Marine flooding surfaces recorded in Permian black shales and coal deposits of the Main Karoo Basin (South Africa): implications for basin dynamics and cross-basin correlation

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Abstract

The marine origin of black shales in the context of the Permian postglacial development of the Karoo Basin, South Africa, is subject of an ongoing controversial discussion. Here, we present and discuss palynological and sedimentological data providing evidence of a transgressive event during the early Guadalupian. Palynofacies assemblages of the black shales of the southern basin include marine phytoplankton that exhibit peak abundance within the Whitehill shales and which also occur within siltstones and glauconitic sandstones on top of the No. 5 coal seam of the north-eastern basin. Palynostratigraphic control makes this marine signal a powerful tool for cross-basin correlation. Moreover, palynofacies analysis demonstrates a facies transition from terrestrial lacustrine and fluvio-deltaic in the northeast to deep marine in the south-western parts of the basin.

Keywords: Marine–nonmarine correlation; black shales; coal; Permian; Karoo; South Africa.

1. Introduction

Previous works on Permian Karoo black shales provide sedimentological and palaeontological evidence for their marine origin (e.g., Haughton et al., 1953; du Toit, 1954; Rilett, 1963; Hart, 1964, 1969, 1970; Ryan, 1968; McLachlan and Anderson, 1973; Teichert and Rilett, 1974; Stanistreet et al., 1980; Oelofsen, 1987; Visser, 1987, 1989, 1992, 1993, 1994; Visser and Young, 1990; Smith et al., 1993; Johnson et al., 1997, 2006; Scheffler et al., 2006; Buatois et al., 2010; Götz, 2015). Despite this, there is ongoing controversy and discussion concerning the marine or lacustrine origin in the context of the postglacial development of the Karoo Basin (e.g., Cole and McLachlan, 1991; Faure and Cole, 1999; Herbert & Compton, 2007; Chukwuma and Bordy, 2016; Schulz et al., 2016). This discussion includes the palaeoecology of the famous Permian mesosaurs (Oelofsen, 1981; Oelofsen and Araújo, 1983), interpretations ranging from freshwater, brackish, coastal, lagoonal, hypersaline to normal marine (see Modesto, 2006; Piñeiro et al., 2012; Silva et al., 2017 and references therein). Marine condensed sections have been described from black shales of the Prince Albert and Whitehill formations and interpreted to represent postglacial highstand phases corresponding to coal-forming delta deposits of the north-eastern coalfields (Visser, 1992, 1993, 1995). More recently, a cross-basin correlation of the marine Prince Albert and Whitehill shales and fluvio-lacustrine coal deposits using palynological data was presented by Ruckwied et al. (2014). Glauconitic sandstones, indicative of marine transgressions, are documented from coalfields in the north-eastern part of the basin on top of distinct coal seams (Van Vuuren, 1981, 1983; Cadle, 1982; Cairncross, 1986; Cadle et al., 1993), the most prominent being at the top of the No. 5 coal seam in the Witbank and Highveld coalfields (Hancox and Götz, 2014). From this background and in view of the recent interest in Karoo shales as unconventional gas resource (Decker and Marot, 2012; Mowzer and Adams, 2015), new data from recently drilled deep boreholes in the southern Karoo, as well as published borehole and outcrop data from Karoo black shales and coal deposits are discussed to pinpoint marine transgressions and flooding surfaces on a basin scale. Ultimately, the complexity of basin dynamics within a postglacial setting and related implications for cross-basin correlations are highlighted.

2. Geological Setting

The Main Karoo Basin (Fig. 1) comprises a continuous sedimentary succession from the Pennsylvanian to Middle Jurassic known as the Karoo Supergroup (Johnson et al., 2006). It documents the postglacial climate history of central Gondwana marking the transition from the late Palaeozoic Icehouse to the Triassic Hothouse extremes (Montañez et al. 2007; Sun et al., 2012; Scotese, 2016). Depositional environments recorded in the basin fill range from glacio-marine

(Dwyka Group) to marine-deltaic (Ecca Group), to fluvial (Beaufort Group) and aeolian (Stormberg Group). The lower Ecca Group hosts thick coal-bearing successions in the north-eastern part of the basin and black shales (Ecca shales: Prince Albert, Whitehill, Collingham formations; Johnson, 2009) occur in the central and southern basin. The Karoo succession is capped by 1.4 km of basaltic lavas of the Drakensberg Group and intruded by mafic dyke swarms (Veevers et al., 1994; Johnson et al., 1996).

The retro-arc foreland basin model for the Main Karoo Basin (Catuneanu et al., 1998) is the most commonly accepted, explaining the partitioning of the basin by flexural tectonics into proximal foredeep, central forebulge, and distal backbulge flexural provinces. More recently, a transtensional foreland system created by subsidence and tilting in a strike-slip regime (Tankard et al., 2009) and a thin-skinned fold belt that developed from collisional tectonics and distant subduction to the south (Lindeque et al., 2011) have been proposed.

Basin-wide correlation is still constrained by the use of mainly nonmarine vertebrates (tetrapods) of low time resolution and the lack of absolute age controls. However, recently published radiometric dates (Fildani et al., 2009; Rubidge et al., 2013; Day et al., 2015; Gastaldo et al., 2015) have improved the existing biostratigraphic correlation scheme. A first basin-wide palynological correlation was recently attempted by Barbolini (2014). Still, the problem of marine–nonmarine correlation can only be solved by precise palynostratigraphic data such as recently obtained from fluvio-lacustrine coal deposits and marine black shales (Ruckwied et al., 2014). Ultimately, a more robust basin-wide correlation scheme will be required for effective exploitation of South Africa's coal and potential shale gas resources (Hancox and Götz, 2014; Götz, 2014, 2015).

3. Material and Methods

In 2015, two deep research boreholes (KZF-1, KWV-1), drilled in the southern Karoo Basin (Fig. 1) within the framework of the research programme KARIN (Karoo Research Initiative), intersected Permian black shales of the Prince Albert, Whitehill and Collingham formations (De Kock et al., 2016a, 2016b). Palynological samples from both cores were studied for their sedimentary organic matter content and palynomorph assemblages. Two coal exploration boreholes (BHS14, ALBN11) from the Witbank Coalfield, drilled in 2013, intersected five coal seams developed in the Vryheid Formation (Cairncross, 1986; Hancox and Götz, 2014) and palynological samples were analysed from the No. 2 and No. 5 seams. Previously studied core and outcrop material from black shales in the northern and southern Karoo (Ruckwied et al. 2014; Götz, 2015) and from coal seams of the Witbank and Highveld coalfields in the north-eastern part of the basin (Götz and Ruckwied, 2014; Wheeler

and Götz, 2016, 2017) are compared with the new data and other available literature data to provide a novel cross-basin correlation scheme for marine and nonmarine deposits based on palynofacies signatures. The KARIN cores are curated at the Council for Geoscience (CGS), Pretoria. Palynological slides are housed at the Geological Museum Kazan Federal University (GM KFU), collection no. 40. Identified palynomorph taxa are listed in Table 1, arranged under probable botanical affinities.

4. Coal deposits of the north-eastern basin

The majority of the economically extracted coal in South Africa occurs in the Permian Vryheid Formation (Cairncross, 2001; Hancox and Götz, 2014), which ranges in thickness in the Karoo Basin from less than 70 m to over 500 m (Cadle, 1982). Coal seam nomenclature and numbering in the Witbank Coalfield (Fig. 1) distinguishes five to six individual seams (Le Blanc Smith, 1980; Cairncross, 1986; Cairncross and Cadle, 1987, 1988). A palynostratigraphic framework of the coal-bearing succession was provided by Falcon et al. (1984) and later refined by Aitken (1994, 1998). The coals show a mean vitrinite reflectance of 0.7% characteristic of high volatile bituminous coal (Falcon 1986; Falcon and Snyman, 1986; Snyman, 1998; Götz et al., 2012). The palynofacies of the coals are characterized by a high percentage of opaque phytoclasts and distinct pollen and spore assemblages reflecting the change of lowland and upland vegetation in response to postglacial climate amelioration (Falcon et al., 1984; Götz and Ruckwied, 2014; Ruckwied et al., 2014; Wheeler and Götz, 2016, 2017).

In the Witbank Coalfield, the No. 2 coal seam is economically the most important seam containing most of the best quality coal of South Africa (Snyman, 1998). The seam averages 6.5 m in thickness in the central part of the coalfield, and thins to approximately 3 m towards the east. In the western sector it may be up to 7 m thick (Hancox and Götz, 2014). In contrast, seam thickness is more variable in the Highveld Coalfield ranging from 4 m along the northern margin and up to 10 m in valleys in the west. The seam thins to less than 1 m in the east and southeast, and is often not well-developed changing to the south into carbonaceous mudstone. In both coalfields the seam splits into a lower (2L) and upper (2U) seam by clastic intra-seam partings (Hancox and Götz, 2014). The palynofacies of the No. 2 coal seam were studied by Götz and Ruckwied (2014), Ruckwied et al. (2014), and Wheeler and Götz (2016, 2017) in outcrops and from boreholes, including boreholes ALBN11 and BHS14 discussed below. A prominent change in the composition of palynomorph assemblages records the switch from a fern- and conifer-dominated flora in the lower coal seam to a

more diverse *Glossopteris-Gangamopteris* flora in the upper coal seam. This signal is interpreted to indicate the transition from a cold to a fluctuating cool-temperate climate, initiating the switch from icehouse to greenhouse conditions (Falcon et al., 1984; Götz and Ruckwied, 2014; Wheeler and Götz, 2017). A comparable change in floral composition in the adjacent Highveld Coalfield (Wheeler and Götz, 2016), suggests such changes providing a basis for cross-basin correlation (Ruckwied et al., 2014). Palynologically, the No. 2 seam was dated as Artinskian/Kungurian indicating a correlation with black shales of the Prince Albert Formation (Ruckwied et al., 2014). A facies model for the coal-bearing environments based on palynofacies is given in Wheeler and Götz (2017), distinguishing between swamp-, lake- and river/delta-controlled sedimentation in a paralic setting and influenced by glacial meltwater input from the hinterlands.

The No. 3 coal seam is poorly developed in the Witbank and Highveld coalfields with thicknesses generally less than 0.5 m but locally up to 1 m in the Highveld Coalfield. In borehole BHS14 it has a thickness of 0.4 m with a thin glauconite-bearing sandy siltstone above the seam. In borehole ALBN11, the seam is not developed. The No. 4 seam is the second most important source of coal in the Witbank Coalfield and varies in thickness from 2.5 m in the central part of the coalfield to 6.5 m elsewhere. In places, the seam is divided into a lower (4L) and upper (4U) seam. In the Highveld Coalfield, the No. 4 seam is the major economic seam. The No. 4L seam averages 4 m in thickness, whereas the No. 4U seam is only of mineable thickness in the western part of the coalfield with an average thickness of 2 m, varying between 1.5 m and 3.4 m (Hancox and Götz, 2014). A glauconitic sandstone occurs in the northern part of the coalfield on top of the No. 4U seam (Winter et al., 1987). In the BHS14 and ALBN11 boreholes, a lower and upper seam is developed. In BHS14 a total thickness of 4.6 m is encountered, in ALBN11 3.4 m. In borehole ALBN11, a glauconitic sandstone is developed above the upper seam (4U).

The coal seam No. 5 reaches a thickness between 0.5 m and 2 m in the Witbank Coalfield, and in the adjacent southern Highveld Coalfield the thickness ranges between 0.3 m and 3 m (Hancox and Götz, 2014). The roof of the seam is formed by a medium- to coarse-grained, laminated glauconitic sandstone (Fig. 2) reaching a maximum thickness of up to 1 m in the western sector of the Witbank Coalfield, informally referred to as the Glauconite Sandstone Marker. It is also well developed in the adjacent southern Highveld Coalfield (Winter et al., 1987) and in the western Vereeniging-Sasolburg and Free State coalfields where it was studied by Hart (1969, 1970) who first described marine acritarch assemblages from these glauconitic sandstones. In the central sector of the Witbank Coalfield, the sandstone marker is replaced by siltstones, in places glauconite-bearing. From this part

of the coalfield, Venter and Cairncross (1995) described marine phytoplankton from a shale horizon near the top of the No. 5 seam.

The here studied boreholes of the central and southern sector reveal a sandy siltstone (BHS14) and organic-rich siltstone (ALBN11) above the seam (Fig. 3). Palynofacies of the seam shows a general high percentage of opaque equidimensional phytoclasts. In borehole ALBN11 a decrease of opaque lath-shaped, and translucent phytoclasts is observed upsection. A similar trend occurs within the group of pollen grains. Spores and amorphous organic matter (AOM) are dominant in the lower seam, and cuticles debris is recorded. Marine acritarchs occur only within the upper part of the seam where opaque equidimensional phytoclasts and degraded organic particles (DOP, mainly degraded translucent phytoclasts) show a prominent increase. The sample from the siltstone above the seam shows the highest proportion of opaque equidimensional phytoclasts, DOP, and marine phytoplankton (acritarchs). In borehole BHS14 opaque equidimensional particles are dominant throughout the seam with exception of a silty horizon in the lower part. Opaque lath-shaped phytoclasts decrease continuously upsection. The same trend is observed within the group of translucent equidimensional plant remains with exception of the sample from the siltstone in the lower seam. Here, also translucent lath-shaped particles show the highest amount. Pollen grains are most abundant in the upper seam, whereas spores show the highest abundances in the lower seam. Freshwater algae (*Botryococcus* sp., *Tetraporina* sp.) occur in the silty horizon in the lower seam, whereas marine phytoplankton (acritarchs) were detected in the sandy siltstone above the seam. This sample also shows the highest proportion of DOP and no AOM is preserved.

The palynofacies patterns detected in ALBN11 are interpreted to document a shift from swamp to deltaic-marine environments with a clear marine signature on top of the seam marked by maximum abundance of opaque equidimensional particles, DOP and marine acritarchs. In BHS14 a similar shift is observed; however, within the lower seam a lacustrine phase is documented with lowest percentages of opaque equidimensional phytoclasts, highest percentages of translucent particles and the occurrence of freshwater algae. The sandy siltstone above the seam shows a clear marine signature with the highest percentage of opaque equidimensional phytoclasts, DOP, and the occurrence of marine acritarchs. Both boreholes demonstrate that even if a glauconitic sand- or siltstone is not developed, the marine signal on top of the seam can be detected by marine phytoplankton and the change in the composition of sedimentary organic matter.

5. Black shales of the central and southern basin

The Prince Albert Formation overlies the glacio-marine Dwyka tillites with a highly variable thickness of 40 to 150 m along the western and southern outcrop areas (Johnson et al., 2006) and a maximum thickness of up to 300 m in boreholes of the SOEKOR exploration drilling programme (Rowell and de Swardt, 1976). A radiometric date of the base of the Prince Albert Formation (288 ± 3 Ma) was published by Bangert et al. (1999) from the south-western Karoo Basin. Palynological data suggest an Artinskian–Kungurian age (Ruckwied et al., 2014). Olive grey to dark-grey silty shale with intercalated fine-grained sandstone layers occur in the northern part of the basin, whereas dark-grey, pyrite-bearing shale with chert and phosphatic nodules and lenses occurs in the south (Cole, 2005). Present-day total organic carbon (TOC) values range from less than 1.0% up to 3.4% (Aarnes et al., 2011; Geel et al., 2015; De Kock et al., 2017; this study, Tab. 2).

The Whitehill Formation overlies the Prince Albert Formation. Its thickness ranges between 20 and 100 m, thinning from SW to NE (Johnson et al., 2006). It is exposed in outcrops along the basin margin (Chukwuma and Bordy, 2016) and has been identified in the subsurface by numerous boreholes of the SOEKOR exploration drilling programme (Rowell and de Swardt, 1976) and recent research boreholes of the KARIN research programme (De Kock et al. 2016a, 2016b), where it ranges in depth from 450 to 3000 m below surface. Radiometric dates are not yet available for the Whitehill Formation in South Africa. However, palynological data suggest a Roadian age (Ruckwied et al., 2014). In outcrops, the white-weathering shale is distinguished from the dark to olive grey lithologies of the under- and overlying Prince Albert and Collingham/Tierberg formations (Cole and Basson, 1991). Lateral facies changes enable to distinguish a northern shallow and southern deeper depositional environment (Chukwuma and Bordy, 2016). Present-day total organic carbon (TOC) values range from less than 1.0% up to 18.5% (Oelofsen, 1987; Cole and McLachlan, 1991; Aarnes et al., 2011; Geel et al., 2013, 2015; Smithard et al., 2015; De Kock et al., 2016b, 2017; this study, Tab. 2).

The Collingham Formation overlies the Whitehill Formation in the southern and western parts of the basin and is the stratigraphic equivalent of the Tierberg Formation developed in the north-western Karoo Basin (Cole and Basson, 1991). The formation is between 30 and 70 m thick (Viljoen, 1992) and comprises a rhythmic alternation of thin, dark-grey shales and very thin tuff layers (Johnson et al., 2006). The tuff layers are considered to be silicic air-fall tuffs which underwent secondary alteration to K-bentonites (Viljoen, 1992). Recently published U–Pb zircon ages from the Eccas Pass section (McKay et al., 2015) place the base of the formation chronostratigraphically in the early Guadalupian. Palynological data from the Eccas Pass suggest a Roadian age (Götz, 2015) consistent with the radiometric dates of McKay et al. (2015). Present-day total organic carbon (TOC) values

range from less than 1.0% up to 2.8% (Geel et al., 2015; De Kock et al., 2017; this study, Tab. 2). Values from the Tierberg Formation of the northern Karoo Basin are below 1.0% (Aarnes et al., 2011).

Palynofacies assemblages of the studied black shales (Fig. 4) reveal a high percentage of phytoclasts in all parts of the basin, whereas the proportions of amorphous organic matter (AOM), sporomorphs and marine phytoplankton (acritarchs, prasinophytes) are more variable, stratigraphically and laterally. In the northern part of the basin (DP 1/78), the sedimentary organic matter of the Whitehill shales reveals a shallow marine, restricted setting with low marine phytoplankton percentages (leiospheres, prasinophytes), low AOM preservation, high phytoclast input, and a high spores:bisaccates ratio, data plotting in field II of the AOM-Phytoclast-Palynomorph ternary diagram (Fig. 4a). In the south-eastern part (KWV-1), palynofacies suggests a stratified deep basin setting with low marine phytoplankton percentages (prasinophytes), good AOM preservation, high terrestrial input, and a moderate spores:bisaccates ratio, data plotting in field IVa (Fig. 4a). Further to the south (Ecca Pass), the percentage of AOM increases, data plotting in field IVb. In the south-western basin (KZF-1), the palynofacies indicates a distal marine basinal setting with moderate marine phytoplankton percentages (acritarchs, prasinophytes), good AOM preservation, low terrestrial input, and low spores:bisaccates ratios, data plotting in field VII (Fig. 4a). The highest percentage of marine phytoplankton was detected in the middle Whitehill Formation (Fig. 5), most prominent in the south-eastern and northern sections (KWV-1, DP 1/78).

The underlying Prince Albert shales of the northern basin (DP 1/78) are characterized by a high proportion of phytoclasts, translucent particles prevalent, and bisaccate pollen grains, with very low AOM and marine phytoplankton preservation and data plotting in field II of the AOM-Phytoclast-Palynomorph ternary diagram (Fig. 4a). A shallow marginal marine, less-restricted setting is inferred for the Whitehill shales. In the south-eastern part (KWV-1), palynofacies points to a basinal setting with moderate marine plankton percentages (acritarchs), low AOM preservation, and a high proportion of opaque equidimensional phytoclasts, data plotting in field II (Fig. 4a). In the south (Ecca Pass), similar palynofacies are present with low AOM preservation and abundant opaque phytoclasts, data plotting in field II (Fig. 4a). In the south-western basin (KZF-1), palynofacies reveals a stratified deep basin setting with low marine phytoplankton percentages (prasinophytes), good AOM preservation, high terrestrial input, and a moderate spores:bisaccates ratio, data plotting in field IVa (Fig. 4a).

The overlying basal Collingham shales studied in the southern basin (KZF-1, Ecca Pass) reveal a high content of both AOM and prasinophytes, characteristic of a deep, stratified marine basin, data

plotting in field IVb (Fig. 4b). Upsection, a marked shallowing is documented in both areas with palynofacies characterized by a high input of phytoclasts and a high spores:bisaccates ratio, data plotting in fields IVa and III (Fig. 4b). In the northern basin (DP 1/78) palynofacies is dominated by woody debris and reveals a high spores:bisaccates ratio, data plotting in field III (Fig. 4b).

Some authors consider prasinophytes to be an indicator of cold reduced salinity waters (e.g., Leckie et al., 1992). In this case, a change from a predominance of acritarchs to one of prasinophytes could be construed as a signal of decreased salinity. On the other hand, prasinophytes may be associated with stratification rather than salinity per se, and thus may increase distally for this reason, as documented in numerous studies on black shales of Palaeo- and Mesozoic basins (e.g., Tyson, 1987, 1995; Gorin and Feist-Burkhardt, 1990; Prauss et al., 1991; Lüning et al., 2000). In this context it is also worth mentioning that Permian low-diversity organic-walled microplankton assemblages (Fensome et al., 1990; Strother, 1996; Traverse, 2007; Lei et al., 2013) might complicate the identification of variations in marine influence. Thus, palynofacies analysis, the study of all sedimentary organic particles, their changes in composition, size spectra and preservation states (cf. Combaz, 1964, 1980; Tyson, 1993, 1995) – stratigraphically and laterally – as applied here to Karoo shales and coals is seen as a very powerful tool to detect such variations and different depositional environments in the context of the postglacial basin evolution.

6. Correlation

Palynostratigraphy allows for correlation of coal deposits and black shales on a basin scale (Fig. 6). Palynomorph assemblages of the No. 2 and No. 5 coal seams were identified also in marine black shales (Ruckwied et al., 2014; Götz and Wheeler, 2017). The lower part of the No. 2 coal seam (lower seam 2L) is dominated by *Cannanoropollis* spp. (= *Virkkipollenites*), *Potonieisporites* spp. and *Plicatipollenites* sp., and horsetail and fern spores such as *Calamospora* spp., *Microbaculispora* spp., *Punctatisporites* spp., and *Verrucosisporites* spp. The presence of *Florinites* spp. places this assemblage into the *Virkkipollenites–Plicatipollenites–Potonieisporites–Florinites* sub-assemblage, i.e. Biozone Ic of Falcon et al. (1984), revealing an Artinskian–Kungurian age (Ruckwied et al., 2014). The assemblage of the upper seam (2U) is dominated by *Sulcatisporites* spp., *Protohaploxypinus* spp., and *Alisporites* spp. and placed into the *Sulcatisporites–Virkkipollenites–Plicatipollenites–Potonieisporites* sub-assemblage, i.e. Biozone IId of Falcon et al. (1984). The presence of key marker species *Protohaploxypinus limpidus* implies a placement within the *Vittatina costabilis* Interval Zone of Souza and Marques-Toigo (2005). As identified for the Whitehill shales, a high percentage of

Vittatina spp., a general increase of the striate bisaccate pollen group, and the consistent presence of *Guttulapollenites hannonicus* and *Lueckisporites virkkiae* is characteristic of the No. 5 coal seam (Ruckwied et al., 2014; Götz and Wheeler, 2017). Thus, the upper Prince Albert Formation and Whitehill Formation are interpreted to belong to the *Lueckisporites virkkiae* Interval Zone regarded as late Cisuralian (Kungurian) to early Guadalupian (Roadian) (Souza and Marques-Toigo, 2005), whereas the lower Prince Albert Formation still belongs to the early Cisuralian (Artinskian) *Vittatina costabilis* Interval Zone (Ruckwied et al., 2014; Götz and Wheeler, 2017). The basal Collingham Formation is dominated by *Lueckisporites* spp., *Vittatina* spp., and *Weylandites lucifer* (Götz, 2015; Götz and Wheeler, 2017), placing this part of the formation into the *Lueckisporites virkkiae* Interval Zone of Souza and Marques-Toigo (2005). U–Pb zircon ages from the base of the Collingham Formation (268 ± 3.2 Ma; McKay et al., 2015) are in agreement with the palynostratigraphic dates, indicating an early Guadalupian (Roadian) age.

Barbolini (2014) noted the shared taxa between South Africa and Australia, but found challenges in correlation based on endemism and palaeoenvironmental differences. This was explored further in Barbolini et al. (2016), which provides a detailed analysis of potential diachroneity between the pollen assemblages of South Africa and Australia. The comparison of both the palynological record and radiometric dates from both countries highlights the difficulties in large-scale regional correlations using the same index taxa. Furthermore, the limited number of radiometric dates in early Permian (Cisuralian) sections compared to late Permian (Lopingian) sections in both countries is problematic as entire formations are constrained by only one or two dates.

In terms of palynological correlation on an intrabasinal scale, there are also constraints within the Karoo Basin, especially in the Cisuralian. The scheme developed by Anderson (1977) places the No. 5 coal seam into the 3b/3c biozones. Falcon (1975, 1978) developed a zonation based on reference sections in Zimbabwe, and placed the No. 5 coal seam into zone IVg. Aitken (1994), however, suggests a younger age of zone IVh' attributing the different age placements to local environmental variation. This study also suggests that the No. 5 coal seam can be assigned to Biozone F using the scheme of MacRae (1988), which was developed based on samples from the Waterberg and Pafuri sub-basins of the northern Karoo. Aitken (1998) indicates the Whitehill Formation tentatively correlates with the Volksrust Formation based on the assignment of Biozone VI, while the No. 5 coal seam is assigned to the older Biozone V. Barbolini (2014) correlates the Whitehill Formation in the southern part of the basin with the Pietermaritzburg Formation in the northern part by identifying taxa with restricted ranges which may be useful for correlation. This study does note that many of

these taxa are restricted to specific facies in certain parts of the basin and thus cannot be used to directly correlate to a different part of the basin within the same lithostratigraphic horizon. Ultimately, a scheme based on the first appearance of specific index taxa similar to the scheme of sections calibrated by radiometric age dates used in Australia (Price, 1997; Laurie et al., 2016) would potentially be extremely useful in developing more accurate intrabasinal correlations in the Main Karoo Basin. However, abundant ashfall tuff marker beds spanning the Sydney, Gunnedah and Bowen basins allow for verification of absolute ages over large distances (Metcalf et al., 2015; Nicoll et al., 2015; Ayaz et al., 2016; Laurie et al., 2016). This is a more difficult task in the Main Karoo Basin as the ashfall tuff deposits are limited to the southern part of the basin. Thus, future work dating the glauconitic sandstones associated with the coals in the north may offer a solution, but in the interim we propose a correlation based on basin-scale palaeoenvironmental events displayed in distinct palynofacies patterns.

Palynofacies reveals changes in the composition of sedimentary organic matter reflecting different depositional environments (Fig. 7). Within coal seams the change from swamp, lake, river and deltaic to shallow marine environments is documented in stratigraphic and lateral changes of organic particles. The No. 5 coal seam documents a major marine transgression with marine phytoplankton occurrence. In contemporaneous marine black shales of the Whitehill Formation different basinal environments ranging from marginal restricted, shallow to deep marine, with partly stratified water bodies are well recorded in the palynofacies (Fig. 4). The highest variability of phytoclast size and shape is documented in the northern basin (DP 1/78), characteristic of proximal settings (Tyson, 1995). The acritarch peak detected within the Whitehill shales corresponding with the occurrence of marine plankton in siltstones and glauconitic sandstones on top of the No. 5 coal seam is interpreted to indicate a maximum flooding zone. Lower in stratigraphy, glauconitic siltstones and sandstones were detected on top of the No. 3 coal seam (Free State and Vereeniging-Sasolburg coalfields; e.g., Hart 1969; Anderson, 1977; Stavrakis, 1986; Steyn and Van der Linde, 1986) and above the No. 4 coal seam (Witbank and Highveld coalfields; e.g., Le Blanc Smith, 1980; Cadle, 1982; Winter, 1985; Winter et al., 1987), probably also representing flooding intervals. Anderson (1977) described the acritarch species *Micrhystridium karooense* from a glauconitic siltstone on top of the No. 3 coal seam intersected in a borehole south of Sasolburg (Vereeniging-Sasolburg Coalfield). Le Blanc Smith (1980) interpreted the Witbank coals as fluvio-deltaic deposits with periods of peat accumulation invariably terminated by transgression and swamp drowning. Hart (1969, 1970) identified three marine horizons within the coal-bearing Vryheid Formation on top of the No. 2, 3 and 4 coal seams and Cairncross and Cadle (1988) described a marine transgressive sequence above the No. 2 coal seam.

The higher percentages of marine acritarchs, compared to our findings from the Witbank Coalfield, reported by Hart (1969) and Anderson (1977) from boreholes of the northern Free State province reflect the proximal-distal position within the basin, the Witbank coal-bearing facies representing the most proximal setting.

Gondwanan postglacial transgressive events have been recognized as a result of the combined effect of fast glacioeustatic sea-level rise and subsidence along basin margins (López-Gamundí, 2010) and landward marine pulses as reflected in the proximal coal series of the north-eastern Karoo Basin are to be expected. In a sequence stratigraphic context, the Karoo coal seams are thus interpreted as transgressive seams (cf. Diessel, 1992, 1998) formed when creation of accommodation was large (Gastaldo et al., 1993; Aitken and Flint, 1995; Bohacs and Suter, 1997). A similar pattern of multiple transgressive pulses with maximum flooding occurring above coal seams was recognized by Holz (1998, 1999) in early Permian coal deposits of the Paraná Basin and it was demonstrated that variations in the palynological record are related to changes in relative sea level (Holz and Dias, 1998). By contrast, Catuneanu et al. (2002) place the maximum flooding surface within the coal seams on top of laminated siltstones and interpret the Karoo coals to have developed at the maximum regressive surface. The five detected T-R sequences are divided into transgressive systems tracts related to marine flooding of the forebulge area (Catuneanu et al., 1998) and regressive systems tracts reflecting regressions of the distal Ecca shoreline in relation to fluvial-deltaic progradation. With regard to the postulated basin partitioning by flexural tectonics into proximal foredeep, central forebulge, and distal backbulge areas (Catuneanu et al., 1998), the regressive character of the coals seems reasonable. However, compilation of new palynological and sedimentological data presented here, and data available from previous studies on Karoo coals, and comparison with similar settings in South America (Holz, 1999), leads to a different interpretation of the basin architecture and development of accommodation space. From the palynofacies patterns detected in the sections studied from different basin areas, a basin architecture from NE to SW with terrestrial lacustrine, fluvio-deltaic, and shallow to deep marine environments is inferred (Figs. 7, 8). Based on palynostratigraphy, marine black shales of the Prince Albert and Whitehill formations are interpreted as stratigraphic equivalents of the terrestrial coal deposits of the Vryheid Formation (Ruckwied et al., 2014). Facies changes within the Whitehill Formation described by Chukwuma and Bordy (2016) indicate also a deepening from the northern towards the southern parts of the basin. The model of a transtensional foreland system created by subsidence and tilting in a strike-slip regime (Tankard et al., 2009) might thus better account for the observed marine pulses and different depositional environments related to the NE-SW deepening basin architecture than partitioning of

the basin by flexural tectonics as envisioned in the retro-arc foreland basin model by Catuneanu et al. (1998). As discussed in Tankard et al. (2009), the basin evolution is strongly related to the Archean and Proterozoic basement blocks underlying the Karoo. The development of an early/mid Permian southward-deepening ramp syncline related to lithospheric subsidence facilitated by crustal-scale faults, led to stratigraphic northeastwards thinning of the Prince Albert and Whitehill formations above subsiding Namaqua basement onto the elevated Kaapvaal craton, and merging with the coal-bearing Vryheid Formation. Deeper facies above the southern Namaqua and eastern Natal basement blocks and stratigraphic thinning and deposition in marginal and non-marine settings on Kaapvaal basement in the north occurs during late Cisuralian (early/mid Ecca) times, while Guadalupian/Lopingian (late Ecca/Beaufort) times are characterized by pronounced tectonic unloading and uplift in the southern Karoo and subsidence in the northeast. Indeed, palynofacies data so far available for different parts of the basin point to a much more complex basin architecture with partly – regionally and temporally – restricted and stratified areas (Fig. 8). Thus, a transtensional system with spatiotemporal development of areas of different subsidence rates and accommodation space probably accounts best for the detected facies patterns.

As described from the Paraná Basin (Holz et al., 2002), the Karoo coals also appear to have developed during transgressive phases with maximum flooding occurring above the distinct seams. The most prominent marine signature above the No. 5 coal seam might reflect the superposition of maximum flooding zones of 3rd and 2nd order sequences (Roadian (“upper Ecca”) 3rd order Sequence/“Ecca-Beaufort” 2nd order Sequence, corresponding to the “Gondwana I” Sequence of the Paraná Basin; see Milani et al., 1994, 1998; Iannuzzi et al., 2010), and the less pronounced signals above the seams No. 2, 3 and 4 might represent 3rd order signatures (Artinskian and Kungurian (“lower-middle Ecca”) sequences). As the marine event above the No. 5 seam is correlatable with a major basinal marine pulse within the Whitehill Formation, representing “transgressive” black shales (Wignall, 1994), it serves as a cross-basin correlation marker horizon. In a global context, the here detected basin-wide marine signature might record the early Guadalupian (Roadian) initial transgression (Henderson et al., 2012). Interestingly, the Roadian transgression seems to be related to a global CO₂ greenhouse crisis (Retallack, 2011, 2013), marking a phase of drastic climate change. With regard to the recent demand for establishing global marine–nonmarine correlation schemes for the Permian as outlined by Shen et al. (2013) and Schneider et al. (2014), the “Whitehill event” is thus a suitable candidate for improvement of the Karoo stratigraphy.

In contrast to the continuous marine depositional environment for the Prince Albert, Whitehill and basal Collingham formations and major flooding phases recorded in contemporaneous coal deposits favoured here, Schulz et al. (2016) proposed a basin model that includes stratified water bodies comprising anoxic bottom waters overlain by less dense sub-saline waters with high bioproductivity. The authors argue that this analogue to the present-day Baltic Sea describes best the preservation of organic matter with regard to geochemical and mineralogical signals indicating fresh water influence (e.g., Herbert and Compton, 2007). Undoubtedly, there must have been freshwater introduced into the basin associated with the fluvio-deltaic coal-bearing facies of the north-eastern part of the basin. Whether this was sufficient to produce a marked salinity stratification of the whole basin for all or some of the Roadian (Whitehill) time is unclear, but evidently it was insufficient to prevent the observed acritarch signal in the southern part of the basin. If the surface salinity was depressed, any marine influence would be most marked in the bottom water and weakest in the surface waters. A sufficiently freshened surface water would inhibit marine phytoplankton (especially diversity) while sub-halocline faunas would probably be inhibited by dysoxia-anoxia even if not the salinity. On the other hand, following the Baltic model, a marine basin where enhanced meltwater runoff occurs during deglaciation produces a strong salinity stratification. Consequently, a change from the deposition of the Prince Albert to the Whitehill shales would be expected with the marine signal in proximal areas representing times of reduced runoff. This in turn would argue for deglaciation meltwater episodes rather than steady deglaciation rates. However, the meltwater peak after the Dwyka glaciation would be expected much earlier during Artinskian-Kungurian (Prince Albert) times. Considering the Weichselian deglaciation model proposed by Haldorsen et al. (2001) for the early Permian Karoo Basin, deglaciation was completed within thousands rather than millions of years and would have hardly affected the depositional environments of the Prince Albert and Whitehill formations. Sulphur values of Whitehill shales (2-8 wt.%; Geel et al., 2013; Costin and Götz, 2017) are similar to those reported from the non-lacustrine intervals of deep anoxic basins of the Baltic Sea (e.g., Sternbeck and Sohlenius, 1997; Böttcher and Lepland, 2000), indicating marine bottom water inflows that supply sufficient sulphate for sulphate reduction in the deep-water sediments and thus leading to elevated pyrite and sulphur content. It is the saline bottom water inflows that cause the current strong permanent stratification of the Baltic deeps, so the addition of marine influence, rather than just deglaciation, also plays a part in the Baltic model.

The transgression model postulates a marine basin with relatively localised freshwater input only. The transgressive pulse resulted in the change to marine black shales distally and correlative supra-coal acritarch horizons proximally. Such a correlation would apparently preclude a high runoff salinity stratification mechanism for the Whitehill Formation, although the surface salinity was not

necessarily fully marine even during the transgressive maximum. Still, the marine basin became anoxic in the south at the marine maximum, which might have been partly a function of depth. Then again, if both shallow surface waters (in the north-eastern part of the basin) and deep water (in the southern part of the basin) were both marine, before and after the marine peak, increased runoff would have been responsible for the stratification that produces the black shale basin. Hence, the coincidence of the final deglaciation episode with a major transgressive pulse during the Roadian greenhouse crisis of significant warming (Retallack, 2013) is interpreted to have controlled black shale deposition in the deeper basin causing the Whitehill event.

Additionally, trace fossils also indicate marine environments for the Ecca shales with a depauperate *Cruziana* and *Glossifungites* ichnofacies described from the western and southern Karoo Basin (Buatois et al., 2010). Thus, the transgression model presented herein, with its distinct basin-wide flooding phases seems to be more plausible than a water stratification model due to melt water. Still, a lot of questions remain including cyclic climatic variations in runoff, variations in salinity, and frequency of flooding events.

Ultimately, a high-resolution palynofacies analysis of the Karoo shales can in the future contribute to answer these questions which will further stimulate the discussion whether continuous marine conditions characterize black shale deposition during late Cisuralian/early Guadalupian (Ecca) times or whether melt water influx controlled ocean circulation and black shale deposition. So far, no freshwater algae were detected to support freshwater conditions from a palynological point of view. Also geochemical proxies, in particular Rb/K and V/Cr ratios indicate constant marine conditions during the deposition of the Prince Albert Formation and the development of anoxic bottom water conditions in a deep water environment (Scheffler et al., 2006). The data set presented by Scheffler et al. (2006) furthermore shows that marine conditions and anoxic bottom water persisted during deposition of the Whitehill and until the lower Collingham formations.

7. Conclusions

A major transgression event during the early Guadalupian (Roadian) recorded in black shales and coal deposits of the Karoo Basin is proposed for cross-basin correlation based on palynostratigraphy and palynofacies analysis. Palynofacies furthermore reveals changes in the composition of sedimentary organic matter reflecting a basin architecture related to a transtensional foreland system with spatiotemporal development of areas of different subsidence rates and accommodation space. From the palynological record, continuous marine conditions characterize black shale deposition during the late Cisuralian/early Guadalupian. However, in the future the study of a

proximal-distal transect of wells across the Karoo, allowing for more detailed integrated palynological, geochemical and sedimentological data analysis, is needed to unravel the complex postglacial basin and climate history of the Main Karoo Basin.

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Figure Captions

Fig. 1. Karoo Basin and location of studied boreholes (KZF-1, KWV-1, DP 1/78) and outcrops (Ecca Pass, Witbank and Highveld coalfields) of Permian black shales and coal deposits (map modified from Catuneanu et al., 1998). GPS coordinates of studied boreholes and outcrops: Borehole ALBN11 (26°08'39.41"S, E 29°18'15.85"E), borehole BHS14 (26°04'05.00"S, 29°00'43.00"E), borehole KZF-1 (32°50'30.43"S, 19°44'33.02"E), borehole KWV-1 (32°14'43.10"S, 28°35'08.10"E), borehole DP 1/78 (29°23'60.00"S, 24°26'24.00"E), Ecca Pass (33°12'58.60"S, 26°37'38.30"E). Lithostratigraphic units of the Karoo Supergroup (Dwyka, Ecca, Beaufort, Stormberg, and Drakensberg groups, Prince Albert and Whitehill formations) according to Johnson et al. (1997, 2006). Abbreviations used: Guad. = Guadalupian, Lop. = Lopingian (Shen et al., 2013).

Fig. 2. Glauconitic sandstone, a marker horizon above the No. 5 seam in the Witbank and Highveld coalfields, indicating a major transgressive event across the Karoo Basin. Vanggatfontein Exploration Project, borehole VG15-05A. Photo by courtesy of J.P. Hancox with permission of Keaton Energy Holdings.

Fig. 3. Palynofacies of the No. 5 coal seam, Witbank Coalfield (boreholes BHS14, ALBN11). All categories sum to 100% (scale 20%). Percentages refer to total counts of 500 particles per slide. Depositional environments are distinguished by changes in the composition of phytoclast and palynomorph assemblages. Deltaic-marine conditions in the uppermost part of the seam are inferred from marine phytoplankton occurrence. Abbreviations used: AOM – amorphous organic matter, DOP – degraded organic particles.

Fig. 4. Palynofacies of the Prince Albert and Whitehill formations (a) and Collingham and Tierberg formations (b) illustrated in the AOM-Phytoclast-Palynomorph plot (Tyson, 1989, 1993, 1995). Data of borehole DP 1/78 from Ruckwied et al. (2014), Ecca Pass data from Götz (2015). (a) Prince Albert Formation data plotted as triangles and rectangles, Whitehill Formation data plotted as circles and diamond symbol; (b) Collingham Formation data plotted as diamond symbol, Tierberg Formation data as cross symbol. Facies field II represents marginal, dysoxic-anoxic depositional environments, facies field III proximal shelf, facies field IV shelf to basin transition with dysoxic-suboxic (IVa), and suboxic-anoxic (IVb) conditions, respectively. Facies field VII represents distal suboxic-anoxic basinal settings. Insert shows general proximal-distal and oxic-anoxic trends inferred from palynofacies data. A clear N-S deepening trend of the basin is documented during the deposition of the Prince Albert

and Whitehill formations, the Prince Albert shale data indicating slightly shallower depositional conditions (fields II and IVa) in comparison to the Whitehill shale data (fields II, IVa/b, and VII). Collingham shale data (b) from the southern basin parts reveal a prominent shallowing upward trend with data plotting from field IVb to field IVa and field III upsection. Tierberg shale data from the northern basin plot in field III, indicating a proximal shelf setting.

Fig. 5. Marine phytoplankton peaks mark a basin-wide transgression during the deposition of the Whitehill shales with acritarch occurrence above coal seam No. 5 in the Witbank Coalfield. This event (“Whitehill event”) is used for marine-nonmarine correlation and is interpreted to reflect the early Guadalupian (Roadian) initial transgression (Henderson et al., 2012) in the Karoo Basin. The percentages of marine phytoplankton are of the total sedimentary organic matter counts.

Fig. 6. Cross-basin correlation of marine black shales and fluvio-deltaic coal deposits based on palynology. Maximum flooding surfaces highlighted by dashed lines on top of coal seams. A major flooding event is detected within the Whitehill Formation (“Whitehill event”). Radiometric ages for the base of the Prince Albert Formation (marked by star, 288 ± 3 Ma) from Bangert et al. (1999), and base Collingham Formation (marked by star, 268 ± 3.2 Ma) from McKay et al. (2015), corresponding to a base Collingham age of 270 ± 1 Ma published by Stollhofen et al. (2000) from Namibia. Permian timescale from Shen et al. (2013).

Fig. 7. Facies distribution and boundaries of marine black shales and fluvio-deltaic coals of the Karoo Basin based on data compiled from Hart (1964, 1971), Van Vuuren (1983), Visser (1992, 1993), Johnson et al. (2006), Ruckwied et al. (2014), Chukwuma and Bordy (2016), and this study.

Fig. 8. Conceptual facies model of the Karoo Basin within the Panthalassan margin of Gondwana based on palynofacies.

Tab. 1. Alphabetical list of identified palynomorph taxa, arranged under probable botanical affinities according to Balme (1995), Lindström (1995, 2005), and Lindström and McLoughlin (2007). Note: *commonly reported from the Main Karoo Basin as *Alisporites ovatus* (Balme & Hennelly) Jansonius 1962.

Botanical affinity	Taxa
Arthrophyta	<i>Calamospora</i> spp.
Lycophyta	<i>Lundbladispota braziliensis</i> (Pant & Srivastava) Marques-Toigo & Pons emend. Marques-Toigo & Picarelli 1984
Pterophyta	<i>Apiculatisporis levis</i> (Balme & Hennelly) Segroves 1970 <i>Apiculatisporis</i> spp. <i>Cyclogranisporites</i> sp. <i>Deltoidospora</i> spp. <i>Granulatisporites</i> sp. <i>Horriditriletes ramosus</i> (Balme & Hennelly) Bharadwaj & Salujha 1964 <i>Horriditriletes</i> spp. <i>Laevigatosporites</i> spp. <i>Leiotriletes</i> spp. <i>Lophotriletes</i> spp. <i>Microbaculispora</i> spp. <i>Punctatisporites</i> spp. <i>Verrucosisporites andersonii</i> (Anderson) Backhouse 1988 <i>Verrucosisporites</i> spp.
Gymnosperms	
Monocolpate grains	<i>Cycadopites</i> spp.
Praecolpate grains	<i>Marsupipollenites striatus</i> (Balme & Hennelly) Foster 1975 <i>Marsupipollenites triradiatus</i> Balme & Hennelly 1956
Monosaccate grains	<i>Cannanoropollis</i> spp. (= <i>Virkkipollenites</i>) <i>Florinites</i> spp. <i>Plicatipollenites</i> sp. <i>Potonieisporites</i> spp.
Non-taeniate bisaccate grains	<i>Alisporites splendens</i> (Leschik) Foster 1979 <i>Alisporites</i> spp. <i>Limitisporites</i> sp. <i>Platysaccus papilionis</i> Potonié & Klaus 1954 <i>Platysaccus</i> sp. <i>Scheuringipollenites ovatus</i> (Balme and Hennelly) Foster 1975* <i>Sulcatisporites</i> spp.
Taeniate bisaccate grains	<i>Guttulapollenites hannonicus</i> Goubin 1965 <i>Lueckisporites virkkiae</i> Potonié & Klaus 1954

	<i>Lunatisporites</i> spp. <i>Protohaploxypinus limpidus</i> (Balme & Hennelly) Balme & Playford 1967 <i>Protohaploxypinus</i> spp. <i>Striatoabieites multistriatus</i> (Balme and Hennelly) Hart 1964 <i>Striatoabieites</i> spp. <i>Striatopodocarpites cancellatus</i> (Balme & Hennelly) Hart 1963 <i>Striatopodocarpites fusus</i> (Balme & Hennelly) Potonié 1958
Costate grains	<i>Vittatina costabilis</i> Wilson 1962 <i>Vittatina fasciolata</i> (Balme & Hennelly) Bharadwaj 1962 <i>Vittatina subsaccata</i> Samoilovich 1953 <i>Vittatina</i> spp. <i>Weylandites lucifer</i> (Bharadwaj & Salujha) Foster 1975
Freshwater algae	<i>Botryococcus</i> sp. <i>Tetraporina</i> sp.
Marine phytoplankton	
Acritarchs	<i>Micrhystridium</i> spp.
Prasinophytes	<i>Cymatiosphaera gondwanensis</i> (Tiwari) Backhouse 1991 <i>Cymatiosphaera</i> sp. <i>Tasmanites</i> sp.
Leiospheres	<i>Leiosphaeridia</i> spp.

Tab. 2. Present-day TOC content of Permian black shales of the Prince Albert, Whitehill and Collingham formations (KZF-1 borehole, south-western Karoo Basin).

Sample depth (mbs)	Formation	TOC (wt.%)
340.39	Collingham	1.7
371.11	Collingham	1.0
376.82	Collingham	0.9
386.28	Collingham	1.3
398.55	Collingham	2.2
410.14	Collingham	1.7
421.77	Whitehill	5.4
457.30	Whitehill	5.7
461.12	Whitehill	6.1
514.30	Prince Albert	0.3
539.92	Prince Albert	0.3
561.96	Prince Albert	0.8
590.34	Prince Albert	1.0
612.90	Prince Albert	1.8

Figure 1

Figure 2

Figure 3

Figure 4

Figure 6

Figure 7

Figure 8