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Palynological records of the Permian Ecca Group (South Africa): Utilizing climatic icehouse–greenhouse signals for cross basin correlations

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ABSTRACT

The Permian formations of the South African Karoo Basin play a crucial role in understanding Gondwana's climate history during this time of major global changes. In this paper we present two data sets, one from the coal-bearing Vryheid Formation (Witbank Basin) and one from the Whitehill and Upper Prince Albert formations of the DP 1/78 core (NE Karoo).

Our main goal was to study the vegetation changes during this period of global warming and test if the climatic signals could be used to correlate the basinal Ecca group facies with the fluvio-deltaic coal-bearing strata of the Witbank Basin. The palynological record of the No. 2 Coal Seam of the Vryheid Formation indicates a cold climate, fern wetland community, characteristic of lowland alluvial plains, and an upland conifer community in the lower part of the coal seam. Up section, these communities are replaced by a cool-temperate cycad-like lowland vegetation and gymnospermous upland flora. The data set of the DP 1/78 core is interpreted to represent a cool to warm temperate climate represented by a high amount of Gangamopteris and Glossopteris elements.

Both data sets are very different in their composition, which can be explained by the differences in depositional environment; however, our findings reveal a different age of the studied assemblages and thus also suggest that both data sets represent different stages in the transition from icehouse to greenhouse during Permian times. As the stratigraphic correlation between the Main Karroo Basin and the peripheral basins is still under discussion, this paper provides new data to underpin the stratigraphic placement of the Whitehill Formation relative to the coal-bearing Vryheid Formation.

1. Introduction

Our knowledge of the Permian palynology of the South African Karoo Basin is based on a fundamental research carried out in the 1970s and 1980s by Anderson (1977) and Falcon (see 1989 and references therein). No recent works address high-resolution palynostratigraphy of the Permian–Triassic coal-bearing formations in the South African Karoo, whereas new palynostratigraphic zonation schemes were established in other parts of southern Africa (D'Engelbronner, 1996; Nyambe and Utting, 1997; Stephenson and McLean, 1999; Modie and Le Hérissé, 2009). In general, Gondwanan land plant communities changed rapidly during Permian times due to the dramatic climate change subsequent to the melting of the Dwyka ice. This prominent change in vegetation, displayed in palynomorph assemblages, enables a high-resolution correlation.

From this background, it seems imperative to study the palynological record of the Permian succession in much more detail with respect to establish a high-resolution stratigraphic framework and climate history of the Karoo. Here, we report on new palynological data from the No. 2 Coal Seam of the northern Witbank coal field and a core (DP 1/78) drilled in the northeastern part of the Main Karoo Basin with the aim of using climatic signals for basin-wide correlation.

2. Geological setting

The Late Carboniferous to Middle Jurassic Karoo Basin covers approximately one third (i.e. 700 000 km^2) of South Africa (Johnson et al., 2006), extending into Lesotho and in parts of Swaziland and Mozambique (Cole, 1992, Catuneanu et al., 2005). A total thickness of 12 km sediment infill is reached within the southeastern part of the Main Karoo Basin. This sedimentary succession, known as the Karoo Supergroup, is subdivided into the Dwyka Group (Late Carboniferous (Pennsylvanian) to Early Permian (Artinskian); Visser, 1996), the Ecca Group of Permian age, the Permian–Triassic Beaufort Group (Johnson et al., 2006), and the Stormberg Group (Late Triassic to Early Jurassic;

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Catuneanu et al., 1998, Catuneanu et al., 2005). The Karoo succession is capped by 1.4 km of basaltic lavas of the Drakensberg Group and intruded mafic dyke swarms (Veevers et al., 1994; Johnson et al., 1996).

The Karoo Basin forms part of a major series of Gondwanan foreland basins, including the Paraná Basin in South America, the Beacon Basin in Antarctica, and the Bowen Basin in Australia (De Wit and Ransome, 1992; Veevers et al., 1994; Catuneanu et al., 1998; Catuneanu and Elango, 2001; Catuneanu and Bowker, 2002). These basins formed mainly as a result of collision and terrain accretion tectonics along the southern edge margin of Gondwana (De Wit and Ransome, 1992; Veevers et al., 1994). Recent interpretations of the basin evolution and tectonic setting of the Karoo range from a retro-arc foreland basin (Johnson et al., 2006), a transtensional foreland system created by subsidence and tilting in a strike-slip regime (Tankard et al., 2009) to a thin-skinned fold belt that developed from collisional tectonics and distant subduction to the south (Lindeque et al., 2011).

The Karoo Basin hosts important coal resources of South Africa (Johnson et al., 1997; Cairncross, 2001). The Witbank coal field comprises the basin's northeastern and most economic coal deposits (Snyman, 1998) with 5 coal seams (coal seams 1–5 in ascending order) that belong stratigraphically to the Vryheid Formation. One of the most important coal seams of the Witbank coal field, the No. 2 Coal Seam, represents postglacial fluvio-deltaic deposits of the Lower Ecca Group, pointing to a highly proximal setting of the northern basin margin (Falcon, 1989). Further south in the Main Karoo Basin organic-rich shales of the Whitehill Formation have been regarded as time-equivalent to the coal-bearing Vryheid Formation (Viljoen, 1994; Johnson et al., 1996, 1997).

3. Material and methods

During a field campaign in 2011, we sampled an 8 m thick succession of the No. 2 Coal Seam exposed in the Inyanda Coal Mine south of Witbank (Fig. 1) to study palynofacies and palynostratigraphy. Lithologies of 22 samples include fine- to medium-grained sandstones, organic-rich siltstones and coals. We also present here data from the DP 1/78 core (Fig. 1) that was sampled during a data gathering campaign by Shell Exploration & Production. In total, 11 samples of a black shale interval have been analysed.

For palynofacies analysis samples were prepared using standard palynological processing techniques, including HCl (33%) and HF (73%) treatment for dissolution of carbonates and silicates, and saturated $ZnCl_2$ solution ($D \approx 2.2$ g/ml) for density separation. Residues were sieved at a 15 µm mesh size. Slides have been mounted in Eukitt, a commercial, resin-based mounting medium.

Sedimentary organic matter is grouped into sporomorphs, fresh water algae, acritarchs, degraded organic matter, amorphous organic matter and phytoclasts. The phytoclast group has been subdivided into opaque and translucent particles. Equidimensional and needle-shaped phytoclasts have been counted separately. The relative percentage of these components is based on counting at least 300 particles per slide.

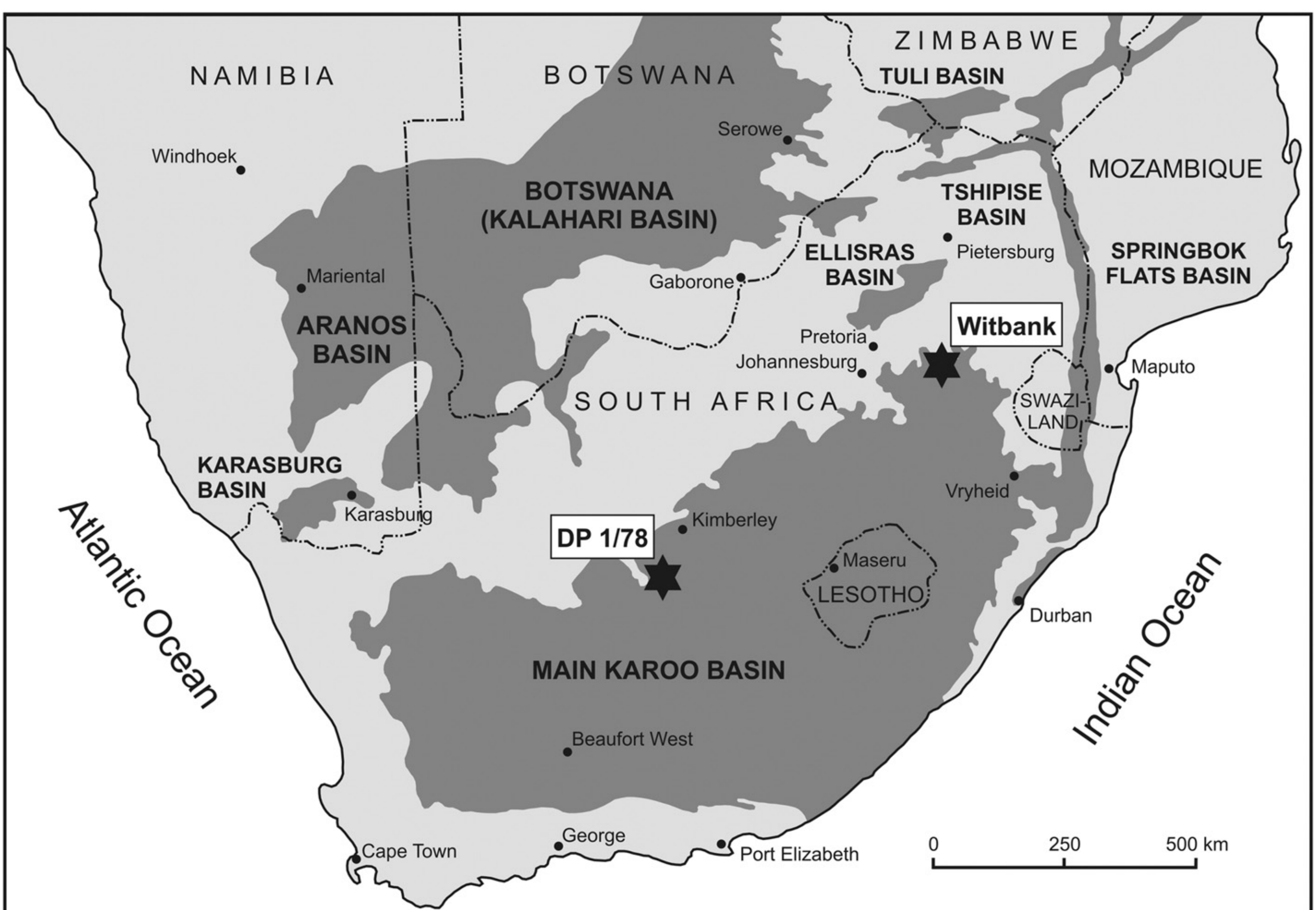

Fig. 1. Location of the studied well section (DP 1/78) and the No. 2 Coal Seam exposed in the Inyanda mine (Witbank). Map modified from Johnson et al. (2006).

4. Sedimentology, palynofacies and palaeoenvironmental interpretation

The northern Witbank coal field is characterized by proximal deposits including coarse-grained to pebbly sandstones, partially with an abrupt upward transition into fine-grained sediments and coal, trough cross-stratified medium- to coarse-grained sandstones, and horizontally laminated, fine- to medium-grained sandstones and organic-rich siltstones. An up to 1 m thick sandstone marker bed separates the No. 2 Coal Seam into a Lower and Upper Coal Seam. In this fluvial-alluvial depositional setting, peat swamps developed on broad abandoned alluvial plains.

Sedimentary organic matter of these proximal deposits is highly degraded and poorly preserved, however relative abundance changes in the palynomorph assemblage and variations in the amount and size and shape of plant debris are clearly documented. Generally, palynofacies is dominated by a high amount of opaque and translucent phytoclasts showing a high variability in size and shape throughout the section. The lower part of the section (Lower Coal Seam) is characterized by a high amount of opaque particles, whereas the upper part (Upper Coal Seam) comprises high amount of translucent plant debris. Amorphous Organic Matter (AOM) is characteristic of laminated, organic-rich siltstones and coals. Degraded organic matter (DOM) is preserved in all sampled lithologies. Freshwater algae (*Tetraporina* spp., *Botryococcus* spp.) are common in the Upper Coal Seam. The lower part of the section (Lower Coal Seam) is dominated by horsetail and fern spores and gymnospermous monosaccate pollen grains whereas the upper part of the section (Upper Coal Seam) is totally dominated by gymnospermous bisaccate (taeniate and non-taeniate) pollen grains with only very few fern spores preserved. The sporomorph assemblages indicate a fern wetland community, characteristic of lowland alluvial plains, and an upland conifer community dominated by monosaccate-producers in the lower part of the coal seam. Up section, these communities are replaced by a cycad-like and lycopsid lowland vegetation and a gymnospermous upland flora of bisaccate-producers, indicating a more temperate climate than the cooler floras in the lower part (Götz and Ruckwied, 2013).

The sampled interval of the DP1/78 well is composed of organic-rich, carbonaceous black shales. The lower part of this interval is interpreted to be part of the Prince Albert Formation and contains a higher amount of silt than the upper part of the interval, which is interpreted to represent deposits of the Whitehill Formation. Palynofacies of the Prince Albert Formation is characterized by rich bleached kerogens with abundant and diverse palynomorphs. Palynomorphs comprise approximately 85% of the sedimentary organic matter. Bisaccate pollen grains dominate the assemblage. Though fully marine indications were not recorded, the assemblages are considered to have been deposited in a distal subaqueous, probably marine environment with ventilated bottom waters.

Samples at the base of the Whitehill Formation are characterized by the frequent occurrence of *Leiosphaeridia* spp. and peak abundance of bisaccate pollen grains including *Vittatina* spp. and *Vittatina saccata*. Such an assemblage together with the occurrence of AOM is interpreted to indicate a distal (restricted) marine environment.

A decrease up-hole in abundance of leiospheres together with an influx of the freshwater/brackish algae *Botryococcus* spp. tentatively indicates an increase in terrestrial (freshwater) influence. This interpretation is supported by the increase (up-hole) in spore types including *Verrucosisporites andersonii*, *Anapiculatisporites* spp. and *Cyclogranisporites* spp., and a general increase in phytoclasts. These particles are thought to be deposited more proximally to source than airborne bisaccate pollen and thus indicate a landward shift in depositional environment. The presence of rare specimens of *Cymatiosphaera gondwanensis* is suggestive of (weak?) marine influences. In summary, the Whitehill Formation therefore is interpreted to represent a distal marine setting

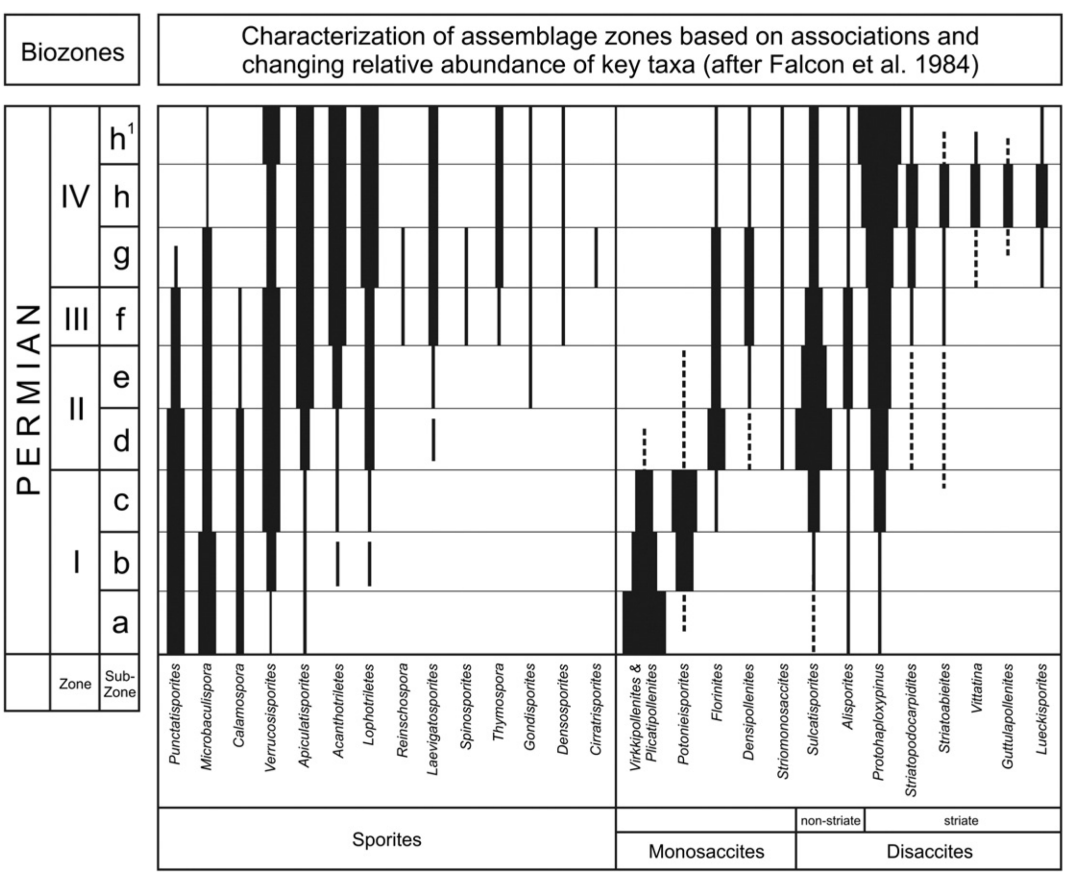

Fig. 2. Palynostratigraphy of the coal-bearing Ecca Group (Lower–Middle Permian) in the northeastern Main Karoo Basin (after Falcon et al., 1984).

with increasing proximity to shore and terrestrial (freshwater) influences up-hole. The high amount of striate and non-striate bisaccates is indicative for a warmer climate during time of deposition relative to the No. 2 Coal Seam assemblages, which imply a cool to temperate climate.

5. Palynostratigraphy

Palynostratigraphy of the Witbank sub-basin and the Northern Main Karoo Basin is well understood. Two schemes have been published by Anderson (1977) and Falcon et al. (1984). In the present study, we focus on the latter (Fig. 2), as it was generated on data sets very close to the Inyanda coal mine, which is analysed herein. To date, there are no palynological data published from the Whitehill Formation, the relatively high maturity in the wide parts of the Main Karoo Basin prevents to apply this method further towards the basin centre and the southern parts of the basin.

The palynological data from the Witbank No. 2 Coal Seam document a climatic shift from cold to cool-temperate conditions. A postglacial monosaccate-producing flora is replaced by a warmer climate bisaccate-producing plant community. The lower part of the No. 2 Coal Seam (Lower Coal Seam) is dominated by *Virkkipollenites* spp., *Potonieisporites* spp. and *Plicatipollenites*, and horsetail and fern spores such as *Calamospora* spp., *Microbaculispora* spp., *Punctatisporites* spp., and *Verrucosisporites* spp. The additional presence of *Florinites* spp. places this assemblage into the Virkkipollenites–Plicatipollenites–Potonieisporites–Florinites sub-assemblage, i.e. Biozone Ic (Falcon et al., 1984). The assemblage of the Upper Coal Seam is dominated by *Sulcatisporites* spp., *Protohaploxypinus* spp., and *Alisporites* spp., with monosaccate elements still present. This part of the seam is within the Sulcatisporites–Virkkipollenites–Plicatipollenites–Potonieisporites sub-assemblage. The presence of key marker species *Striatoabieites multistriatus*, *Protohaploxypinus limpidus* and *Sulcatisporites splendens* implies a correlation with Falcon's Biozone IId (Fig. 3).

Samples of the upper Prince Albert Formation in the DP 1/78 well are dominated by non-striate bisaccate pollen grains, but striate pollen grains, mainly *Protohaploxypinus* spp. and *Striatoabieites* spp. are common. The frequent occurrence of *Lundbladispora braziliensis* as well as the presence of *Marsupipollenites striatus* places this interval into Falcon's Biozone IIIf, i.e. the Sulcatisporites–Protohaploxypinus sub-assemblage (Fig. 4). Samples of the Whitehill Formation are characterized by a high amount of *Vittatina* spp., the general increase of the striate bisaccate group, the consistent presence of *Guttulapollenites* aff. *hanonicus* and *Lueckisporites virkkiae* suggest to place this sediments into the Protohaploxypinus–Vittatina–Guttulapollenites–Lueckisporites sub-assemblage, i.e. biozones IVg and IVh (Falcon et al., 1984).

6. Age interpretation, correlation and conclusions

The Vryheid Formation was previously dated as Artinskian, with possible extensions into the Kungurian by various authors (McLachlan and Anderson, 1973; MacRae, 1988; Catuneanu et al., 2002). In general the authors stated that the Vryheid Formation was deposited during a more extended period of time and that deposition continued at least during the early Middle Permian. Floral composition of the lower two coal seams (No. 1 and No. 2) clearly shows a Lower Permian signature which matches with the previous age interpretation; however, the upper coal seams (Nos. 3, 4, and 5), especially coal seam No. 5, clearly indicate a Middle Permian age. Samples of the Inyanda Coal Mine from the No. 2 Coal Seam are very comparable to the assemblages described by Falcon et al. (1984). However, the samples of the Lower Coal Seam (No. 2) show clearly the signature of Falcon's Biozone Ic. This differs from the results of Falcon's original work where all data from the No. 2 Coal Seam match with Biozone IId. Due to the fact that palynofacies suggest a swamp dominated palaeoenvironment, the authors assume that a diachronous sedimentation of the coals within the Witbank Basin is most likely the explanation for this difference. The age interpretation for these samples is Artinskian to Kungurian.

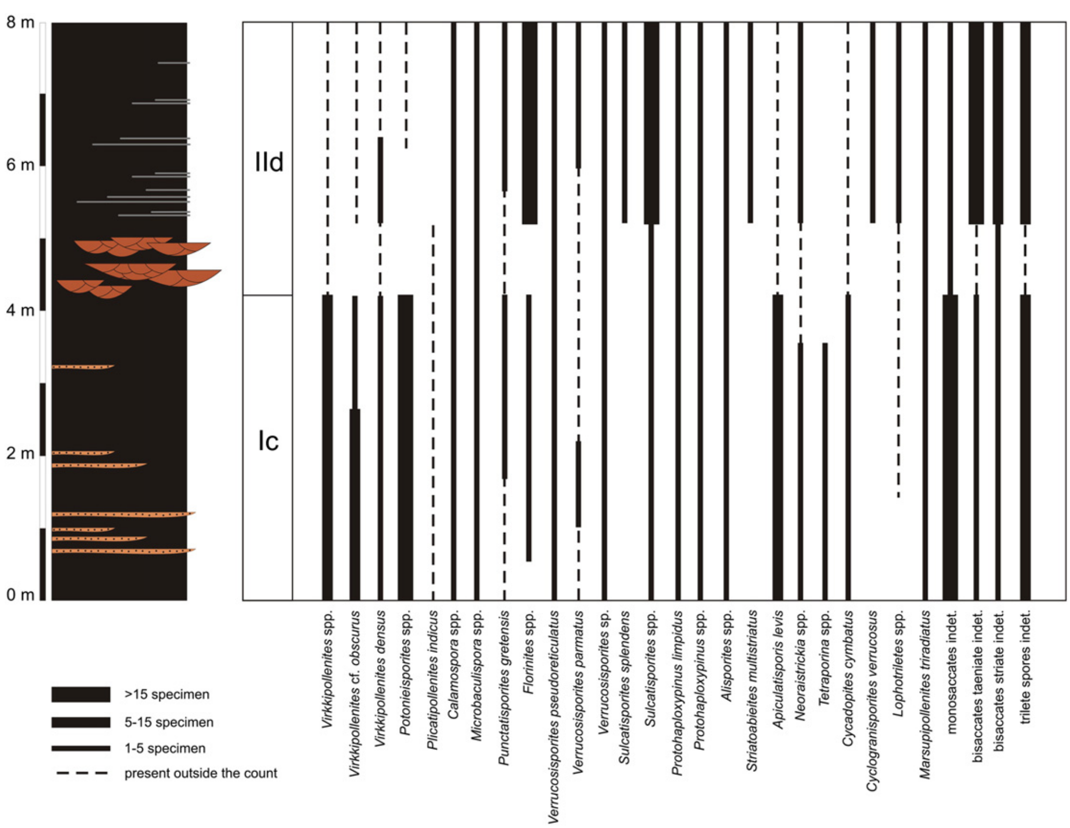

Fig. 3. Palynomorph distribution chart of the No. 2 Coal Seam, Inyanda Mine (Witbank). Biozones Ic and IId after Falcon et al. (1984).

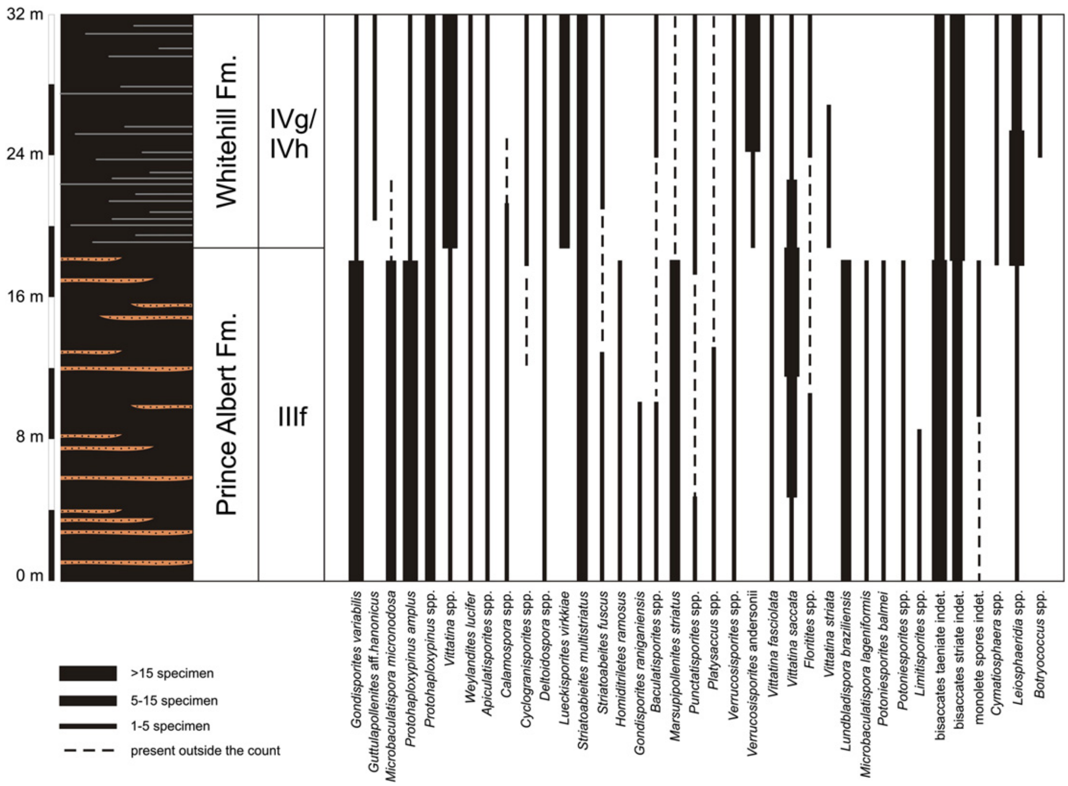

Fig. 4. Palynomorph distribution chart of the DP 1/78 core (NE Karoo). Biozones IIIf and IVg/h after Falcon et al. (1984).

Data from the DP 1/78 well represent the first palynological data for the upper Prince Albert Formation and Whitehill Formation. Samples of the Prince Albert Formation show a very similar composition as samples from the No. 4 Coal Seam of the Witbank Basin (Falcon et al., 1984). Retallack (2006) reports *Lundbladispora braziliensis* not above the Guadalupian. Souza et al. (2005) describe a similar assemblage from the Paraná Basin in Brazil. Their *Vittatina costabilis* interval is defined as a zone with the first appearance of *Vittatina* spp. at the base and the first appearance of *Lueckisporites virkkiae* at the top. Due to the similarities to this assemblage we suggest to place the Prince Albert Formation chronostratigraphically into the uppermost Early Permian to lowermost Middle Permian. Samples from the Whitehill Formation seem to yield similar palynomorph assemblages as described from the No. 5 Coal Seam of the Witbank Basin (Falcon et al., 1984). The presence of *Lueckisporites virkkiae* suggests a correlation with the *Lueckisporites virkkiae* Interval zone of the Brazilian Paraná Basin (Souza et al., 2005), which is interpreted to be Guadalupian in age. An absolute age obtained from a tuff in the overlying Collingham Formation in the Namibian part of the Karoo, dated as 270 My (Stollhofen et al., 2000), supports a Roadian age.

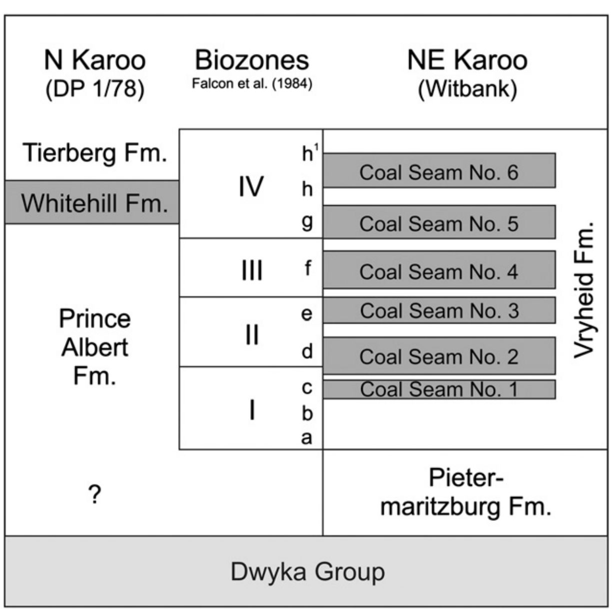

Fig. 5. Correlation of the Prince Albert and Whitehill formations (N Main Karoo) and Vryheid Formation (Witbank Basin, NE Karoo) based on new palynological data from the DP 1/78 well and the No. 2 Coal Seam.

The comparison of the two assemblages from the Witbank Basin and the DP 1/78 well strongly suggests that the sediments of the Vryheid Formation and the uppermost Prince Albert Formation and Whitehill Formation have been deposited at the same time (Fig. 5). This agrees with previous correlations by Viljoen (1994) and Johnson et al. (1996, 1997), but disagrees with Catuneanu et al. (2002) who suggested that the Whitehill Formation is significantly older and equivalent to the Pietermaritzburg Formation.

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