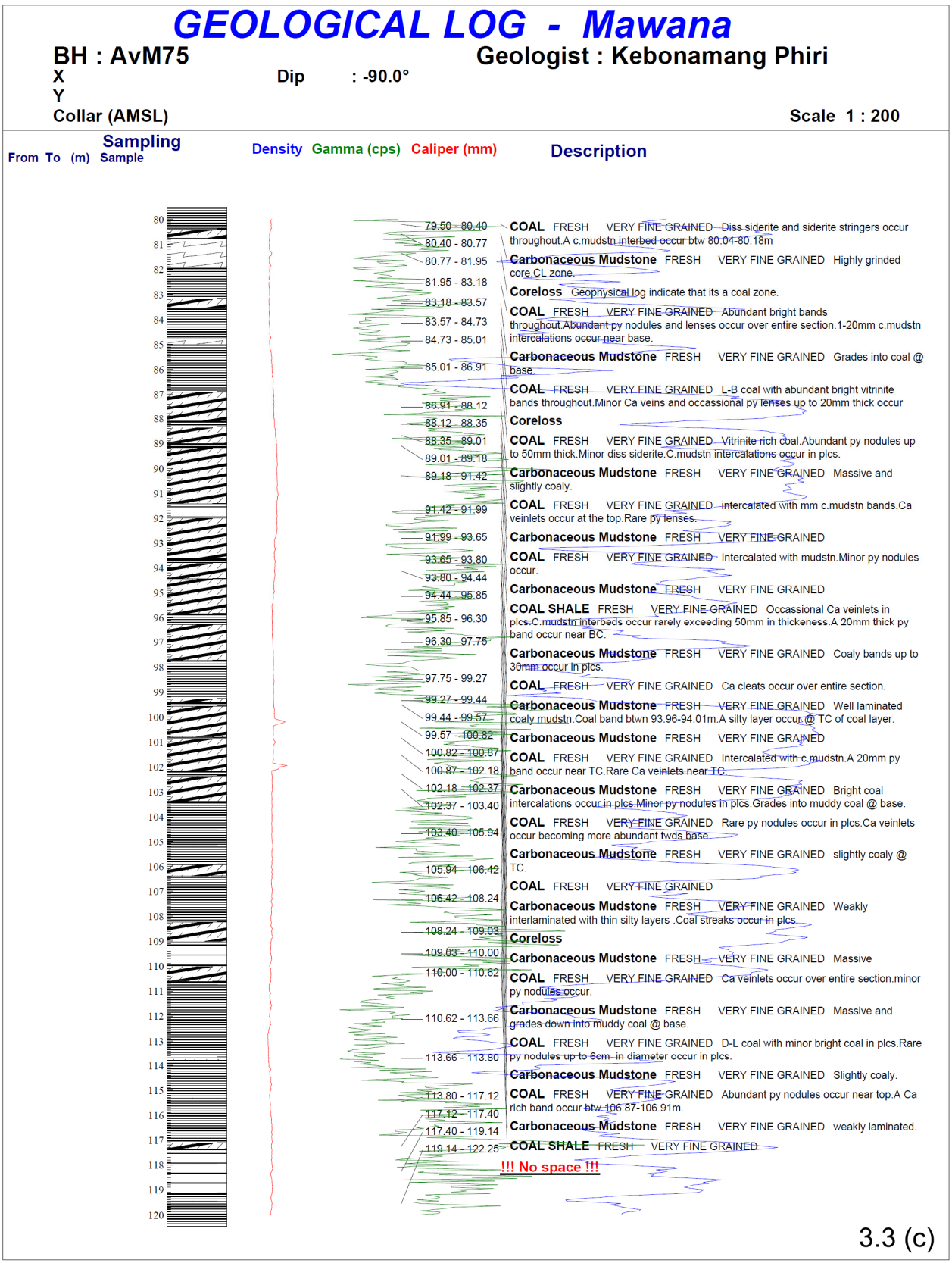


Figure 3.3 **Geological log of Core AVM 75, Mmamantswe, Botswana. Property of Aviva Corp. Ltd. Samples taken are indicated to the left of the stratigraphic column. Non-productive samples are marked with a cross, and productive samples with a tick mark.**

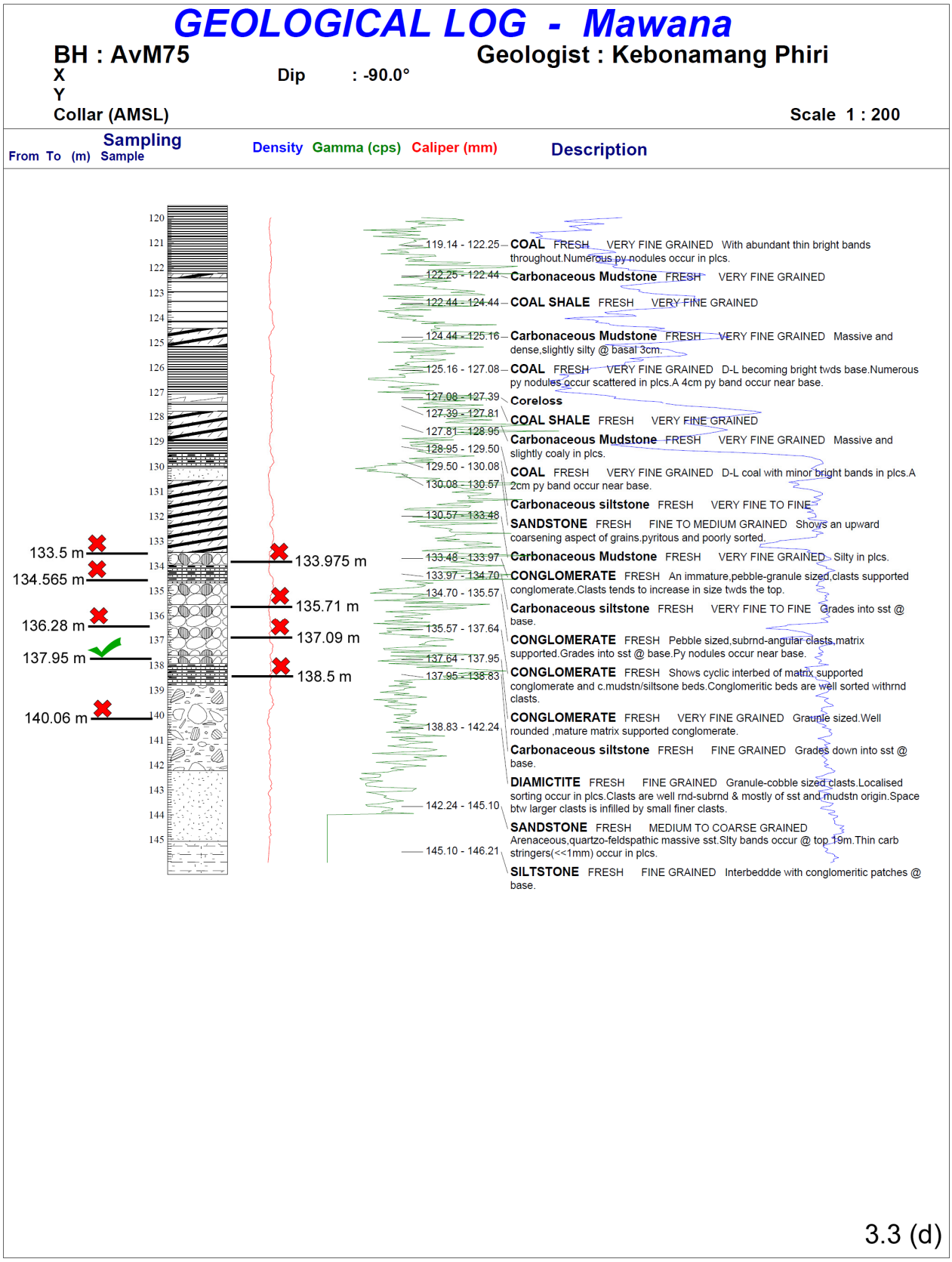


Figure 3.3 **Geological log of Core AVM 75, Mmamantswe, Botswana. Property of Aviva Corp. Ltd. Samples taken are indicated to the left of the stratigraphic column. Non-productive samples are marked with a cross, and productive samples with a tick mark.**

CHAPTER FOUR - DISCUSSION

4.1 PREPARATION METHODS

There are a wide variety of recommended preparation methods in the literature, depending on what kind of sediments one is preparing, as well as what type of facilities may be available. This study tested a variety of different treatment combinations for preparing palynomorphs from low-volatile bituminous coals and interbedded mudstones.

With coals, the most delicate procedure is oxidation. Too little time spent in oxidising solutions results in "dirty" slides with lots of AOM, however too much time under oxidation damages or destroys palynomorphs (Figure 4.1).

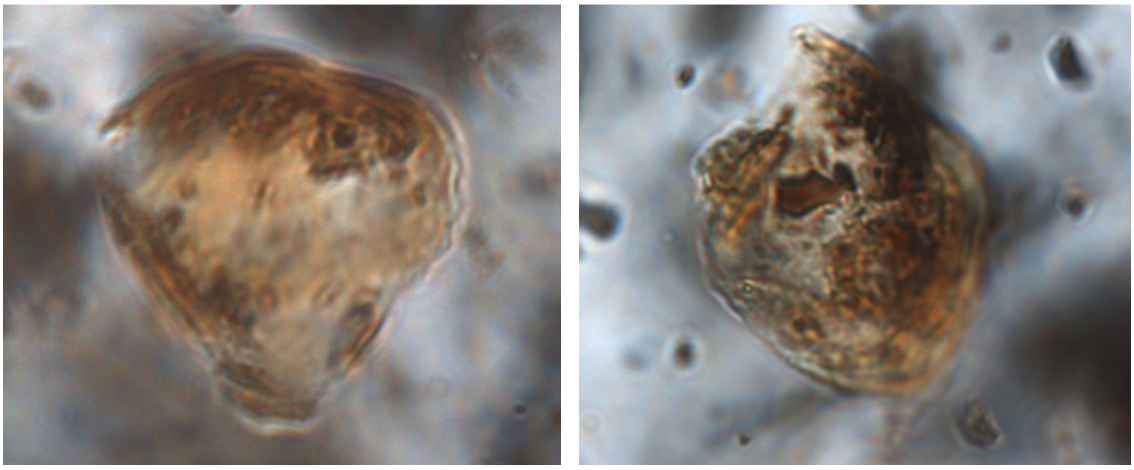


Figure 4.1 **Damaged palynomorphs most likely resulting from over-oxidation, rendering them unidentifiable (AVM 67 / 65.44m)**

Oxidising coal sediments in Schulze's solution for 1 – 48 hours (e.g. Anderson, 1977; MacRae, 1978; Aitken, 1994) resulted in virtually all palynomorphs in the sample being destroyed. The more gentle method of boiling in potassium hydroxide for 15 minutes worked well on both coals and carbonaceous mudstones from Mmamantswe and allowed a lot of organic debris to be removed. However, following oxidation with

acetolysis was essential to achieve a clear slide that could be counted (Figure 4.2). This is because acetolysis clears a sample of non-sporopollenin tissues (Wood *et al*., 1996).

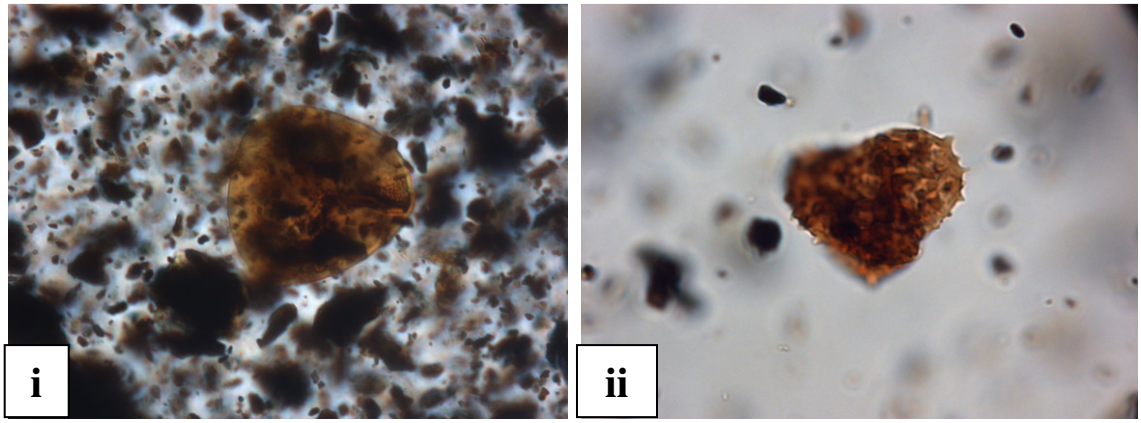


Figure 4.2 **Comparison of non-acetolysed (i) and acetolysed (ii) palynomorphs. Both slides were initially prepared in the same way, with acids, oxidation, and mineral separation.**

Acetolysis eliminates the need for staining when working with extant spores, as it darkens colourless grains a yellow to orange colour (Traverse, 2007). This raised concerns over whether using the T.A.I. (Thermal Alteration Index) for fossil palynomorphs was valid. To test this, a sample particularly rich in palynomorphs was prepared without undergoing acetolysis. From this slide, twelve species were identified that were also common to acetolysed samples, and compared for colour variation. Specimens were identical in colour for every comparison. This supports using the T.A.I. for samples prepared with acetolysis.

Colouration of the assemblage generally ranged from a dark orange to light brown. This would correspond to a T.A.I. value of 3.0 – 3.5. Although this value corresponds to high- and medium-volatile coal rank, it must be kept in mind that this value was obtained only from the interbedded carbonaceous mudstones. The coals were not productive, although some dark brown or blackened bodies were observed which may have been metamorphosed spores. Across the core, a small number of taxa were medium yellow in colour, and identified as fossils, not modern contaminants. Lighter colouration can indicate a lesser degree of thermal alteration, meaning that palynomorphs of different ages are present in the sample (reworking). It was observed that only grains with very thin exines were lighter in colour. It is known that

palynomorphs with the same thermal history can sometimes vary in colour, due to variations in wall thickness and composition of individual grains (Pross *et al*., 2007), and small temperature increases within a single sample (Yule *et al*., 1998). Exine thickness was thus taken to be the most plausible reason for colour variation in the assemblage. Reworking is unlikely as all grains were identified from literature on the Late Carboniferous and Permian periods, and additionally there was no geological evidence of reworking seen in the cores.

4.2 SLIDE MOUNTING

The life of a slide is determined by its exposure to oxygen (Traverse, 2007). Glycerin jelly has a life of approximately 30 - 40 years as it slowly permits auto-oxidation. DPX is a synthetic mountant that dries solid over 1 - 3 days and is supposed to produce a "permanent" slide. Good results were not obtained in this study using DPX, as material clumped on the slide rendering miospores invisible. However, this was attributed to the sample preparator being accustomed to working with glycerin jelly only. DPX has been used successfully in previous studies (MacRae, 1978; Aitken, 1994) and may well be a good choice for mounting.

Although glycerin jelly slides may have a lifespan of 40 years, it is far more likely that within this time span, slides will be lost, broken, or borrowed from the collection and not returned. This information is then forever lost, as most if not all of the original sample will have been used up during preparation. The answer lies in electronic databases. Thanks to advances in technology, high-resolution colour photographs of every morphotype can be safely stored in cyberspace, and if backed up properly, will last indefinitely. Databases can also be stored in more than one institution at a time, or accessed online, facilitating maximum use of the information.

4.3 PALYNOMORPH SIZES

The unusually small size of the Mmamantswe palynomorphs is peculiar but not unheard of – for example, Alfred Traverse states that "spores / pollen, unlike dinoflagellate cysts, unfortunately do not have anything like perfect integrity as to size and

morphological type per species" (Traverse, 2007: p. 95). While this may be true, it is felt that a specific factor or combination of factors must have been responsible for such an obvious and widespread reduction in size across the Mmamantswe assemblage. The cause may be attributed to preparation methods, post-depositional processes, conditions during accumulation of the peat, or inherent to the flora of the area. These are discussed below.

Various laboratory procedures can affect pollen and spore size (Moore *et al*., 1991; Wood *et al*., 1996; Meltsov *et al*., 2008):

- 'Prolonged' treatment in oxidants like KOH or Schulze's solution causes swelling of miospores
- Acetolysis also causes swelling
- Acetolysed grains are larger than potassium hydroxide (KOH) treated grains
- HF may cause shrinkage of pollen
- Glycerine jelly causes long-term swelling (over a number of years)
- If solvents, especially benzene, are not allowed to evaporate before mounting, they can cause shrinkage by up to 10% in 3 weeks
- Pollen grains dehydrated after chemical treatment with tertiary butyl alcohol are larger than pollen grains not dehydrated
- Pollen grains mounted in silicon oil are smaller than grains mounted in glycerine

When the above is evaluated, it is evident that preparation was not the cause of size reduction. Only HF may cause shrinkage of grains, but was used in all other studies as well. Acetolysis was used in the present study and Aitken (1994), but causes swelling of grains similar to oxidation treatments like Schulze's solution.

Next, post-depositional alteration was considered, but no known substance or geochemical process exists that would shrink palynomorphs by such a significant amount. Another possible reason could be selective preservation, with larger miospores not being preserved for some reason. However, this does not explain the existence of the smaller spores in the first place. If the Mmamantswe coal deposits were formed in a higher-energy environment, like a floodplain as suggested by Smith (1984), larger heavier grains may have been prone to destruction. However, the make-up of the assemblage indicates its autochthonous origin. The Mmamantswe flora formed in a low-energy swamp environment, ruling out the above hypothesis.

The microenvironment of the coal swamp may have allowed for a mutation to become entrenched within the local flora. However, homoplasy is an unlikely explanation as trilete, monolete, alete and saccate genera are all reduced in size. Rather, this suggests an adaptive factor acting upon the palynomorphs in this locality.

The function of spores and pollen is fertilization, and they are either transported by wind, water or insects. Smooth grains, or those 15-35 µm in size, tend to be wind-pollinated, while ornately sculptured grains over 40 µm are usually insect-pollinated (Traverse, 2007). The palynomorphs from Mmamantswe are certainly wind-pollinated because of their age. Adaptations to wind pollination are seen in the monosaccate and bisaccate pollens that evolved in the Carboniferous. The air-filled sacci reduced pollen density and acted as "wings" to carry them further distances (e.g. Falcon, 1989). Accordingly, a small grain size would have promoted widespread distribution and been advantageous for reproduction – up to a point. Grains under about 10 µm in diameter would not have the impact velocity to adhere to a stigma (Basinger & Dilcher, 1984). It is interesting that the smallest grains from Mmamantswe are around 15 µm – just above the limit where further reduction in size would have been a disadvantage.

Pollen determines mating success of the parent plant, and mating opportunities increase if more pollen is produced. If such a strategy was adopted, plants could compensate by making smaller grains so not to use more resources (Sarkissian & Hardner, 2001). While this may be plausible, why was the strategy not adopted by the same species of plants in other locations?

Adaptive pressures to travel further and produce more grains may both be related to the hypothesis discussed in Section 3.3, that the pH of the swamp was generally high due to inconsistent subsidence. If oxidation by high pH caused routine destruction of many palynomorphs, there would have been adaptive pressure on local plants to adopt the strategy of producing more grains. Additionally, some smaller grains would have been carried by wind out of the oxidising environment of the coal swamp, increasing their chances of survival.

A further suggestion is that availability of minerals to the producing plant can affect pollen size (Bell, 1959; Lau & Stephenson, 1993, 1994). If the Mmamantswe area was

deficient in this regard, plants may have reduced their investment in pollen size. Detailed analysis of coal composition may be able to support this hypothesis.

It has also been suggested that increases in post-depositional temperature may cause a reduction in palynomorph size (Raynaud & Robert, 1976). Due to the higher coal rank at Mmamantswe compared to other coal localities in southern Africa, palynomorphs would have undergone increased thermal maturation for a prolonged period of time. This warrants future investigation by comparison of the same species of palynomorphs from low- and high-volatile bituminous coals.

Finally, modern angiosperms respond rapidly to natural selection for size (Sarkissian & Hardner, 2001). Changes in pollen size always happened in conjunction with changes in flower size, pollen number, length of style, and ovule number. Studies on gymnosperms and lower order plants are necessary to determine whether changes in spore size may also have affected other characters of the plant. This would have strong significance from an evolutionary viewpoint.

4.4 BOTANICAL RECONSTRUCTION

Correlating palynomorphs to their parent plants is important for understanding evolutionary patterns. Since palynomorphs are far more abundant, and often more easily obtainable than macroplant fossils, they can be a useful tool for areas in which larger fossils have not been preserved, or an excavation cannot be mounted. Unfortunately, at the present time, correlation of the micro- and macroflora is inconsistent at best. It is known that the same macroplant can be found in association with different morphospecies or even morphogenera of pollen, either due to various developmental stages, or states of preservation (Remy & Remy, 1955; Bek & Opluštil, 1998). At the same time, because miospores are morphotaxa, they may legitimately "belong" to unrelated plants (Taylor *et al*., 1996). These parent plants may come from different areas, or date from different time periods as well, illustrating the complex problem of applying artificial divisions to biological organisms. For a more in-depth discussion of this predicament, see Taylor *et al*. (1996).

The parent plant (or plants) associated with miospores found in this study, along with some other notable palynomorph species from Permian sites in southern Africa, are listed below (Table 4.1). Miospores have only been assigned to parent plants in cases where they have been directly removed from fructifications. Additionally, correlations are drawn for Carboniferous (Pennsylvanian) or Permian macroplants only. Some of these plants are from the Northern Hemisphere. They have been included here to give a general idea on what kinds of plants produced particular spores / pollen where a Gondwana equivalent has not yet been found. Gondwana plant species are highlighted in bold type.

Table 4.1 **Correlations of Carboniferous and Permian miospores to their parent plants or groups. References are listed for each association, and Gondwana plant genera are in bold.**

MORPHOGENUS	TURMAL GROUP	PARENT PLANTS	TAXON	REFERENCE
Calamospora	Laevigate trilete spore	***Calamites***	Sphenophyta	Traverse, 2007
		Sphenophyllum	Sphenophyta	Good, 1978
		Palaeostachya	Sphenophyta	Gastaldo, 1978a ; Bek & Opluštil, 1998
		Calamostachys *Macrostachya*	Sphenophyta Sphenophyta	Bek & Opluštil, 1998
		Protocalamostachys	Sphenophyta	Hemsley *et al*., 1994
		Scolecopteris	Marattiales	Millay, 1979
		Sawdonia	Zosterophyllophyta	Gensel *et al*., 1975
		Dawsonites / *Psilophyton* (likely synonymous)	Trimerophyta	Allen, 1980 ; Gensel, 1980b
		Hostinella	Lycophyta	Allen, 1980
		Oricilla	Zosterophyllophyta	Gensel, 1982b
		Protobarinophyton *Barinophyton*	Lycophyta	Gensel, 1980b Taylor & Brauer, 1983
Laevigatisporites	Laevigate trilete spore	*Mazocarpon* *Sigillariostrobus*	Lycophyta	Scott & King, 1981
Punctatisporites	Laevigate trilete spore	*Pecopteris*	Marattiales	Laveine, 1969
		Scolecopteris	Marattiales	Millay, 1979, 1982a
		Botryopetris	Leptosporangiate fern	Millay & Taylor, 1982
		Biscalitheca	Zygopteridales	Millay & Rothwell,

				1983
		Telangium	Pteridospermophyta	Eggert & Taylor, 1968
		Potoniea illinoensis	Pteridospermophyta	Stidd, 1978
		Zosterophyllum	Zosterophyllophyta	Gensel, 1982a
Cyclogranisporites	Granulate trilete spore	*Pecopteris*	Marattiales	Laveine, 1969 ; Millay, 1979
		Acitheca	Marattiales	Mapes & Schabilion, 1979
		Scolecopteris	Marattiales	Millay & Taylor, 1984
		Noeggerathiae-strobus	Noeggerathiales	Beck, 1981
		Feraxotheca	Pteridospermophyta	Millay & Taylor, 1977
		Crossotheca	Pteridospermophyta	Millay *et al*., 1978
		Schopfiangium	Pteridospermophyta	Stidd *et al*., 1985
		Archaeopteris	Progymnospermophyta	e.g. Gensel, 1980b
		Rhynia	Rhyniophyta	Allen, 1980
Granulatisporites	Granulate trilete spore	*Botryopetris*	Leptosporangiate fern	Good, 1979
		Feraxotheca	Pteridospermophyta	Millay & Taylor, 1977
		Crossotheca	Pteridospermophyta	Millay et al., 1978
		Rhynia	Rhyniophyta	Allen, 1980
Cyclobaculisporites	Verrucate trilete spore	*Dichotomopteris*	Leptosporangiate fern	Lele *et al*., 1981
Verrucosisporites	Verrucate trilete spore	*Biscalitheca*	Zygopteridales	Bharadwaj & Venkatachala, 1968 ; Courvoisier & Phillips, 1975
		Scolecopteris	Marattiales	Jennings & Millay, 1978
		Eoangiopteris	Marattiales	Millay, 1978
		Millaya	Marattiales	Mapes & Schabilion, 1979
		Schopfiangium	Pteridospermophyta	Stidd *et al*., 1985
Acanthotriletes	Echinate trilete spore	*Botryopetris*	Leptosporangiate fern	Good, 1979 ; Millay & Taylor, 1982
		Eviostachya	Sphenophyta	Gensel, 1980b
		Dichotomopteris Neomariopteris	Leptosporangiate fern	Lele *et al*., 1981
Apiculatisporis (Brevitriletes)	Echinate trilete spore	*Corynepteris*	Zygopteridales	Galtier & Scott, 1979 ; Hemsley *et al*., 1984

		Dizeugotheca	Marattiales	Lele *et al*., 1981
Lophotriletes	Echinate trilete spore	*Botryopetris*	Leptosporangiate fern	Good, 1979
		Dichotomopteris *Neomariopteris*	Filicales	Lele *et al*., 1981
Convolutispora	Reticulate trilete spore	*Pecopteris*	Marattiales	Laveine, 1969
		Biscalitheca	Zygopteridales	Cridland, 1966
		Senftenbergia	Leptosporangiate fern	Remy & Remy, 1955
Triquitrites	Zonotrilete spore	*Phlebopteris*	Leptosporangiate fern	Potonié, 1962
Cristatisporites	Zonotrilete spore	*Sporangiostrobus*	Lycophyta	Chaloner, 1962 ; Leisman, 1970
Gondisporites	Zonotrilete spore	**Lycopods**	Lycophyta	Bharadwaj & Venkatachala, 1968
Laevigatosporites	Monolete laevigate spore	*Bowmanites*	Sphenophyta	Courvoisier & Phillips, 1975 ; Potonié & Kremp, 1956
		Sphenophyllum	Sphenophyta	Bek & Opluštil, 1998
		Lycopsids	Lycophyta	Potonié, 1967
		Pecopteris	Marattiales	Laveine, 1969
		Scolecopteris	Marattiales	Millay, 1979 ; Millay & Taylor, 1984
		Zeilleria *(L. minimus)*	Leptosporangiate fern	Thomas & Crampton, 1971
Thymospora	Monolete sculptate spore	*Scolecopteris*	Marattiales	Wilson & Venkatachala, 1963 ; Millay & Taylor, 1984
		Asterotheca	Marattiales	Wilson & Venkatachala, 1963
		Pecopteris	Marattiales	Doubinger & Grauvogel-Stamm, 1971
Florinites	Mono-saccate	*Ernestiodendron* *Lebachia* *Walchiostrobus*	Coniferales	Potonié & Kremp, 1956 ; Bharadwaj & Venkatachala, 1968
		Cordaitanthus	Cordaitales	Millay & Taylor, 1974, 1976
Potoniesporites (Vestigisporites – Bharadwaj, 1964)	Mono-saccate	*Lebachia*	Coniferales	Rothwell, 1982 ; Mapes, 1983 ; Rothwell & Mapes, 1988

		Barthelia	Coniferales	Rothwell & Mapes, 2001
		Walchianthus	Coniferales	Rothwell & Mapes, 1988
		Thucydia	Coniferales	Hernandez-Castillo *et al*., 2001
Illinites	Non-taeniate bisaccate	**Conifers**	Coniferales	Bharadwaj & Venkatachala, 1968
Pityosporites	Non-taeniate bisaccate	**Conifers**	Coniferales	Potonié & Kremp, 1956
Lueckisporites	Taeniate bisaccate	Early conifers e.g. *Sashina*	Coniferales	Clement-Westerhof, 1974
Protohaploxypinus	Taeniate bisaccate	***Arberiella* (Glossopteridales)**	Pteridospermophyta	Zavada, 1991
Striatopodocarpites	Taeniate bisaccate	***Arberiella* (Glossopteridales)**	Pteridospermophyta	Zavada, 1991
Vittatina	Polyplicate	**Gnetales / conifers**	Coniferales	Potonié, 1967
Entylissa	Mono-colpate	**Ginkgos / cycads**	Ginkgophytes / Cycadophytes	Potonié & Kremp, 1956

The microfloral assemblage from Mmamantswe reflects a parent flora of mostly lower order lycopods, sphenophytes and ferns. Seed ferns, gnetales, conifers, ginkgos, cycads and glossopterids were also present but belonged to the upland floras, accordingly they are not as well-represented in the peat deposit. This is consistent with postulated early Permian floras across Gondwana.

4.5 PALAEOENVIRONMENTAL RECONSTRUCTION

Most conspicuous in its absence is any striate bisaccate *Protohaploxypinus* pollen, produced by the glossopterids. Additionally, other saccate and non-saccate striates were extremely rare. Striates were already present in Gondwana by the Upper Carboniferous, earlier than in the northern hemisphere. Although an assemblage dominated by striate pollen is a hallmark of the Late Permian – Early Triassic, a fair amount of striate pollen was expected to be found in this sample. This was not the case, with only eight specimens of *Lueckisporites fusus*, the only "striate" bisaccate, and one specimen of *Vittatina scutata*, the only non-saccate striate. The scarcity of striates, the characteristic pollen of the Permian, is a strong taphonomic indicator of the local palaeoenvironment in which these coal floras existed.

Almost all coal swamp palynofloras are autochthonous deposits of woody swamps (Traverse, 2007). However, Smith (1984) concluded that most coal deposits in Botswana were allochthonous because plant remains within the coals are very fragmented. Falcon (1978) illustrates how different peat accumulation scenarios result in characteristic microfloral assemblages. *In situ* deposition results in low species diversity, with the assemblage mostly composed of spores, and little pollen. *In situ* deposition, with accompanying wind and water dispersal results in fair species diversity, with an equal ratio of spores to pollen. A site which receives palynomorphs predominantly from wind dispersal results in an abundant species diversity, mostly consisting of pollen with few spores.

The scarcity of striate pollen in the Mmamantswe assemblage indicates a definite autochthonous origin, meaning that parent floras (higher order gymnosperms) were simply not growing in or around the coal swamp. Input was almost entirely from the many lower order plants in the swamp itself. Additionally, the swamp must have been low-lying, as peat deposits on high level plateaux are subject to receiving canopy component pollens from upvalley winds (Moore *et al*., 1991). This is similar to the assemblage of Kemp (1975), who also did not find any striates from the Buckeye Formation, Antarctica (which correlates to Biozone A of MacRae, 1988). Kemp attributed this to preservational factors, and not a biostratigraphic indicator.

Stephenson and McLean (1999) observed a close relationship between palynology and lithology at Morupule, Botswana. Small trilete miospores dominated coals, while carbonaceous mudstones were abundant in gymnospermous bisaccate pollen. Although not the same pattern as observed at Mmamantswe, this finding shows that microfloral make-up may be strongly influenced by environmental controls.

4.6 CHRONOLOGY

Across Gondwana, glacial assemblages of the Late Carboniferous are dominated by monosaccate pollen along with trilete spores, and non-striate and striate bisaccates are only a minor component. In the Middle Permian, an ‘explosion’ of striate pollen took place, and by the Late Permian, striates, particularly bisaccates, dominate microfloral assemblages. These characteristic patterns of change through the Permian are

recognised and described by many (Hart, 1970; Falcon, 1975; Anderson, 1977; MacRae, 1988; Besems & Schuurman, 1987; Venkatachala *et al*., 1995; McLoughlin *et al*., 1997; Traverse, 2007; Prevec *et al*., 2009). In fact, the difference between Early and Late Permian microfloral assemblages is so great that Traverse places the Palaeophytic - Mesophytic boundary in the mid-Permian (patterns of plant evolution do not exactly mirror those of marine life and terrestrial vertebrates, thus the Palaeophytic, Mesophytic, and Cenophytic periods demarcate distinct eras of vascular plant life). The Lower Permian floras are actually more similar to the Upper Carboniferous floras than to those of the Upper Permian.

The Mmamantswe microfloral assemblage does not resemble the No. 4 and 5 Seams, Witbank (Falcon *et al*., 1984; Aitken, 1994), or the Top Seam, Vereeniging (Millsteed, 1994). These assemblages are dominated by striate bisaccates, with fewer trilete spores and monosaccates, and a minor component of monolete and alete spores. Conversely, the Mmamantswe assemblage is dominated by trilete and alete spores. Non-taeniate bisaccate and monosaccate pollen was scarce, and striates extremely rare (only two species).

A transition from monosaccate dominance in Zone 1, to equal numbers of bisaccates and monosaccates in the upper zones, was seen. However, due to the relative lack of abundance of the saccate genera, identifying patterns within these groups required some caution. The presence of non-taeniate bisaccates in Zone 1, although they were extremely rare, suggests that the Mmamantswe samples do not represent a glacial flora, as Late Carboniferous assemblages tend to contain monosaccate pollen only, along with spores (see references above). For example, Australian glacial palynofloras are dominated by trilete spores with up to 10% monosaccate pollen, while Indian glacial assemblages are dominated by monosaccates instead, and few trilete spores (Traverse, 2007). This assemblage was of the “Australian” type, with a maximum of 5 % monosaccate pollen in Zone 1. Three species of monosulcate pollen (one striate) were also found, confirming that the sample must be Permian in age.

As the Mmamantswe palynoflora does not possess the characteristic “signature” of either the Late Carboniferous glacial floras, or the mid-Permian coal floras, but rather elements of both eras, it is thought to represent a cross-over assemblage dating to soon after the Permo-Carboniferous boundary.

4.7 GONDWANA CORRELATIONS

Microfloral patterns that assist with establishing chronology and correlations across Gondwana are the appearance and diversification of monosaccates, cheilocardioid spores, *Cycadopites* pollen, and taeniate and nontaeniate bisaccates (Stephenson, 2008). Generally, trilete, alete and monolete spores are relatively long-ranging through time, and do not assist much with correlations. Quantitative changes in these spores represent fluctuating conditions in the immediate environment (Falcon, 1978). Floras producing the saccate pollens were less subject to localised fluctuations in water availability and represent upland and climax vegetation (Falcon, 1989). Therefore, the saccate pollens are important biostratigraphical tools, and enable correlations across Gondwana. Accordingly, the following species of saccate pollens were primarily considered when correlating the Mmamantswe assemblage to a recognised biozone:

Monosaccates:

- *Sulcatisporites splendens*
- *Cannanoropollis densus*
- *Florinites similis*
- *Cordaites rotata*
- *Potonieisporites barrelis*

Bisaccates:

- *Lueckisporites fusus*
- *Illinites unicus*
- *Pinuspollenites labdacus*
- *Vestigisporites gondwanensis*

It was hypothesised that Mmamantswe would be most similar to other closely situated coalfields. This was generally not the case. Stephenson and McLean's work in Morupule, Botswana (1999) contained many of the same genera as seen at Mmamantswe, but not many of the same species. Due to most of the similar taxa being long-ranging spores, it is difficult to say how closely the two assemblages are associated. Most of the saccates (many of which are striate bisaccates) from Morupule were not found at Mmamantswe, suggesting a different age for these deposits

(Morupule coals are Aktastinian* in age). However, it is known that certain saccate genera are "missing" from Mmamantswe due to environmental controls. Since it is impossible to infer exactly what species are not present, perhaps Morupule and Mmamantswe floras were in fact very similar. More palynological work around Botswana is necessary to gain greater clarity on this issue.

When compared to the species lists of Falcon (1975), Anderson (1977), and MacRae (1988), it is clear that species from Mmamantswe do not fit neatly into a designated biozone, probably due to biased preservation resulting from the autochthonous assemblage of the peat swamp. For this reason, the cores from Mmamantswe are tentatively correlated with the following Assemblage Zones: Assemblage Zones II and III of Falcon (1975a); Biozones B and C of MacRae (1988); and Zones 1, 2 and 3 of Anderson (1977).

Although the Waterberg assemblage of MacRae (1988) had the most species in common with Mmamantswe, patterns of biozonation did not correspond very well. Biozone A of MacRae is dominated by triletes (up to 98% of the total count) and monosaccates (up to 56%). Many species present in this biozone were not present at Mmamantswe, eliminating it from consideration. Biozones B and C corresponded well to Mmamantswe on the species encountered. However, many of the distinctive concurrent range zone taxa selected by MacRae are long-ranging spores, complicating correlation. In Biozone E, there is a marked increase of zonotriletes, similar to that found in the upper part of the Mmamantswe core. However, Biozone E contained equal amounts of non-taeniate bisaccates and striates. This was certainly not the case at Mmamantswe. Importantly, the increase in zonotriletes at this level may not be a stratigraphic marker, but simply indicate wetter swampier conditions (Beukes, 1985). Zonotrilete spikes also occurred at slightly different intervals in MacRae (1988) and Falcon (1975), suggesting that perhaps this spike is not a reliable stratigraphic indicator.

The Assemblage Zones of Falcon (1975) present a problem. Assemblage Zone I contains many of the same genera as Mmamantswe. This zone was quantitatively dominated by monosaccates, which was not the case in the present study, although monosaccates were dominant over bisaccates in the lower part of the

*See Appendix C for International Stratigraphic Chart

Mmamantswe core, suggesting a link between these zones. Assemblage Zone II was a transition zone containing elements of Zones I and III, and also resembled the upper part of the Mmamantswe core. Assemblage Zone III is termed the *Densosporites*-Gondispore assemblage, and although *Densosporites* was not found at all, *Gondisporites* showed a marked increase in Zone 5 at Mmamantswe (upper part of the core). However, bisaccates represented 20-40% of the Falcon assemblage, and Striatiti, 10-20%, unlike in Botswana.

The later study by Falcon in the Witbank coalfield (No. 2 Seam) yielded an assemblage that showed greater similarity to the Mmamantswe microflora. Both seams contained an abundance of trilete spores. Additionally, the introduction of many new taxa was observed throughout the accumulation of the No. 2 Seam, suggesting a warming climate. This is a similar pattern to that observed at Mmamantswe. The lower part of the No. 2 Seam was monosaccate-rich, while Mmamantswe contained more monosaccates than bisaccates in the lowermost Zone 1. In the upper part of the No. 2 Seam, striate bisaccate and plicate pollen are observed for the first time. The same patterns are visible in the Mmamantswe sediments, except that the bisaccates are non-striate, and many of the same species are present. Since the No. 2 Seam has been correlated to the Bottom and Middle Seams in Vereeniging (Millsteed, 1994), a link to the latter coals can also be made. The No. 2 Seam was assigned to the "Dwyka-Ecca" changeover and given an Early Permian age (Falcon, 1988, 1989).

Zones 1, 2 and 3 of Anderson (1977) are also problematic. Each zone contains some taxa common to Mmamantswe, but not others. However, higher zones bear less of a resemblance to the Mmamantswe microflora and accordingly are excluded as possible correlations. Zones 1, 2 and 3 are assigned to the Dwyka, Lower Ecca, and Middle Ecca sediments, which does not give fine resolution when establishing chronology.

Mmamantswe showed only superficial similarities with the following Biozones: Zones I and II of Aitken (1998), and Concurrent Range Zones I and II (MacRae, 1978). Many species included in these zones were not found in Botswana. Accordingly, no correlations are made using these systems at the present time. No strong similarities were seen between Mmamantswe and localities in Australia, South America, India or Madagascar.

The assemblage that bore the greatest resemblance to Mmamantswe was from Milorgfjella, Dronning Maud Land, Antarctica (Larrson *et al*., 1990). The Milorgfjella microflora is Asselian-Sakmarian in age, and was dominated by trilete spores (50-70%). *Punctatisporites gretensis*, *Punctatisporites parvus*, *Granulatisporites* spp., *Microbaculispora tentula*, *Horriditriletes* spp. and *Verrucosisporites andersonii* were the most abundant taxa. Gymnosperm pollen grains included *Plicatipollenites* spp. and *Cannanoropollis* spp. The monosulcate *Cycadopites cymbatus* also present. A comparison of the species lists shows almost all of the same genera, and many of the same species present in both Botswana and Antarctica. This resemblance is attributed to similar chronologies as well as similar palaeoenvironments. Smaller grains from both Milorgfjella and Mmamantswe were well-preserved, while larger saccates were fragmentary or torn. This was attributed to gymnosperm pollen being transported from higher upland floras into the autochthonous coal swamp.

4.8 IMPLICATIONS FOR THE PERMO-CARBONIFEROUS BOUNDARY

All of the major Biozonation schemes for Permo-Carboniferous sediments in southern Africa are not recent. This creates problems with stratigraphical correlation. The South African Committee for Stratigraphy revised the lithostratigraphy of the Karoo in 1980, redefining the Dwyka Group as glaciogenic sediments only. The 'Upper Dwyka Shales' and 'White Band', containing *Mesosaurus*, were moved to the Ecca Group. This has problematic implications for publications before 1980, most notably that of Anderson (1977). Additionally, Zone 1 of Falcon (1975), termed "Dwyka", represents the lowest coals and carbonaceous shales of the Black Shales and Coals. Due to this, there is discrepancy in the literature between palynological and lithological ages.

Backhouse (1991) assigned Zone 1 of Anderson (Dwyka sediments) an Asselian age by comparison with Western Australian calibrated palynozones. This conflicts with Bangert *et al*., (1999) assigning a Carboniferous age to the Dwyka sediments. However, the most recent International Stratigraphic Chart (2009) places 290 Ma in the middle Sakmarian, significantly younger than the age of the Permo-Carboniferous boundary as referred to by Bangert *et al*.. Due to constant revisions of lithostratigraphy, the same time period mentioned in papers that are published years apart does not necessarily refer to the same age anymore.

Further complicating matters is that many palynologists and geologists automatically assigned any diamictites / tillites to the Dwyka Group (Plumstead, 1966; Utting, 1976) without being aware that tillites also formed through the Permo-Carboniferous boundary and early Ecca due to isolated highland "cold spots" where portions of ice remained (Falcon, 1989). Additionally, glacial runoff formed numerous river systems causing reworking of some already-formed diamictites and incorporation into early Ecca lithologies. This was illustrated in South Africa during the earlier part of the 20th century, where tillites / glacigene deposits were used as a marker to stop drilling for coal (Falcon, 1975b). However, further investigation revealed thin coal bands in "Dwyka" sediments of the Free State, southern Transvaal, Springbok Flats and Namibia. These must be reworked sediments from earlier true tillites, in order to contain coal.

It is thought by the author that the above are the cause for why it is difficult to precisely place the Permo-Carboniferous boundary in Gondwana by palynology. Although biostratigraphic correlations (for refs see Stephenson *et al*., 2007) place deglaciation in the late Asselian or early Sakmarian, the absolute dating study of Bangert *et al*., (1999) puts the boundary in the earliest Asselian. The use of biostratigraphic correlation may imply that deglaciation was an isochronous and rapid event, with flora and fauna across a wide region all being subject to similar climatic influences. This was most likely not the case. Deglaciation was actually a complex and slow process involving four deglaciation sequences, with ice melting at different rates depending on geography and microclimate (Visser, 1990; Herbert & Compton, 2007). Until such time as finer resolution regarding the timing of deglaciation can be established, the Mmamantswe assemblage is tentatively placed in the Sakmarian and Early Artinskian periods, slightly older than the coals of Morupule and a similar age to the No. 2 Seam, Witbank.

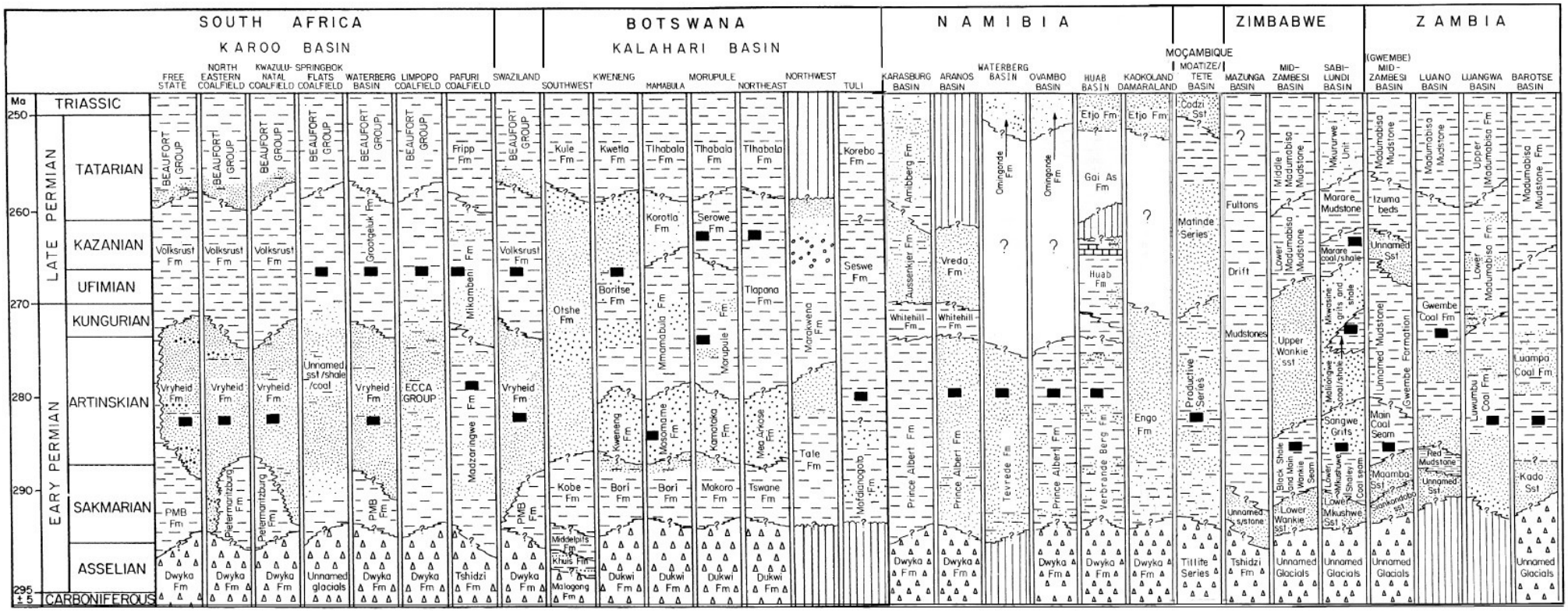
It is suggested that the discrepancy that currently exists between Permo-Carboniferous palynological and lithological data is artificial, resulting from changes in definition of stratigraphic units, and mistaken assignment of lithologies to particular time frames. It does not reflect a natural conflict inherent in the floras themselves. Unfortunately, a complete revision of all the earlier biozonation schemes would be necessary to truly solve this problem. A comparison of the current palynological and lithological interpretation of the Carboniferous and Permian periods is presented below, in order to identify specific inconsistencies.

4.9 CORRELATION OF PERMIAN STRATA IN SOUTHERN AFRICA

Researchers from South Africa (MacRae, 1988; Millsteed, 1994; Visser, 1992; Cairncross, 2001), Botswana (Key *et al*., 1998), Zimbabwe (Kreuser, 1994; Oesterlen and Millsteed, 1994), and Zambia (Utting, 1978; Kreuser, 1994) agree that the palynological age for Permian coal deposits is Artinskian–Kungurian and for younger coals, Ufimian–Kazanian (Figure 4.3). However, this does not always agree with lithological correlations, emphasising the stratigraphic complexity of Karoo sediments in both the Main and subsidiary basins. Complexity is due to local facies discontinuities, structural highs and faulting, with only a single depository being unlikely (Cairncross, 2001). Additionally, absolute ages for the Permian coals are difficult to determine (Cairncross, 2001). For these reasons there is some disagreement in the literature regarding correlation of Karoo strata. Both palynological and geological interpretations are summarised below.

Cairncross (2001) correlated the Permian strata of south-central Africa, incorporating palynological data (Figure 4.3). The various formations do not correlate exactly with the various Permian time periods. Ages of coal-bearing strata have been determined by palynology (using above references), thus all are confined to either the Artinskian–Kungurian, or the Ufimian–Kazanian. In the Mmamabula area of Botswana, the Mmamabula and Korotlo Formations are shown as **not** containing coal (or being "main" coal-forming formations), both of which are incorrect (Smith, 1984). The upper part of the Mmamabula Formation and the entire Korotlo Formation are equivalent to the Volksrust and Grootegeluk Formations of the Waterberg Coalfield (Figure 4.3).

Figure 4.3 **Correlation of the various formations of the Ecca Group in South Africa, Botswana, Zimbabwe, Zambia, Namibia and Mozambique by palynology (from Cairncross, 2001). Black squares represent "the main coal-forming periods". The "Korotla" (sic) Formation is actually the Korotlo Formation, and the "Mosomame" (sic) Formation, the Mosomane Formation.**



The above interpretation differs somewhat from that of Catuneanu *et al*. (2005), who present a synthesis of work drawn from lithological studies around southern and central Africa (Table 4.2). Ages of coal-bearing strata generally agree with the available palynological data. However, there are some discrepancies, with coal present in the pre-Artinskian formations of Madzaringwe in South Africa, Lower Mkushwe Shale & Black Shale of Zimbabwe, Luwumbu Coal Formation in Zambia, and the Productive Series in Mozambique. The Grootegeluk and Korotlo Formations are regarded as being equivalent, while the Mmamabula Formation corresponds to the upper Vryheid Formation in the Waterberg. As in Cairncross (2001), the Mmamabula and Korotlo Formations are shown as **not** containing coal, whereas they actually do (Smith, 1984).

Table 4.2 **Correlation of the various formations of the Ecca Group in South Africa, Botswana, Zimbabwe, Zambia, Namibia and Mozambique by lithology (after Catuneanu *et al*., 2005). Formations do not necessarily correlate exactly to time periods. Lithologies are indicated in brackets (mds = mudstones, sst = sandstones, slt = siltstones, cgl = conglomerates, lms = limestones). Coal-bearing formations are highlighted in bold type. As in Fig. 4.3, for Korotla (sic) Formation, read Korotlo, and Mosomame (sic) Formation, read Mosomane.**

<table>
<tr><th colspan="6">ECCA GROUP</th></tr>
<tr><td></td><td colspan="4">Early Permian</td><td>Late Permian</td></tr>
<tr><td>BASIN</td><td>Asselian</td><td>Sakmarian</td><td>Artinskian</td><td>Kungurian</td><td>Ufimian/Kazanian</td></tr>
<tr><td>S.A.</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Main Karoo (southwest)</td><td rowspan="3">Prince Albert (mds)</td><td rowspan="3">Whitehill (carbonaceous mds)& Collingham (tufa, mds)</td><td>Skoorsteenberg (sst, mds), Tierberg (mds)</td><td colspan="2">Kookfontein (mds) & Waterford (sst)</td></tr>
<tr><td>(south)</td><td>Laingsburg (sst, mds), Vischkuil (mds, sst)</td><td colspan="2" rowspan="2">Fort Brown, Waterford (mds, sst)</td></tr>
<tr><td>(southeast)</td><td>Ripon (sst)</td></tr>
<tr><td>(north and northeast)</td><td colspan="2" rowspan="2">Pietermaritzburg (mds, slt)</td><td colspan="2" rowspan="2">Vryheid (mds, sst, slt, cgl, coal)</td><td rowspan="2">Volksrust Shale (mds, slt)</td></tr>
<tr><td>Lebombo</td></tr>
<tr><td>Springbok Flats</td><td colspan="5">Hammanskraal (sst, mds, coal)</td></tr>
</table>

ECCA GROUP					
	Early Permian				Late Permian
BASIN	**Asselian**	**Sakmarian**	**Artinskian**	**Kungurian**	**Ufimian/Kazanian**
Lephalale (Ellisras)	Wellington (mds)	**Swartrant (sst, mds, coal)**			**Grootegeluk (mds, coal)**
Tshipise (Soutpansberg)	**Madzaringwe (sst, mds, coal)**			**Mikambeni (slt, mds, coal)**	
BOTSWANA					
Kalahari (southwest)	Kobe (mds)		Otshe (pebbly sst)		
Morupule & southeast	Makoro (mds)		Kamotaka (pebbly sst)	**Morupule (carbonaceous mds, coal)**	Serowe (carbonaceous mds)
Kweneng & West Central Kalahari	Bori (mds)		Kweneng (sst)	**Boritse (sst, coal)**	
Mmamabula & east			**Mosomame* (pebbly sst, coal)**	Mmamabula (carbonaceous mds, pebbly sst)	Korotla* (slt)
(northeast)	Tswane (mds)		Mea Arkose (pebbly sst)	Tlapana (mds)	
(northwest)	Tale (mds, pebbly mds)			Marakwena (pebbly sst)	
Tuli	Mofdiahogolo (mds)		**Seswe (mds, carbonaceous mds, coal, sst)**		
ZIMBABWE					
Tuli (Save)	Unnamed sandstone	Fultons Drift Mudstones			
Save	Lower Mkushwe Sandstone	**Lower Mkushwe Shale (coal)**	Songwe Grits (pebbly sst, sst)	**Malilongwe Shale (coal) & Mkwasine (pebbly sst, sst, mds)**	**Marare Mudstone (coal)**
Mid-Zambezi (Wankie)	Lower Wankie Sandstone	**Black Shale (mds, coal)**	Upper Wankie Sandstone		Lower Madumabisa Mudstone
ZAMBIA					
Mana Pools (Gwembe)	Siankandobo & Maamba (sst)		**Gwembe Coal (sst, mds, coal)**		

<table>
<tr><th colspan="6">ECCA GROUP</th></tr>
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<tr><td>BASIN</td><td>Asselian</td><td>Sakmarian</td><td>Artinskian</td><td>Kungurian</td><td>Ufimian/Kazanian</td></tr>
<tr><td>Lukusashi (Luano)</td><td colspan="2">Unnamed sst & red muds</td><td colspan="2"></td><td></td></tr>
<tr><td>Luangwa</td><td colspan="4">Luwumbu Coal Formation (sst, slt, mds, coal)</td><td rowspan="2">Lower Madumabisa (sst, mds)</td></tr>
<tr><td>Barotse (central Zambia)</td><td colspan="2">Kado Sandstone</td><td colspan="2">Luampa Coal (sst, mds, coal)</td></tr>
<tr><td colspan="6"></td></tr>
<tr><td>NAMIBIA</td><td colspan="2"></td><td colspan="2"></td><td></td></tr>
<tr><td>Karasburg</td><td>Prince Albert (mds)</td><td rowspan="2">Whitehill (mds)</td><td colspan="3">Aussenkjer (sst, mds)</td></tr>
<tr><td>Aranos</td><td>Prince Albert (sst, mds, coal)</td><td>Vreda (sst)</td><td>*missing*</td><td>*missing*</td></tr>
<tr><td>Waterberg</td><td>Tevrede (cgl, sst, mds, coal)</td><td></td><td colspan="2">*missing*</td><td>*missing*</td></tr>
<tr><td>Ovambo</td><td colspan="2">Prince Albert (sst, slt, mds, coal)</td><td colspan="2">*missing*</td><td>*missing*</td></tr>
<tr><td>Huab</td><td colspan="2">Verbrande Berg (sst, mds, carbonaceous mds, coal) & Tsarabis (sst, slt, mds) Huab (=Whitehill) (slt, mds, lms)</td><td colspan="2">*missing*</td><td>*missing*</td></tr>
<tr><td colspan="6"></td></tr>
<tr><td>MOZAM-BIQUE</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Tete</td><td colspan="4">Productive Series (pebbly sst, sst, carbonaceous mds, coal)</td><td>Matinde Series (sst, mds)</td></tr>
<tr><td colspan="6"></td></tr>
</table>

Of note is that the Dibete Formation is not represented in the diagrams of Cairncross (2001) or Catuneanu *et al*. (2005). However, the Upper coal seam at Mmamabula is contained within the Dibete Formation (Smith, 1984), thus its importance is clear.

4.10 LITHOLOGY OF MMAMANTSWE

The coal seams at Mmamantswe can be correlated to the Vryheid and Volksrust / Grootegeluk formations of the Ecca Group, with most of the coal hosted in the 50-60m of Volksrust Fm, interbedded with mudstones (Cronwright M., pers. comm.). However, the palynology indicates they were deposited at an earlier time than the accepted ages for these formations. Accordingly, the discrepancy between palynological and lithological results at Mmamantswe may imply diachronous deposition of Karoo lithologies in Botswana and South Africa. However, lithostratigraphical groups in Botswana and South Africa were deposited contemporaneously according to chronological studies (Key *et al*., 1998). Additionally, the Mmamabula and Morupule lithologies appear to agree with South African time frames for the Ecca formations. Since Mmamantswe differs significantly from other Botswana sites, this supports the hypothesis of it being a relatively protected autochthonous deposit.

An autochthonous origin for the Mmamantswe coals is also suggested by the core lithology. Mmamantswe is an unusual locality because no sandstones are interbedded with the coal layers, unlike most Permian coals in southern Africa (e.g. Cadle *et al*., 1993; Cairncross, 2001). Smith (1984) suggested allochthonous floodplain deposits were responsible for peat accumulations in Botswana. However, this is contra-indicated by the lack of sandstone deposits at Mmamantswe, further supporting a swamp-lacustrine depositional environment.

Most interestingly, the lithology of Mmamantswe is differs from that of its close coal-bearing neighbours, the Waterberg and Mmamabula. The Waterberg consists of basement granites, tillites, next a unit of sandstones and siltstones, and then coal interbedded with carbonaceous mudstones, siltstones, sandstones and conglomerates (MacRae, 1988). Mmamabula hosts basement Waterberg quartzites instead of tillites, and coals are interbedded with sandstones as well as mudstones (Smith, 1984; Williams & Loveday, 2006). The combination of a different lithology as well as an unusual palynology at Mmamantswe suggests a protected microclimate with depositional controls that differed from other peat accumulations in southern Africa. Topography was likely responsible for this. It has already been recognised that there are lithological differences between Mmamabula and Mmamantswe (Smith, 1984). They are attributed to a small graben at Mmamantswe with pre- and post-Karoo faulting. However, it is

commonly stated in the scientific literature that the Mmamabula / Mmamantswe / Dibete area is continuous with the Waterberg (Ellisras) Coalfield of South Africa (e.g. Haughton, 1963; Green, 1966, 1973; Rust, 1975; Stephenson & McLean, 1999; Cairncross, 2001; Fichani, 2003). This is also maintained in company technical reports who are involved in mining in the area (Figure 4.4).

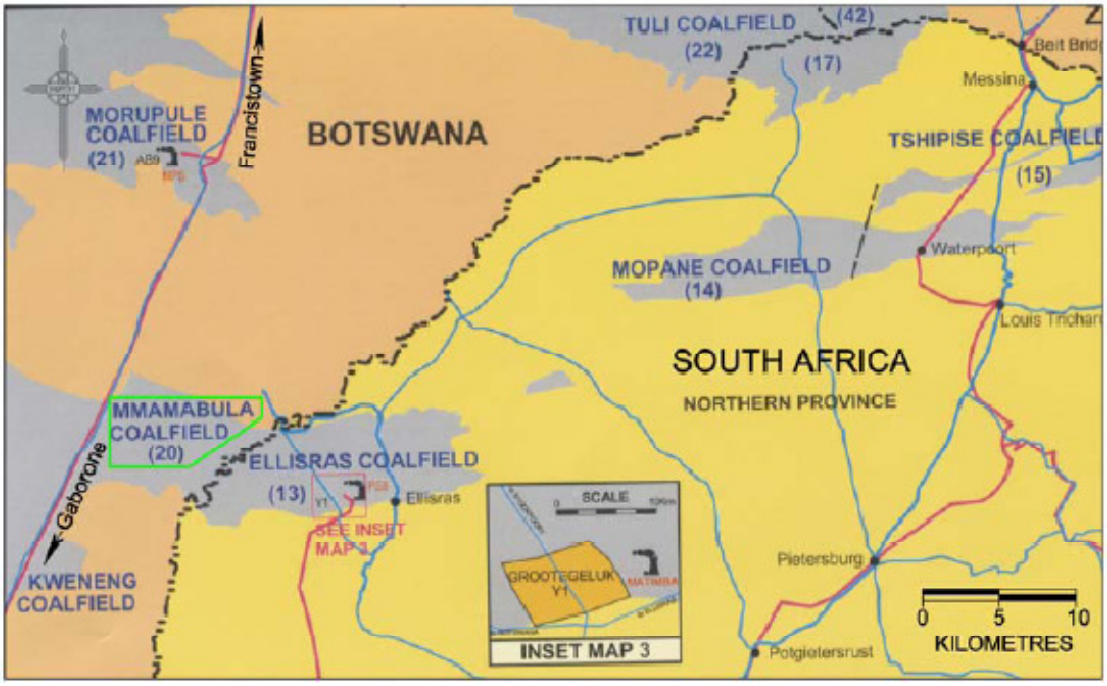

Figure 4.4 **Locations of the Mmamabula – Mmamantswe and Waterberg (Ellisras) coalfields (Williams & Loveday, 2006).**

The Grootegeluk mine in the Lephalale area of the Waterberg is 50km due east of the Mmamabula area. Geologically, the Mmamantswe and Grootegeluk coal measures in the Waterberg coalfield are very similar (Cronwright, M., pers. comm.), suggesting they formed in similar environments. Both the Soutpansberg (Tshipise) and Waterberg coals were deposited in a floodplain setting under anoxic conditions, producing vitrinite-rich coals which are interbedded with carbonaceous mudrocks or siltstones (Roberts, 1991; Snyman & Botha, 1993). This is the same environmental setting as postulated for the Mmamabula area coals, and corresponds with the lithology of the area. However it does not correspond with the environmental setting of Mmamantswe, complicating the task of determining whether the Mmamabula and Waterberg coalfields are congruent. Ideally the palynology of Mmamabula should be investigated in order to solve this problem.

4.11 CONCLUSIONS AND FUTURE WORK

The Mmamantswe microfloral assemblage has been assigned an Early Permian age (Sakmarian and Early Artinskian) and is most similar to the microflora from Milorgfjella, Antarctica. The coal seam assemblage which bears the greatest resemblance to Mmamantswe is the No. 2 Seam, Witbank, South Africa. Similarities are as a result of palaeoenvironmental controls as well as chronology. Further sampling from coal strata in Botswana and South Africa, as well as a revision of the biozonation schemes for the Karoo and subsidiary basins, is thought necessary to more accurately correlate palynological to lithological ages in southern Africa.

Palynology can be a useful tool for both stratigraphic correlation and palaeoenvironmental reconstruction. As with all other forms of data from the fossil record, palynology works best when integrated with lithology, macroflora and absolute dating if possible. Sampling of new strata and reassessment of work by previous authors will go some way towards improving the palynomorph record for southern Africa. This has both research and economic significance. In the present day, energy sources all over the world are becoming increasingly limited. It is vital to accurately assess the return of mining operation in advance, by using as many stratigraphic tools as possible in order to promote more selective and sustainable exploration. Palynological assessments can provide an additional means of predicting coal quantity and quality, by comparison with existing productive coal seams, and by estimation of thermal maturity.

Although many coal assemblages in southern Africa have been studied for the above reasons, the Mmamantswe palynoflora upholds the notion that coal floras tend to be autochthonous assemblages. This is not as helpful for stratigraphic correlation both intra-basinally and across Gondwana. In order to better understand the floras living at this time, deposits not containing coal should also be investigated, in order to provide a more complete look at the floral composition of the Permian. Additionally, the results from Mmamantswe indicate that environment can have a strong influence on quantitative trends among spores and pollen. This suggests that defining biozones, or making correlations on the basis of abundance patterns alone, may be unsound. Qualitative and quantitative data should always be used in conjunction to establish biostratigraphy.

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APPENDIX A: Coalfields of south-central Africa (addendum to Figure 1.4)

South Africa

1 – Free State

2 – North Eastern Coalfield

3 – Kwazulu-Natal Coalfield

4 – Springbok Flats

5 – Waterberg Basin

6 – Limpopo

7 – Pafuri

8 – Swaziland

Botswana

9 – Southwest

10 – Kweneng

11 – Mmamabula

12 – Morupule

13 – Northeast

14 – Northwest

15 – Tuli

Namibia

16 – Karasburg Basin

17 – Aranos Basin

18 – Waterberg Basin

19 – Ovambo Basin

20 – Huab Basin

21 – Damaraland

Angola

22 – Angola

Zimbabwe

23 – Mazunga Basin

24 – Mid-Zambesi Basin

25 – Sabi-Lundi Basin

Zambia

26 – Gwembe / Mid-Zambesi Basin

27 – Luano Basin

28 – Luangwa Basin

29 – Barotse Basin

Malawi

30 – Southern Coalfields

31 – Ngana area

32 – Livingstonia area

Mozambique

33 – Moatize / Tete Basin

Tanzania

34 – Ruhuhu Basin

35 – Mhukuru Basin

36 – Luwegu Basin

APPENDIX B: Tilia data

Raw data input contained in the original Tilia program is included on the accompanying CD. VarCodes for each species refer to their plate positions. Codes for turmal groups were designated so as not to conflict with default codes in the Tilia program. All groups contributed to the total pollen sum.

Codes for Turmal Groups

Azonotriletes - C
Monoletes - D
Aletes – E
Incertae sedis & hilates - I
Zonotriletes – H
Monosaccates - J
Bisaccates - K
Monosulcates - L

APPENDIX C: International Stratigraphic Chart for the Carboniferous and Permian periods

Divisions are not to scale (from *ICS*, August 2009)

Period	Epoch	Stage	Substage	Age (Ma)
PERMIAN	Late (Lopingian)	Tatarian	Changhsingian	251.0 ± 0.4
			Dorashmian	253.8 ± 0.7
		Kazanian	Wujiapingian	
			Dzhulfian	
			Longtanian	
			Rustlerian	
			Saladoan	260.4 ± 0.7
	Middle (Guadalupian)	Ufimian	Capitanian	265.8 ± 0.7
			Wordian	268.0 ± 0.7
			Roadian	270.6 ± 0.7
	Early (Cisuralian)	Kungurian	Irenian	
			Filippovian	
			Leonard	275.6 ± 0.7
		Artinskian	Baigendzinian	

				Aktastinian	
			Sakmarian	Sterlitamakian	284.4 ± 0.7
				Tastubian	
				Leonard	
				Wolfcamp	
			Asselian	Krumaian	294.6 ± 0.8
				Uskalikian	
				Surenian	
				Wolfcamp	
CARBONIFEROUS	Pennsylvanian	Upper	Gzelian		299.0 ± 0.8
			Kasimovian		303.4 ± 0.9
		Middle	Moscovian		307.2 ± 1.0
		Lower	Bashkirian		311.7 ± 1.1
	Mississippian	Upper	Serpukhovian		318.1 ± 1.3
		Middle	Visean		328.3 ± 1.6
		Lower	Tournaisian		345.3 ± 2.1
					359.2 ± 2.5

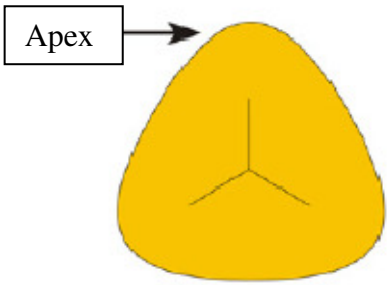
APPENDIX D: GLOSSARY

This glossary was primarily compiled using the work of Punt *et al*. (2007) & Traverse (2007). Schematic illustrations are taken from Punt *et al*. (2007).

Alete – spores without a laesura

Allochthonous – miospores that are deposited a significant distance from their parent plant (*ant*. Autochthonous)

Amb – the "shape" or outline of a palynomorph



AOM – amorphous organic matter

Apex – (pl. apices) the tip or corner of a trilete spore

Apiculate – projections of the exine (positive ornamentation) e.g. baculi, echinae

Autochthonous – miospores that are deposited close to / in the same microenvironment as their parent plant (*ant*. Allochthonous)

Auriculate – zonate spores with a thickened projection of exine in the equatorial region

Baculate – a type of pollen ornamentation (see Figure 2.3) consisting of baculi

Bisaccate – pollen with two sacci, originating from conifers, Caytoniales and seed ferns

Bladder – used to describe the saccus of a monosaccate pollen grain

Cenophtytic – informal geological period of Traverse referring to the time of dominance for angiosperms. Dates from the Aptian to the Albian.

Cheilocardioid – heart-shaped spores

Cingulum – thickened outer extension projecting from the equator of a cingulate spore

Colpate – to describe pollens that have an exine with longitudinal grooves (colpi, *sing*. colpus)

Colporate – pollen with colpi also containing pores

Coronate – extension resembling a *cingulum*, but fringed

Corpus – the central body of a saccate pollen grain

Diploxynoid – shape describing a bisaccate pollen grain where the outlines of sacci and corpus are discontinuous, thus they form three distinct parts (ant. *Haploxynoid*)

Echinate - a type of pollen ornamentation (see Figure 2.3) consisting of echinae

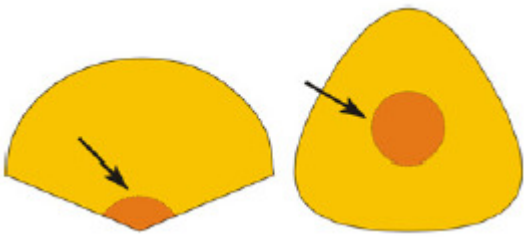
Equatorial view – lateral view from an aspect roughly halfway between the poles, and perpendicular to the polar axis

Exine – the outer, extremely resistant layer of palynomorphs, made up primarily of sporopollenin

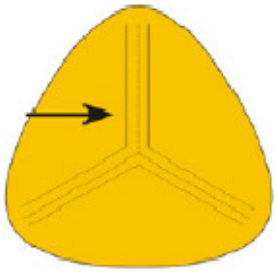
Gemmate - a type of pollen ornamentation (see Figure 2.3) consisting of gemmae

Haploxynoid – bisaccate pollen in which the outlines of corpus and sacci form a more or less continuous oval shape (*ant*. Diploxynoid)

Hilate – spores with a germinal aperture (hilum)



Labrum – lip-like thickening of the laesura (*pl*. Labra)



Laesura – trilete or monolete scar on the proximal face of a spore resulting from contact with the other three original members of the tetrad

Laevigate – describes the smooth exine of a spore (*syn*. *Psilate*)

LO analysis – adjusting the focus of a grain under light microscopy to establish whether its ornamentation consists of projecting elements, or if it is negatively sculptured. Projecting elements are bright in high focus and dark in low focus, while the opposite is true for negatively sculpture.

Mesophytic - informal geological period of Traverse referring to the time of dominance for coniferophytes, ginkgophytes, cycadophytes, and other gymnosperms. Dates from the mid-Permian to the Aptian (start of the *Cenophytic*).

Microflora – used here to refer to the assemblage of palynomorphs from a particular locality or floral province

Miospore – spores or pollen under 200 µm in size

Monolete – spore with a single-radius laesura

Monosaccate – pollen with a single saccus or bladder that extends all around the corpus, normally at the equator

Monosulcate – pollen with a single distal sulcus, used interchangeably with *monocolpate*

Morphotaxon (*morphospecies*, *morphogenus*) – artificial but necessary classing of fossil spores and pollen on the basis of their morphological characteristics and not their natural plant affinities

Ornamentation – used here to refer to projecting elements stemming from the exine of the miospore

Palaeophytic - informal geological period of Traverse referring to the time of the first land plant spores (Ordovician), to the beginning of the *Mesophytic*.

Palynomorph – a microscopic, robust-walled organic body found in prepared residues, normally in large numbers. Includes spores, pollen, dinoflagellates, acritarchs, cysts, scolecodonts, and chitinozoans.

Polar view – view from directly above one of the poles of the grain (ant. *Equatorial view*)

Pollen – the several-celled microgametophyte of seed plants

Polyplicate – pollen with many longitudinal thinnings in the exine, that are not colpi

Radius – a single arm of a trilete laesura

Reticulate – a type of pollen sculpture (see Figure 2.3) consisting of muri

Rugulate – a type of pollen sculpture (see Figure 2.3) consisting of irregular ridges which anastamose

Saccus – a wing-like extension extending beyond the main body of a pollen grain, found mainly in coniferous pollen

Sculpture - used here to refer to negative voids in the exine of the miospore

Spore – tiny unicellular reproductive body. If belonging to an embryophytic plant, it develops into a gametophyte, or may be fungal or algal in origin.

Sporopollenin – extremely resistant organic substance making up the majority of spore and pollen exine. It is destroyed only by oxidation or prolonged high temperature.

Striate – type of pollen sculpture (see Figure 2.3) consisting of multiple parallel grooves in the exine. Although not technically the same, the term is generally used interchangeably with *taeniate*.

Sulcus – single distal, elongate, longitudinal furrow in the exine of pollen

Taeniate – very similar to striate, but technically taeniae are strap-like, while striae are "streaky"

T.A.I. – Thermal Alteration Index, using organic matter colouration and vitrinite reflectance data to establish thermal maturity of a rock

Torus – invagination of the exine surrounding the radii of a trilete laesura (syn. *Kyrtome*)

Trilete – spore with a three-armed laesura (Y-mark)

Turma (*anteturma*, *infraturma*, *subturma* etc.) – an artificial system of grouping developed by Robert Potonié for fossil spores and pollen (mostly useful for Palaeozoic miospores)

Verrucate - type of pollen sculpture (see Figure 2.3) consisting of verrucae

Zonate – spore with a thin zone or similar equatorial extension