Palynofacies of the Lower Number 4 Coal Seam (Highveld Coalfield, South Africa)

by

Susan Serfontein

Student number: 27023398

Submitted in partial fulfillment of the requirements for the degree of MSc Geology

In the Faculty of Natural and Agricultural Sciences

University of Pretoria

Pretoria

November 2014

Supervisor: Dr. N. Lenhardt

Co-supervisor: Prof. A.E. Götz

Abstract

A palynofacies study of the lower number 4 coal seam in the Highveld coalfield of the Karoo Basin, South Africa, was conducted to get more insight into the palaeoenvironment. The lower number 4 coal seam was sampled near Secunda, approximately 200 km south east of Pretoria.

The Main Karoo Basin is classified as a retro-arc foreland basin, which covers an area of approximately 700 000 km^2 and can reach a maximum thickness of up to 12 km. The accumulation of coal in the Karoo Basin occurred during the Permian in the Vryheid Formation of the Ecca Group.

There are two palynofacies assemblages representing different depositional environments. The first palynofacies assemblage identified in the bottom section of the coal seam is characterised by the presence of high amounts of spores and equidimensional phytoclasts. This indicates that it may have formed during wet cooler conditions with less transport.

The second palynofacies assemblage and top section of the coal seam is characterised by an increase in bisaccate pollen grains and improved sorting of the phytoclasts. This signature may indicate a higher fluvial influx into the swamp with the higher amount of taeniate bisaccate pollen grains showing that the palaeoenvironment was warmer during deposition. The *Protohaploxypinus sp.* from the glossopterid plant was the dominant flora in the upland area while the lowland is indicative of fern wetland communities.

The lower number 4 coal seam depositional environment therefore changed from swamp to increased fluvial input into the swamp.

There are also barren samples that were due to the igneous intrusion in the proximity of the sampled area. The igneous intrusion formed a devolitalisation zone that reached a thickness of 17 to 19 m. The increase in temperature adjacent to the dolerite dyke caused the organic matter surrounding it to mature, which could possibly create gas pockets.

Declaration

I, Susan Serfontein declare that the thesis/dissertation, which I hereby submit for the degree MSc Geology at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

SIGNATURE: ....

DATE: 04/12/2014

Acknowledgements

I would like to thank my supervisor, Dr. N. Lenhardt, for his advice and patience in reviewing all the chapters of my research project. I also wish to extend a special word of thanks to my co-supervisor, Prof. A.E. Götz, for sample preparation and her guidance with and contributions to my studies. I am grateful to J.P. Bussio for providing me with the samples. I would also like to acknowledge my friends for taking the time to read and give me feedback on my project.

Finally, I would like to express my gratitude to my parents, Bernard and Louise Serfontein, for their support and financial assistance during my studies.

Table of contents

List of figures

List of tables

Chapter 1: Introduction

South Africa is the sixth largest coal producer in the world and has ca. 75% of the coal resources in Africa (Wagner & Hlatshwayo, 2005). The coal is economically important as an export product and as the main source of energy in South Africa. The country's vast coal deposits can be found in the Ecca Group of the Main Karoo Basin. The Karoo Basin is a retro-arc foreland basin (Johnson, 1991; Catuneanu *et al.*, 1998) that covers the rock record from Late Carboniferous to the Mid-Jurassic (Cadle *et al.*, 1993).

The Highveld coalfield is one of nine coalfields in South Africa that are mined and is the second largest coal producer in the country (Wagner & Hlatshwayo, 2005). It is located approximately 200 km south east of Pretoria, and to the south of the Witbank coalfield in Mpumalanga Province, South Africa (Hancox & Götz, 2014).

According to the geological record, principal coal accumulation occurred during the Mississippian-Pennsylvanian, Permian, Jurassic, Cretaceous and Tertiary periods. The Mississippian-Pennsylvanian period coal is found in northern America and Europe whilst Permian coal occurs in southern Africa and Australia. Tertiary period coal is found in New Zealand and also in northern America. The Tertiary coals range from lignite to anthracite, while the Carboniferous-Early Permian usually has a higher rank. The coal in the Highveld coalfield was deposited during the Mid-Permian in the Vryheid Formation of the Ecca Group in the Main Karoo Basin (Falcon, 1986). The coals were deposited in a deltaic environment with fluvial input from the melting glaciers in the northern highlands (Wagner & Hlatshwayo, 2005). The climate was interpreted to be cold to cool temperate conditions during the Early Permian and during the Late Permian and Triassic the climatic conditions were hot and dry (Falcon, 1986).

1.1 Motivation and aims

Many aspects of the coal in the Karoo Basin have been studied extensively but there was a lack of interest in the palynofacies of these coals. The results of this study have implications for understanding the history of the coal deposits and will give more insight into the Highveld coalfield depositional history as well as in the adjacent areas. By combining these results with similar studies of the Karoo Basin, a global account of the palaeodepositional environment during the coal formation in the Permian can be given.

The aim of this study is to examine the palynofacies of the lower number 4 coal seam in the Highveld coalfield. Palynofacies analysis provides information about the degree of thermal maturation and kerogen type. In organic maturation studies there is a strong correlation between data obtained from instrumental geochemical studies (thermal alteration index and vitrinite reflectance) and palynofacies analysis (Elgmati, 2011). Palynofacies analysis can be used as an inexpensive preliminary study to determine the kerogen type and degree of thermal maturation. These parameters offer useful information for shale gas exploration. In the Karoo Basin the impact of the igneous intrusion also needs to be considered. The contact metamorphism caused by the intruding dolerite dyke and sills increases the thermal maturity of the surrounding rocks and can cause fracturing which can lead to gas escaping (Aarnes *et al.*, 2010). This research will enhance the understanding of the palaeoenvironmental changes and depositional history of the lower number 4 coal seam in the Highveld coalfield.

1.2 Previous research

Most research on the palynology of sedimentary successions in the Main Karoo Basin focussed on the Witbank coalfield. So far, Aitken (1994) was the only individual to conduct palynostratigraphical research on the Highveld coalfield. Falcon *et al.* (1984) documented general palynological research on the number 1 to 5 coal seams in the Witbank coalfield. These coal seams showed progressive changes in the diversity and relative abundances of taxa in the sequence and a wide variety of miospores in the coal seam.

Falcon *et al.* (1984) noted that from seam 1 upwards, the monosaccate pollen grains decrease and the non-taeniate and taeniate bisaccate pollen grains increase. Coal seam 1 is dominated by monosaccate pollen grains (>75%) with taeniate bisaccate pollen grains being rare. Seam 2 represents the transitional phase in which monosaccate pollen grains start decreasing and bisaccate pollen grains increase (figure 1.1).

Seams 3 and 4 are dominated by non-taeniate bisaccate pollen grains with a slight increase in the taeniate bisaccate pollen grains. The number 4 coal seam shows an increase in pollen diversity with taeniate bisaccate pollen grains dominating. In coal seam 5, higher proportions of taeniate bisaccate pollen grains are present (Falcon *et al.,* 1984).

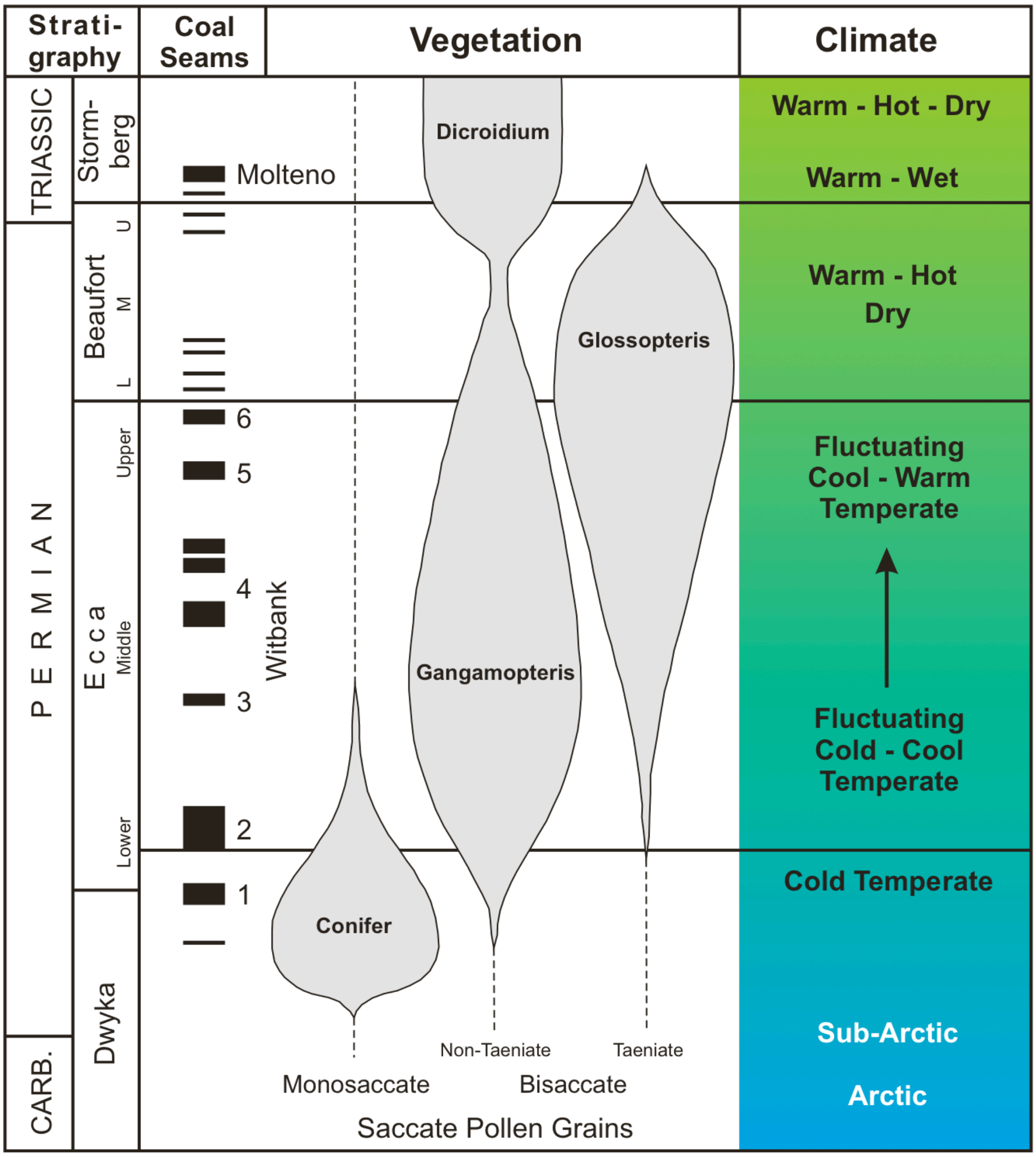


Figure 1.1: Palynomorph occurrence in the coal seams of the Witbank coalfield due to climate change (from Hancox & Götz, 2014, modified from Falcon, 1986)

The coal seams in the Witbank coalfield showed two distinct climatic changes. Coal seams 1 and 2 are characterised by gymnospermous monosaccate pollen grains that indicate colder temperatures. The younger coal seams, that is, numbers 3, 4 and 5, are characterised by gymnospermous taeniate and non-taeniate bisaccate pollen grains that indicate that the environment warmed (Falcon *et al*., 1984). Coal seams 2 to 5 have a wider variety of miospores with pollenites being dominant. This is an indication that the floras responsible for the formation of the coal are higher-order gymnosperms, glossopterids and pteridosperms (Falcon *et al*., 1984).

Götz and Ruckwied (2014) were responsible for the most recent work on palynofacies on the number 2 coal seam in the Witbank coalfield. They suggest that it was deposited during a crucial period of climate change in the Permian. During the deposition of the coal seam, the climate changed from icehouse to greenhouse conditions. The coal seam is separated into an upper and lower part and is divided by a sandstone bed that can be up to 1 m thick. The lower part of the coal seam (Lower Coal Seam) represents the icehouse conditions. It has a high amount of opaque particles that are blade shaped and is dominated by fern and horsetail spores as well as gymnospermous monosaccate pollen grains. There is little indication by the organic particles and their sorting that long-distance transport occurred. The spores indicate wet habitat, and that combined with the phytoclasts, suggest a swamp-dominated depositional environment (Götz & Ruckwied, 2014).

The fluvial sandstone bed separating the Lower and Upper Coal Seam is rich in degraded organic matter and opaque equidimensional phytoclasts. Pollen grains are relatively abundant and no amorphous organic matter (AOM) was preserved. The sandstone bed represents channel fill deposits (Götz & Ruckwied, 2014).

The upper part of the number 2 coal seam (Upper Coal Seam) is characterised by translucent phytoclasts and is dominated by gymnospermous bisaccate pollen grains. Freshwater algae are a common occurrence with only some fern spores preserved. This is an indication of lake-dominated depositional setting and represents greenhouse conditions (Götz & Ruckwied, 2014)

Götz and Ruckwied's (2014) results of the number 2 coal seam of the Witbank coalfield suggest that the monosaccate-producing gymnospermous flora is replaced by bisaccate-producing plants and the climate changes from cold to cool temperate conditions (figure 1.1).

Other palynological research on the coal-bearing deposit in the Karoo Basin was conducted by Millsteed (1993, 1999) and MacRae (1988). Millsteed focused on coal deposits in the Free State near Vereeniging, while MacRae (1988) did palynostratigraphical work on the Soutpansberg-Parfuri Basins and the Waterberg Basin in the Limpopo Province.

Millsteed (1999) described palynomorph assemblages from the coal-bearing deposits of Vereeniging-Sasolburg in the Free State. Three assemblages were identified, namely sporites, transitional and pollenites.

The sporites assemblage is the oldest and is dominated by spores with minor pollen grains (Millsteed, 1999). The transitional assemblage samples are from the interburden between the two coal seams. It shows a drop in spore abundance and an increase in bisaccate pollen grains. The pollenites assemblage is dominated by taeniate bisaccate pollen and the minor occurrence of trilete spores (Millsteed, 1999).

These assemblages compare favourably to the results of Falcon *et al*. (1984) with coal seam 2 comparing to the relative abundances of the sporites assemblage and coal seam 4 to the pollenite assemblage (figure1.2).

MacRae (1988) studied the palynomorph assemblages of the Waterberg and Pafuri Basins and composed six biozones from A to F in ascending order of the stratigraphy.

Biozones A and B have extremely high abundance of monosaccate pollen grains and very little taeniate bisaccate pollen. Biozone D has abundant non-taeniate pollen grains followed by taeniate pollen, and a few spores with the monosaccate pollen grains being poorly represented. Biozone E represents equal amounts of non-taeniate and taeniate pollen grains. Taeniate pollen grains dominate Biozone F with non-taeniate pollen being less abundant. There are only minor occurrences of spores (MacRae, 1988).

Biozone F of MacRae (1988) compares to Millsteed's (1999) sporites assemblage and coal seam number 4 of Falcon *et al*. (1984) as seen in figure 1.2.

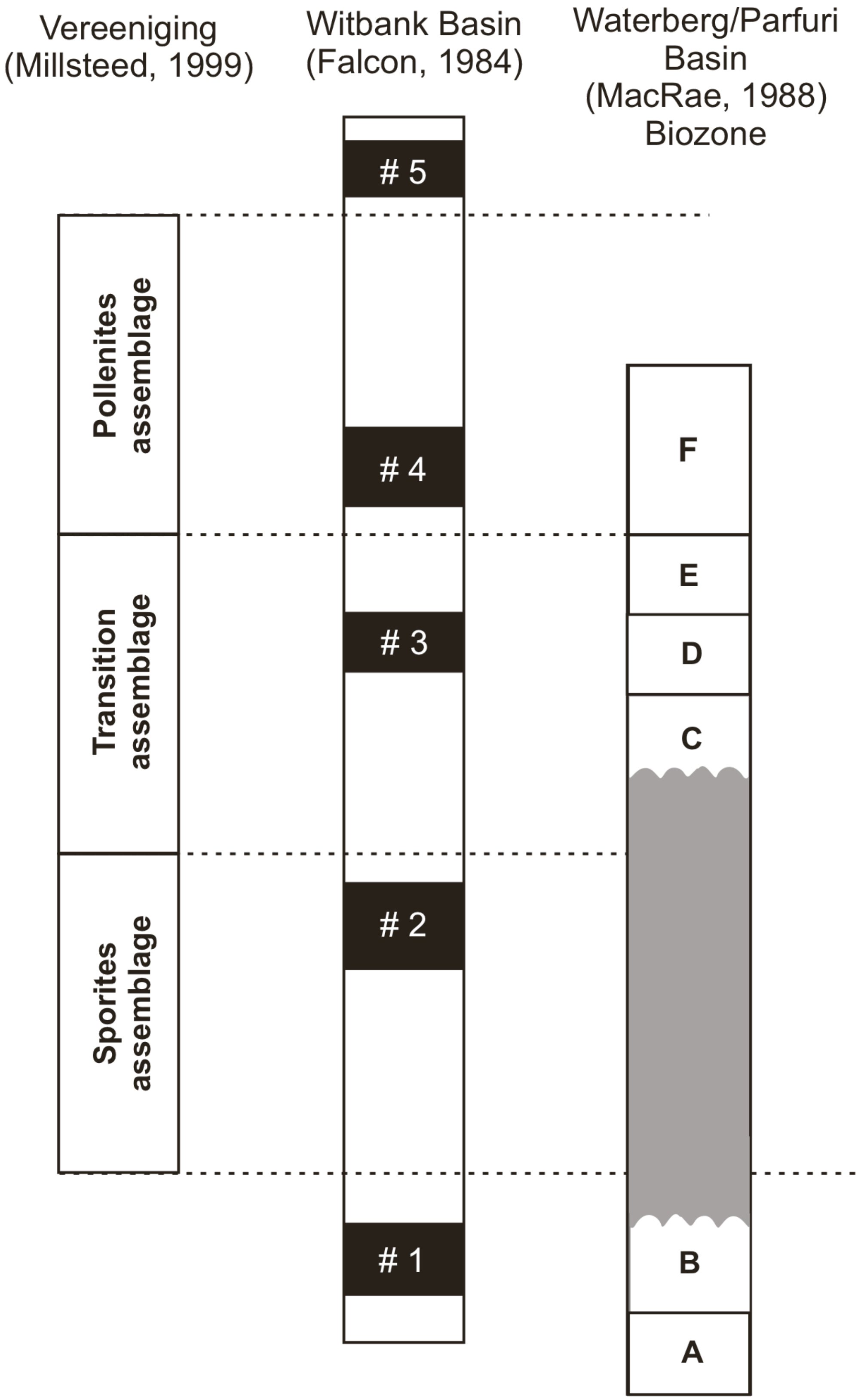


Figure 1.2: Diagram comparing the discussed informal palynological biozones. This is a broad grouping of the strata and not the precise stratigraphic relationships (Millsteed, 1999)

As stated earlier, the only other research in the Highveld coalfield was by Aitken (1994). However, his work focused on the palynostratigraphy and not the palynofacies of the number 5 coal seam. The results of the study indicate that taeniate bisaccate pollen grains dominate the sequence and that there is a decrease in non-taeniate bisaccate pollen. This also concurs with the results of Falcon *et al.* (1984).

Aitkin (1994) studied the number 5 coal seam in the Highveld coalfield and found that it represents a large accumulation of vegetation. The pollen grains dominate the vegetation in comparison with the amount of spores with taeniate pollen grains to non-taeniate pollen grains that have a ratio of 3:1. The dominance and increase of taeniate pollen grains and the decrease of the other taxa are believed to be the result of the drifting of the sub-continent towards lower latitudes. This resulted in a warmer temperate climate during the deposition of the number 5 coal seam, which corresponds to the findings of Falcon *et al.* (1984).

Most studies on the palynofacies of the coal deposits in South Africa were done in the 1980s and some in the 1990s. New research only started during the preceding few years. The increase in South Africa's dependence on coal as an energy source means that there is a need for new research on these deposits. The Karoo Basin sedimentation was terminated by the extensive outflow of the Drakensberg lavas. The emplacement of a Large Igneous Province (LIP) in sedimentary basins can trigger global climate change by the generation of gas around the dykes and sills (Aarnes *et al*., 2010). This is important to consider when researching the Permian-Triassic extinction event.

1.3 Materials and methods

Fourteen samples were collected for palynological studies from the lower number 4 coal seam near Secunda at the iThemba Lethu shafts in the Highveld coalfield, Mpumalanga (figures 1.3 & 1.4). Here, the coal seam, which is ca. 140 m below the surface, has a thickness of approximately 4 m on average (figure 1.5 & 1.6).

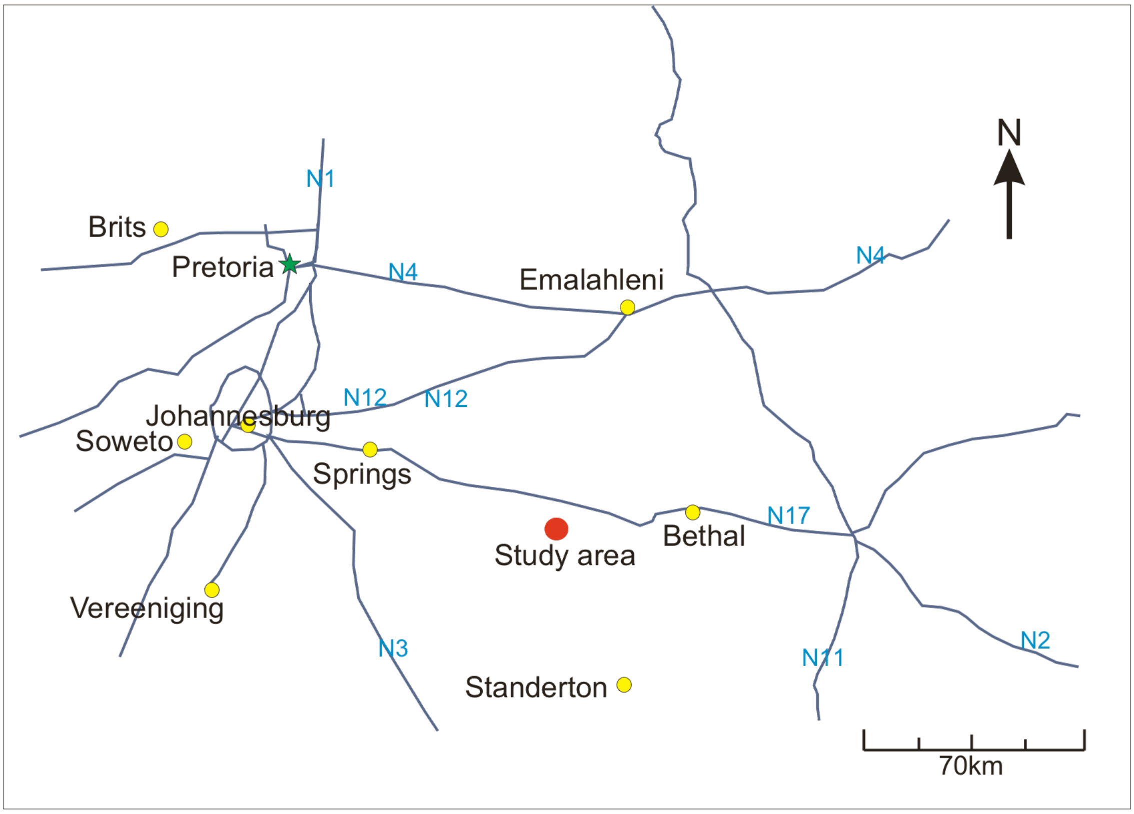


Figure 1.3: Geographic location of the study area (modified from AfriGIS, 2014)

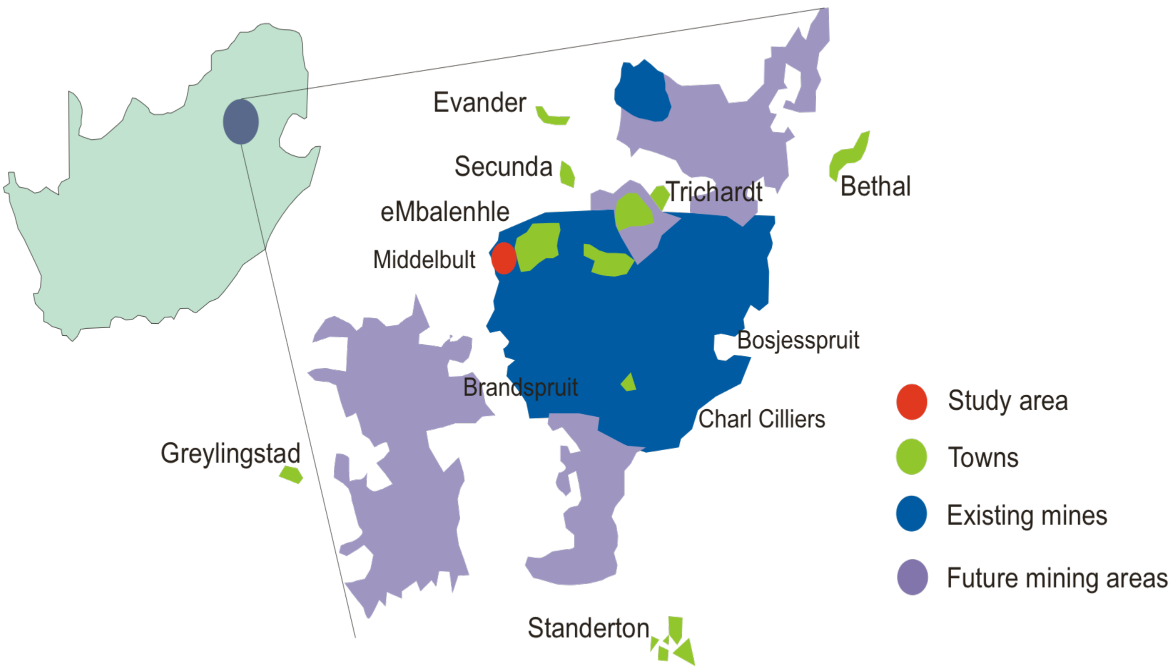


Figure 1.4: Location of study area within the Sasol mining operations in the Highveld coalfield (Bussio, 2012)

From the fourteen samples taken for palynological analysis the samples DK 4, DK 6, DK 9, DK 10, DK 11, DK 12, DK 13, DK 16 and DK 17 were taken ca. 2 m above the base of the coal seam, and in distances ranging from 2 to 17 m away from a dolerite dyke (figure 1.4). Sample DK 20 D was taken at 1 m and DK 20 B at 2 m from the base. DK 20 L and DK 20 S were taken at 2.5 and 3 m from the base, respectively. The latter four samples were all taken 20 m away from the dolerite dyke.

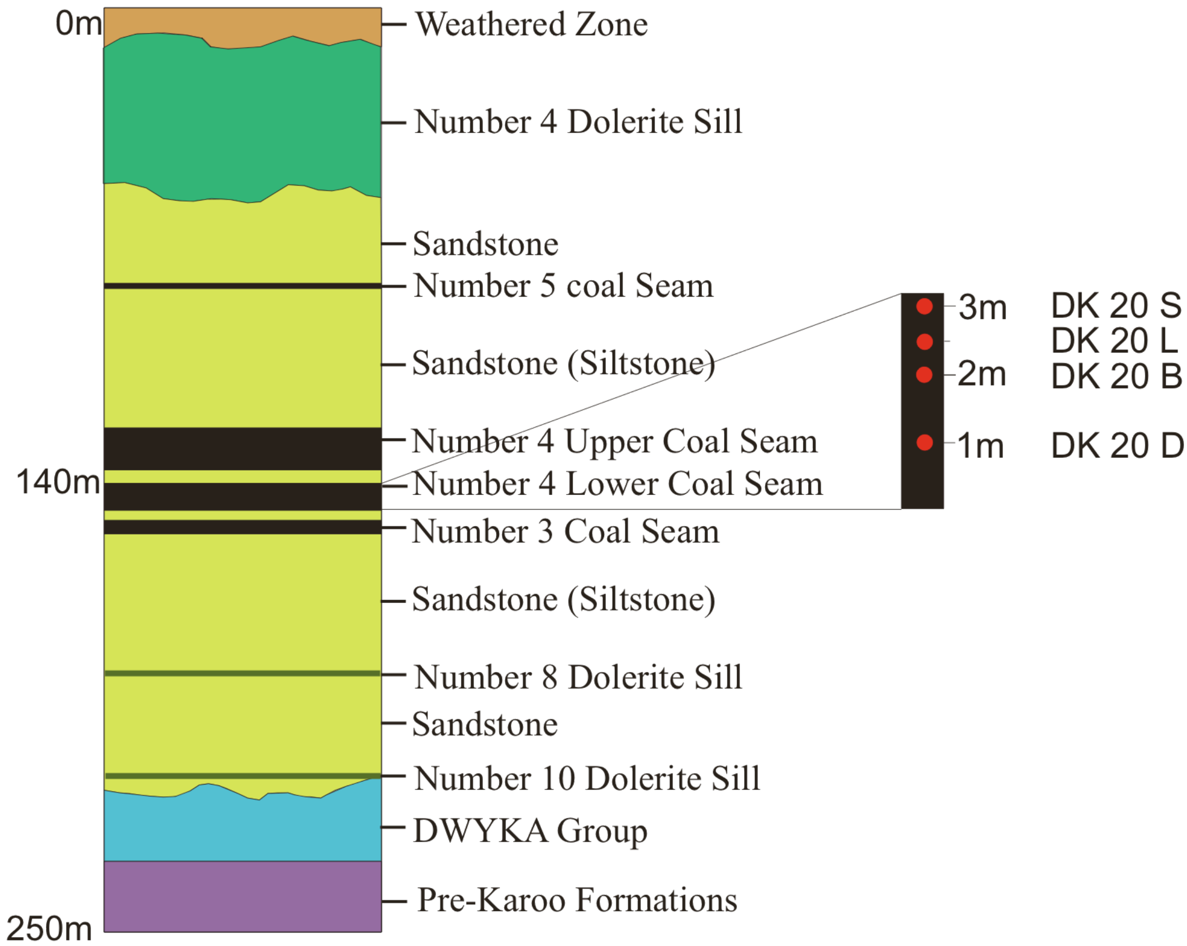


Figure 1.5: Generalised stratigraphy with sample location of the study area near Secunda, defined by the Sasol mining area (modified from Bussio, 2012)

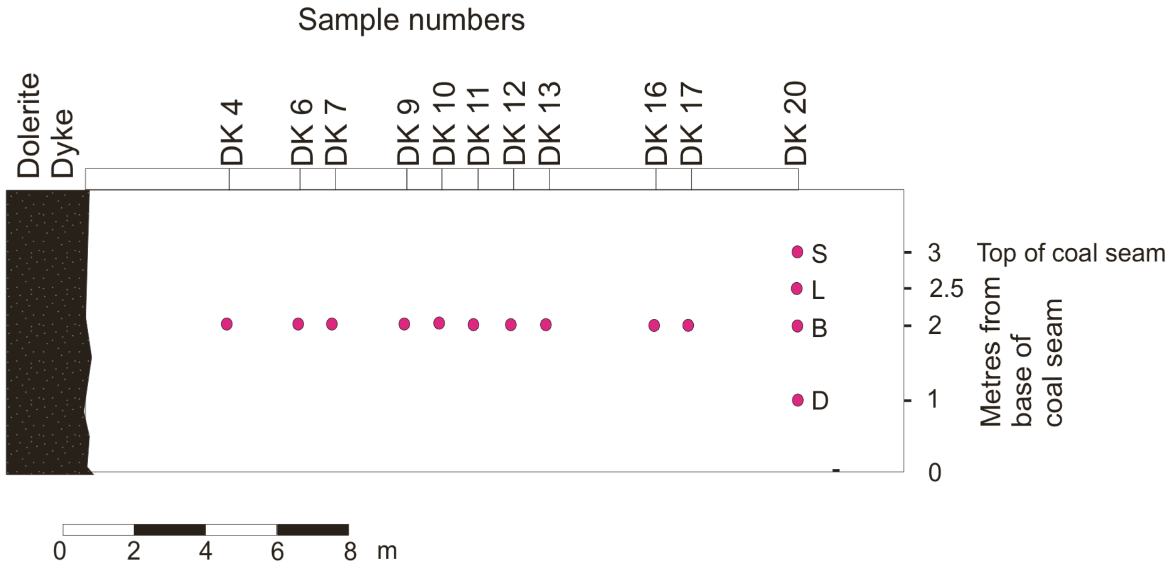


Figure 1.6: Location of samples taken from the lower number 4 coal seam

For the analysis, palynomorphs were extracted using standard palynological processing techniques (Vidal, 1988). To ensure that the chemical reactions proceeded as completely as possible, the samples were crushed and cleaned of possible contaminants (Anderson, 1977). The 14 samples were then treated with HCl (33%) to remove carbonates and HF (73%) to remove silicates. For the removal of insoluble minerals, zinc chloride ($ZnCl_2$) with a specific gravity (S.G) of 2.22 was used. For the removal of organic material, a specific gravity of 2 is needed because it causes pollen grains to float (S.G. of 1.4) and clastic material like quartz and calcite with specific gravities > 2 to sink (Funkhouser & Evitt, 1959).

The samples that were collected for this study contained high amounts of organic matter. To remove the excessive organic matter and lighten the palynomorphs oxidation treatment was applied to the samples. The period of oxidation needs to be controlled because the fossil palynomorphs can swell or rupture if exposed for too long (Moore *et al.*, 1991). The period of oxidation can vary from a few seconds to 48 hours (Anderson, 1977). The residue was cleaned by sieving, using 4 µm gauze. After each process, the samples were concentrated by centrifuging and washed with distilled water (Faegri & Iversen, 1964).

The standard medium used for mounting in pollen analysis is glycerine. The drawback of glycerine is that the slides only have a lifespan of 15 to 20 years because the palynomorphs swell in the mounting medium owing to oxidation (Traverse, 1988). All sample preparation was conducted at Rhodes University, Grahamstown.

The prepared slides were examined using a standard transmitted light microscope and the specimens were photographed. Data was collected by counting, which was based on up to

200 counts per slide. The sedimentary organic matter was grouped into phytoclasts, spores, pollen grains, degraded organic matter (DOM) and amorphous organic matter (AOM). The relative percentages were calculated on the basis of counting.

1.4. Palynofacies studies

Palynofacies studies examine the preservation of particulate organic matter and palynomorphs to provide information on the depositional environment of sediments and the depositional palaeoenvironments of sedimentary rocks. Combaz (1964) was responsible for introducing the term ”palynofacies” in the literature and stated that it can be described as the organic matter (palynomorphs and plant debris) in sedimentary rocks that is resistant to acid and represents a specific depositional environment. According to Tyson (1995), palynofacies can be associated with a distinctive range of hydrocarbon-generating potential, that is, it can help to determine the type and amount of hydrocarbons that could have been generated by the host sediment during burial. It is this fact that makes palynofacies so important for the industry.

Palynofacies is used to determine different parameters of organic maturation studies. It can determine the potential of a hydrocarbon source rock, the depositional polarity and the maturity of the sediments. The maturity of the coal-bearing sediments is significant because the hydrocarbon potential is affected by thermal input. Palynofacies can discriminate between open marine, “restricted” marine, and brackish and fresh water depositional environments. It can also be used to identify stratigraphic units and determine their age (Cross, 1964).

According to Batten and Stead (2005), the following four main types of organic matter are preserved in sedimentary rocks:

(1) microfossils with distinctive morphology, pollen grains and the protective walls of spores

(2) fragments with a structure similar to woody tissues

(3) unstructured material with an amorphous appearance

(4) compounds that are soluble and can be extracted by using organic solvents (Batten, 1996a; Batten & Stead, 2005)

In order to identify the palaeoenvironment as reflected by the occurrence of organic matter, identification of palynomorphs is necessary to form a detailed interpretation. This will include a study of the relative abundances of the palynomorphs and associated organic material (Batten & Stead, 2005).

When establishing a palynofacies, the initial step is to determine the lithofacies. This includes examining the colour, composition, texture and fossil content (Batten & Stead, 2005) of the sedimentary host rock. The next step is to categorise the relative abundances of the palynomorphs and other organic matter (Batten & Stead, 2005). When the relative abundances are known, they can be used to determine the palaeoenvironment. For example, if a sample has a high percentage of palynomorphs with spores being dominant, this may indicate oxidising environments that are in moderate proximity to a fluvio-deltaic source (Tyson, 1995).

Palynomorphs include the reproductive structures of plants such as pollen grains and spores, although acritarchs, dinoflagellates and scolecodonts are also included (Punt *et al.*, 2007). Palynomorphs are preserved in sediments but can be destroyed by strong oxidising and alkaline environments (Traverse, 1988).

Spores are the reproductive bodies of non-flowering plants like fungi, cryptogams and ferns (Punt *et al.*, 2007). The first spores in geological records date back to the late Ordovician period and have a tetrahedral arrangement (Willis & McElwain, 2002). The first single spore with distinct trilete marks can be found in early Silurian deposits (Grey & Shear, 1992; Willis & McElwain, 2002). Spores may have one laesura that is a single mark of a tetrad arm. When a spore has three laesura, it is called trilete, while a spore with one laesura is called monolete (see table 1.1). If the spore has no laesurae, it is an alete (inaperturate) (Punt *et al.*, 2007).

A pollen grain represents the microspore of seed plants and is part of their reproductive system (Hesse *et al.*, 2009). The fossil record shows that the first morphologically distinct pollen grains occurred during the Late Carboniferous and originated from gymnosperms (Traverse, 1988). The first pollen produced by angiosperms occurred in the early Cretaceous (Willis & McElwain, 2002; Hochuli & Feist-Burkhardt, 2013). The morphology of a pollen grain is used for its classification and is based on the shape, wall sculpting and structure of the grains (Faegri & Iversen, 1964).

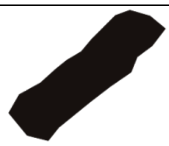
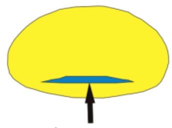
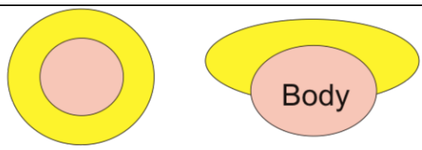
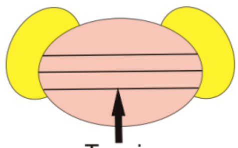
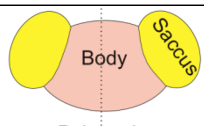
The part of a pollen grain wall that is thinner, thicker or different from the rest is called the aperture, and its function is believed to be germination (Hesse *et al.*, 2009). The polarity of the aperture will determine the terminology used, namely the colpi, pores or sacci. The sacci are an exinous expansion that forms an air sac (Hesse *et al.*, 2009). A bisaccate pollen grain has two sacci, while a monosaccate pollen grain has a single saccus (see table 1.1) (Punt *et al.,* 2007). An exinous layer, the aperture membrane, usually covers the aperture. The different surface features of the membrane are called the ornamentation (Hesse *et al.*, 2009). The aperture membrane can be lost after acetolysis, while the ornamentation is exceptionally variable and marks extremes within the morphology (Hesse *et al*., 2009).

Phytoclasts are fragments that form because of the decay of higher plants or fungi (Mendonça Filho *et al.*, 2012). Phytoclasts are the remnants of lignified higher plants such as wood. The lignin (xylem) is highly resistant to decay and is preserved in sediments. Coal has a high concentration of phytoclasts because of the anoxic condition during preservation (Mendonça Filho *et al.*, 2012). Lignin decays because of “mouldering” and “white rot” fungi that need oxygen to flourish (Mendonça Filho *et al.*, 2012).

Phytoclasts can be opaque or translucent (see table 1.1). Opaque phytoclasts are divided into equidimensional (equant) and blade-shaped (lath) phytoclasts (Mendonça Filho *et al.*, 2012). The equidimensional or equant phytoclasts usually exhibit a length/width ratio of < 2. These clasts are black or opaque and have sharp outlines with no internal structures (see table 1.1). The blade-shaped phytoclasts have a length/width ratio of > 2 and are also opaque.

The translucent phytoclasts are normally brown in colour and can be equidimensional or blade shaped (Mendonça Filho *et al.*, 2012).

Table 1.1: Description of palynomorphs that will be identified in this study (adapted from Traverse, 1988, and Punt *et al.*, 2007)

Phytoclast	Opaque	Equidimensional	
		Blade shape	
	Translucent		
Spores	Monolete		
	Trilete		
Pollen	Monosaccate		
	Bisaccate	Taeniate	
		Non-taeniate	

Various techniques are used to analyse the total organic matter in sediments (Tyson, 1995). The following are a few routine analyses: total organic carbon (TOC) and microscopy (Tyson, 1995).

The TOC is used to measure the quantity of the organic matter in samples. Total organic carbon is also used to estimate hydrocarbon potential but needs to be used in combination with other proxies like lithological composition, thermal maturation and sedimentation rate to name a few (Elgmati, 2011). There are concerns in the use of TOC to accurately determine the amount of organic matter due to the problem of dilution (Tyson, 1995). The measurement is a relative percentage making it dependent on other factors like supply and preservation of siliciclastic and biogenic material (Mendonça Filho *et al.*, 2012). . The total organic carbon is controlled by the input and preservation of organic matter and the dilution of the organic matter by mineral matter (Tyson, 1995).

The TOC of a source rock is made out of the organic carbon in the extractable hydrocarbons, the live carbons that can be transformed into hydrocarbon and the dead carbon that cannot produce hydrocarbons (figure 1.7) (Jarvie *et al.*, 2007). The more hydrocarbon are extracted from the source rock the less the total organic content will be (Elgmati, 2011).

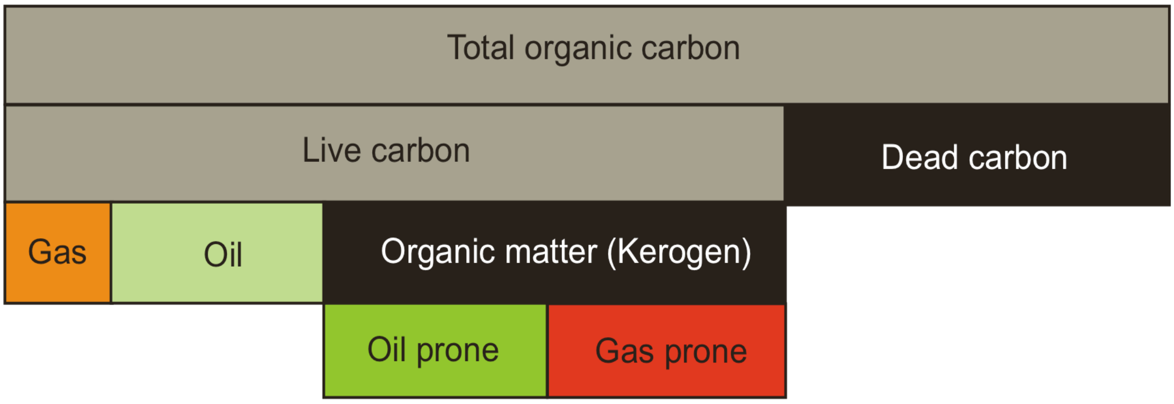


Figure 1.7: The composition of organic matter in a rock sample (Elgmati, 2011)

Microscopy is another method for analysing the organic matter in sediment. By studying the palynomorphs under a microscope the palynofacies can be determined. The palynomorphs of metamorphosed or recrystallised rocks are rarely studied, owing to the increase in temperature; any type of metamorphism will progressively destroy palynomorphs (Traverse, 1988). However, metamorphosed rocks can be studied if more than one technique is used. When palynomorphs of metamorphosed rocks are examined under transmitted light they appear to be opaque but combining it with reflected light will reveal the morphology (Pflug & Reitz, 1992). This allows for identification of the palynomorphs.

Chapter 2: Geological setting

2.1 Palaeogeography

The Main Karoo Basin is classified as a retro-arc foreland basin (Johnson, 1991; Catuneanu *et al*., 1998), which covers an area of approximately 700 000 km^2 and can reach a maximum thickness of up to 12 km (Johnson, 1976; Johnson *et al*., 1997; Johnson *et al*., 2006). Basin fill is documented from the Late Carboniferous to the Middle Jurassic period with a complete rock record (Cadle *et al*., 1993).

During the formation of the Main Karoo Basin, the tectonic regime was defined by extension in the north and compression and accretion in the south. The compression and accretion in the south was due to the subduction along the paleo-Pacific margin, while the extension in the north was due to the spreading processes along the Tethyan margin of Gondwana (Wopfner, 1994).

The convergence in the south formed when the paleo-Pacific plate was subducted at a shallow angle beneath the supercontinent (Lock, 1980). This compression and accretion formed the 6000 km long Pan-Gondwanian fold-thrust belt. A small piece of this fold-thrust belt is preserved in South Africa as the Cape Fold Belt (Catuneanu *et al*., 2005). The Karoo retro-arc foreland system, which includes the main Karoo Basin, formed as a result of the supralithospheric loading caused by the crustal thickening and shortening in the Cape Fold Belt (Johnson *et al*., 1996; Catuneanu *et al*., 1998; Catuneanu *et al*., 1999; Bordy & Catuneanu, 2001, 2002a, b, c, Catuneanu, 2004).

The Karoo Basin developed in front of the Cape Fold Belt (CFB) with the sedimentary fill controlled by the orogenic cycles of loading and unloading in the CFB. The basal and top contacts of the Karoo show changes in the tectonic setting. There is a change from extensional to foreland and from foreland to extensional (Catuneanu *et al*., 1998). During an episode of orogenic loading the proximal region relative to the CFB showed subsidence and accumulation of sediment while the distal region shows uplift and decrease accumulation (figure 2.1). The reverse is true when orogenic unloading occurs. The depocentre of the Karoo Basin alternates during orogenic loading (proximal) and unloading (distal) (Catuneanu *et al*., 1998).

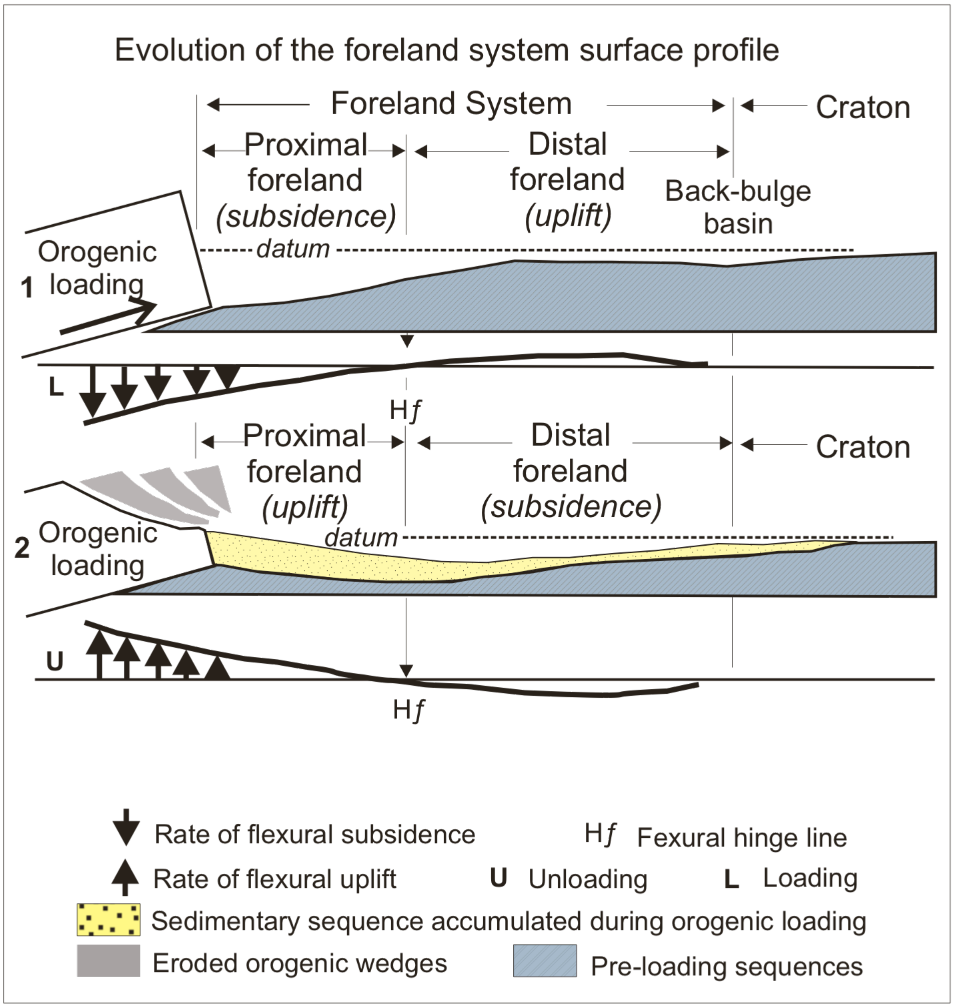


Figure 2.1: Evolution of the foreland system (Catuneanu *et al.*, 1998)

The Karoo Basin's location in Gondwana during the early Permian was positioned in the Arctic Circle at approximately 70° south of the equator (figure 2.2A). During the late Permian, Gondwana drifted north to approximately 65°, as seen in figure 2.2B (Rayner, 1995). Gondwana's position would have a dramatic influence on the climate of the Karoo Basin (Rayner, 1995).

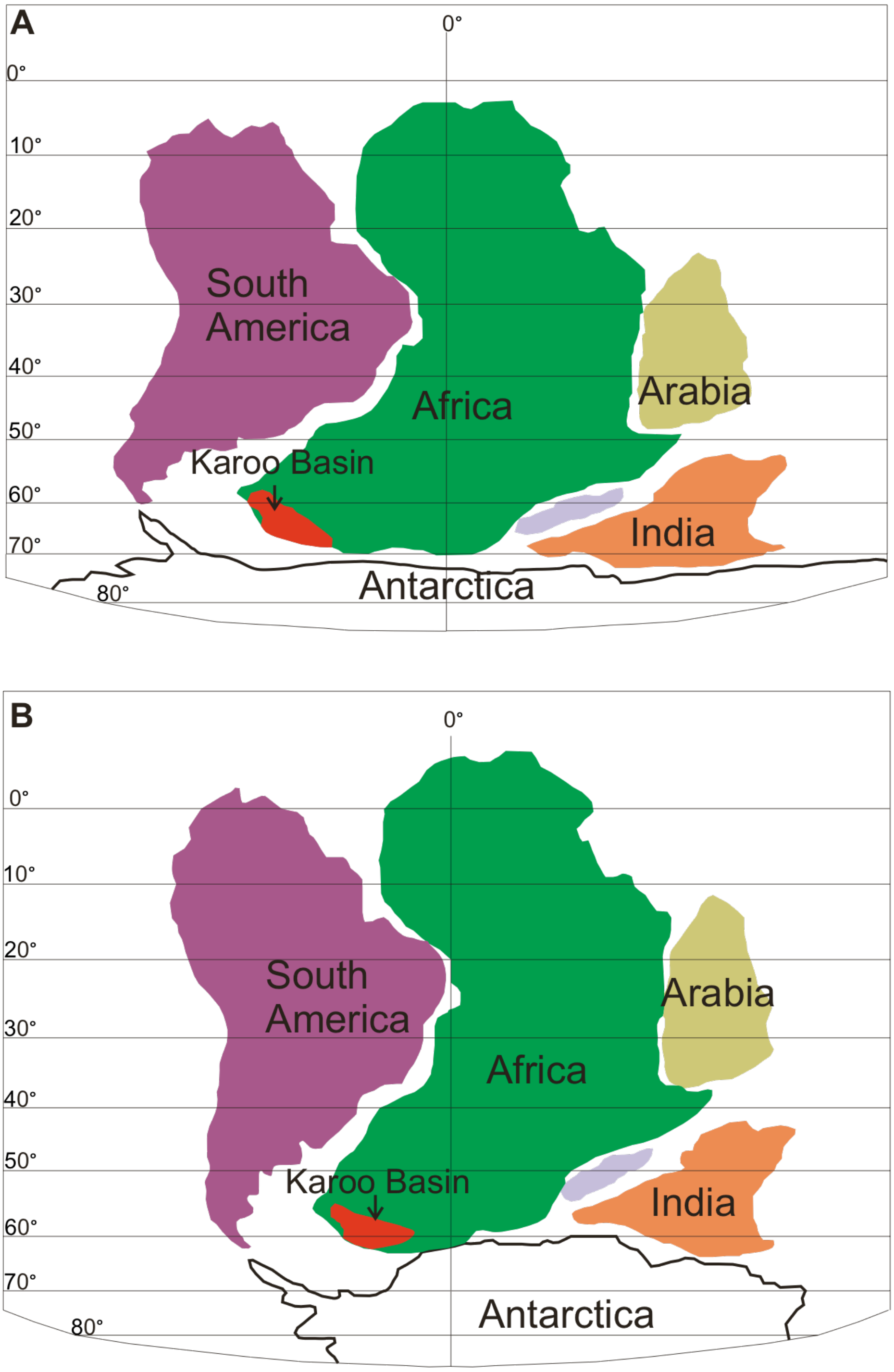


Figure 2.2: Position of the Karoo Basin during the Late Carboniferous/Early Permian (A) and the Late Permian (B) (modified from Cadle *et al.*, 1993)

The Karoo Basin is divided into four groups, which are in stratigraphical order: the Dwyka, Ecca, Beaufort and Stormberg Groups (figures 2.3 & 2.4). The sedimentation in the Karoo Basin was terminated by the extensive outflow of the Drakensberg lavas (Cadle *et al.*, 1993).

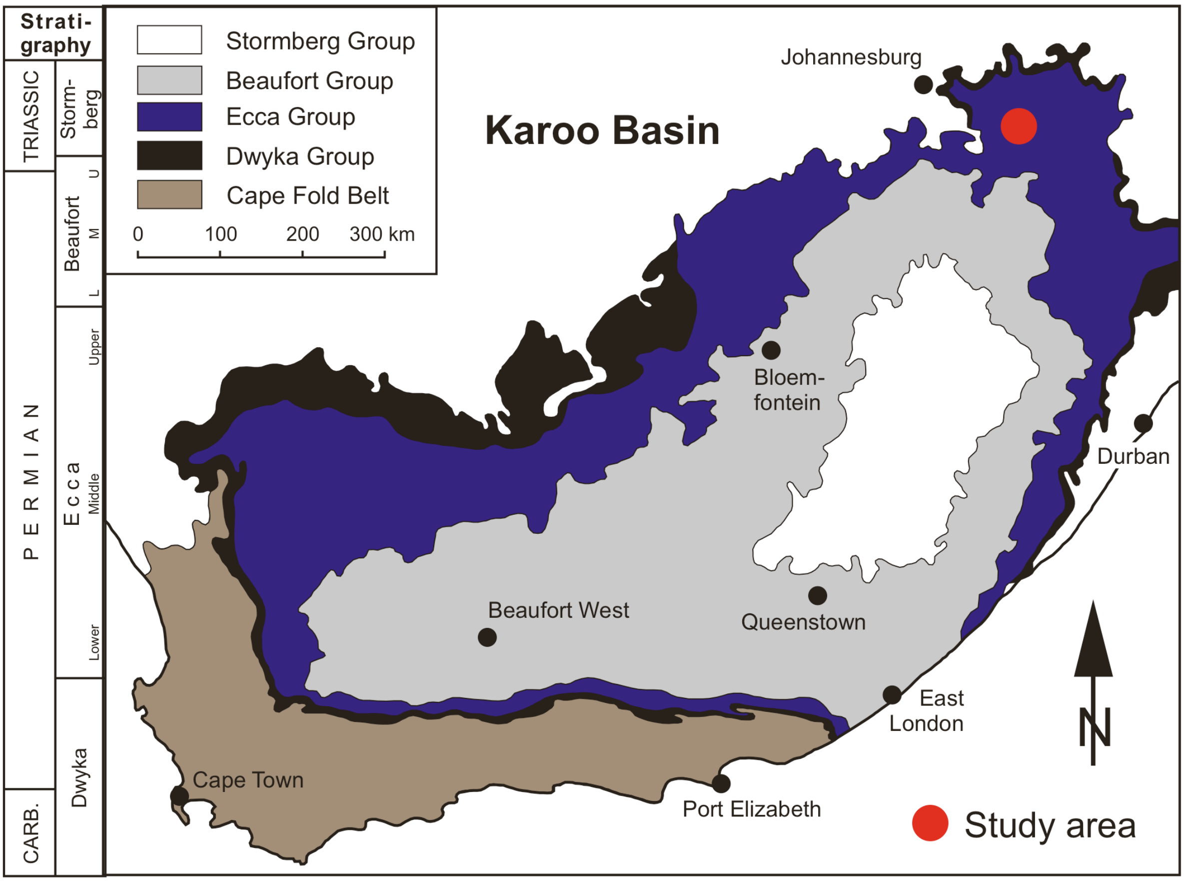


Figure 2.3: The Main Karoo Basin stratigraphy and the location of the study area (from Götz & Ruckwied, 2014, based on Catuneanu *et al.,* 2005)

2.2 Stratigraphy

The Dwyka Group represents the earliest deposits of the Karoo Basin. It exhibits different lithologies in the northern and southern parts of the Karoo Basin, leading to the recognition of the southern Elandsvlei Formation and the northern Mbizane Formation facies (Visser, 1986; Visser *et al*., 1980). It formed from the Early Carboniferous until the Early Permian, reaching thicknesses of up to 800 m in the main basin (Visser *et al*., 1980). The group contains various sedimentary units, reflecting a glacial or glacial-related origin (Johnson *et al*., 1996) that was caused by advancing and retreating ice sheets (Crowell & Frakes, 1972, 1975).

The northern facies is recognised by rapid thickness changes, variable lithologies, high mudrock content and a small amount of massive diamictites (Visser, 1986). This facies represents mainly valley-fill deposits formed by the retreating glaciers (Visser, 1983).

The southern facies contains a large number of dark-grey, carbonaceous, pyrite-bearing, splintery shales as well as dark chert and phosphatic nodules and lenses (Johnson *et al*., 1997).

The Ecca Group formed after the retreat of the glaciers during the Early Permian and continued until the Late Permian. Sedimentation occurred at the southern margin from the north and south. It consists of mudstone, siltstone, sandstone, minor conglomerates and local occurrences of coal (Caincross, 1989; Johnson *et al*., 1996; Johnson *et al*., 1997). The sediments at the northern margin differ from those in the south, reflecting deposition on the stable Kaapvaal Craton. Owing to the deep-water sediments at the southern margin of the basin, it is suggested that it is a fore-deep basin that was actively filled by sediments from the bordering highland areas (Cadle *et al*., 1993).

The northern Ecca Group is divided into the Pietermaritzburg, Vryheid and Volksrust Formations while the southern Ecca is the Prince Albert, Whitehill, Ripon, Collingham and Fort Brown Formations (Cadle *et al*., 1993; Catuneanu *et al*., 1998). The northern Ecca Group corresponds to the distal facies and the southern formations correspond to the proximal facies (figure 2.4). The proximal and distal regions result in contrasting stratigraphies that are separated by the stratigraphic hing line (Catuneanu *et al*., 1998).

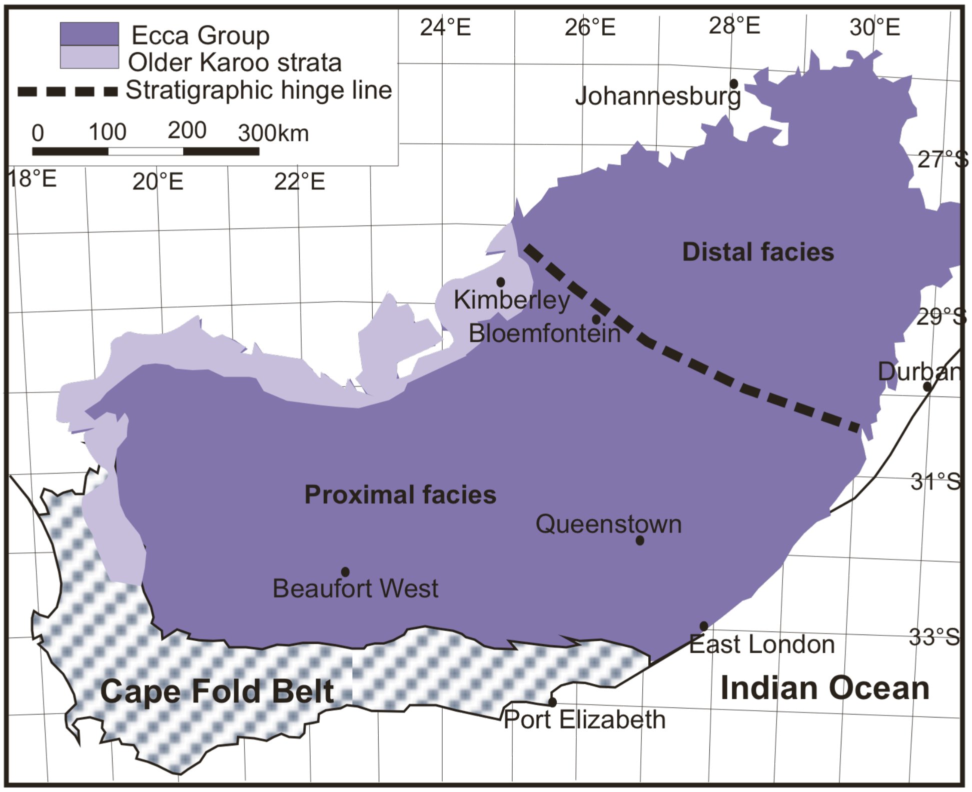


Figure 2.4: Map of the Ecca Group showing the stratigraphic hing line separating the proximal and distal facies (Catuneanu *et al.,* 1998)

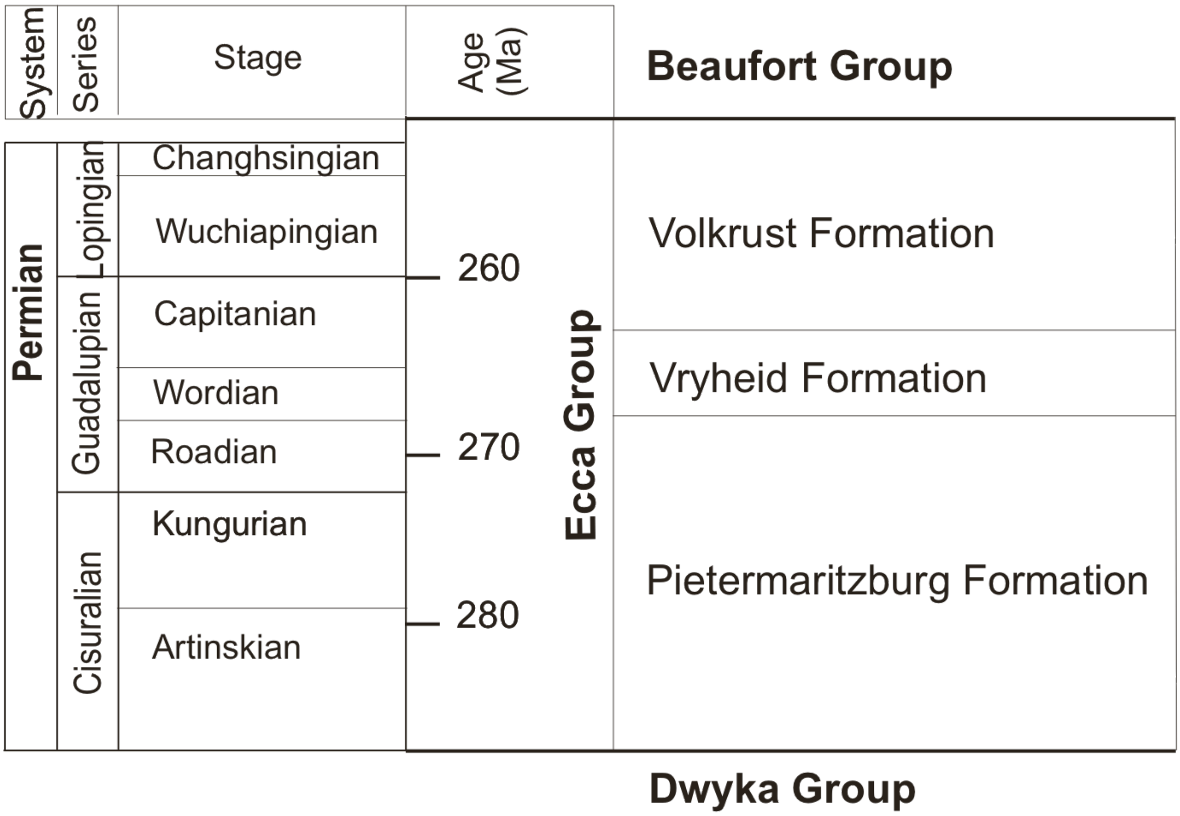


Figure 2.5: General stratigraphy of the north eastern part of the Main Karoo Basin with the International Permian timescale (compiled from Catuneanu *et al.,* 2002, Shen *et al*., 2013 and Cohen *et al*., 2014)

The Pietermaritzburg Formation underlies the Vryheid Formation almost completely in the north-eastern part of the Karoo Basin (figure 2.5). However, the Pietermaritzburg and Vryheid Formations span vastly different geological periods (Johnson *et al*., 1997). The Pietermaritzburg Formation consists of a repetitive succession of blue-grey silty mudrock and crops out at the eastern section of the Karoo Basin. The lack of structures in the Ecca shelf mudrock can be explained by microbioturbation (Hobday, 1973). The formation coarsens upward with heavily bioturbated sandy and silty beds near the top (Johnson *et al*., 1997). The coarser sediments indicate shoreline progradation. As the climate warmed, it caused glaciers to melt, and the water from the glaciers formed river systems that entered the basin from the northwest and northeast. This formed a new phase in the depositional history of the northern Karoo Basin (Johnson *et al*., 1997). According to Johnson *et al.* (1997), there is evidence of marine conditions in the Ecca sea. Trace fossils and the occurrence of glauconite, indicative of saline conditions in the sediments covering the Pietermaritzburg Formation, support this (Caincross, 1979; Le Blanc & Smith, 1980; Mason *et al*., 1983).

The Vryheid Formation of the Ecca Group consists of alternating layers of shale, sandstone and conglomerate in which economically exploitable coal can be found. These coarse layers represent different environments such as deltaic, fluvial and shallow marine environments (Cadle *et al*., 1993).

The Vryheid Formation consists of different upward-coarsening lithofacies that is mainly deltaic in origin (Johnson *et al*., 1997). In the eastern part of the Formation, an upward-coarsening cycle can be found consisting of dark grey, muddy siltstone at the base with coarse to pebbly, planar cross-stratified feldspathic sandstone at the top. The sediments at the base represent shelf suspension deposition in anoxic water of moderate depth. Alternating immature sandstone, dark siltstone and mudstone represent pro-delta sediments. These alternating sediments represent a variation in fluvial input and seasons during stormy or fair weather (Johnson *et al*., 1997). The horizontally, laminated, well-sorted and medium-grained sandstone that grades into ripple cross-laminated, fine-grained sandstone and siltstone represents distal distributary mouth bar sediments (Johnson *et al*., 1997). At the delta front, slump structures and high-density turbidites exist, that indicate slope instability (Van Vuuren, 1983). Proximal mouth bar deposits consist of trough cross-stratified medium- to coarse-grained sandstone. The orientation of the trough represents both distributary channels and basinal currents. The coarse feldspathic sandstones show unimodal palaeocurrent patterns at the top and can be interpreted as distributary channel fills (Johnson *et al*. 1997).

The eastern facies of the Vryheid Formation can be divided into three intervals: the coarsening-upward interval; the lower and upper deltaic interval; and the fining-upward middle fluvial interval (Johnson *et al*., 1997) as seen in figure 2.6.

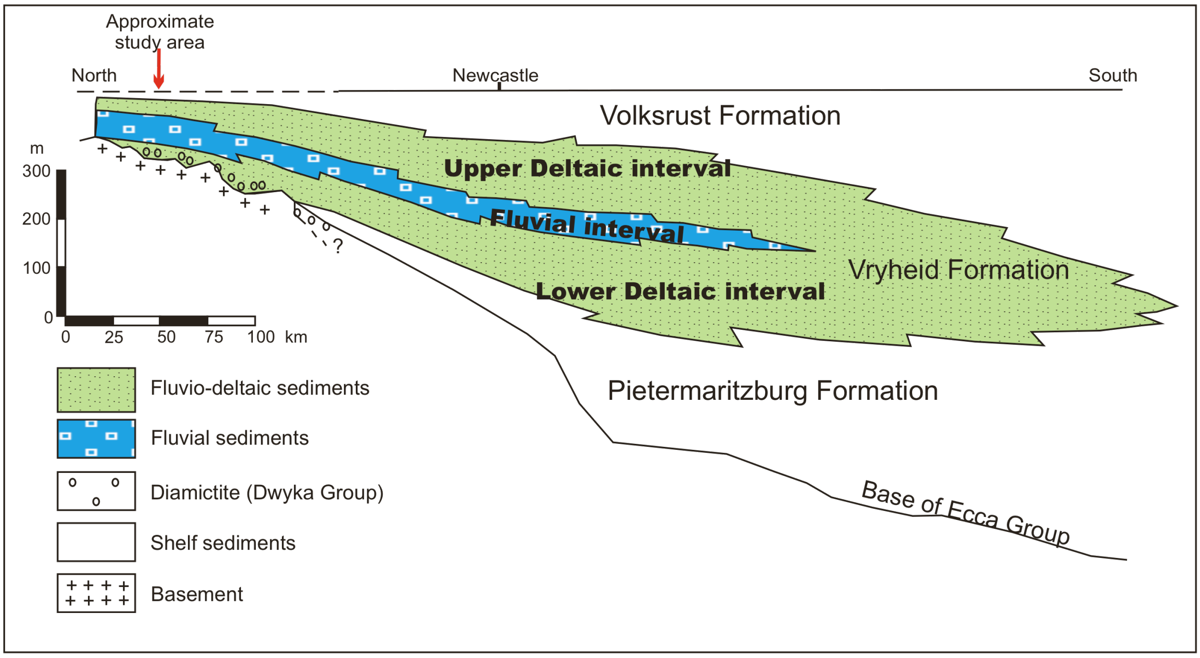


Figure 2.6: A schematic north-south section through the north-eastern part of the Ecca Group (modified from Tavener-Smith *et al*., 1988)

In the lower deltaic interval (Lower Sandstone), two recognisable genetic sequences can be found with five upward-coarsening cycles in the eastern part of the Vryheid Formation (Van Vuuren, 1983; Winter, 1985; Cairncross & Cadle, 1987). The lower-most cycle is believed to have formed by Gilbertian deltas from the northeast, resulting from glacial outwash streams entering freshwater lakes (Le Blanc Smith & Eriksson, 1979). Successive phases of progradation represented by coarse feldspatic sandstones are separated by silty drapes (Johnson *et al*., 1997).

The next interval is the fluvial (coal-bearing) interval. In the east, where the fluvial interval is best developed and reaches its maximum thickness, there are up to six upward-fining successions (Johnson *et al*., 1997). The economically exploitable coals are found in the fluvial succession and many researchers attributed the coals to broad abandoned alluvial and upper delta plains colonised by plants (Le Blanc Smith, 1980; Cadle *et al*., 1993). The palaeocurrents indicate that the source was in a north-easterly direction (Johnson *et al*., 1997). The fluvial interval was terminated by a major transgression marked by the presence of glauconitic, medium-grained, burrowed sandstone above the number 4 coal seams along the eastern part of the basin (Johnson *et al*., 1997).

The coal formation occurred from the Early to Late Permian in two formational generations. In the northern Karoo Basin, the coal seams represent swamps associated with paralic and fluvial deltaic deposition (Catuneanu *et al*., 2005). The coal seams capped the upward-coarsening deltaic and upward-fining fluvial successions (Cairncross & Cadle, 1987; Cairncross, 1989, 2001).

The upper deltaic interval comprises sandstone that is more feldspatic, micaceous and finer grained than that of the lower deltaic succession, suggesting reduced wave reworking (Johnson *et al*., 1997). The ichnofauna in the lower deltaic interval is more diverse and has a denser population in comparison with the upper deltaic interval. This can be attributed to differences in salinity or alternatively higher sedimentation rates in the upper deltaic succession that inhibited the growth of fauna (Van Vuuren, 1983; Roberts, 1986).

The western facies of the Vryheid Formation exhibits less genetic sequences because of a decrease in thickness from the south-west towards the north-western margin of the basin (Johnson *et al*., 1997). It has only two genetic sequences consisting of one or more upward-coarsening cycles (Van Vuuren & Cole, 1979; Van Vuuren, 1983). The sandstones in the western facies are better sorted and finer grained than those in the eastern facies of the Vryheid Formation. According to Van Vuuren (1983), the origin of the Vryheid Formation in the west is a wave-influenced deltaic system. The uneven floor of the pre-Karoo rocks along the north-western margin resulted in sheltered environments that formed coal swamps (Johnson *et al*., 1997).

The Volksrust Formation is interfingered with the underlying Vryheid Formation and overlying the Beaufort Group (Johnson *et al*., 1997). This formation is predominantly argillaceous and is confined to the north-eastern parts of the Karoo Basin. This formation is widely believed to be an open “shelf” sequence and consists of grey to black silty shale with thin siltstone or sandstone lenses (Johnson *et al*., 1997). However, Tavener-Smith *et al*. (1988) conducted a detailed study that concluded that the upper and lower parts of an outcrop northeast of Durban were possibly deposited in lacustrine to lagoon environments. The shallow water environments were supported by the presence of palaeosols, plant remains (Glossopteris, Phyllotheca) and trace fossil types. The measurements taken here were probably close to the origin, which is most likely located in the northeast. In the southwest, deeper water conditions prevailed (Johnson *et al*., 1997).

The sediments of the Beaufort and Stormberg Groups represent the change in basin evolution and depositional systems during the Late Permian and Early Triassic periods (Cadle *et al*., 1993). The Beaufort Group comprises upward-fining fluvial sediments (Johnson *et al*., 1996). The southern margin of the Karoo Basin subsided and the main source of the sediments in the basin was mainly from the highlands in the south (Cadle *et al*., 1993). However, in the extreme north-eastern area of the basin, there was some sediment from the northern source area (Turner, 1977). The environment changed from marine and transitional to one dominated by braided and meandering rivers with extensive floodplains and muds dominating over lenticular sands (Johnson *et al*., 1996).

The sedimentation in the Karoo Basin was terminated by the extensive outflow of the Drakensberg lavas at approximately 183 Ma (Johnson *et al*., 1996). The Drakensberg lavas form part of the Mesozoic Karoo Igneous province and is an example of continental flood basalt (Walker & Poldervaart, 1949). During the break up of Gondwana, extensive magmatic and volcanic activity occurred. The peak of the volcanic activity is recorded at 183±1 Ma for South Africa and Lesotho (Svensen *et al*., 2007).

In the main Karoo Basin the network of dyke and sills are called the Karoo dolerite suite. These dolerite sills and dykes are feeders to the flood basalt province. There are multiple dolerite intrusion events that predate and postdate the flood basalt and due to this it is difficult to associate them with a single intrusive or tectonic event (Duncan & Marsh, 2006).

The sill and sheet dolerite intrusions range from a few meters to 200 m in thickness. The sills were emplaced over a period of 3 Ma by a sustained magmatic event as concluded by Jourdan *et al*., 2009. The sills are dominantly tholeiitic basalt to basaltic andesite. The sills commonly led to the formation of diatremes (hydrothermal vents). Diatremes have steep walls with funnel-shaped pipe-like structures (Duncan & Marsh, 2006). These structures are common in the Karoo Basin.

The dykes are about 10 m wide and extend 5-30 km along the strike (Duncan & Marsh, 2006). The trend of the dyke in the central and eastern Karoo is between north and northwest. In the western Karoo the orientation of the dykes do not have a preferred orientation (Duncan & Marsh, 2006).

Chapter 3: Coal

3.1 Formation and classification

Coal is a combustible biochemical sedimentary rock that consists mainly of carbonised plant material. Coal is formed by the accumulation of plant remains that became compacted and hardened over millions of years (Modie, 2007). For the formation of coal, two requirements should be met. The first is that there should be a big enough organic source like a densely vegetated floodplain and secondly the organic matter needs to be preserved. Coal forms by both biological and geological processes acting on the plant remains (Kumar, 2012).

The properties of coal are influenced by the depositional history, diagenesis and tectonic dynamics (Kumar, 2012). Other factors that also have an impact on coal formation are vegetation type and composition and floodwater (figure 3.1). For the development of coal-quality peats in a swamp the following are the most important factors: the water table needs to have a low pH and the surface where the vegetation builds up should be anaerobic (Bordy & Prevec, 2008).

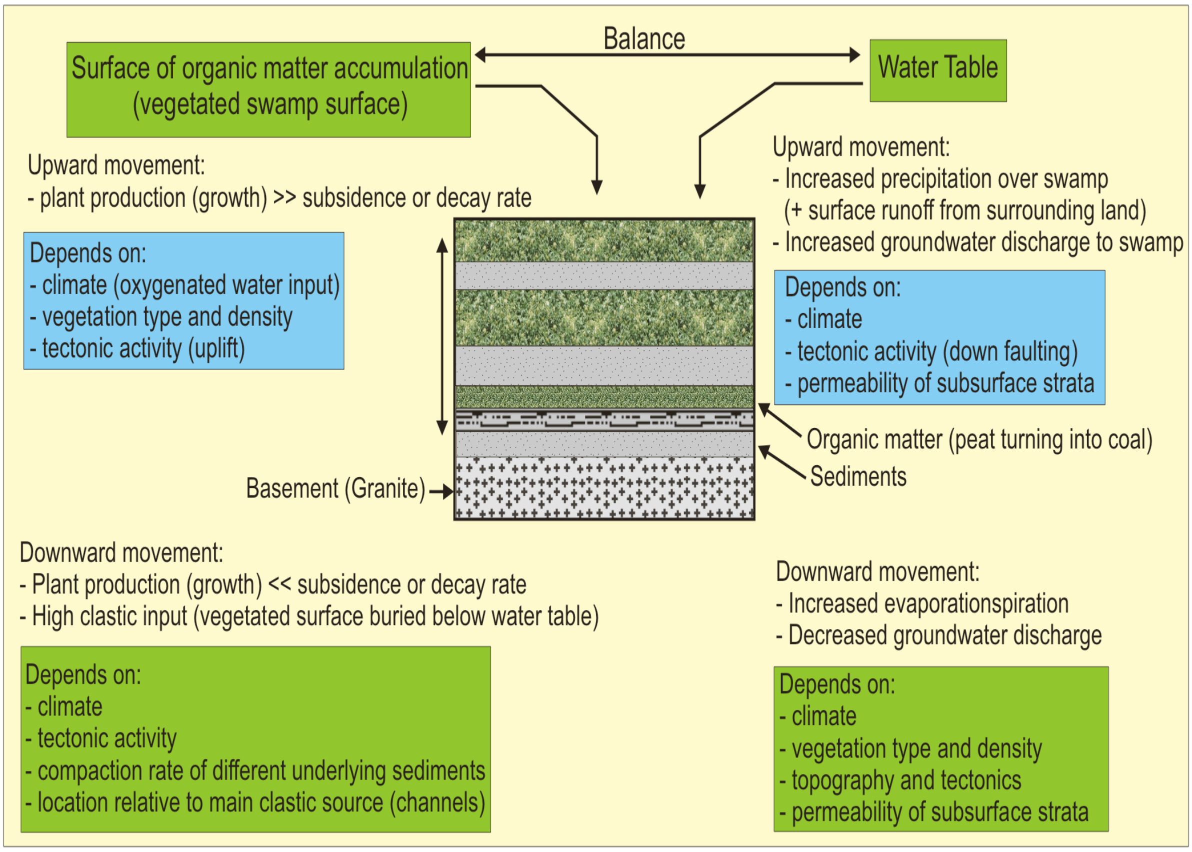


Figure 3.1: Coal-forming processes and the parameters that will influence it (from Kumar, 2012, based on Bordy & Prevec, 2008)

For optimal peat formation as seen in figure 3.1, the surface of the vegetated swamp should coincide with the water table. For this to occur there should be a balance between the water that enters and leaves the swamp (McCabe, 1984). The water budget is dependent on the amount of pecipitation, groundwater discharge, overland runoff and evapotranspiration rates (Bordy & Prevec, 2008). The vegetated area that is proportional to the water table is dependent on the plant production versus decay rate, subsidence and tectonic movement or compaction of the sediments.

There are two ways to analyse coal: proximate and ultimate analysis. Proximate analysis determines the moisture, ash, volatile matter and fixed carbon content (Snyman, 1998).

The ultimate analysis determines the carbon, hydrogen, oxygen, nitrogen and organic sulphur content of the coal and is done by a skilled chemist in a laboratory (Snyman, 1998). The methods include leaching to determine the sulphate sulphur content and instrumental infrared techniques for the total sulphur content (Snyman, 1998).

Proximate analysis can be done fairly quickly in most coal laboratories and is very precise (Snyman, 1998). The moisture content is determined by the mass loss of air-dried coal when heated to 105-110˚C. The moisture content gives a good indication of how porous the coal is. The material that is discharged when the air-dried coal is heated to 900˚C in the absence of air is known as the volatile matter. After the volatile matter has been discharged, the leftover organic material is the fixed carbon content. The ash content is the solid residue left behind after the complete combustion of coal. Coal can be ranked by the extent of metamorphism that was caused by an increase in pressure and temperature after the organic matter had been buried (Snyman, 1998).

Moisture, fixed carbon and volatile matter are used to classify the three main types of coal. Other properties include their colour and rank (table 3.1).

Table 3.1: The main types of coal with their properties (Boggs, 2006)

	Anthracite	Bituminous	Lignite
Fixed carbon	High	Medium-high	Low
Moisture content	None	Intermediate	High
Volatile matter	Low	Intermediate	High
Rank	High	Intermediate	Low
Colour	Black and dense	Black	Brown to brownish black
Other	Hard, bright and shiny	Hard with alternating black and dull layers	Retains structures of original woody plant fragments

Peat is occasionally included as a type of coal, but owing to its high moisture content and its formation by unconsolidated plant residue, it is not regarded as a true coal (Boggs, 2006). Coal can further be classified into semi-anthracite, semi-bituminous and sub-bituminous coal. However, there are no clear boundaries.

Coal petrography is the study of coal under a microscope to determine their type and rank. The term “macerals” is used for organic units that consist of plant debris such as woody tissues, bark, fungi and spores within the coal (Boggs, 2006). Macerals are divided into three groups referred to as vitrinite, inertinite and liptinite (table 3.2).

Table 3.2: Description of the three main types of macerals (Boggs, 2006)

Group	Description	Subtypes
Vitrinite	Originated from bark and wood and is mostly part of bright coals (translucent phytoclasts).	Collinite – structureless Tellinites – preserve some of the cellular texture
Inertinite	Composed of fine organic debris, woody tissue and fungal remains and has a moderately high carbon content (opaque phytoclast).	Fusinite – cell structures of carbonised or oxidised cell walls Semifusinite – transitional state between fusinite and vitrinite Schlerotinite – composed of fungal schlerotia remains or altered resins Micronite – structureless, opaque, granular macerals Inertodetrinite – finely divided, structureless clastic form of inertenite
Liptinite/exinite	Derived form spores, cuticles, resin and algae. Structures and shapes can be identified unless compacted and squashed (all palynomorphs).	Sporinite – composed of the remains of yellow translucent bodies Cutinite – formed from cuticles Resinite – remains of plants resins and waxes Alginite – remains of algal bodies

3.2 The impact of igneous intrusions on coal

The impact of igneous intrusion on coal is important in the Highveld coalfield because of its high occurrence. The igneous intrusions, such as dolerite dykes and sills, cause devolatilised zones around them, and these in turn change the chemical and physical properties of the coal (Saghafi *et al*., 2008). Due to metamorphism, a contact aureole forms around the intrusion impacting the maturity of the organic matter (Aarnes *et al*., 2010) and the quality of the coal (Bussio, 2012).

The contact metamorphism resulting from the impact of dolerite dykes on the stability of the roof rocks causes fracturing and unstable conditions in the surrounding rocks. The zone surrounding the dolerite dyke is a trap for methane gas (Saghafi *et al*., 2008) and can increase the possibility of outbursts (Anderson, 1995). Where dolerite dykes occur, there is also an increase in the joints and faults in the coal seams. These factors decrease the utilisation of the coal reserves (Saghafi *et al*., 2008).

In the Secunda region of the Highveld coalfield, the thickness of the dolerite dykes ranges from 0.1 to 5 m and this has an impact on the size of the devolitalisation zone (Saghafi *et al*., 2008). Density and proximate analysis was conducted by Saghafi *et al*. (2008), and the results show that the moisture content increases with increasing distance from the dyke and flattens out at 20 m. The effect of the dolerite intrusion can be observed for up to 20 m from the dyke.

Bussio (2012) researched the dolerite sills in the Highveld coalfield and found that the metamorphic effect of the dolerite sills causing the devolatilisation zone is a possible combination of hydrothermal fluids and contact metamorphism. The aureole that forms around the dolerite sills has its own unique metamorphic signature causing complex relationships between the intrusion and the coal seam.

The relationship between the thickness of the intrusion and the size of the contact aureole is complex. Many factors influence the size of the contact aureole. A study by Aarnes *et al.,* 2010 showed that the size of the aureole can be anything between 30% and 200% of the thickness of the intrusion. Factors influencing the size include the host rock temperature, sill thickness and intrusion temperature. The thicker the sill, the longer period of time the surrounding rocks is subjected to heat causing a bigger aureole. The type of flow regime of the igneous intrusion also impacts on the contact aureole size (Bussio, 2012). When the flow regime is turbulent, a smaller aureole will form, but when it is a laminar flow, the contact aureole will be bigger due to more heat released over a longer period of time (Bussio, 2012).

Contact metamorphism of organic matter could be a source of gas that can trigger global climate change. The change from organic matter to hydrocarbons by contact aureole is a rapid process (Aarnes *et al*., 2010). The thermogenic gases that formed are then released into the atmosphere by vertical pipe-like structures resulting in global climate change (Neumann *et al*., 2011).

According to Aarnes et al. (2010) there is a link between global warming, mass extinction and the emplacement of Large Igneous Provinces (LIP) in sedimentary basins. Events include the Emeischan volcanic province (end-Guadalupian event, ca. 252 Ma) and the Karoo igneous province (Toarcian event, ca. 182.6 Ma).

3.3 Preservation and thermal maturation of palynomorphs

Different factors influence the preservation of palynomorphs, starting from the time the grains are released from the parent plant. They are then transported by wind and water to its burial and ultimate analysis (Tweddle & Edwards, 2010). Most pollen grains are destroyed during transportation or soon after being deposited (Campbell, 1999).

The mechanical damage of the pollen grains is rare during transportation by wind and water. However, a study by Campbell and Campbell (1994) indicated that during wet and dry cycles, there is evidence of an impact on the corrosion and breakage of the pollen. This impact on the pollen may be the result of multiple phases of transportation and deposition before burial (Tweddle & Edwards, 2010). It is thought that this degradation is mainly due to the pollen grains' exposure to oxygen or fungi and bacteria (Elsik, 1971).

During the burial, some mechanical damage occurs as a result of the compaction of the sediments, but this is however not significant, although the pollen may be flattened. Oxidation is probably the main factor in the degradation and destruction of pollen during transportation and burial. The potential for preservation is different for each type of organic matter as seen in figure 3.2.

Origin	Group	Constituent
Higher plant debris	Phytoclast	Opaque phytoclasts
		Translucent phytoclasts
Higher plant	Sporomorphs	Pollen grains
		Spores
Degraded plant debris	Degraded organic matter Amorphous organic matter	
Degraded algae		

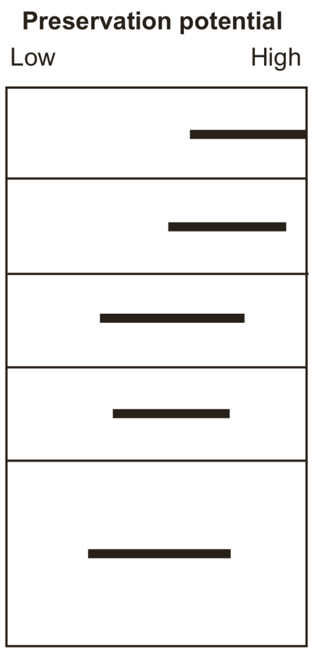


Figure 3.2: The preservation potential of the different sedimentary organic matter identified in this study (Götz & Ruckwied, 2014)

The pollen grains are subject to the same burial processes and thermal alteration as the rest of the sediments (Campbell, 1999). This makes it possible to predict the organic materials' degree of maturation by studying the thermal alteration of the pollen and spores (Elgmati, 2011). The maturity of the sediments is used in evaluating the potential for gas and oil.

The thermal maturation of sediments occurs over a long period of time that changes sedimentary organic matter into hydrocarbon due to chemical changes (Traverse, 2007). Source rocks are classified according to the amount of heat they are subject to and are classified as immature at low temperatures and mature and over mature at high temperatures (Peters & Cassa, 1994).

To determine the hydrocarbon maturity, Batten (1980) composed the spore colour index (SCI) (figure 3.3). Coal-bearing sediments are subject to partial degrees of metamorphism and this is reflected in the colour of the palynomorphs. The palynomorphs darkens in colour from yellow, which is immature, to orange, brown and black that indicates the sediments are increasingly mature (Yule *et al.,* 1988).

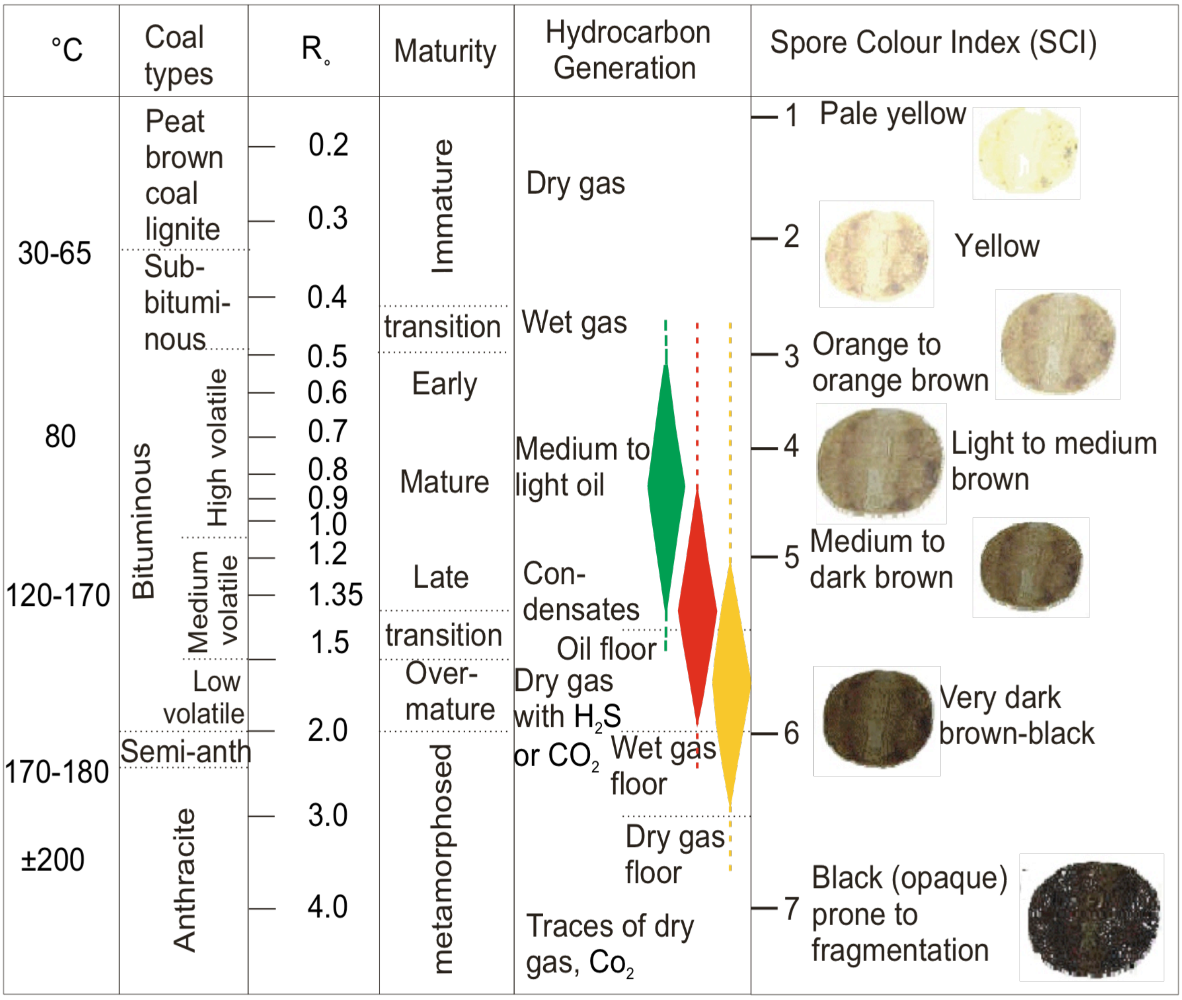


Figure 3.3: Spore colour index (SCI) from Batten (1980)

The spore colour index consists of a sliding scale that is judged by the eye against a chart. It tends to be problematic as it is somewhat subjective (figure 1.1). Another disadvantage of this method is that an increase in temperature can cause the colour of the pollen grain to change (Yule *et al.*, 1998). There are other more reliable methods such as microspectrophotometry that examines reflection and the transmitted light properties of a material to determine the maturity of the hydrocarbons (Yule *et al.*, 1998). Owing to costs and complex software, this method is not frequently used (Barbolini, 2010).

The most accurate way to determine the maturity and temperature history of a sedimentary basin is by using numerical modelling. These models can predict the palaeotemperature, maturation and petroleum generation. The main tool for determining the maturity estimation is vitrinite reflectance. Vitrinite is organic particles derived from higher plant materials and is a key constituent in coals and is found in most other sedimentary rocks. With increasing burial temperature the vitrinites' chemical properties as well as reflectance change systematically (Hartkopf-Fröder *et al.*, 2015).

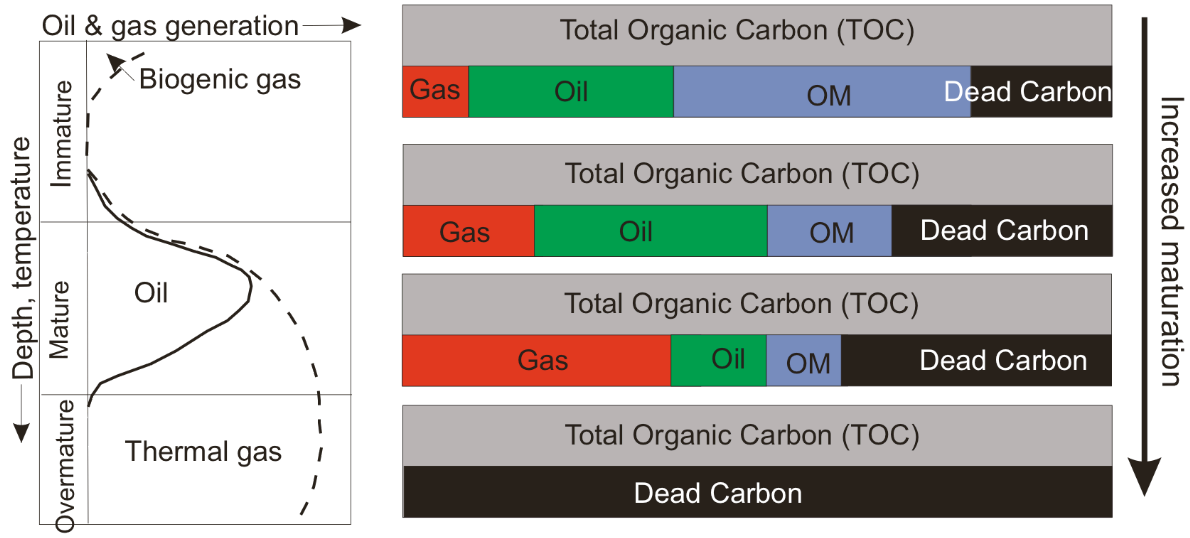


Figure 3.4: Oil and gas generation with an increase in thermal maturation and burial (from Elgmati, 2011, based on Jarvie, 2004)

To generate oil or gas, the organic matter is broken down by an increase in temperature and pressure during burial. Oil is generated when the sediments are mature, but at the higher maturities, oil generation declines and gas is formed (figure 3.4). Over-mature sediments are prone to gas generation (Elgmati, 2011).

Chapter 4: The South African coalfields

There are 19 different coalfields in South Africa with a recent review on them published by Hancox and Götz (2014). In South Africa, there are various coalfields (figure 4.1) with the Highveld coalfield covering an area of approximately 7 000 km^2 (Jordaan, 1986).

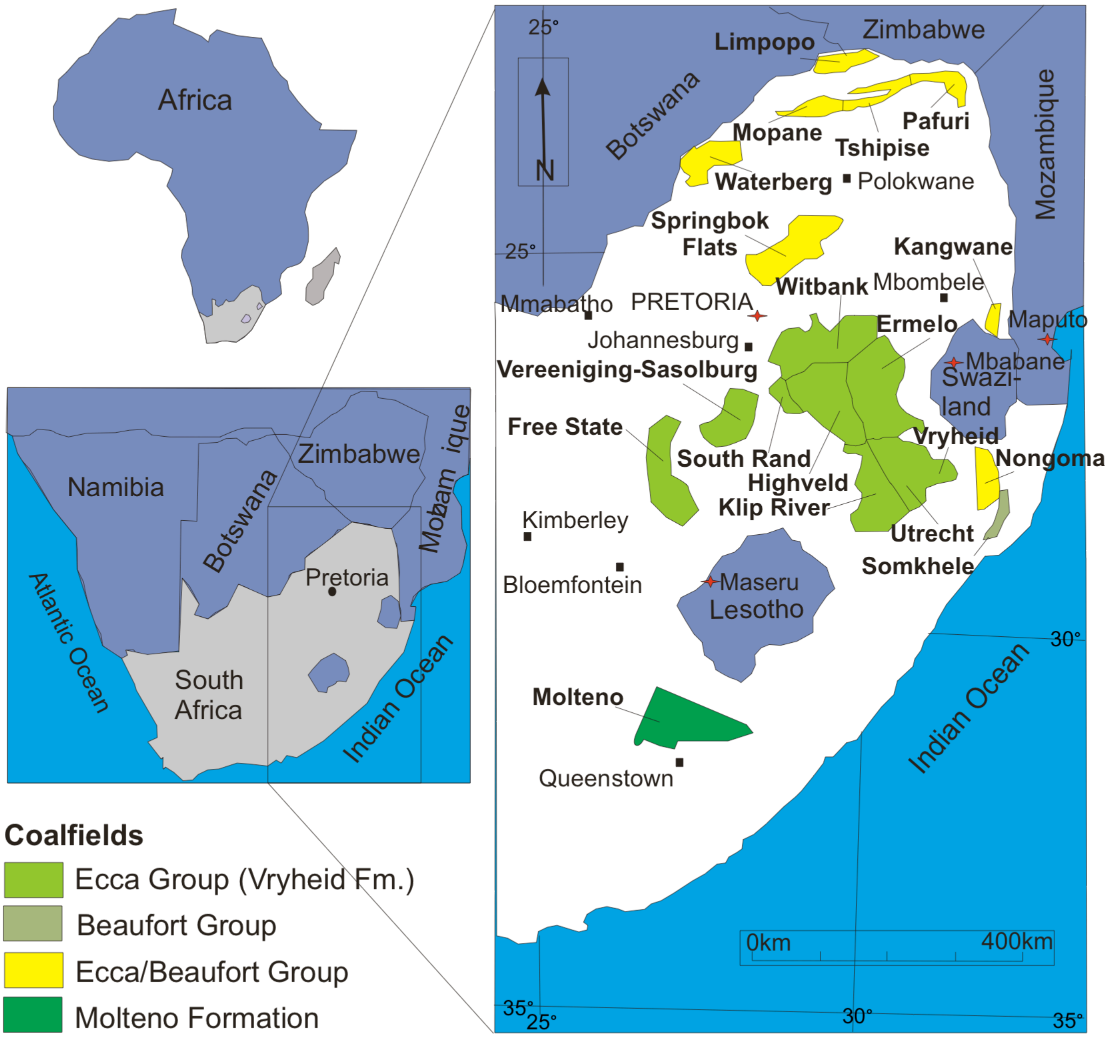


Figure 4.1: Map of the coalfields of South Africa (from Hancox & Götz, 2014)

The Smithfield Ridge forms the boundary to the north of the coalfield (figure 4.2) whilst outcrops of granite rocks from the Witwatersrand Supergroup form the boundary to the west and south-west (Hancox & Götz, 2014).

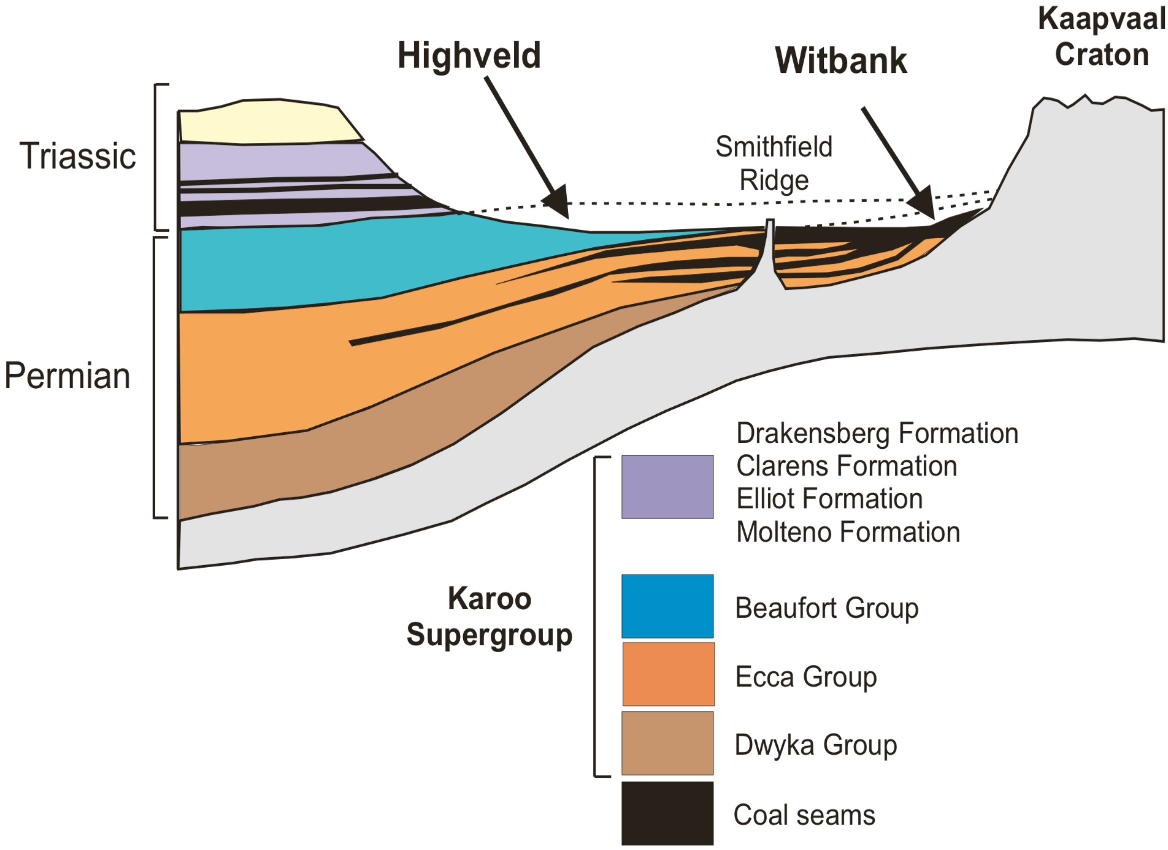


Figure 4.2: A schematic north-south section through the Witbank and Highveld coalfield that is separated by the Smithfield Ridge (from Hancox & Götz, 2014, based on Falcon, 1986)

The coals in the Highveld coalfield are generally classified as medium to highly volatile bituminous and sub-bituminous coals and are mined extensively (Saghafi *et al*., 2008). The main use for these coals is the production of synthetic fuels (Van Dyk *et al*., 2006).

The exploitable coal seams of South Africa are of Permian age and have a high inertinite and variable semifusinite and vitrinite content and are low in sulphur (Cadle *et al*., 1993). The Karoo coal's organic matter content is highly variable and rich in inorganic (mineral) matter. The variability in the coals can be attributed to the degree of composition of the organic matter and the type of plant material that accumulated to form the coal. The type of vegetation that accumulated and formed the peat swamps of Africa ranges from sub-arctic mosses to cool temperate deciduous forests and cold temperate conifers (Falcon, 1986).

The Vryheid Formation in the Ecca Group coal deposits exhibits high inertinite contents, implying that the coal deposits were subject to high rates of oxidation and microbial degradation (Cadle *et al*., 1993). These coal deposits have been tectonically undisturbed since their deposition. The only major disturbances are the intrusive dolerite dykes and sills (Cairncross, 2001).

The mineable coal in this Highveld coalfield is from the Ecca Group where five different coal seams can be identified (Saghafi *et al*., 2008). The most economically important coal seam in the Highveld coalfield is the lower number 4 seam (Hagelskamp & Snyman, 1988; Snyman 1998).

The number 1 coal seam is the deepest, with a thickness that is usually less than 0.5 m. This seam is irregular and not fully developed (Saghafi *et al*., 2008). It is topographically controlled and mainly developed in the eastern part (Hancox & Götz, 2014). This assemblage has abundant sporites and monosaccate pollen grains. It represents the mixed plant communities that include horsetails, ferns and lycopods (Falcon *et al*., 1984).

The number 2 coal seam occurs approximately 30 m below the lower number 4 coal seam at a thickness of less than 1.5 m (Saghafi *et al*., 2008). It is mined selectively due to mudstone and siltstone parting throughout the seam (Hancox & Götz, 2014). It has an increase in species diversity and the microflora represents a transitional phase from icehouse to greenhouse conditions (Falcon *et al*., 1984; Götz & Ruckwied, 2014).

The number 3 coal seam is thin and poorly developed with high proportions of transported organic detritus (Falcon *et al*., 1984a). It is less than 0.5 m thick and when the separation between no 3 and 4 coal seams is less than 1 m, it is mined together (Hancox & Götz, 2014).

The number 4 coal seam consists of the number 4 lower and the number 4 upper seams. These seams are separated by sandstone with a thickness between 2 and 3 m (Hancox & Götz, 2014).

The number 4 upper coal seam's thickness varies between 0.3 m and 1.3 m, while the number 5 coal seam is approximately 1.5 m thick (Saghafi *et al*., 2008). The lower number 4 coal seam (the coal seam on which this study focuses) is mostly dull coal with an interbedded bright coal zone and an average thickness of 4 m. It has abundant pollenites flora and the taeniate and non-taeniate pollen grains are also abundant. The taeniate bisaccate pollen grains appear to increase and indicate a higher occurrence of higher-order plants (Falcon *et al*., 1984a).

The number 5 coal seam's thickness is between 0.3 to 3.0 m at a depth of 5 to 150 m. It is not mined due to a hard siltstone parting making it uneconomical (Hancox & Götz, 2014). It has higher proportions of taeniate bisaccate pollen grains (Falcon *et al*., 1984).

Karoo magmatism erupted at 183 Ma and formed the extrusive Drakensberg flood basalts and the intrusive dykes and sills found in the lower Karoo sedimentary rocks. The intrusions of the Highveld coalfield are a representation of the intrusive igneous activity at the end of the formation of the Karoo Supergroup (Smith *et al*., 1993).

Dolerite intrusions are much more common in the Highveld coalfield than in the Witbank coalfield, and cause structural complications as well as the devolatilisation of the coal (Snyman, 1998). The intrusions also cause displacement of the coal (Hancox & Götz, 2014). The thickness of the dykes in this region varies between 0.1 m and 5 m, while the sills are approximately 40 m thick (Saghafi *et al*., 2008). Due to the negative effect of the dolerite intrusion on the coal quality, research and mapping of these are important for mine planning (Hancox & Götz, 2014).

The dolerite sills in the Highveld coalfield were classified by the Sasol geologists and are the B4, B6 and B8 sills. The dolerite dykes and sills in this area are considered to be the same age (Hancox & Götz, 2014).

Bussio (2012) researched the Secunda dolerite sills DO4, DO8 and DO10 due to their close proximity to the number 4 coal seam in the Highveld coalfield. The DO4 dolerite sill crops out on the surface while DO8 intersects the number 4 coal seam in certain locations. The DO4 sill range in thickness from 0.2 m to 74.43 m and has a continuous stratigraphic position within the coalfield. In certain places it is in close proximity to the lower number 4 coal seam but it rarely intersects.

The DO8 sill is concentrated in the north-eastern side of the coalfield were it intersects the no 4 coal seam. It has a thickness that spans from 0.1 m to 44.65 m. DO10 is the least continuous and is located below the coal seam but it protrudes upwards getting into close proximity to the seam (Bussio, 2012).

Chapter 5: Results

All samples within a distance of less than 20 m away from the dolerite dyke appeared to be barren or only contained charcoal in which none of the original organic palynomorphs could be identified. The last four samples taken at 20 m provided enough material to proceed with the analyses. These samples were used for determining the palynofacies, and visual counting of up to 200 palynomorphs was done.

The following samples did not yield any identifiable palynomorphs: DK 4, DK 6, DK 7, DK 9, DK 10, DK 11, DK 12, DK 13, DK 16 and DK 17, and are referred to as non-productive samples. The non-productive samples were taken within 20 m of the dolerite dyke intrusion. These samples consisted mainly of phytoclasts that were roughly the same size as those shown on plate 1A and 1B. Brownish materials were present in some samples that were remnants of plant cuticles (plate 1C).

The samples that were useful in determining the palynofacies of the lower number 4 coal seam were those taken further away from the dyke at 20 m. The following samples will be discussed in more detail: DK 20D, DK 20S, DK 20B and DK 20L, with figure 5.1 showing the percentages of the visual counting.

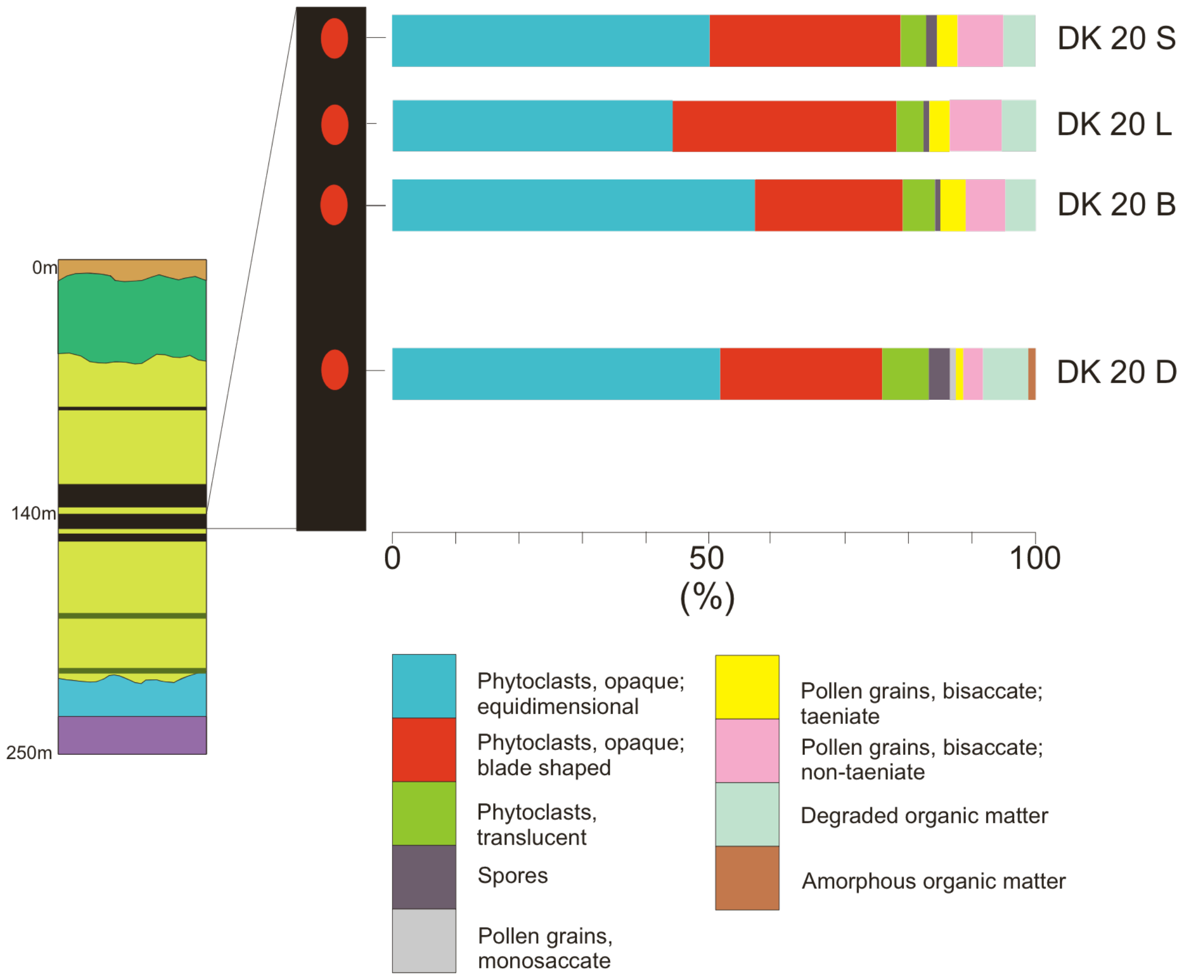
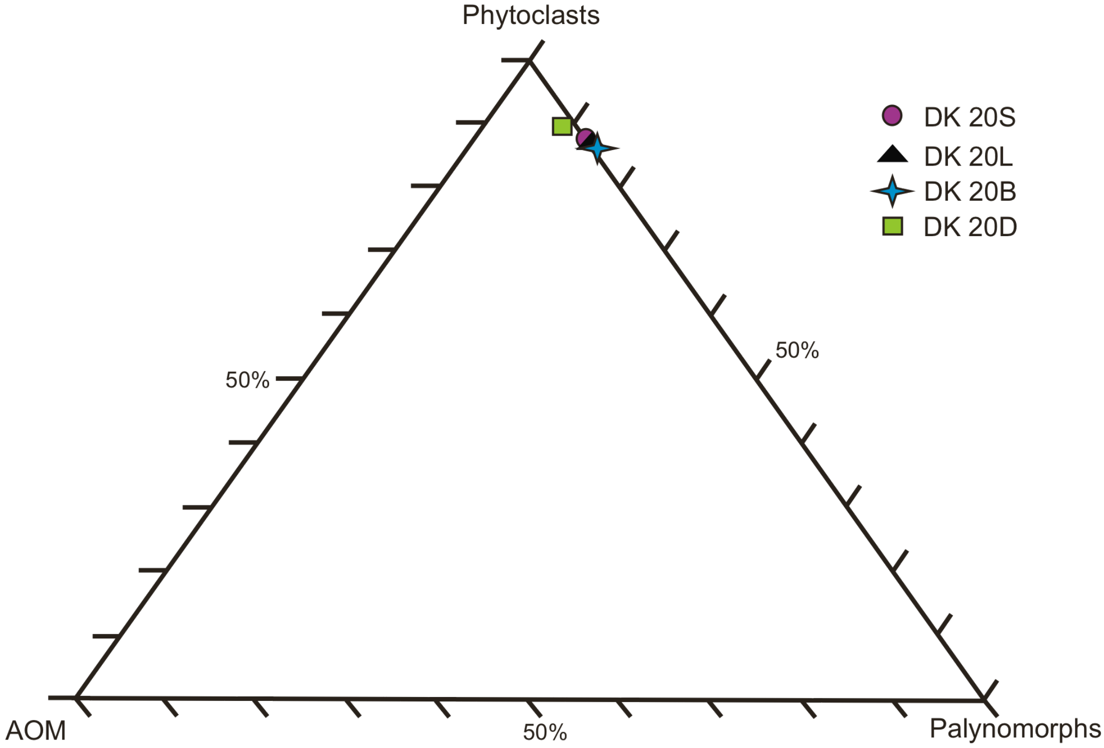


Figure 5.1: Quantitative representation of the organic matter and palynomorphs in the studied samples

a)



b)

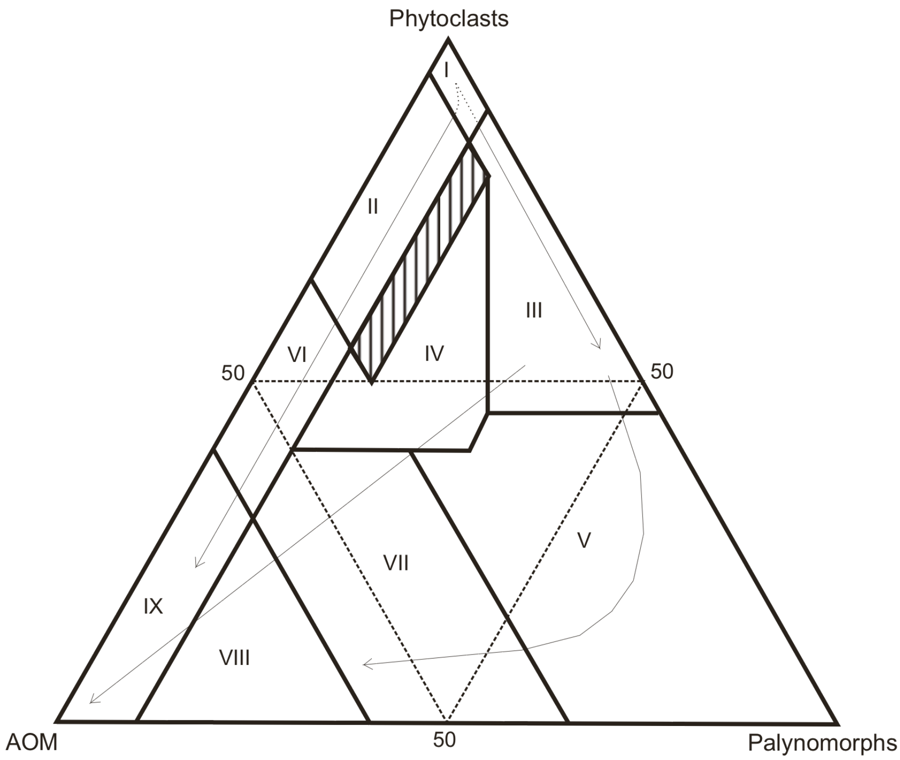


Figure 5.2: a) Ternary AOM – total palynomorphs – total phytoclasts plot; b) palynofacies fields and environments (Tyson, 1995)

Table 5.1: Summary explanation of palynofacies fields and environments (Tyson, 1995)

Palynofacies field and environment	
I	Highly proximal shelf or basin
II	Marginal dysoxic-anoxic basin
III	Heterolithic oxic shelf ('proximal shelf')
IV	Shelf to basin transition
V	Mud-dominated oxic shelf ('distal shelf')
VI	Proximal suboxic-anoxic shelf
VII	Distal dysoxic-anoxic 'shelf'
VIII	Distal dysoxic-oxic 'shelf'
IX	Distal suboxic-anoxic basin
➔	Proximal – distal sediment transport (basinward)

The most dominant field is III and represents a proximal setting of high terrestrial discharge, oxic conditions and low AOM preservation.

5.1 Bottom section: DK 20D

Sample DK 20D was taken 1 m from the base of the lower number 4 coal seam. Sample DK 20D contains a variety of clast sizes with opaque phytoclasts being dominant (plate 1D). The equidimensional opaque phytoclasts is dominant in this sample with an abundance of blade-shaped phytoclasts. Translucent phytoclasts and tracheids are present in this sample (plate 1F), as well as degraded organic matter (DOM) and amorphous organic matter (AOM).

The sample comprised only small amounts of pollen grains and spores (plate 1E, 1F). It contained 3.4% spores and 2.98% non-taeniate bisaccate pollen grains. DK 20D has the highest percentage of degraded organic matter compared to the other DK 20 samples. It is also the only sample with monosaccate pollen grains and amorphous organic matter (plate 2B).

5.2 Middle section: DK 20B and DK 20L

Sample DK 20B was taken at 2 m from the base of the coal seam and 1 m above DK 20D. The sample had a variety of clast sizes and showed more signs of fragmentation and sorting than DK 20D (plate 2C). Although a variety of larger phytoclasts could be found here, a general increase in smaller clasts are visible. In this sample, the clast sizes are more balanced than in sample DK 20D.

Equidimensional phytoclasts are also dominant in this sample at 56.2%. The result of the visual counting indicates the absence of monosaccate pollen grains and a decrease in spores, compared to sample DK 20D lower in the coal seam. There is also an increase in non-taeniate (plate 1E) and taeniate bisaccate pollen grains (plate 2D). Degraded organic material decreased from DK 20D to DK 20B.

Sample DK 20L was 2.5 m from the base of the coal seam. Smaller particles are dominant with some larger clasts (plate 3A). No monosaccate pollen grains or amorphous organic matter are present. There is a small increase in non-taeniate pollen grains and blade-shaped phytoclasts.

The blade-shaped opaque phytoclasts increased in this sample compared to the other three samples, with a decrease in the equidimensional opaque phytoclasts (plates 3A, 3B).

5.3 Top section: DK 20S

This sample was taken 3 m from the base of the lower number 4 coal seam and is the topmost sample. The larger clasts are rare in this sample, with smaller phytoclasts dominating. The phytoclasts are smaller and better sorted than in the previous samples (plate 3C).

There is non-taeniate (7.7%) and taeniate pollen (3.1%) with very little spores present. No monosaccate pollen grains or amorphous organic matter are evident in DK 20S. The palynomorphs are highly fragmented.

The only sample with amorphous organic matter and monosaccate pollen grains are the bottom sample DK 20D. There is a general decrease in clast size from the base to the top of the coal seam.

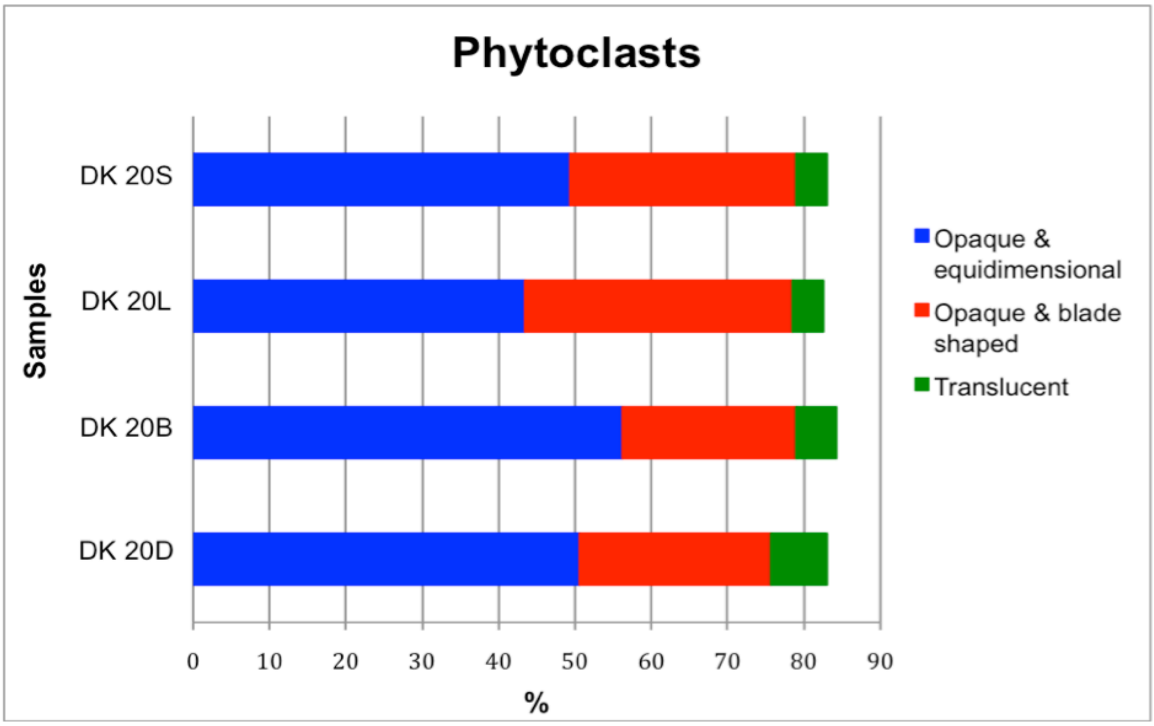


Figure 5.3: The percentage of different phytoclasts in each sample studied

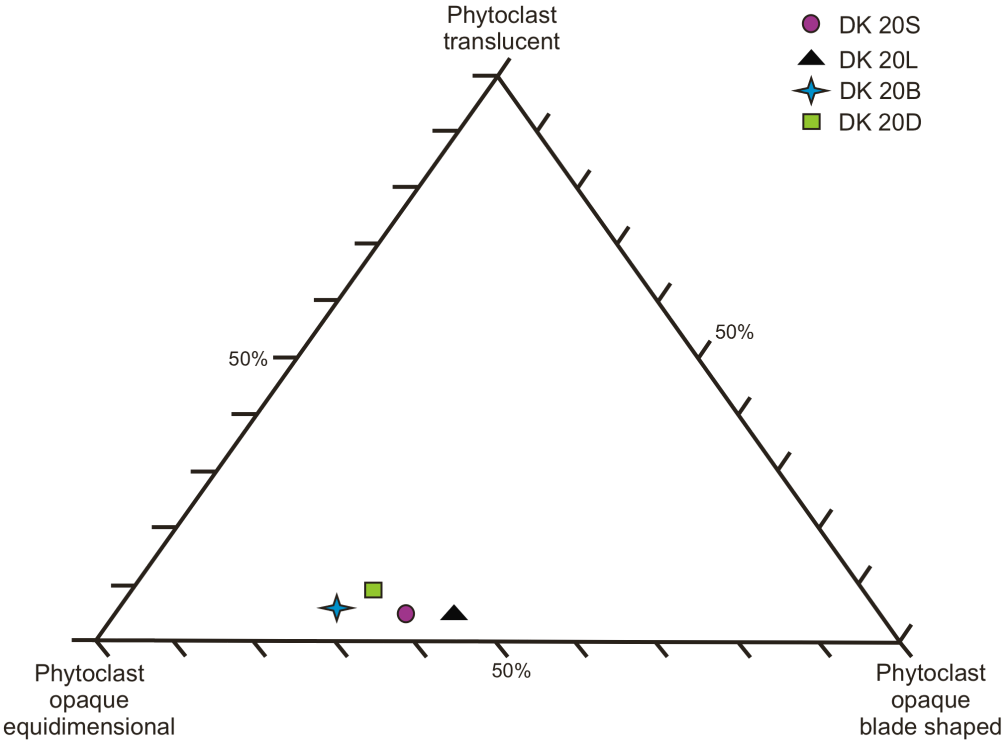


Figure 5.4: Ternary diagram of different phytoclasts in each sample studied

The opaque equidimensional phytoclasts decreased in the middle of the coal seam and then increased again towards the top. The blade-shaped opaque phytoclasts increased towards the top and then decreased slightly in the top sample. In all samples there are less than 10%

translucent phytoclasts that decreased slightly. There is a general increased fragmentation of the clasts and in opaque phytoclasts from the bottom of the coal seam towards the top.

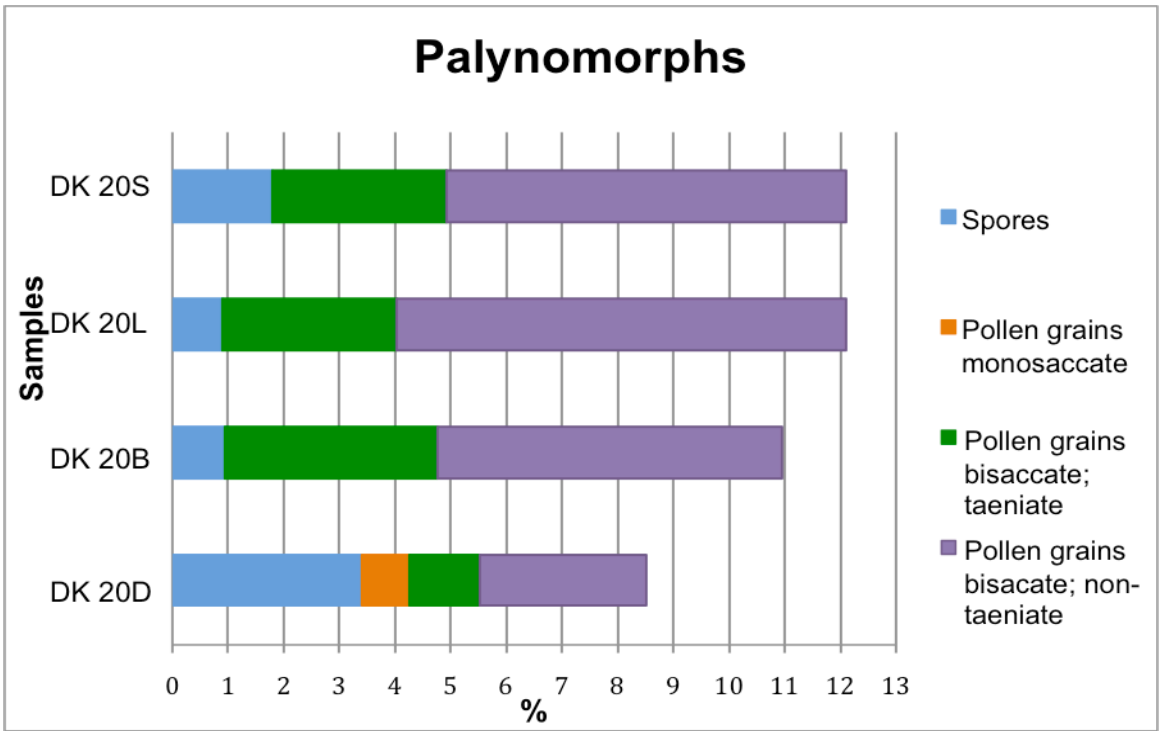


Figure 5.5: The percentage of palynomorphs in each sample studied

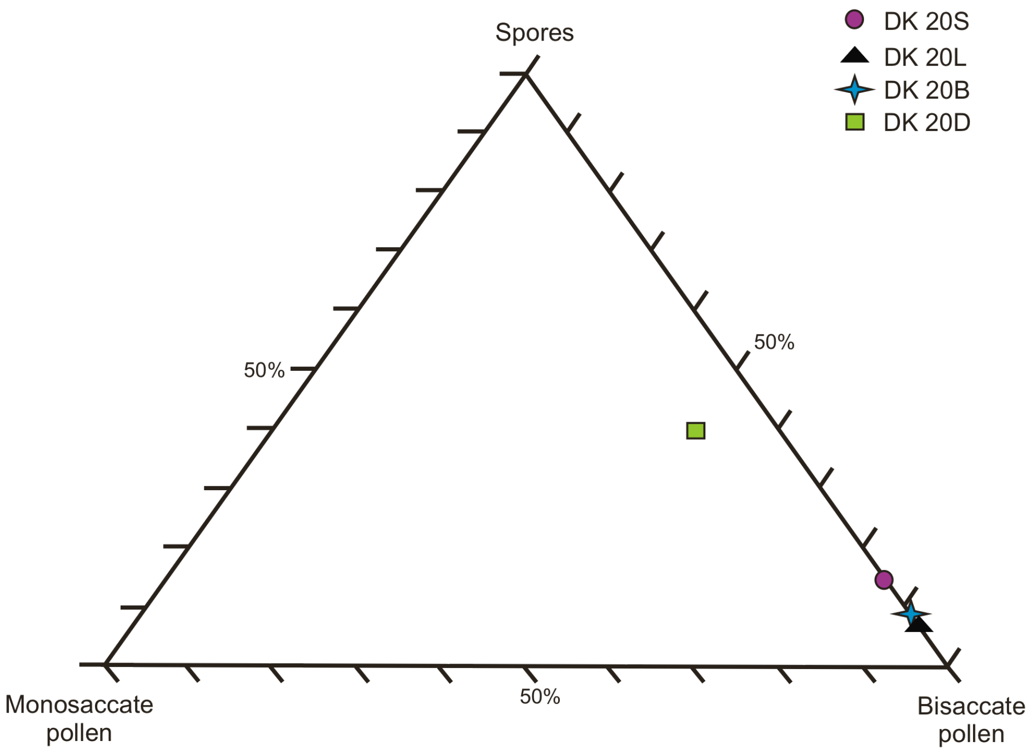


Figure 5.6: Ternary diagram of palynomorphs in each sample studied

From the bottom section towards the top section of the coal seam there is a general increase in taeniate and non-taeniate bisaccate pollen grains. The spores also decreased, while the monosaccate pollen grains only occurred in the bottom section of the coal seam as depicted in figure 5.5 & 5.6.

The tables below documents the palynomorphs that were identified in the samples studied. There were four types of spores with trilete marks and three types of pollen grains.

The palynomorphs in the samples were not well preserved and it was difficult to take clear photographs. Photographs from Modie (2007) and Pendleton (2012) were used to illustrate the different spore and pollen grains in this study.

Table 5.2: Spore identified in samples

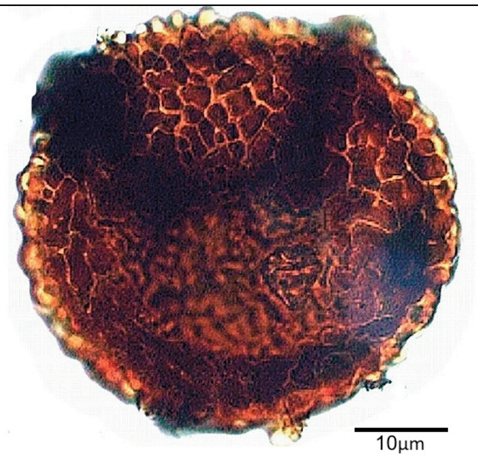
Species	*Acanthotriletes triquetrus*
Natural affinity	Ferns, lycopsida
Reference	Potonié and Kremp, 1954

(Pendleton, 2012)

The *Acanthotriletes sp.* is a small, triangular trilete spore with echinate ornamentation (Good, 1979). Echinate is described as spines of not longer than 1µm that cover the exine (Punt *et al.*, 2007). The exine is moderately thin and the laesurae may or may not be evident (Pendleton, 2012).

Table 5.3: *Verrucosisporites* sp. identified in samples

Species	*Verrucosisporites sp.*
Natural affinity	Ferns, pteridosperms
Reference	Smith and Butterworth, 1967

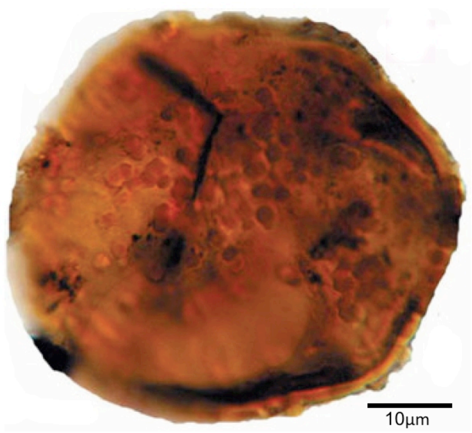


(Modie, 2007)

The *Verrucosisporites* sp. has a wart-like sexine element – the sexine is the outer layer of the exine – that is called verruca, which is wider than 1µm and not higher than its width (Punt *et al*., 2007). Pteridosperms are reproduced by seeds and have fern-like foliage (Willis & McElwain, 2002).

Table 5.4: *Punctatisporites* identified in samples

Species	*Punctatisporites*
Natural affinity	Ferns, sphenophyta
Reference	Potonié and Kremp, 1954



(Modie, 2007)

Punctatisporites is a laevigate trilete spore, which means it has a smooth exine (Punt *et al*., 2007). From a polar view it is circular or slightly oval with a thick exine (Pendleton, 2012).

Table 5.5: *Microbaculispora sp*. identified in samples

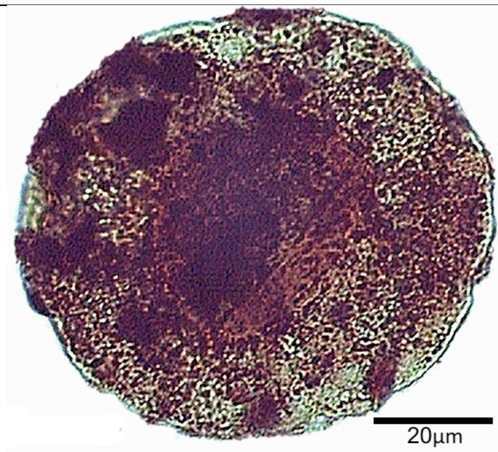
Species	*Microbaculispora sp.*
Natural affinity	Sphenophyta, filicophyta
Reference	Bharadway, 1962

The *Microbaculispora sp.* is triangular in outline with the exine covered in a variety of baculate ornaments (Pendleton, 2012). Baculum is a cylindrical freestanding element, longer than 1µm and situated on a generally thick exine (Punt *et al*., 2007). All the spore species identified in the samples are trilete spores.

Sphenohyta developed in wet swampy conditions and had a large root system while filicopsids (ferns) grew in drier upland areas, where it was the largest of the ferns found in coal swamps (Willis & McElwain, 2002).

Table 5.6: *Florinites* identified in samples

Species	*Florinites*
Natural affinity	Cordiatales
Reference	Scholpf *et al*., 1944

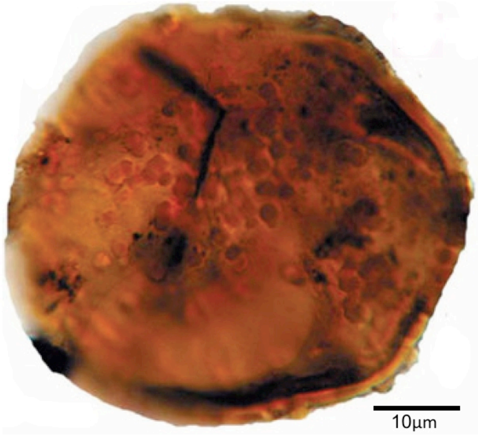


(Modie, 2007)

The only monosaccate pollen grain to be identified in the samples is the *Florinites.* This is an alete pollen grain and from polar view it is sub-circular to oval (Modie, 2007). Cordaitales were abundant during the Permain and grew in mangrove-type habitats to drier uplands (Willis & McElwain, 2002).

Table 5.7: *Protohaploxypinus* identified in samples

Species	*Protohaploxypinus*
Natural affinity	Pteridosperm
Reference	Morbey, 1975



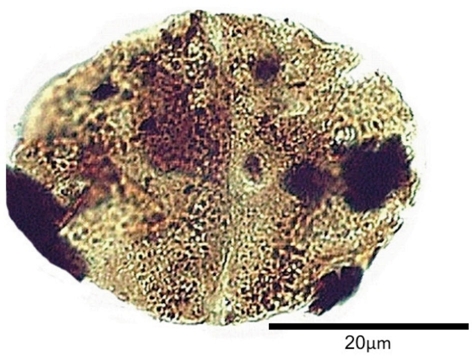
(Modie, 2007)

Both the *Protohaploxypinus* and *Alisporites* sp. are taeniate bisaccate pollen grains and come from Pteridosperms that flourished during the Permian period (Willis & McElwain, 2002).

The *Protohaploxypinus* in alete and in polar view show that the sacci is more or less continuous with the outline of the body. The body can be circular or oval with the grain appearing to have a smooth ellipsoidal form (Punt *et al.,* 2007).

Table 5.8: Genus *Alisporites sp.* identified in samples

Species	*Alisporites ovatus.*
Natural affinity	Pteridosperm
Reference	Daugherty, 1941



(Modie, 2007)

The body of the *Alisporites* sp. is oval to a rounded tetragonal shape with the sacci overlapping half of the body (Pendleton, 2012). It is haploxylonoid but can be slightly diploxylonoid in polar view (Hart, 1965).

Chapter 6: Discussion

The productive samples are at 20 m from the dolerite dyke, and at this distance, the dolerite dyke had little impact on the palynomorph preservation. These samples yielded enough palynomorphs to be used for interpreting the palaeoenvironmental and climatic conditions during the deposition of the lower number 4 coal seam.

The productive samples represent the lower number 4 coal seam of the Highveld coalfield in the southern hemisphere during the Middle to Late Permian. During this time, the vegetation was dominated by swamp-dwelling lycopsids, sphenopsids and seed plants (Willis & McElwain, 2002). The glossopterid plant is indicative of higher latitude environments and continental upland and is believed to be the flora that dominated during the Late Permian (Pigg & McLoughlin, 1997; Van de Wetering *et al.*, 2013).

There is evidence of two different palynofacies assemblages in the lower number 4 coal seam that will now be discussed. The bottom section indicates swamp conditions, while the interval between the middle and top sections shows indications of higher fluvial input.

The first palynofacies assemblage is situated at the bottom section of the coal seam and is characterised by the occurrence of AOM and monosaccate pollen grains. AOM is formed by the biodegradation of terrestrial material (Tyson, 1995), and if monosaccate pollen grains dominate, this may be an indication of cooler climatic conditions (Falcon, 1986; Götz & Ruckwied, 2014). The occurrence of monosaccate pollen grains and AOM, together with the lower amount of bisaccate pollen grains and higher amount of spores, as well as opaque equidimensional phytoclasts in the bottom section, all indicate that it could have formed during cooler conditions with less transportation (Falcon, 1986; Götz & Ruckwied, 2014). The parent plant of the monosaccate pollen grew at an area marginal to the swamp (Traverse, 1988) increasing the amount in the bottom section. This reveals that the bottom section of the coal seam was deposited under swamp conditions where reducing conditions were occurred forming the AOM.

Opaque phytoclasts are formed by the biodegradation of woody material and are normally found in well-oxygenated environments (Tyson, 1995; Jha *et al.*, 2014). The opaque phytoclasts are also believed to be more resistant than translucent phytoclasts (Van Bergen & Kerp, 1990) and can reflect more fluvial conditions, while their dominance reflects more distally sourced material (Tyson, 1995; Pittet & Gorin, 1997).

According to Batten and Stead (2002), when equidimensional opaque phytoclasts are dominant in fresh or brackish water, high oxygen and low energy conditions exist, which are caused by the periodical exposure of the floodplain or riverbed. However, in the case of this study, where the equidimensional opaque phytoclasts are also dominant, it is presumed that the river was in flood, causing higher energy and oxygen levels and an influx of bisaccate pollen grains.

The increase in opaque phytoclasts with the decrease of translucent phytoclasts from the bottom towards the top of the coal seam suggests that more energy and oxygen were available. Decay of woody material forms opaque phytoclast that indicate increased oxygenation and warmer conditions. Increases in opaque phytoclasts are an indication of the gradual warming of palaeoclimatic conditions (Van Bergen & Kerp, 1990).

The second palynofacies assemblage occurs at the interval between the middle and top sections of the coal seam. There is an increase in blade-shaped opaque phytoclasts and a greater degree of sorting. This suggests that the organic material was transported over a greater distance owing to the fact that transportation tends to change the larger equidimensional phytoclasts to blade-shape phytoclasts (Tyson, 1995).

The higher amount of taeniate bisaccate pollen grains in this section shows that the palaeoenvironment was warmer during deposition than the bottom section (Falcon, 1986; Götz & Ruckwied, 2014). The interpretation of this was that there was more fluvial input into the swamp area found in the bottom section of the coal seam.

Gymnospermous bisaccate pollen grains, *Alisporites sp.* and *Protohaploxypinus sp.,* were identified. *Protohaploxypinus sp*. is presumed to be pollen from the glossopterid plant that is characteristic of higher latitude environments and continental upland (Falcon, 1986; Pigg & Trivett, 1994). The spores, *Microbaculispora sp.*, *Punctatisporites* and *Verricosisporites sp.*, are fern and horsetail spores that are indicative of a fern wetland community (Götz & Ruckwied, 2014).

The spores, *Microbaculispora sp.*, *Punctatisporites* and *Verricosisporites sp.*, were identified in all the samples, but are more dominant in the lower section of the coal seam. Spore-producing floras need water to reproduce and are found in lowland areas close to swamps (Willis & McElwain, 2002). Flooding will favour the growth of fern wetland communities (Jha *et al.*, 2014), causing an increase in the amount of spores right after a flood event. It is thought that the spore-producing flora was dominant in the lowlands adjacent to the swamp.

The *Protohaploxypinus sp.* from the glossopterid plant was the dominant flora in the upland area. Owing to the increase of the taeniate bisaccate pollen grains from the glossopterid plant upwards in the coal seam, it is thought that a river from the upland area transported the pollen grains towards the swamp. The bisaccate pollen grains are adapted to drier and warmer conditions and can also be transported by the wind over great distances (Falcon, 1989).

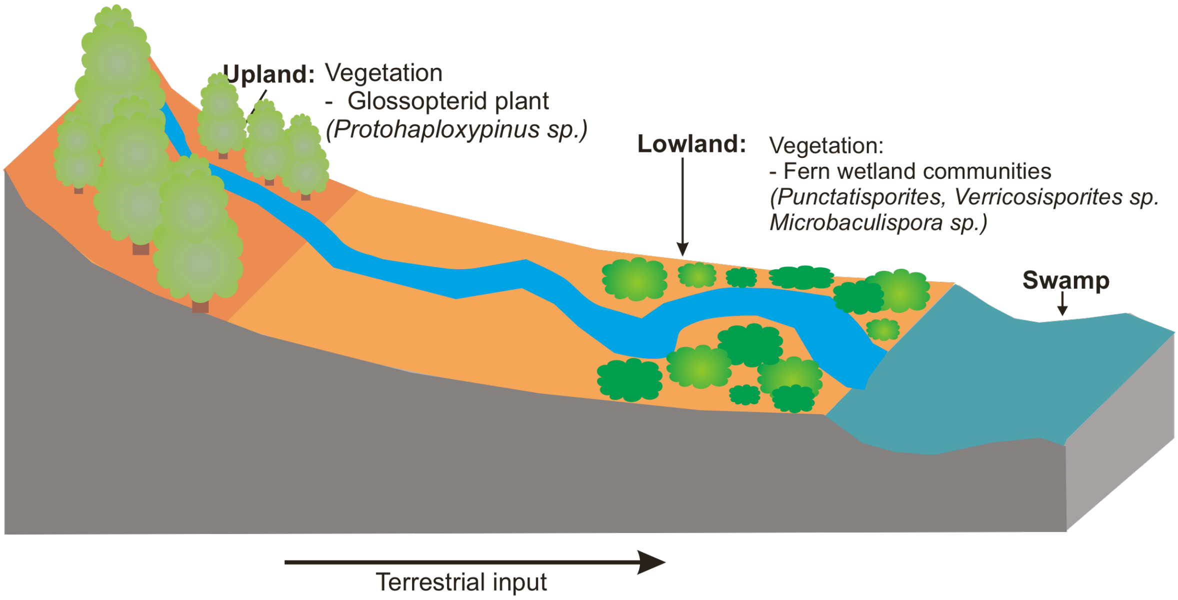


Figure 6.1: Diagram of the possible upland and lowland vegetation with fluvial input into the swamp

The increase in water and turbulence caused by the river in flood increased the amount of oxygen (Smith & Scott, 2005), resulting in further degradation of the phytoclasts. The more turbulent river flow increased the fragmentation and sorting of the phytoclasts. From the highland areas the river fragments and degrades the organic matter before depositing it in the lowland swamp.

The fluvial influx caused the water depth to rise and could be responsible for decreasing oxygen levels (Collinson *et al.,* 1992) and the formation of the AOM at localised areas in the swamp. This is represented by the AOM found in the bottom section of the coal seam. During the period the river was in flood, there was also an increase in the amount of organic matter in the swamp (Talbot & Allan, 2009). The upshot of this was dilution of the amount of spores compared to the other organic matter in the swamp.

It is therefore evident that during the formation of the lower number 4 coal seam in the Highveld basin, the palynofacies changed from swamp area to fluvial input into the swamp. This was caused by a river flowing into the swamp at a higher rate, bringing with it an increased amount of water and organic material.

The results of the lower number 4 coal seam show that there is an increase in energy from the bottom of the seam towards the top. The Cape Fold Belt is responsible for the tectonic regimes during the deposition of the Karoo Basin. Prior to the deposition of the Vryheid Formation in the Karoo Basin, there was according to Catuneanu *et al*. (1998) orogenic loading of the Cape Fold Belt. This meant that there was uplift in the distal region (Vryheid Formation) and subsidence in the proximal region. At this stage the depocentre was in the proximal area (Catuneanu *et al*., 1998).

As the Vryheid Formation started to develop, it corresponds with the beginning of orogenic unloading of the Cape Fold Belt. During this stage the proximal region undergoes uplift and the distal region subsidence (Catuneanu *et al*., 1998) and the depocentre moves from the proximal to the distal region.

Over time the unloading of the Cape Fold increases as erosion continues. The distal region (Vryheid Formation) of the basin continues to deepen over time. The depocentre of the Karoo Basin will be in the distal section at this stage, increasing the accumulation of sediment (Catuneanu *et al*., 1998).

Looking at the lower number 4 coal seam palynofacies results there is higher energy conditions and an increase in sediment in the top section of the coal seam. This increase in fluvial input and energy could be due to the increase in gradient between the upland and lowland/swamp areas. The increase in gradient could be caused by the general subsidence of the base during the formation of the Vryheid Formation. This coincides with the general energy increase seen in the subsidence of the distal regions during the formation of the Ecca Group. Over time subsidence continues and the deposition of sediments increase burying the plant remains in the swamp and this will eventually form the coal over millions of years.

The palynomorph diversity of the lower number 4 coal seam is low, although those that were identified showed a strong similarity to Biozone III after Falcon *et al.* (1984), as indicated in figure 6.2.

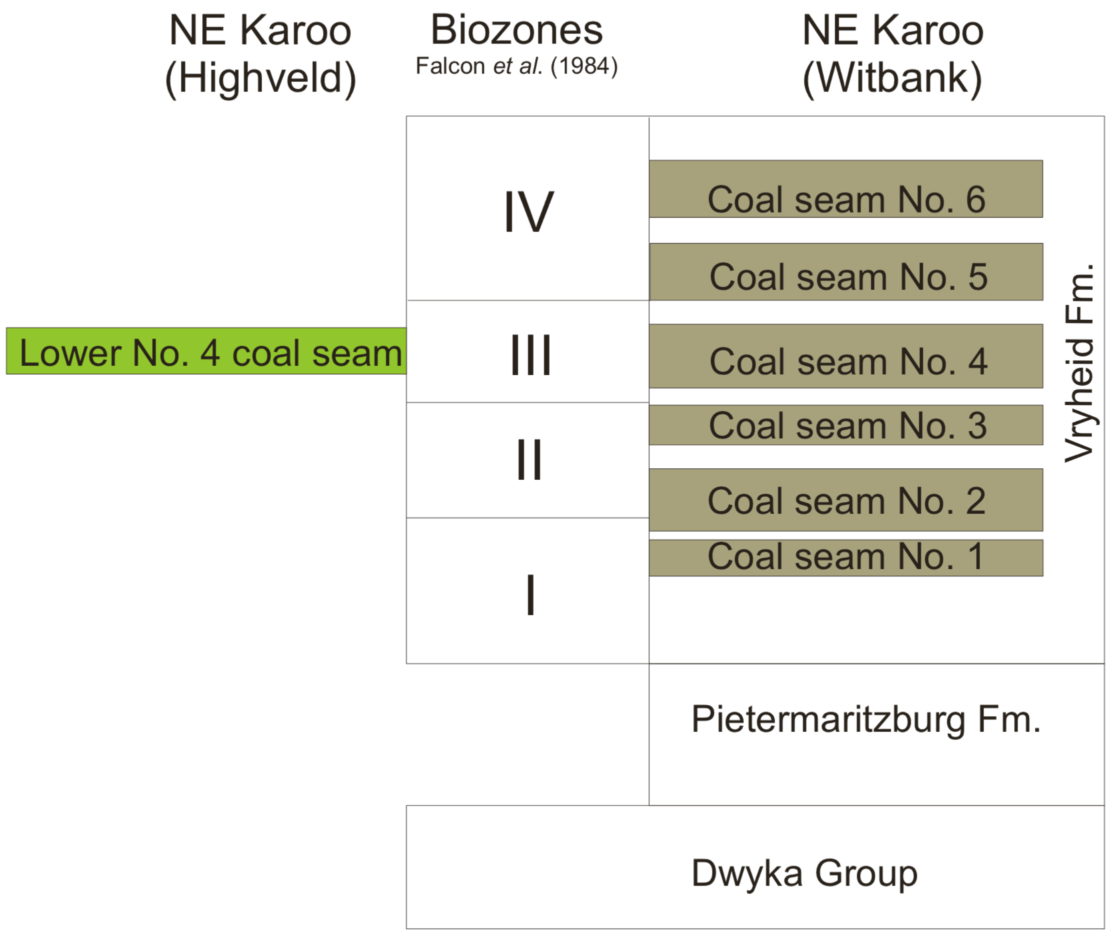


Figure 6.2: Correlation of the lower number 4 coal seam of the Highveld coalfield to the Witbank coalfield (modified from Ruckwied *et al*., 2014)

To determine the palynomorphs to parent plants, paleobotanist and palynologist have been extracting palynomorphs from in situ reproductive organs of fossil plants (Pendleton, 2012). The work is catalogued by Balme (1995) and Traverse (2008) with new articles emerging from Bek *et al*., 2009 and Bek and Libertin, 2010.

Palynomorphs are far more abundant than macroplant fossils and are better preserved, which makes them easier to use in palaeoenvironmental reconstruction (Barbolini, 2010). Palynomorphs can be linked to their parent plant, which increases scientists' understanding of the evolutionary patterns. Pollen is more valuable in determining the age of strata because they are less affected by water availability and represent stable upland parent flora (Falcon, 1989). This correlation between the palynomorph and parent plant is inconsistent because of the fact that some palynomorphs were linked to different macroplants. This occurred as a result of different stages of development or preservation states (Bek & Opluštil, 1998). The parent plant may even be different time periods and areas (Barbolini, 2010).

All the sedimentary organic matter identified in the study has a relatively high preservation potential but due to the igneous intrusion the sporomorphs and degraded organic matter within the devolatilisation zone were destroyed. The only sedimentary organic matter that could be identified in the devolatised zone were opaque phytoclasts.

The following are possible factors explaining why some samples were barren: Sediments can have low palynomorph abundances owing to unfavourable conditions during coal formation, metamorphism and/or slide preparation. During the deposition of coal, there could be a lack of pollen and spores because the climatic conditions were unfavourable for widespread plant life (Barbolini, 2010). Extremely high or low surface temperature will inhibit the growth of plants. Also, during the processing of the coal when removing organic matter by oxidation, the palynomorphs can swell and rupture if they are oxidised for too long (Moore *et al.,* 1991). The most logical reason for the non-productive samples for this study is the contact metamorphism caused by the dolerite intrusion. The contact metamorphism formed an aureole around the intrusion. From the palynomorph it is estimated that the devolitalisation zone reached a thickness of approximately 17 to 19 m. The thickness of the dolerite intrusion has no correlation to the size of the devolitalisation zone (Bussio, 2012), but can be between 30 to 200% of the thickness of the dolerite dyke (Aarnes *et al*., 2011). The effect of the intrusion however flattens out at 20 m from the dolerite dyke (Saghafi *et al*., 2008) and future sampling should take that into account.

The igneous intrusion has its own unique metamorphic signature that changed the physical and chemical properties of the coal (Saghafi *et al*., 2008, Bussio, 2012) and subsequently destroyed the palynomorphs. The quality of the coal surrounding the dolerite dyke is impacted by the thermal maturation of the organic matter (Elgmati, 2011). The coal surrounding the dolerite dyke will be lower in quality and structurally weakened (Saghafi *et al*., 2008). There is a possibility of gas forming by thermal maturation surrounding the dolerite dyke but due to fracturing the gas is likely to escape (Elgmati, 2011).

The thermal maturation of a pollen grain in the devolatilisation zone and at 20 m from the dolerite was compared to the spore colour index. The pollen in the devolatilised zone is extensively metamorphosed and black making the SCI unusable. The pollen grain at 20 m was medium brown and compares to a SCI of 4 with a vitrinite reflectance of 0.6 – 0.8 (figure 3.2). This indicates that the sediment are early mature and that the samples should be high volatile bituminous coal. The lower number 4 coal seam in the Highveld is generally classified as high volatile bituminous coal (Saghafi *et al*., 2008).

If further studies were to be conducted on the lower number 4 coal seam with more horizontal sampling, the results would provide more detailed information on the different events that occurred during the formation, and whether these events were localised or occurred over a greater distance.

The palynofacies study of the lower number 4 coal seam in the Highveld coalfield is essential for palaeoenvironmental analysis and interpretation of depositional conditions.

Chapter 7: Conclusion

The study of palynofacies is essential for understanding the palaeoclimate and palaeoenvironment during the deposition of sediments.

The productive samples at 20 m from the dolerite dyke show two palynofacies:

- The first palynofacies assemblage were identified in the bottom section of the coal seam is characterised by the presence of high amounts of spores and equidimensional phytoclasts. The equidimensional phytoclasts show that less transport occurred while the spore-producing flora is believed to be dominant in the lowlands adjacent to the swamp. This indicates that it may have formed during wet cooler conditions with less transport.

- The second palynofacies assemblage is at the top section of the coal seam. It is characterised by an increase in bisaccate pollen grains and improved sorting of the phytoclasts. This signature may indicate a higher fluvial influx into the swamp with the higher amount of taeniate bisaccate pollen grains showing that the palaeoenvironment was warmer during deposition.

- The *Protohaploxypinus sp.* from the glossopterid plant was the dominant flora in the upland area with fern wetland communities dominating the lowland areas.

The lower number 4 coal seam shows that the warming conditions continued during its deposition, with the further increase of taeniate and non-taeniate bisaccate pollen grains and a decrease in spores moving towards the top of the coal seam.

The barren samples were caused by an igneous intrusion in the proximity of the sampled area. The increase in temperature adjacent to the dolerite dyke caused the organic matter surrounding it to mature, which could possibly create gas pockets.

The pollen grains at 20 m from the intrusion show a SCI of 4 indicating a vitrinite reflectance of 0.6 to 0.8, characteristic of early mature, high volatile bituminous coal.

Chapter 8: Outlook

Future studies should include more horizontal and vertical samples of the lower number 4 coal seam to determine whether the change in palynofacies is a localised event or can be prevalent throughout the coal seam. Sampling should also include the upper number 4 coal seam and intermediate sediments.

One limitation of this study, however, is the lack of usable samples owing to the unforeseen impact of the igneous intrusion.

There is renewed interest in the Karoo Basin due to its potential for shale gas. The igneous intrusions could thermally mature the organic sediments in regions not adjacent to the dyke and this can increase the potential for gas. The intrusion can also structurally weaken and fracturing the surrounding rocks. The fractures are pathways by which the gas can escape. Determining the degree of thermal maturation of sedimentary organic matter is a possible method for determining the potential for shale gas in the Karoo Basin.

Chapter 7: References

Aarnes, I., Svensen, H., Connolly, J.A.D. and Podladchikoc, Y.Y. (2010) How contact metamorphism can trigger global climate changes: Modeling gas generation around igneous sills in sedimentary basins. *Geochimica et Cosmochimica Acta.,* **74**: 7179-7195.

AfriGIS (2014) R547, Secunda, Mpumalanga. Google Maps (accessed on 3 November) Available at https://www.google.co.za/maps/dir/-26.4962178,29.0370427//@-26.1617408,28.4393178,9z/data=!4m2!4m1!3e0.

Aitken, G.A. (1994) Permian palynomorphs from the No. 5 seam, Ecca Group, Witbank/Highveld Coalfields, South Africa*. Palaeontol, Afr.*, **31**: 97–109.

Anderson, J.M. (1977) The biostratigraphy of the Permian and Triassic. Part 3. A review of Gondwana palynology with particular reference to the northern Karoo Basin, South Africa. *Mem. Bot. Surv. S. Afr.*, **4**: 1–33.

Anderson, S.B. (1995) *Outbursts of methane gas and associated mining problems experienced at Twistdraai Colliery*. In: Lama, R. (ed.), *Proceedings of the Int. Symposium Cum Workshop on Management and Control of High Gas Emissions and Outbursts*, Wollongong, Australia, pp. 423–434.

Balme, B.E. (1995) Fossil *in situ* spores and pollen grains: An annotated catalogue. *Review of Palaeobotany and Palynology*, **87**: 81–323.

Barbolini, N. (2010). *Palynology of a coal seam in Karoo deposits of Botswana and correlation with southern African coal-bearing strata*. MSc. thesis (unpublished) University of Witwatersrand, Johannesburg, South Africa. 1–204 pp.

Batten, D.J. (1980) *Use of transmitted light microscopy of sedimentary organic matter for evaluation of hydrocarbon source potential*. Proceedings of the 4th International Palynological Conference, Lucknow, India, pp. 589–594.

Batten, D.J. (1996) *Palynofacies and palaeoenvironmental interpretation*. In: Jansonius J. and McGregor D.C. (eds) *Palynology: principles and application*, American Association of Stratigraphic Palynologists Foundation, pp.1011–1064.

Batten, D.J. and Stead, D.T. (2005*) Palynofacies analysis and its stratigraphic application*, In: Koutsoukos, E.A.M. (eds), *Applied stratigraphy*, Springer Dordrecht, Netherlands, pp. 203–226.

Bek, J. and Opluštil, S. (1998) Some lycopsid, sphenopsid and pteropsid fructifications and their miospores from the Upper Carboniferous basins of the Bohemian Massif. *Palaeontographica B,* **248**: 127–161.

Bharadwaj, D.C. (1962) The miospore genera in the coals of Raniganj stage (Upper Permian), India. *The paleobotanist.* **9**(1 & 2): 68–106.

Boggs, S. (2006). *Principles of sedimentology and stratigraphy*. 4th Ed. Pearson Prentice Hall. Upper Saddle River NJ. 1–655 pp.

Bordy, E.M. and Catuneanu, O. (2001) Sedimentology of the upper Karoo fluvial strata in the Tuli Basin, South Africa. *J. Afr. Earth Sci.,* **33** (3): 605–629.

Bordy, E.M. and Catuneanu, O. (2002a) Sedimentology of the Beaufort-Molteno Karoo fluvial strata in the Tuli Basin, South Africa. *S. Afr. J. Geol*., **105**: 51–66.

Bordy, E.M. and Catuneanu, O. (2002b) Sedimentology and palaeontology of upper Karoo aeolian strata (Early Jurassic) in the Tuli Basin, South Africa. *J. Afr. Earth Sci*., **35**: 301–314.

Bordy, E.M. and Catuneanu, O. (2002c) Sedimentology of the lower Karoo Supergroup fluvial strata in the Tuli Basin, South Africa. *J. Afr. Earth Sci*., **35**: 503–521.

Bordy, E.M., Prevec, R. (2008) Sedimentology, palaeontology and palaeoenvironments of the Middle (?) to Upper Permian Emakwezini Formation (Karoo Supergroup, South Africa). *S. Afr. J. Geol*. **111**: 429–456.

Bussio, J.P. (2012) *Effect of dolerite intrusions on coal quality in the Secunda coalfields of South Africa*. MSc thesis (unpublished), University of Pretoria, Pretoria, South Africa. 100pp.

Cadle, A.B., Cairncross, B., Cristie, A.D.M. and Roberts, D.L. (1993) The Karoo Basin of South Africa: type basin for the coal bearing deposits of southern Africa. *Int. J. of Coal Geol,* **23**:117–157.

Cairncross, B. (1979) *Depositional framework and control of coal distribution and quality, Van Dyks Drift area, northern Karoo Basin*. MSc. thesis (unpublished), University of Natal, Pietermaritzburg, South Africa, 1–83pp.

Cairncross, B. (1989) Paleodepositional environments and tectono-sedimentary controls of the postglacial Permian coals, Karoo Basin, South Africa. *Int. J. of Coal Geol.*, **12**: 365–380.

Cairncross, B. (2001) An overview of the Permian (Karoo) coal deposits of southern Africa. *J. Afr. Earth Sc.,* **33**: 529–562.

Cairncross, B. and Cadle, A.B. (1987) A genetic stratigraphy for the Permian coal-bearing Vryheid Formation in the east Witbank Coalfield, South Africa. *S. Aft. J. Geol.,* **90**: 219-230.

Campbell, I.D. (1999) Quaternary pollen taphonomy: examples of differential redeposition and differential preservation. *Palaeogeography, Palaeoclimatology, Palaeoecology,* **149**: 245–256.

Campbell, I.D. and Campbell, C. (1994) Pollen preservation: experimental wet-dry cycles in saline and desalinated sediments. *Palynology,* **18**: 5–10.

Catuneanu, O. (2004) Basement control on flexural profiles and the distribution of foreland facies: the Dwyka Group of the Karoo Basin, South Africa. *Geology,* **32**(6): 517–520.

Catuneanu, O., Hancox, P.J. and Rubidge, B.S. (1998) Reciprocal flexural behaviour and contrasting stratigraphies: a new basin development model for the Karoo retroarc foreland system, South Africa. *Basin Res.,* **10**: 417–439.

Catuneanu, O., Kun-Jager, E.M., Rubidge, B.S. and Hancox, P.J. (1999*) Lateral changes of the Dwyka facies: implications for the initiation of the Cape Orogeny and the associated Karoo foreland system*. In: Abstracts of proceedings, American Association of Petroleum Geologists Annual Meeting, 11–14 April, San Antonio, TX. 1–22 pp.

Catuneanu, O. Wopfner, H., Eriksson, P.G., Cairncross, B., Rubidfe, B.S., Smith, R.M.H. and Hancox, P.J. (2005) The Karoo basins of south-central Africa. S. Afr. J. Sci., **43**: 211 – 253.

Cohen, K.M., Finney, S.C., Gibbard, P.L. and Fan, J.-X. (2013) The ICS International Chronostratigraphic Chart, *Episodes*, **36**(3): 199-204.

Collinson, J.W., Vavra, C.L. and Zawiskie, J.M. (1992) *Sedimentology of the Polarstar Formation (Permian), Ellsworth Mountains, West Antarctica*. In: Webers, G.F., Craddock, C. and Splettstoesser, J.F. (eds) *Geology and paleontology of the Ellsworth Mountains, West Antarctica.* Geological Society of America, Boulder, Colorado, USA, pp 63–81.

Combaz, A. (1964) Les palynofacies. *Revue de Micropaléontologie,* **7:** 309–321.

Cross, A.T. (1964) Plant microfossils and geology: an introduction. *Palynology in Oil Exploration,* **11**: 3-13.

Crowell, J.C. and Frakes, L.A. (1972) Late Palaeozoic glaciation: Part V, Karoo Basin, South Africa. *Bull. Geol. Soc. Am.*, **83**: 2887–2912.

Crowell, J.C. and Frakes, L.A., (1975). *The late Paleozoic glaciation*. In: K.S.W. Campbell (Eds), *Gondwana Geology*. 3rd Gondwana Symp., Australian Nat. Univ. Press, Canberra, pp. 313–331.

Daugherty, L.H. (1941) *The Upper Triassic floras of Arizona*. Publ. Carneg. Inst. Washington, U.S.A. 1–108pp.

Elgmati, M. (2011) *Shale gas rock characterization and 3D submicron pore network reconstruction*. MSc thesis (unpublished), Missouri University of science and technology, Missouri, United States of America. 1–90pp.

Elsik, W.C. (1971) *Microbial degradation of sporopollenin*. In: Brookf, J., Grant, P.R., Muir, M., Van Gijzel, P. and Shaw, G. (eds) *Sporopollenin*, Academic Press, New York, NY, pp. 480–511.

Duncan, A.R. and Marsh, J.S. (2006). *The Karoo Igneous Province*. In*:* Johnson, M.R., Anhaeusser, C.R. and Thomas, R.J. (eds.),*The Geology of South Africa.* Geological Society of South Africa, Johannesburg/Council for Geoscience, Pretoria, pp. 461-499.

Faegri, K. and Iverson, J. (1964) *Textbook of pollen analysis*. Munksgaard. Denmark.

1–229 pp.

Falcon R.M.S. (1986) *A brief review of the origin, formation and distribution of coal in Southern Africa.* In: Anhaeusser, C.R. and Maske, S. (eds*) Mineral deposits of Southern Africa.* Geological Society of South Africa. Johannesburg, pp 1879–1898.

Falcon, R.M.S. (1989) Macro- and micro-factors affecting coal-seam quality and distribution in Southern Africa with particular reference to the No. 2 Seam, Witbank Coalfield, South Africa. *Int. J. Coal Geol,* **12**: 681–731.

Falcon R.M.S., Pinheiro H., and Sheperd P. (1984) The palynobiostratigraphy of the major coal seams in the Witbank Basin with lithostratigraphic, chronostratigraphic and palaeoclimatic implications. *Comunicações dos Serv Geol Portugal,* **70**: 215–243.

Funkhouser, J.W. and Evitt, W.R. (1959) Preparation techniques for acid-insoluble microfossils. *Micropaleontology,* **5**(3): 369–375.

Good, C.W. 1979. *Botryopteris* pinnules with abaxial sporangia. *American Journal of Botany* **66**(1): 19-25.

Götz, A.E. and Ruckwied, K. (2014) Palynological records of the Early Permian postglacial climate amelioration (Karoo Basin, South Africa). *Palaeobiodiversity and Palaeoenvironments*, **94**(2): 229–235.

Hagelskamp, H.H.B. and Snyman, C.P. (1988) On the origin of low-reflecting inertinites in coals from the Highveld Coalfield, South Africa. *Fuel,* **67**: 307–313.

Hancox, J.P. and Götz, A.E. (2014) South Africa's coalfields: a 2014 perspective. *Int. J. of Coal Geol.*, **132**: 170-254.

Hart, G.F. (1965) *The systematics and distribution of Permian miospores.* University of Witwatersrand press, Pietermaritzburg, 1–257pp.

Hartkopf-Fröder, C., Königshof, P., Littke, R., Schwarzbauer, J., (2015) Optical thermal maturity parameters and organic geochemical alteration at low grade diagenesis to anchimetamorphism: A review, *International Journal of Coal Geology*, doi: 10.1016/j.coal.2015.06.005

Hesse, M., Hallbritter, H., Weber, M., Buchner, R., Frosh-Radivo, A. and Ulrich, S. (2009) *Pollen terminology: an illustrated handbook*. Springer Wien New York, Austria. 1–273pp.

Hobday, D.K. (1973) Middle Ecca deltaic deposits in the Muden-Tugela Ferry area of Natal. *Trans. Geol. Soc. S. Afr.*, ***76:*** 309–318.

Hochuli, P.A. and Feist-Burkhardt, S. (2013) Angiosperm-like pollen and Afropollis from the Middle Triassic (Anisian) of the Germanic Basin (Northern Switzerland). *Front. Plant Sci,* **4**(344): 1–14

Jarvie D.M. (2004*) Evaluation of Hydrocarbon Generation and Storage in Barnett Shale, Ft. Worth Basin, Texas,* Humble Geochemical Services Presentation.

Jarvie, D.M., Hill, R.J., Ruble, T.E., and Pollastro, R.M. (2007) Unconventional Shale-Gas Systems: The Mississippian Barnett Shale of North-Central Texas as One Model for Thermogenic Shale-Gas Assessment. *AAPG Bulletin* **91**: 475-499.

Jha, N.K., Sabina, P., Aggarwal., N. and Mahesh, S. (2014) Late Permian palynology and depositional environment of Chintalapudi sub basin, Pranhita-Godavari basin, Andhra Pradesh, India. *J Asian Earth Sci*, **79**: 382-399.

Johnson, M.R. (1976) *Stratigraphy and sedimentology of the Cape and Karoo sequences in Eastern Cape Province.* Ph.D. thesis (unpublished), Rhodes University, Grahamstown. 1–366pp.

Johnson, M.R. (1991) Sandstone petrography, provenance and plate tectonic setting in Gondwana context of the south-eastern Cape Karoo Basin*. S. Afr. J. Geol.* **94**(2/3): 137–154.

Johnson, M.R., Van Vuuren, C.J., Hegenberger, F.W., Key, R. and Shoko, U. (1996) Stratigraphy of the Karoo Supergroup in southern Africa: an overview. *J. Afr. Earth Sci.,* **23**: 3–15.

Johnson, M.R., Van Vuuren, C.J., Visser, J.N.J., Cole, D.I., Wickens, H.D., Christie, A.D.M. and Roberts, D.L. (1997) *The foreland Karoo Basin, South Africa.* In: Selley RC (ed.) *Sedimentary basins of Africa*. Elsevier, Amsterdam, pp 269–317.

Johnson, M.R., Van Vuuren, C.J., Visser, J.N.J., Cole, D.I., Wickens, H. de V., Christie, A.D.M., Roberts, D.L. and Brandl, G. (2006). Sedimentary rocks of the Karoo Supergroup. In: Johnson, M.R., Anhaeusser, C.R., Thomas, R.J. (eds) *The Geology of South Africa.* Geological Society of South Africa, Council for Geoscience, Pretoria, pp. 461–499.

Jordaan, J. (1986) *Highveld Coalfield* In: Anhaeusser, C.R. and Maske, S. (eds) *Mineral deposits of Southern Africa. vol. II. Geol. Soc. S. Afr.*, Johannesburg, pp. 1985–1994.

Jourdan, F., Bertrand, H., Scharer,U., Blichert-toft, J., Feraund, G., and Kampunzu. (2007) Major and Trace Element and Sr, Nd, Hf, and Pb Isotope Compositions of the Karoo Large Igneous Province, Botswana-Zimbabwe: Lithosphere vs Mantle Plume Contribution. *Journal of Petrology,* **48**(6): 1043–1077.

Kumar, P. (2012) *Palynological investigation of coal-bearing deposits of the Thar coal field Sindh, Pakistan.* MSc. thesis (unpublished) Lund University, Sweden. 1–36 pp.

Le Blanc Smith, G. (1980) *Genetic stratigraphy and palaeoenvironmental control on coal distribution in the Witbank Basin coalfield*. Ph.D. thesis (unpublished), University of Witwatersrand, Johannesburg, South Africa. 242 pp.

Le Blanc Smith, G. and Eriksson, K.A. (1979) A fluvioglacial and glacio-lacustrine deltaic depositional model for Permo-Carboniferous coals of the northeastern Karoo basin, South Africa. *Palaeogeogr. Palaeoclimatol. Palaeoecol*., **27**: 67–84.

Lock, B.E. (1980) Flat-plate subduction and the Cape Fold Belt of South Africa. *Geology,* **8**: 35–39.

MacRae, C.S. (1988) Palynostratigraphic correlation between the Lower Karoo sequence of the Waterberg and Pafuri coal-bearing basins and the Hammanskraal plant macrofossil locality, Republic of South Africa. *Mem. Geol. Surv. S Afr.,* **75**:1–217

Mason, T.R., Stanistreet, I.G. and Tavener-Smith, R. (1983) Spiral trace fossils from the Permian Ecca Group in Zululand. *Lethaia,* **16**: 241-247.

McCabe, P.J. (1981) *Deposition environments of coal and coal-bearing strata*. In: Rahmani, R.A. and Flores, R.M. (eds) *Sedimentology of coal and coal-bearing sequences*. Special publication, International association of Sedimentologists, **7**: 13-42.

Mendonça Filho, J.H., Menezes, T.R., Mendonça, J.O., de Oliveira, A.D., da Silva, T.F., Rondon, N.F. and da Silva, F.S. (2012). *Organic Facies: Palynofacies and Organic Geochemistry approaches*, In: Panagiotaras, D. (ed.) *Geochemistry: Earth's system processes*, InTech.

Millsteed, B.D. (1993) Palynological evidence for the age of the Permian Karoo coal deposits near Vereeniging, Northern Orange Free State, South Africa. *S. Afr. J. Geol*., **97**: 15–20.

Millsteed, B.D. (1999) Palynology of the Early Permian coal-bearing deposits near Vereeniging, Free State, South Africa. *Bull. Counc. Geosci. S. Afr.* **124**: 1–77.

Modie, B.N. (2007) *The Palaeozoic palynostratigraphy of the Karoo Supergroup and Palynofacies insight into palaeoenvironmental interpretations, Kalahari Karoo Basin, Botswana*. Ph.D. thesis (unpublished), Université de Bretagne Occidentale, Brest. 1–301 pp.

Moore, P.D., Webb, J.A., and Collinson, M., (1991) *Pollen analysis*. Blackwell, London. 1–216pp.

Neaumann, E., Svensen, H., Galerne, C.Y. and Planke, S. (2011) Multistage evolution of dolerites in the Karoo Large Igneous Province, central South Africa. *Journal of Petrology*. **52**: 959–984.

Pendleton, J.L. (2012) *Palynological and palaeobotanical investigation of the Carboniferous deposits of the Bristol Coalfield, U.K.; biostratigraphy, systematics and palaeoecology*. Ph.D thesis (unpublished). University of Sheffield, England. 1–594pp.

Peters, K.E. and Cassa M.R. (1994) *Applied source rock geochemistry*. In: Magoon, L.B. and Dow, W.G. (eds) *The Petroleum System – from Source to Trap*, AAPG Memoir. **60**: 93–120.

Pflug, H.D, and Reitz, E., (1985) Earliest phytoplankton of eukaryotic affinity. *Naturwissenschaften,* **72**: 656-657.

Pigg, K.B. and McLoughlin, S. (1997) Anatomically preserved Glossopteris leaves from the Bowen and Sydney basins, Australia. *Rev. Palaeobot. Palynol*., **97**: 339–359.

Pigg, K.B. and Trivett, M.L. (1994) Evolution of the Glossopterid gymnosperms from Permian Gondwana. *Journal of Plant Research,* **107**: 461–477.

Pittet, B. and Gorin, G. E. (1997) Distribution of sedimentary organic matter in a mixed carbonate-siliciclastic platform environment: Oxfordian of the Swiss Jura Mountains. *Sedimentology,* **44**: 915–937.

Potonié, R. & Kremp, G. (1954) Die Gattungen der paläozoischen *Sporae dispersae* und ihre Stratigraphie. *Geologisches Jahrbuch*, **69**: 111–194.

Punt, W., Hoen, P.P., Blackmore, S., Nilsson, S. and Le Thomas, A. (2007) Glossary of pollen and spore terminology*Rev. Palaeobot. Palynol*., **143**(1-2): 1–81.

Rayner, R.J. (1995) The palaeoclimate of the Karoo: evidence from plant fossils. *Palaeogeography, Palaeoclimatology, Palaeoecology,* **19**: 385–394.

Roberts, D.L. (1986*) Depositional framework and controls on peat accumulation in the Vryheid Formation of northern Natal (Utrecht and Newcastle areas)*. Ph.D thesis (unpublished), Natal University, Pietermaritzburg, South Africa. 1–233 pp.

Ruckwied, K., Götz, A.E. and Jones, P. (2014) Palynological records of the Permian Ecca Group (South Africa): utilizing climatic icehouse-greenhouse signals for cross basin correlations. *Palaeogeogr. Palaeoclimatol. Palaeoecol*., **413:** 167-172

Saghafi, A., Pinetown, K.L., Grobler, P.G. and Van Heerden J.H.P (2008) CO_2 storage potential of South African coals and gas entrapment enhancement due to igneous intrusions. *Int. J. of Coal Geol,* **73**: 74–87.

Schopft, J.M., Wilson, L.R. and Bentall, R. (1944) An annotated synopsis of Paleozoic fossil spores and the definition of generic groups*, Report of Investigations - Illinois, State Geological Survey*, **91**: 1-66.

Shen, S.Z., Schneider, J.W., Angiolini, L and Henderson, C.M. (2013) The international Permian timescale: March 2013 update. New Mexico Museum of Natural History and Science Bulletin, **60**: 411-416

Smith, A.H.V. and Butterworth, M.A. (1967) Miospores in the coal seams of the Carboniferous of Great Britain. *Special Papers in Palaeontology*, **1**: 1–324.

Smith, P.G. and Scott J.G. (2005) *Dictionary of water and waste management*. Elsevier Butterworth-Heinemann, Oxford, Great Britain. 1–480 pp.

Smith, R.M.H., Erikkson, P.G. and Botha, W.J. (1993) A review of the stratigraphy and sedimentary environments of the Karoo-aged basins of Southern Africa. *J. Afr. Earth Sci.,* **16**(132): 143–169.

Snyman, C.P. (1998) *Coal*. In: Wilson, M.G.C and Anhaeusser, C.R. (eds) *The mineral resources of South Africa*, sixth ed. Council for Geoscience, Pretoria, pp. 136–205.

Svensen, H., Planke, *S.,* Chevallier, *L.,* Malthe-Sorenssen, A., Coorfu, F. and Jamtveit, B. (2007) Hydrothermal venting of greenhouse gases triggering Early Jurassic global warming. *Earth and Planetary Science Letters,* **256:** 554–566.

Talbot, M.R. and Allan, P.A. (2009) *Lakes* In: Reading, H.G. (ed.) *Sedimentary Environments: processes, facies and stratigraphy.* Blackwell, Victoria, Australia, pp. 83-124.

Tavener-Smith, R., Cooper, J.A.G. and Rayner, R.J. (1988) Depositional environments in the Volksrust Formation (Permian) in the Mhlatuze River, Zululand. S. Afr. J. Sci.*,* **91**(2): 198–206.

Traverse, A. (1988*) Paleopalynology*. Unwin Hyman, Boston, MA. 1–600 pp.

Traverse, A. (2007) *Paleopalynology*, Second Edition (Topics in Geobiology 28). Springer, Dordrecht, Netherlands. 1–813 pp.

Turner, J.R. (1977*) Palaeoenvironmental study of the Lower Beaufort in the northeastern Karoo Basin*. MSc. thesis (unpublished), Natal University, Pietermaritzburg, South Africa. 1–138 pp.

Tyson, R. V. (1995) *Sedimentary organic matter: organic facies and palynofacies.* Chapman and Hall, London. 1–615 pp.

Tweddle, J.C. and Edwards, K.J. (2010) Pollen preservation zones as an interpretative tool in Holocene palynology, *Rev. Palaeobot. Palynol.*, **161**(1–2): 59–76.

Van Bergen, P. F. and Kerp, J. H. F. (1990) *Palynofacies and sedimentary environments of a Triassic section in southern Germany*. In: Fermont, W. J. J. and Weegink, J. W. (eds) *The* *proceedings of the International Symposium on Organic Petrology*. Mededelingen rijks geologische dienst, **45**: 23–36.

Van de Wetering, N., Mendonça Filho, J.H. and Esterle, J. (2013) Palynofacies changes and their reflection on preservation of peat accumulation stages in the Late Permian coal measures of the Bowen Basin, Australia: A new system for coal palynofacies characterization. *Int. J. of Coal Geol,* **120**: 57–70.

Van Dyk, J.C., Keyser, M.J. and Coertzen, M. (2006) Syngas production from South African coal sources using Sasol-Lurgi gasifiers. *Int. J. of Coal Geol,* **65**: 243–253.

Van Vuuren, C.J. (1983) *A basin analysis of the northern facies of the Ecca Group*. Ph.D. thesis (unpublished)*,* University Orange Free State, Bloemfontein, South Africa. 1–249pp.

Van Vuuren, C.J. and Cole, D.I. (1979) *The stratigraphy and depositional environments of the Ecca Group in the northern part of the Karoo Basin*. In: Anderson, A.M. and Van Biljon, W.J. (eds), *Some sedimentary basins and associated ore deposits of South Africa. Geol. Soc. S. Air. Spec. Publ.,* **6**: 103–111.

Vidal. G. (1988) A palynological preparation method. *Palynology,* **12**: 215–220.

Visser, J.N.J. (1983) An analysis of the Permo-Carboniferous glaciation in the marine Kalahari Basin, Southern Africa. *Palaeogeogr. Palaeo- climatol. Palaeoecol.,* **44**: 295–315.

Visser, J.N.J. (1986). Lateral lithofacies relationships in the glacigene Dwyka Formation in the western and central parts of the Karoo Basin. *Trans. Geol. Soc. S. Afr.,* **89**: 373–383.

Visser, J.N.J., Lock, J.C. and Jordaan, M.J. (1980) Permian deltaic sedimentation in the western half of the Karoo Basin. *Trans. Geol. Soc. S. Afr.*, **83**: 415–424.

Wagner, N.J. and Hlatshwayo, B. (2005) The occurrence of potentially hazardous trace elements in five Highveld coals, South Africa. *Int. J. of Coal Geol.*, **63**: 228–246.

Walker F. and Poldervaart A. (1949) *Karoo dolerites of the Union of South Africa. Geological Society of America Bulletin*, **60**: 591-706.

Willis, K.J. and McElwin, J.C. (2002) The evolution of plants. Oxford University Press, New York. 1–195 pp.

Winter, M.F. (1985) *Lower Permian palaeoenvironments of the northern Highveld Coalfield and their relationship to the characteristics of coal seams*. Ph.D. Thesis (unpublished), University of Witwatersrand, Johannesburg, South Africa, 1–254 pp.

Wopfner, H. (1994) The Malagasy Rift, a chasm in the Tethyan margin of Gondwana. *J. Southeast Asian Earth Sci.*, **9**: 451–461.

Yule, B., Roberts, S., Marshall, J.E.A., and Milton, J. A. (1998) Quantitative spore colour measurement using colour image analysis. *Org. Geochem.*, **28**(3/4): 139–149.

Appendix A: Plate 1

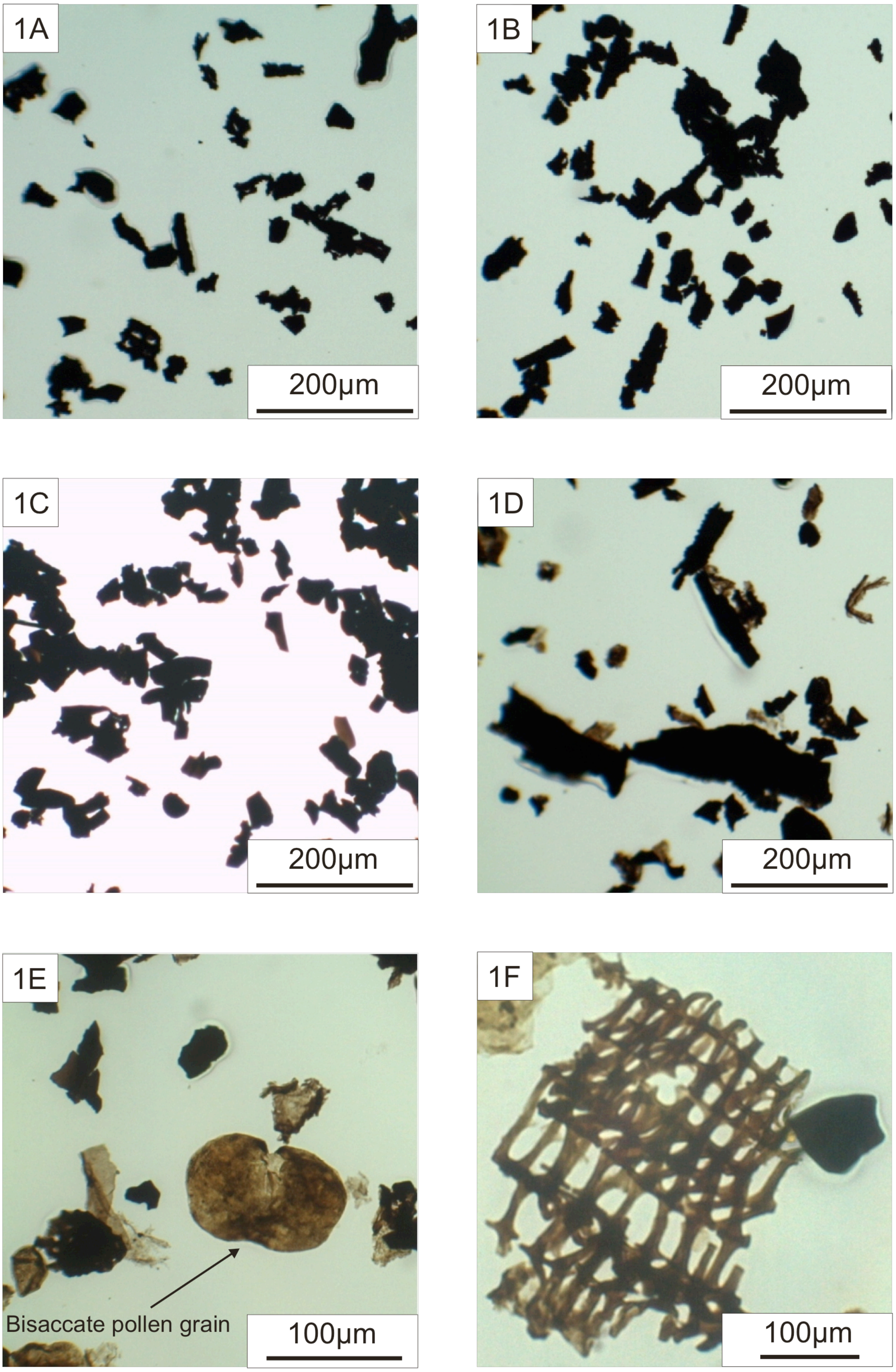


Plate 1:

a) Non-productive sample: equidimensional and blade-shaped, opaque phytoclasts

b) Non-productive sample: equidimensional and blade-shaped, opaque phytoclasts

c) Non-productive sample: Opaque phytoclasts and translucent phytoclasts present

d) Overview of DK 20D: Phytoclasts (opaque and translucent) of different size and shape.

e) DK 20D: Bisaccate pollen grain, translucent and equidimensional, opaque phytoclasts

f) DK 20D: Tracheid fragment and equidimensional, opaque phytoclast

Plate 2

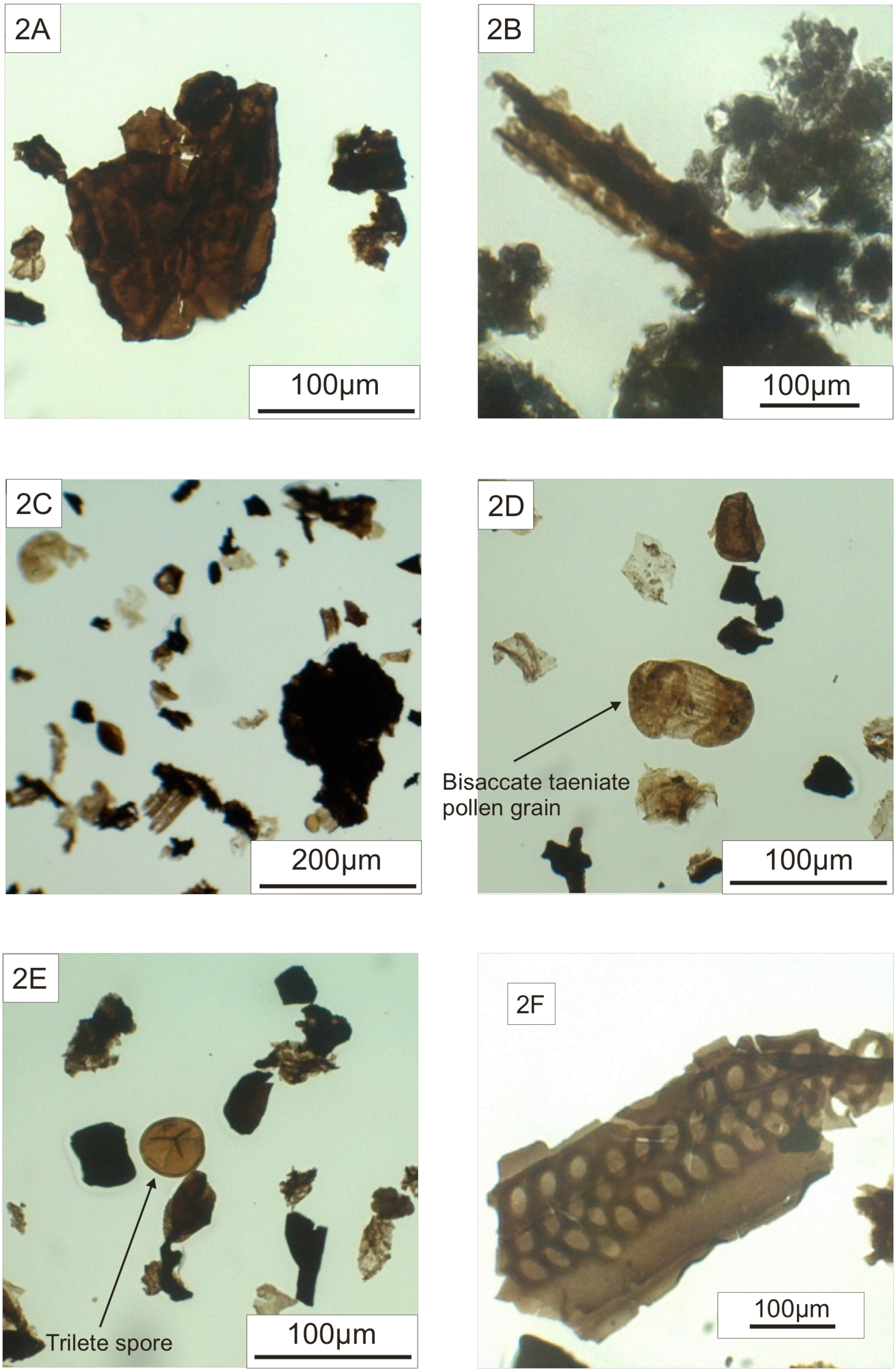

2A
100µm
2B
100µm
2C
200µm
2D
Bisaccate taeniate pollen grain
100µm
2E
Trilete spore
100µm
2F
100µm

Plate 2:

a) DK 20D: Cuticle and translucent phytoclasts

b) DK 20D: Amorphous organic matter and translucent phytoclast

c) Overview of sample DK 20B: Phytoclasts of different size and shape, including some large plant debris

d) DK 20B: Bisaccate taeniate pollen grain and equidimensional, opaque and translucent phytoclasts

e) DK 20B: Trilete spore and opaque and translucent phytoclasts

f) DK 20B: Tracheid fragment

Plate 3

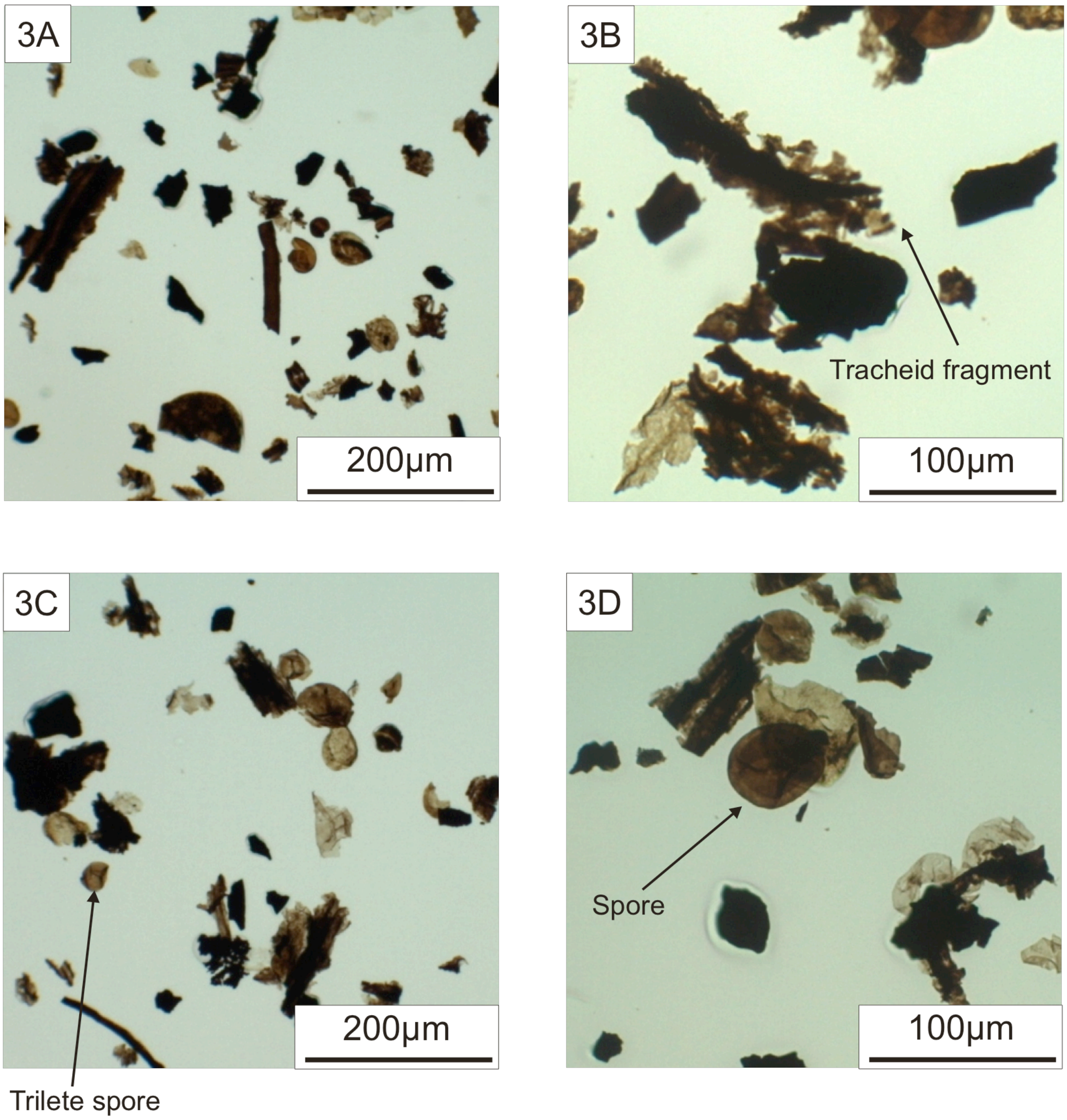

3A
200µm
3B
Tracheid fragment
100µm
3C
200µm
Trilete spore
3D
Spore
100µm

Plate 3:

a) Overview of sample DK 20L: Some large blade-shaped opaque phytoclasts, equidimensional phytoclasts dominant

b) DK 20L: Tracheid fragment and equidimensional opaque and translucent phytoclasts

c) Overview of sample DK 20S: Equidimensional phytoclasts are dominant, better sorting of phytoclasts, small trilete spore is visible

d) DK 20S: Trilete spore and phytoclasts of different sizes and shapes

Appendix B: Palynofacies counts

Sample	Phytoclasts, opaque; equidimensional	Phytoclasts, opaque; blade shaped	Phytoclasts, translucent	Spores	Pollen; monosaccate	Pollen; bisaccate taeniate	Pollen ; bisaccate non-taeniate	Degraded organic matter	Amorphous organic matter	Total
DK 20 S	110	66	9	4	0	7	16	11	0	223
% in sample	49,33	29,60	4,04	1,79	0,00	3,14	7,17	4,93	0,00	100,0
DK 20 L	97	78	9	2	0	7	18	12	0	223
% in sample	43,50	34,98	4,04	0,90	0,00	3,14	8,07	5,38	0,00	100,0
DK 20 B	118	48	11	2	0	8	13	10	0	210
% in sample	56,19	22,86	5,24	0,95	0,00	3,81	6,19	4,76	0,00	100,0 0
DK 20 D	119	59	17	8	2	3	7	17	3	235
% in sample	50,64	25,11	7,23	3,40	0,85	1,28	2,98	7,23	1,28	100,0
DK 20 S	110	66	9	4	0	7	16	11	0	223
% in sample	49,33	29,60	4,04	1,79	0,00	3,14	7,17	4,93	0,00	100,0