

Palynofacies patterns of the Highveld coal deposits (Karoo Basin, South Africa): Clues to reconstruction of palaeoenvironment and palaeoclimate

ALEXANDER WHEELER¹ and ANNETTE E. GÖTZ^{2,3}

¹The University of Queensland, School of Earth Sciences, St. Lucia, QLD 4072, Australia;
e-mail: alex.thomas.wheeler@gmail.com

²Keele University, School of Physical and Geographical Sciences, Keele, Staffordshire ST5 5BG,
United Kingdom; e-mail: a.e.goetz@keele.ac.uk

³Kazan Federal University, 18 Kremlyovskaya St., Kazan 420008, Republic of Tatarstan, Russian Federation

Received 30 January 2016, accepted for publication 10 May 2016

ABSTRACT. The early Permian represents a crucial period of climate change in Gondwana. This climate signature is captured in the palynological record that represents the floral assemblage of the region. Palynofacies analysis of the No. 2 Coal Seam of the Highveld Coalfield provides a high-resolution picture of this climatic shift, as well as detailing the vegetation patterns and local environments. Core samples taken from two localities were studied with respect to the characteristics of the plant debris and the palynomorph assemblages to differentiate between regional and local signatures. At both of the sampling localities, the No. 2 Coal Seam is split into a Lower Coal Seam and an Upper Coal Seam by a siltstone and a sandstone intraseam parting, respectively. The uneven palaeotopography and distal depositional environment of the Highveld Coalfield distinguish it from the northern Witbank Coalfield as a river-dominated delta plain, with differences in the palaeoenvironment at each locality. Results from the Lower Coal Seam indicate a fern-dominated lowland and conifer-dominated upland. This gives way to a *Glossopteris*-dominated lowland and a diverse gymnospermous assemblage in the upland of the Upper Coal Seam. This change in floral composition is also observed in the adjacent Witbank Coalfield and is likely caused by climate amelioration related to the movement of Gondwana away from the South Pole.

KEYWORDS: palynofacies, palaeoenvironment, palaeoclimate, Permian, Highveld Coalfield, South Africa

INTRODUCTION

Coal deposits of South Africa's Main Karoo Basin and more specifically the No. 2 Coal Seam, developed throughout the Highveld and Witbank coalfields of the north-eastern part of the basin (Hancox & Götz 2014), capture a crucial climatic shift in the Permian of Gondwana (e.g. Scheffler et al. 2003). As glaciers receded, the climate supported the development of peat-forming wetlands, and the palynological record of the floral assemblages enables reconstruction of changes in palaeoclimate and palaeoenvironment (Falcon et al. 1984, Falcon 1986, 1989). A palynological assemblage reflects its parent

plant community, which in turn is controlled by the climatic and environmental conditions (Gastaldo 1994). This makes palynofacies a powerful tool to document changes in climate and environment at high time resolution and also provides a correlation tool for exploration of potential remaining coal resources in the northern part of South Africa.

Because of the economic significance of the Witbank Coalfield, a number of palynological studies have already been done in the past (Falcon et al. 1984, Falcon 1975, 1989, Aitken 1993, 1994, 1998), with the aim of establishing

biozonation schemes for correlation. Recently, Götz & Ruckwied (2014), Ruckwied et al. (2014), and Wheeler (2015) used palynofacies analysis to investigate palaeoclimate and palaeoenvironment signatures of the No. 2 Coal Seam for basin-wide correlation. Palynostratigraphy reveals an Artinskian to Kungurian age (Ruckwied et al. 2014).

In contrast, palynological studies of the Highveld coals are rare (Aitken 1993, 1994, 1998); the present study aims to fill this gap and also highlights the potential of palynofacies as a powerful tool for reconstructing palaeoenvironment and palaeoclimate. Here we present two datasets from the No. 2 Coal Seam of the Highveld Coalfield to demonstrate changes in the local environment at each locality. Furthermore, stratigraphic changes in the composition of sedimentary organic matter are used to identify the climate shift from cold to

cool-temperate conditions, recently identified in the No. 2 Coal Seam of the adjacent Witbank Coalfield.

GEOLOGICAL SETTING

The Main Karoo Basin represents a retro-arc foreland basin which formed between the Late Palaeozoic and Early Mesozoic (Catuneanu et al. 2005). The sedimentary sequence which fills the basin is known as the Karoo Supergroup and is divided into five main groups (Dwyka, Ecca, Beaufort, Stormberg, Drakensberg; Figs 1 and 2) which were deposited over the course of ca 120 million years from the Pennsylvanian to the Middle Jurassic and terminated with the eruption of the Drakensberg basaltic lavas. The fluvio-deltaic Vryheid Formation of the Permian Ecca Group

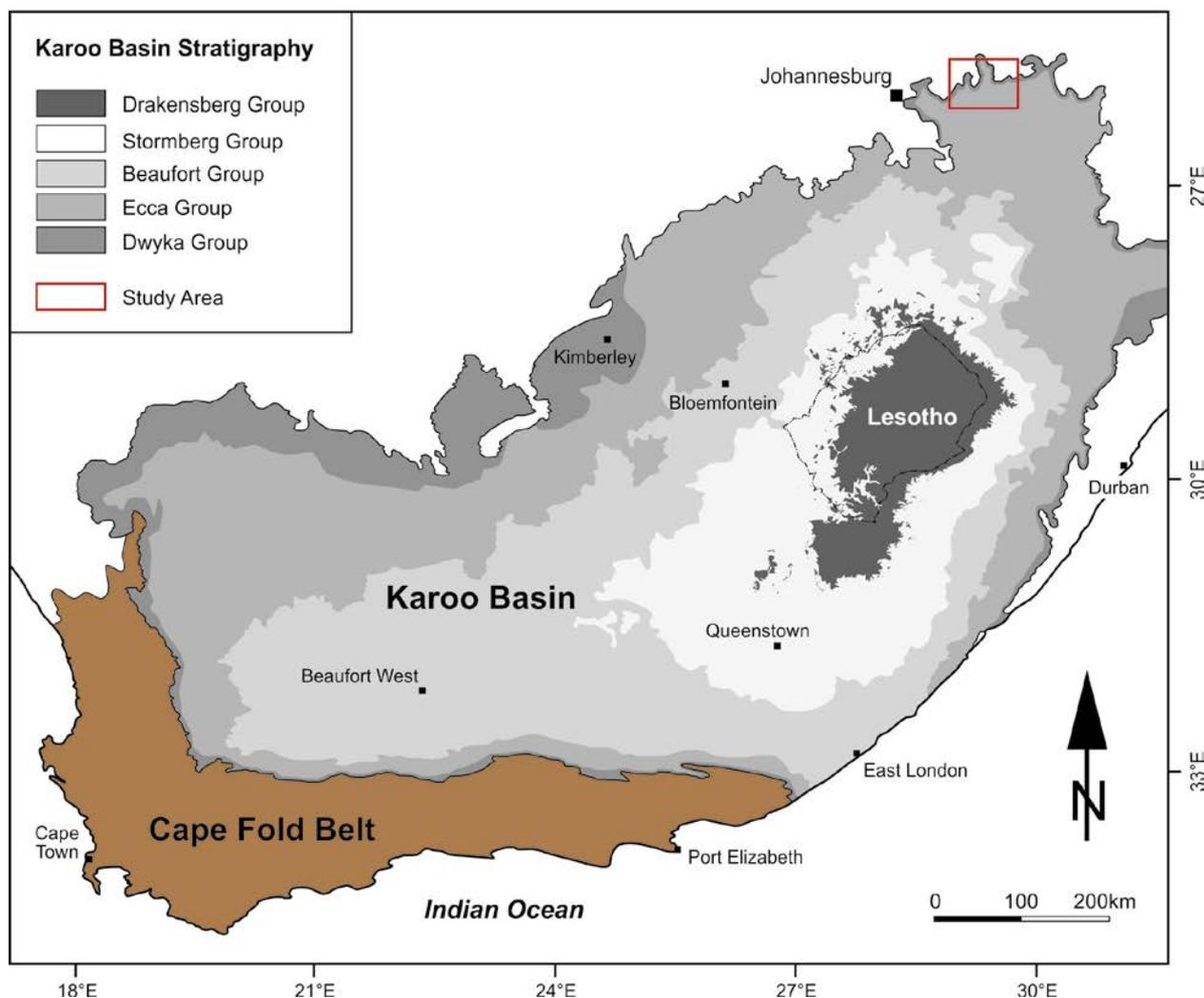


Fig. 1. Map showing the extent and distribution of the Dwyka, Ecca, Beaufort, Stormberg and Drakensberg groups of the Main Karoo Basin (modified after Catuneanu et al. 1998). The fluvio-deltaic Vryheid Formation of the Ecca Group hosts the economically most important coals in the north-eastern part of the basin (study area)

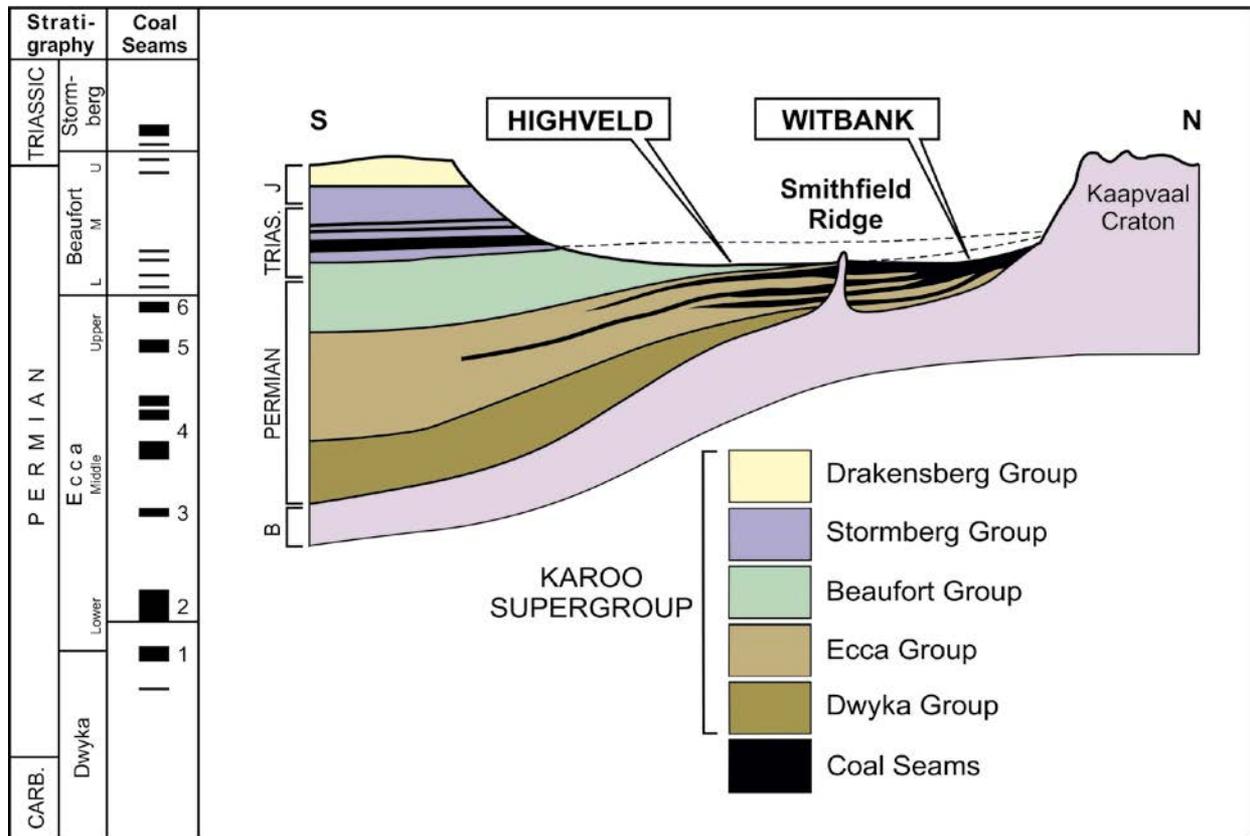


Fig. 2. N–S schematic cross-section of the north-eastern Main Karoo Basin, showing the separation of the Witbank and Highveld coalfields by the Smithfield Ridge (modified after Hancox & Götzt 2014), and stratigraphic column showing the position of the studied Coal Seam No. 2 within the Ecca Group. Abbreviations used: L – Lower, M – Middle, U – Upper, B – Pre-Karoo Basement, J – Jurassic

hosts the economically most important coals in the north-eastern part of the basin. Palaeontologically, the Vryheid Formation is best known for the rich fossil plant assemblages of the *Glossopteris* flora, which is the source vegetation for most of the Vryheid Formation coals. Palaeobotanical studies of the well-preserved plant fossils date back to the early 20th century (Etheridge 1901, 1903, Leslie 1903, Seward & Leslie 1908). Subsequent work was done by Plumstead (1952, 1956, 1957, 1958, 1966, 1969), Kovacs-Endröy (1976), Anderson & Anderson (1985), Rayner & Coventry (1985), Adendorff (2005), Prevec et al. (2008), and Prevec (2011).

The Highveld Coalfield covers an area of ca 7000 km², extending over a distance of ca 95 km from the west to the east, and ca 90 km in a north–south direction. It is separated from the Witbank Coalfield in the north by the Smithfield Ridge (Fig. 2), which formed a topographical palaeohigh during the deposition of Vryheid Formation sediments (Hancox & Götzt 2014).

The most comprehensive study of the Highveld Coalfield was made by Cadle (1995),

addressing the sedimentology and depositional environment of the coal-bearing Vryheid Formation. Winter (1985) analysed the palaeoenvironment of the coal deposits in the northern part of the coalfield, and Jordaan (1986) gave an overview of the Highveld Coalfield, its sedimentology and stratigraphy, coal qualities, and dolerite intrusions. The general characteristics of the coalfield are also summarized in Snyman (1998) and Hancox & Götzt (2014).

Four main seam sequences are distinguished in the Highveld Coalfield (Winter 1985), the No. 2 Seam of the first depositional sequence representing the thickest seam. It is developed at a depth of ca 30 m in the northern margin of the coalfield and up to a depth of 240 m in the southwest. It ranges in thickness from 4 m along the northern margin up to 10 m in valleys in the west. The seam thins to less than a metre in the east and southeast, and may change down dip into carbonaceous mudstone (Hancox & Götzt 2014). Silt-, sand- and mudstone partings are present and distributed throughout the seam, splitting it into a Lower (2L) and Upper (2U) seam.

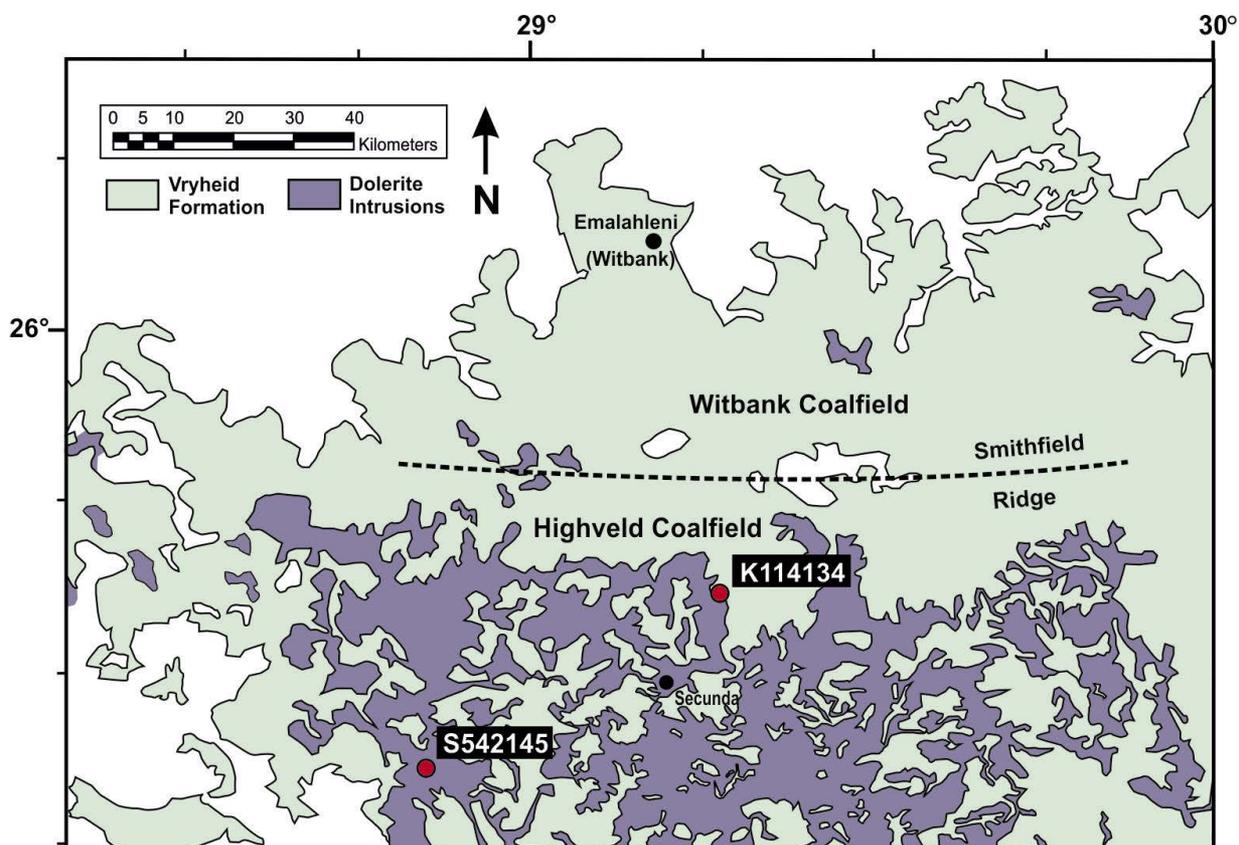


Fig. 3. Map showing the extent of the Witbank and Highveld coalfields, the exposure of dolerite, and the position of sampling localities within the Highveld Coalfield (based on Department of Mines 1978, Department of Mineral and Energy Affairs 1986)

MATERIALS AND METHODS

Core samples of the No. 2 Coal Seam were collected from two drill sites (K114134 and S542145) in the Highveld Coalfield (Fig. 3), representing organic-rich siltstones from the Lower and Upper Seam and intraseam partings. Palynomorphs of samples from intraseam partings are of interest, since they reflect more of the allochthonous assemblage and thus give information on upland floras in addition to the information on the lowland vegetation as documented in palynomorph assemblages of the coals.

Twelve samples were collected in the northern part of the coalfield at location K114134 (26°23'30.30"S,

029°17'14.10"E), covering a total seam thickness of 5.20 m. A 0.30 m thick sandstone intraseam parting is present at this locality. The Lower Coal Seam is 1.80 m thick and the Upper Coal Seam is 3.10 m thick. Five samples were collected from the Lower Coal Seam, 2 from the intraseam parting and 5 from the Upper Coal Seam. The samples are numbered 1 to 12 from the bottom to the top. Between 501 and 514 particles were counted for each of the palynological slides studied.

Eight samples were collected in the central-western part of the coalfield at location S542145 (26°37'46.13"S, 028°51'19.72"E), covering a total seam thickness of 5 m. A 0.30 m thick siltstone intraseam parting is present at this locality. The Lower

| Origin | Group | Constituent | preservation potential low high |
|-----------------------|---|-------------------------|---|
| higher plant debris | phytoclasts | opaque phytoclasts | ██████████ |
| | | translucent phytoclasts | ██████████ |
| pollen | sporomorphs | pollen grains | ██████████ |
| spores | | spores | ██████████ |
| degraded plant debris | degraded organic matter amorphous organic matter | | ██████████ |
| degraded algae | | | ██████████ |
| fresh water algae | <i>Tetraporina</i> spp. <i>Botryococcus</i> spp. | | ██████████ |

Fig. 4. Classification scheme of particulate organic matter (POM) and preservation potential of each category (from Götz & Ruckwied 2014)

Coal Seam is 2 m thick and the Upper Coal Seam is 2.70 m thick. Three samples were collected from the Lower Coal Seam, 1 from the intraseam parting, and 4 from the Upper Coal Seam. The samples are numbered 1 to 8 from the bottom to the top. Between 501 and 509 particles were counted for each of the palynological slides studied.

A total of 20 samples were prepared using standard palynological processing techniques as described in Vidal (1988), though with higher concentrations of acids to account for the high mineral content of the siltstones. Sedimentary organic matter is classified based on the scheme used in Götz & Ruckwied (2014). This scheme divides the material into categories based on the origin and preservation potential (Fig. 4). Relative abundances and ratios of the organic particles determined are used to interpret changes in palaeoenvironment and palaeoclimate.

RESULTS

Palynofacies analyses reveal spatio-temporal changes in the composition of particulate organic matter in the Highveld Coalfield,

and are presented for the studied localities K114314 and S542145 below.

K114134 LOCALITY

Generally, the palynofacies is dominated by phytoclasts of various sizes and shapes. Small translucent particles reveal wood remains, cuticles and plant tissues (Pl. 1, fig. 1). Monosaccate pollen grains are present in the Lower Coal Seam in moderate abundance (Pl. 1, fig. 1) but decrease and disappear in the Upper Coal Seam (Fig. 5). The relative abundance of non-taeniate bisaccate pollen grains increases steadily from the Lower to the Upper Coal Seam. Taeniate bisaccate pollen grains appear in the intraseam parting and become more abundant in the Upper Coal Seam. The spore/pollen ratio is high in the Lower Coal Seam but shows a distinct drop in the Upper Coal Seam (Fig. 6). Amorphous organic matter (AOM) is present in moderate abundance in the Lower

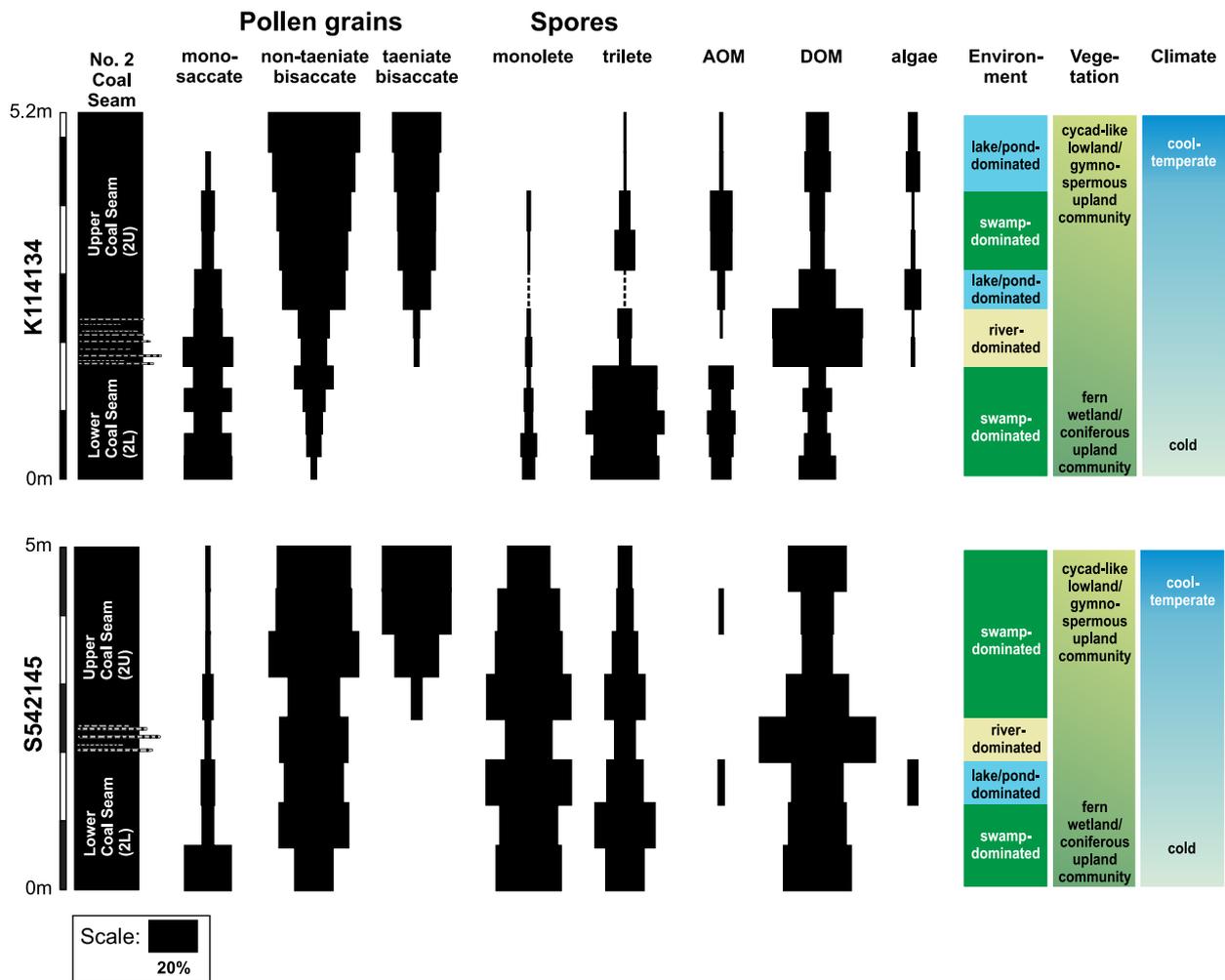


Fig. 5. Relative abundance of palynomorphs, AOM and DOM at sampling localities K114134 and S542145. **AOM** – amorphous organic matter. **DOM** – degraded organic matter. Palaeoenvironment and palaeoclimate interpretation of the No. 2 Coal Seam, inferred from changes in relative abundance of palynomorphs, AOM, DOM, and freshwater algae

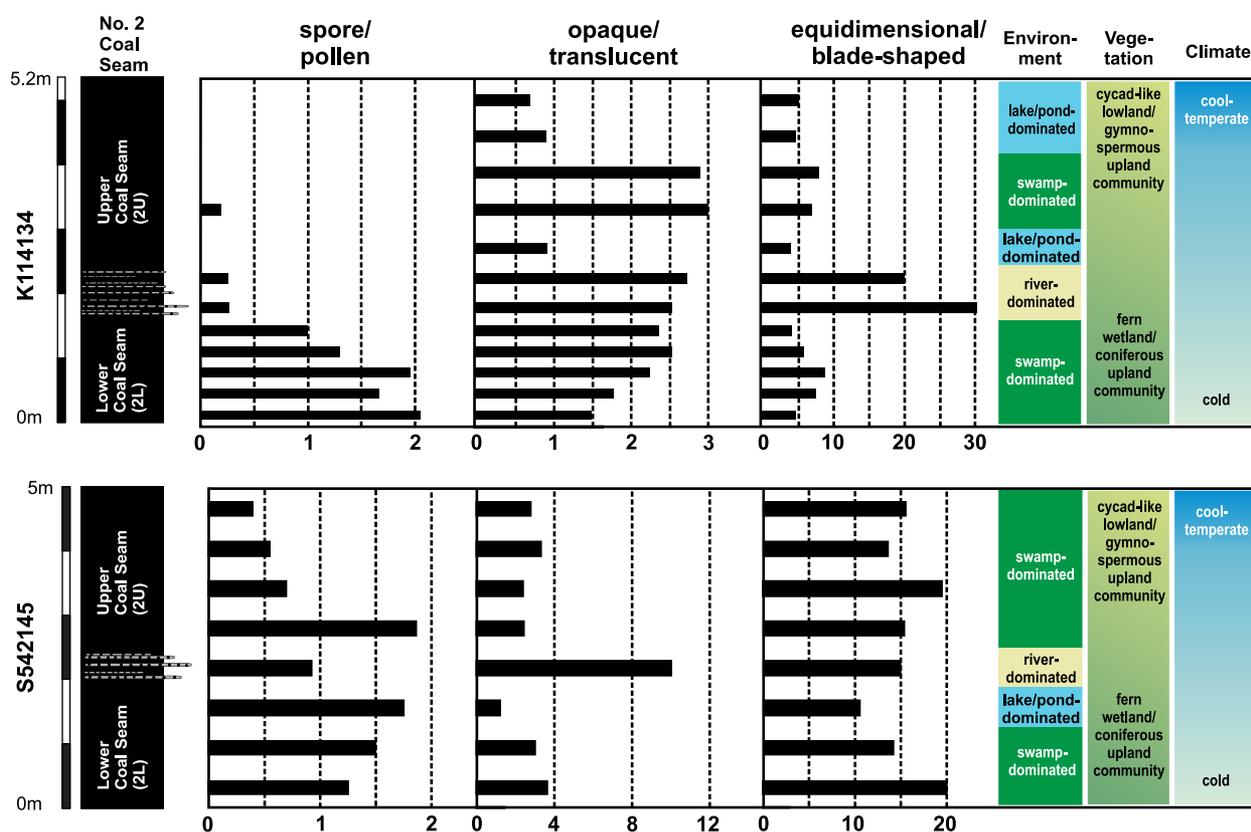


Fig. 6. Spore/pollen, opaque/translucent phytoclast and equidimensional/blade-shaped phytoclast ratios at sampling localities K114134 and S542145. Palaeoenvironment and palaeoclimate interpretation of the No. 2 Coal Seam, inferred from changes in ratios of spores and pollen grains, and phytoclasts

Coal Seam. In the Upper Coal Seam it is abundant in samples 9 and 10 (Pl. 1, fig. 5). These samples also show a slight increase in trilete spore abundance, and high opaque/translucent phytoclast ratios. In the sandstone parting, high abundance of degraded organic matter (DOM) and a sharp increase in the equidimensional/blade-shaped phytoclast ratio are observed (Pl. 1, fig. 4). Algae are present in low abundance in the sandstone parting and in samples 9 and 10, and in moderate abundance in samples 8, 11 and 12.

S542145 LOCALITY

The palynofacies is dominated by phytoclasts with a high amount of large cuticles, wood remains and plant tissues (Pl. 1, fig. 6). In the Lower Seam a prominent change in phytoclast size and shape is observed. While large and equidimensional particles are dominant in the lower part (Pl. 1, fig. 2), a high amount of blade-shaped phytoclasts is characteristic of the upper part of the seam (Pl. 1, fig. 3). The abundance of monosaccate pollen grains is moderately high in sample 1 but decreases to low abundance in all other samples (Fig. 5).

Non-taeniate bisaccate pollen grains are present throughout the No. 2 Coal Seam and show a slight increase in abundance in the Upper Coal Seam. Taeniate bisaccate pollen grains appear in the Upper Coal Seam (Pl. 1, fig. 6). The spore/pollen ratio decreases in the Upper Coal Seam but monolete spores are moderately abundant throughout the No. 2 Coal Seam (Fig. 6). AOM can only be observed in very low abundance in samples 3 and 7. DOM has high abundance in the siltstone parting, which coincides with an increase in the opaque/translucent phytoclast ratio. Algae are present only in sample 3.

DISCUSSION

FLORAL COMPOSITION

The most abundant spore genera observed in the Highveld Coalfield were mainly the same as those observed in the Witbank Coalfield (*Calamospora*, *Microbaculispora*, *Punctatisporites*, *Verrucosisporites*) and indicate diverse lowland vegetation comprising ferns, horsetails, lycopods, and sparse cordaitalean trees (Falcon 1989). Evidence of cordaitalean

trees is also provided from the Vereeniging region west of the Highveld Coalfield by findings of Seward & Leslie (1908), who described *Cordaites* remains from the conglomerates underlying Coal Seam No. 1. In the Highveld Coalfield, *Florinites*-type monosaccate pollen, associated with *Cordaites* (Balme 1995, Traverse 2007), was observed only at S542145 in the Lower Coal Seam. This locality also featured distinctly high abundance of monolete spores, which distinguish it from other localities in the Witbank and Highveld coalfields. The presence of the monosaccate pollen genus *Potonieisporites*, which has an affinity with the conifer genus *Walchia* (Balme 1995, Traverse 2007), suggests that conifers are the dominant upland vegetation in the Lower Coal Seam (Falcon 1986). The conifers would likely occupy the drier upland areas as opposed to the lower, wetter swamplands in which *Cordaites* would find an ecological niche (Traverse 2007). However, it has to be noted that *Cordaites* is reported from very different habitats, including upland areas (e.g., Raymond & Phillips 1983, Falcon-Lang & Scott 2000). In the Upper Coal Seam, the relative low abundance of spores, the increase in non-taeniate pollen (which have an affinity with *Gangamopteris*; Falcon 1986), and the appearance of taeniate bisaccate pollen (which have an affinity with *Glossopteris*; Falcon 1986) indicate a shift in lowland vegetation from fern-dominated marsh to tree-dominated swamp. The increase in other bisaccate pollen genera (e.g. *Pityosporites*, *Lueckisporites*) suggests that the conifers which previously thrived in post-glacial upland conditions have been replaced by a more diverse gymnospermous assemblage (Falcon 1975, 1986, 1989). However, since almost all of the known botanical affinities of spores and pollen genera as documented in Balme (1995) and discussed in Traverse (2007) are based on material from the Euramerican Province, reconstruction of Gondwanan floras using these assignments remains difficult. Possibly *Florinites* and *Potonieisporites* were produced by plants whose macroplant remains are not yet known, or these miospores were produced by plants which are well known but of which we do not have any information on the in situ pollen. This problem also shows the need for integrated palaeobotanical-palynological studies on Gondwana localities.

PALAEOENVIRONMENT

The Highveld Coalfield features an uneven palaeotopography which results in the irregular distribution of the coal (Van Vuuren & Cole 1979) and a palaeoslope oriented to the south and south-east (Hagelskamp et al. 1988). Deposition of sediments would have occurred on the broad plains south of the Smithfield Ridge (K114134) and into the two major north-south-trending palaeovalleys which have been inferred for the Highveld Coalfield (Hagelskamp et al. 1988). One of these is a continuation of the Vischkuil Valley (S542145) which begins in the Witbank Coalfield (Hancox & Götz 2014). The palaeotopography would form an important control on the local palaeoenvironment as well as on the distribution of various plant types. Palaeocurrent analysis indicates that sediments are sourced mainly from the east and north-east, with fewer channels coming out from the Witbank Coalfield (Ryan 1968). The presence of a sandstone intraseam parting at K114134 and a siltstone intraseam parting at S542145 gives sedimentological evidence of different depositional environments of a broad river-dominated delta plain. A braided river system close to the Smithfield Ridge (location K114134) might have changed southwards into a meandering system (location S542145) related to the south-trending palaeoslope (Hagelskamp et al. 1988). This is also documented in the phytoclast assemblages, revealing different fragmentation of particles related to different hydrodynamics and different distances from the source area: that is, more and less transport, respectively. The phytoclasts of samples from the sandstone parting are small and mainly equidimensional, whereas the phytoclasts of samples from the siltstone parting show high variety of sizes and shapes. The palynofacies results support the sedimentological interpretation of extensive river-dominated delta plains during Vryheid times and agree with the findings of Cadle & Hobday (1977), who proposed three major phases of sedimentation in the Highveld Coalfield: a lower deltaic-dominated phase, a river-dominated phase in which coal deposition occurs, and an upper deltaic phase. The fluvio-deltaic model is also supported by the overregional studies of Le Blanc Smith & Eriksson (1979) and Cadle et al. (1993).

PALAEOCLIMATE

There is a clear signal at both localities of a switch from high monosaccate pollen grain abundance in the Lower Coal Seam to high bisaccate pollen grain abundance in the Upper Coal Seam. This represents a switch from monosaccate-producing flora to bisaccate-producing flora, which is interpreted as indicative of a shift from cold to cool-temperate climate in the course of early Permian Gondwanan climate amelioration (Visser 1996, López-Gamundí 1997, Wopfner 1999, Goldberg 2004, Stephenson et al. 2007). The appearance of taeniate bisaccate pollen grains in the Upper Coal Seam suggests climate amelioration to the point at which glossopterids can spread abundantly. This may be related to the shift of Gondwana away from the South Pole to lower latitudes during the Permian (Caputo & Crowell 1985, Visser 1986). The same turnover in dominant vegetation has also been described in the adjacent Witbank Coalfield (Falcon 1986, Götz & Ruckwied 2014, Wheeler 2015). Studies on the early Permian in other parts of southern Africa (D'Engelbronner 1996, Modie & Le Herisse 2009, Nyambe & Utting 1997) and globally (Backhouse 1991, Iannuzzi et al. 2010, Stephenson et al. 2005) also show a change in the dominant vegetation, suggesting a Gondwana-wide climatic shift.

CONCLUSIONS

Palynofacies analysis of the No. 2 Coal Seam of the Highveld Coalfield shows a distinct change in the area's vegetation in both the lowland and upland. The monosaccate pollen-producing flora is replaced by a diverse assemblage of non-taeniate bisaccate pollen-producing gymnosperms and taeniate bisaccate pollen-producing glossopterids. This turnover in floral composition has also been noted in the adjacent Witbank Coalfield and is related to amelioration of the early Permian climate. The No. 2 Coal Seam captures in detail a distinct shift from post-glacial cold to a cool-temperate climate. The palaeoenvironment at each locality shows distinct differences due to the uneven palaeotopography of the Highveld Coalfield and the position of the locality relative to the Cargonian Highlands and Smithfield Ridge in the north, from which sediments and organic particles are sourced. The heavily fragmented nature of the organic

material and distinct intraseam partings of siltstone and fine-grained sandstone at both localities indicate a more distal depositional setting than in the Witbank Coalfield, dominated by large braided and meandering rivers and wide but shallow lakes and ponds.

ACKNOWLEDGEMENTS

This study was funded in part by the DST-NRF Centre of Excellence for Integrated Mineral and Energy Resource Analysis (CIMERA). Additional funding was provided by the National Research Foundation of South Africa (NRF), grant no. 94589. The constructive comments of two anonymous reviewers are gratefully acknowledged.

REFERENCES

- ADENDORFF R. 2005. A revision of the ovuliferous fructifications of glossopterids from the Permian of South Africa. PhD Thesis, University of the Witwatersrand, Johannesburg.
- AITKEN G.A. 1993. Palynology of the Number 5 seam in the Witbank/Highveld Coalfields. Unpubl. MSc Thesis. University of the Witwatersrand, Johannesburg.
- AITKEN G.A. 1994. Permian palynomorphs from the Number 5 Seam, Ecca Group, Witbank/Highveld Coalfields, South Africa. *Palaeontol. Afric.*, 31: 97–109.
- AITKEN G.A. 1998. A palynological and palaeoenvironmental analysis of Permian and Early Triassic sediments of the Ecca and the Beaufort groups, Northern Karoo Basin, South Africa. PhD Thesis, University of the Witwatersrand, Johannesburg.
- ANDERSON J.M. & ANDERSON H.M. 1985. The Palaeoflora of southern Africa. Prodomus of Southern African Megafloras Devonian to Lower Cretaceous. A.A. Balkema, Rotterdam.
- BACKHOUSE J. 1991. Permian palynostratigraphy of the Collie Basin, western Australia. *Rev. Palaeobot. Palynol.*, 67(3): 237–314.
- BALME B.E. 1995. Fossil in situ spores and pollen grains: An annotated catalogue. *Rev. Palaeobot. Palynol.*, 87(2–4): 81–322.
- CADLE A.B. 1995. Depositional systems of the Permian Vryheid formation, Highveld Coalfield, South Africa. Their relationship to coal seam occurrence and distribution. PhD Thesis, University of the Witwatersrand, Johannesburg.
- CADLE A.B. & HOBDAK D.K. 1977. A subsurface investigation of the Middle Ecca and Lower Beaufort in northern Natal and the southeastern Transvaal. *Transact. Geol. Soc. South Africa*, 80: 111–117.
- CADLE A.B., CAIRNCROSS B., CRISTIE A.D.M. & ROBERTS D.L. 1993. The Karoo Basin of South

- Africa: type basin for the coal bearing deposits of southern Africa. *Int. Journ. Coal Geol.*, 23: 117–157.
- CAPUTO M.V. & CROWELL J.C. 1985. Migration of glacial centers across Gondwana during Paleozoic Era. *Bull. Geol. Soc. Am.*, 96: 1020–1036.
- CATUNEANU O. 2002. Sequence stratigraphy of clastic systems: concepts, merits, and pitfalls. *J. Afric. Earth Sci.*, 35(1): 1–43. DOI: 10.1016/S0899-5362(02)00004-0
- CATUNEANU O., HANCOX P.J. & RUBIDGE B.S. 1998. Reciprocal flexural behaviour and contrasting stratigraphies: a new basin development model for the Karoo retroarc foreland system, South Africa. *Basin Research*, 10: 417–39.
- CATUNEANU O., HANCOX P.J., CAIRNCROSS B. & RUBIDGE B.S. 2002. Foredeep submarine fans and forebulge deltas: orogenic off-loading in the underfilled Karoo Basin. *J. Afric. Earth Sci.*, 35: 489–502. DOI: 10.1016/S0899-5362(02)00154-9
- CATUNEANU O., WOPFNER H., ERIKSSON P.G., CAIRNCROSS B., RUBIDGE B.S., SMITH R.M.H. & HANCOX P.J. 2005. The Karoo basins of south-central Africa. *J. Afric. Earth Sci.*, 43: 211–253. DOI: 10.1016/j.jafrearsci.2005.07.007
- D'ENGELBRONNER E.R. 1996. New palynological data from Karoo sediments, Mana Pools basin, northern Zimbabwe. *J. Afric. Earth Sci.*, 23(1): 17–30.
- DEPARTMENT OF MINERAL AND ENERGY AFFAIRS. 1986. 2628 East Rand [map]. 2nd Edition. 1:250,000. Pretoria: The Government Printer.
- DEPARTMENT OF MINES. 1978. 2528 Pretoria [map]. 2nd Edition. 1:250,000. Pretoria: The Government Printer.
- ETHERIDGE Jr. R. 1901. Notes on fossil plants from the Saint Lucia Bay Coalfield, Enseleni River, Zululand: 69–76. In: Anderson W. (ed.), *First Report of the Geological Survey of Natal and Zululand. Survey General's Department, Natal. Davis and Sons, Pietermaritzburg.*
- ETHERIDGE Jr. R. 1903. The fructification of *Schizoneura australis*, Etheridge fil. *Records of the Geological Survey of New South Wales*, 7: 234–235.
- FALCON R.M.S. 1975. Application of palynology in sub-dividing the coal-bearing formations of the Karoo Sequence in South Africa. *South African J. Sci.*, 71(11): 336–344.
- FALCON R.M.S. 1986. A brief review of the origin, formation and distribution of coal in Southern Africa: 1879–1898. In: Anhaeusser C.R. & Maske S. (eds), *Mineral Deposits of Southern Africa*, vol II. The Geological Society of South Africa, Johannesburg.
- 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. Journ. Coal Geol.*, 12(1): 681–731.
- FALCON-LANG H.J. & SCOTT A.C. 2000. Upland ecology of some later Carboniferous cordaitalean trees from Nova Scotia and England. *Palaeogeogr., Palaeoclim., Palaeoecol.*, 156: 225–242.
- FALCON R.M.S., PINHEIRO H.J. & SHEPERD P. 1984. The palynobiostatigraphy of the major coal seams in the Witbank Basin with lithostratigraphic, chronostratigraphic and palaeoclimatic implications. *Comu. Serv. Geol. Portugal*, 70: 215–243.
- GASTALDO R.A. 1994. The genesis and sedimentation of phytoclasts with examples from coastal environments: 103–127. In: Traverse A. (ed.), *Sedimentation of organic particles*. Cambridge University Press.
- GÖTZ A.E. & RUCKWIED K. 2014. Palynological records of the Early Permian postglacial climate amelioration (Karoo Basin, South Africa). *Palaeobiodiv. Palaeoenviron.*, 94(2): 229–235. DOI: 10.1007/s12549-013-0134-8
- GOLDBERG K. 2004. Floral diversity in the assessment of paleoclimate in the Paraná Basin, southern Brasil. *Journ. Geol.*, 112(6): 719–727. DOI: 10.1086/424866
- HAGELSKAMP H.H.B., ERIKSSON P.G. & SNYMAN C.P. 1988. The effect of depositional environment on coal distribution and quality parameters in a portion of the Highveld Coalfield, South Africa. *Intern. Journ. Coal Geol.*, 10(1): 51–77.
- HANCOX J.P. & GÖTZ A.E. 2014. South Africa's coalfields – a 2014 perspective. *Intern. Journ. Coal Geol.*, 132: 170–254. DOI: 10.1016/j.coal.2014.06.019
- IANNUZZI R., SOUZA P.A. & HOLZ M. 2010. Stratigraphic and paleofloristic record of the Lower Permian postglacial succession in the southern Brazilian Paraná Basin. *Geol. Soc. Am. Special Papers*, 468: 113–132. DOI: 10.1130/2010.2468(05)
- JORDAAN J. 1986. Highveld Coalfield: 1985–1994. In: Anhaeusser C.R. & Maske S. (eds), *Mineral Deposits of Southern Africa*, vol. II. Geological Society of South Africa, Johannesburg.
- KOVACS-ENDRÖY É. 1976. Notes on some *Glossopteris* species from Hammanskraal (Transvaal). *Palaeontol. Afric.*, 19: 67–95.
- LE BLANC SMITH G. & ERIKSSON K.A. 1979. A fluvio-glacial and glacio-lacustrine deltaic depositional model for Permo-Carboniferous coals of the north-eastern Karoo basin, South Africa. *Palaeogeogr., Palaeoclim., Palaeoecol.*, 27: 67–84.
- LESLIE T.N. 1903. The fossil flora of Vereeniging. *Transact. Geol. Soc.*, vol. VI: 82–88.
- LÓPEZ-GAMUNDÍ O.R. 1997. Glacial-postglacial transition in the late Paleozoic basins of southern South America: 147–168. In: Martini I.P. (ed.), *Late Glacial and Postglacial Environmental Changes*, OUP, Oxford.
- MODIE B.N. & LE HÉRISSE A. 2009. Late Palaeozoic palynomorph assemblages from the Karoo Supergroup and their potential for biostratigraphic correlation, Kalahari Karoo Basin, Botswana. *Bull. Geosci.*, 84(2): 337–358.

- NYAMBE I.A. & UTTING J. 1997. Stratigraphy and palynostratigraphy, Karoo Supergroup (Permian and Triassic), mid-Zambezi Valley, southern Zambia. *J. Afric. Earth Sci.*, 24(4): 563–583.
- PLUMSTEAD E.P. 1952. Description of two new genera and six new species of fructifications borne on *Glossopteris* leaves. *Transact. Geol. Soc. South Africa*, 55: 281–328.
- PLUMSTEAD E.P. 1956. Bisexual fructifications borne on *Glossopteris* leaves from South Africa. *Palaeontographica B*, 100: 1–25.
- PLUMSTEAD E.P. 1957. Coal in Southern Africa. Witwatersrand University Press, Johannesburg.
- PLUMSTEAD E.P. 1958. Further fructifications of the Glossopteridae and a provisional classification based on them. *Transact. Geol. Soc. South Africa*, 61: 1–58.
- PLUMSTEAD E.P. 1966. The story of South Africa's coal. *Optima*, 16(12): 387–402.
- PLUMSTEAD E.P. 1969. Three thousand million years of plant life in Africa. Alex L. Du Toit Memorial Lectures 11. Geological Society of South Africa, Pretoria.
- PLUMSTEAD E.P. 1970. Recent progress and the future of palaeobotanical correlation in Gondwanaland. In: Haughton S.H. (ed.), *Proceedings 2nd IUGS Symposium on Gondwana Stratigraphy and Palaeontology*. Council for Scientific and Industrial Research, South Africa.
- PREVEC R. 2011. A structural re-interpretation and revision of the type material of the glossopterid ovuliferous fructification *Scutum* from South Africa. *Palaeontol. Afric.*, 46: 1–19.
- PREVEC R., MCLOUGHLIN S. & BAMFORD M.K. 2008. Novel double wing morphology revealed in a South African ovuliferous glossopterid fructification: *Bifariata intermittens* (Plumstead 1958) comb. nov. *Rev. Palaeobot. Palynol.*, 150: 22–36. DOI: 10.1016/j.revpalbo.2008.01.001
- RAYMOND A. & PHILLIPS T.L. 1983. Evidence for an Upper Carboniferous mangrove community: 19–30. In: Teas H.J. (ed.), *Tasks for vegetation science*, 8.
- RAYNER R.J. & COVENTRY M.K. 1985. A *Glossopteris* flora from the Permian of South Africa. *South Afric. J. Sci.*, 81: 21–32.
- RUCKWIED K., GÖTZ A.E. & JONES P. 2014. Palynological records of the Permian Ecca Group (South Africa): Utilizing climatic icehouse–greenhouse signals for cross basin correlations. *Palaeogeogr., Palaeoclim., Palaeoecol.*, 413: 167–172. DOI: 10.1016/j.palaeo.2014.05.003
- RYAN P.J. 1968. Stratigraphy of the Ecca Series and Lowermost Beds (Permian) in the Great Karoo Basin of South Africa. PhD Thesis, University of the Witwatersrand, Johannesburg.
- SCHEFFLER K., HOERNES S. & SCHWARK L. 2003. Global changes during Carboniferous–Permian glaciation of Gondwana: Linking polar and equatorial climate evolution by geochemical proxies. *Geology*, 31(7): 605–608. DOI: 10.1130/0091-7613(2003)031<0605:GCDCGO>2.0.CO;2
- SEWARD A.C. & LESLIE T.N. 1908. Permo-Carboniferous plants from Vereeniging (Transvaal). *Quart. J. Geol. Soc. London*, 64: 109–126.
- SNYMAN C.P. 1998. Coal. The Mineral Resources of South Africa. Handbook, 16: 136–205.
- STEPHENSON M.H., LENG M.J., VANE C.H., OSTERLOFF P.L. & ARROWSMITH C. 2005. Investigating the record of Permian climate change from argillaceous sedimentary rocks, Oman. *J. Geol. Soc.*, 162(4): 641–651. DOI: 10.1144/0016-764904-096
- STEPHENSON M.H., ANGIOLINI L. & LENG M.J. 2007. The Early Permian fossil record of Gondwana and its relationship to deglaciation: A review: 169–189. In: Williams M., Haywood A.M., Gregory F.J. & Schmidt D.N. (eds), *Deep-Time Perspectives on Climate Change: Marrying the Signal from Computer Models and Biological Proxies*. The Micropalaeontological Society, Special Publications. The Geological Society, London.
- TRAVERSE A. 2007. Paleopalynology, 2nd edition: 1–487. In: Landman N.H. & Jones D.S. (eds), *Topics in Geobiology*, 28. Springer.
- VAN VUUREN C.J. & COLE D.I. 1979. The stratigraphy and depositional environments of the Ecca Group in the northern part of the Karoo Basin: 103–111. In: Anderson A.M. & Van Biljon W.J. (eds), *Some Sedimentary Basins and Associated Ore Deposits of South Africa*, 6. Rand Afrikaans University, Johannesburg.
- VIDAL G. 1988. A palynological preparation method. *Palynology*, 12: 215–220.
- VISSER J.N.J. 1986. Lateral lithofacies relationships in the glaciogene Dwyka Formation in the western and central parts of the Karoo Basin. *Transact. Geol. Soc. South Africa*, 89: 373–383.
- VISSER J.N.J. 1996. Controls on Early Permian shelf deglaciation in the Karoo Basin of South Africa. *Palaeogeogr., Palaeoclim., Palaeoecol.*, 125: 129–139.
- WHEELER A. 2015. Palaeoenvironmental and palaeoclimatic reconstruction of the Witbank coal deposits (Karoo Basin, South Africa). MSc Thesis, University of Pretoria, Pretoria.
- WINTER M.F. 1985. Lower Permian Palaeoenvironments of the Northern Highveld Coalfield and Their Relationship to the Character of the Coal Seams. PhD Thesis, University of the Witwatersrand, Johannesburg.
- WOPFNER H. 1999. The Early Permian deglaciation event between East Africa and northwestern Australia. *J. Afric. Earth Sci.*, 29: 77–90.

PLATE

Plate 1

Palynofacies of Coal Seam No. 2, Highveld Coalfield

1. Lower Seam (K114314, sample K2), swamp setting. High amount of monosaccate and bisaccate pollen grains. bs = bisaccate pollen grain, ms = monosaccate pollen grain
2. Lower Seam (S542145, sample S2), swamp setting. High amount of spores. sp = spore
3. Lower Seam (S542145, sample S3), lake setting. Phytoclasts of various sizes and shapes. High amount of blade-shaped phytoclasts. ope = opaque equidimensional, opb = opaque blade-shaped, tre = translucent equidimensional, trb = translucent blade-shaped
4. Intraseam (K114314, sample K6), fluvial setting. High amount of opaque equidimensional phytoclasts and degraded organic matter (DOM). ope = opaque equidimensional
5. Upper Seam (K114314, sample K9), swamp setting. High amount of amorphous organic matter (AOM)
6. Upper Seam (S542145, sample S7), swamp setting. High amount of bisaccate and striate bisaccate pollen grains. Large cuticles, wood remains and plant tissues. bs = bisaccate pollen grain, sbs = striate bisaccate pollen grain

