Review of Palaeobotany and Palynology 269 (2019) 78–93

Contents lists available at ScienceDirect

Review of Palaeobotany and Palynology

journal homepage: www.elsevier.com/locate/revpalbo

Palynology of the Muarádzi sub-basin, Moatize-Minjova Coal Basin, Karoo Supergroup, Mozambique

Zélia Pereira [a,*], Paulo Fernandes [b], Gilda Lopes [c,1], João Marques [d], Maria Vaz [e], Marta Costa [f], João Correia [f], Lígia Castro [f], Francesca Galasso [b,g,2]

[a] *Laboratório Nacional de Energia e Geologia (LNEG), Rua da Amieira, Apartado 1089, 4466-901 S. Mamede Infesta, Portugal*
[b] *Centro de Investigação Marinha e Ambiental (CIMA), Universidade do Algarve, Campus de Gambelas, 8005-139 Faro, Portugal*
[c] *Department of Earth Science, University of Bergen, P.O. Box 7803, N-5020 Bergen, Norway*
[d] *Gondwana Empreendimentos e Consultorias, Limitada, Rua B, no. 233, Bairro da COOP, Caixa Postal 832, Maputo, Mozambique*
[e] *Departamento de Geociências, Ambiente e Ordenamento do Território, Faculdade de Ciências da Universidade do Porto, Rua do Campo Alegre, 687, 4169-007 Porto, Portugal*
[f] *Departamento de Ciências de Terra, GeoBioTec, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Quinta da Torre, 2829-516 Caparica, Portugal*
[g] *Department of Physics and Geology, University of Perugia, Via Pascoli, 06123 Perugia, Italy*

ARTICLE INFO

Article history:
Received 9 November 2018
Received in revised form 30 May 2019
Accepted 16 June 2019
Available online 21 June 2019

Keywords:
Palynostratigraphy
Lopingian
Karoo
Pollen and spores
Palynomorphs
Gondwana supercontinent

ABSTRACT

The detailed palynostratigraphic study of four boreholes in the Muarádzi sub-basin, Moatize-Minjova Coal Basin (MMCB) southeast of Moatize, allowed the assignment of relative ages to the stratigraphic units. Three assemblages were studied in detail and are assigned to the Lopingian. Assemblage L1 is characterized by the rich occurrence of *Guttulapollenites* and *Weylandites*. Assemblage L2 is defined on the first occurrence (FO) of abundant *Thymospora pseudothiessenii* together with *Indotriradites niger*, *Kraeuselisporites* spp., *Polypodiisporites mutabilis* and *Polypodiidites* sp. Assemblage L3 is characterized by the first occurrence of *Osmundacidites senectus* together with the taxa described from the previous assemblages. Palynological correlation with other Karoo basins is discussed and three distinct palynostratigraphic events emerge based on the FO and abundance of key taxa (as for instance, FO of *G. hannonicus*, *T. pseudothiensenii* and *O. senectus*). A close palynological correlation between Mozambique (Moatize-Minjova Basin), Tanzania (Selous Basin), Zambia (mid-Zambezi Basin) and Madagascar palynoevents is established. This major region can be assigned to the northern Karoo-aged basins of south-central Africa and the palynoevents can be correlated with Lopingian assemblages of Pakistan, India and some basins of East Antarctica. The southern Karoo-aged basins of south-central Africa, including South Africa and Zimbabwe, show different Lopingian palynoevents and a direct correlation is demanding. These palynological data may open new perspectives for coal exploration in the MMCB as the coal deposits show a wider stratigraphic distribution, reaching until the latest Lopingian.

1. Introduction

Sedimentary successions of the Karoo Supergroup, ranging in age from the Permian to the Lower Jurassic, are well represented in various basins situated along the Zambezi River valley in the Tete Province, central-west Mozambique (Fig. 1). These sequences were unconformably deposited over crystalline Precambrian basement rocks. Currently, the presence of widespread coal seams located in the lower part of the Karoo stratigraphic sequences, represents an important natural resource and asset for Mozambique's economy (Cairncross, 2001; Lächelt, 2004; Vasconcelos, 2013; Hancox, 2016). Likewise, coal and coal-bearing rock strata also constitute valuable sedimentary archives to better understand the paleoclimatic and paleoecological changes that affected terrestrial ecosystems in this region during the late Paleozoic (Retallack, 1995, 2013; Gastaldo et al., 1996; Wignall, 2007; Retallack, 2013). Major climatic changes that followed the late Carboniferous–early Permian glaciation were recorded in these sequences, and the transition from icehouse to greenhouse conditions are registered in the palynological record (Falcon et al., 1984; Götz and Ruckwied, 2014; Ruckwied et al., 2014; Wheeler and Götz, 2016; Götz et al., 2017). Following upwards, the Karoo stratigraphic sequences in this region also holds the record of the end-Permian mass extinction, as well as the global warming trend of the Triassic Period, attested by the rapid change from coal swamps to arid environments which are characterized in the stratigraphy by the deposition of red-beds (Retallack et al., 1996; Lindström and McLoughlin, 2007; Pereira et al., 2016). Palynology can provide the

---

[*] Corresponding author.
E-mail address: zelia.pereira@lneg.pt (Z. Pereira).

[1] Presently at Centro de Investigação Marinha e Ambiental (CIMA), Universidade do Algarve, Campus de Gambelas, 8005-139 Faro, Portugal.

[2] Currently at University of Zurich.

https://doi.org/10.1016/j.revpalbo.2019.06.006

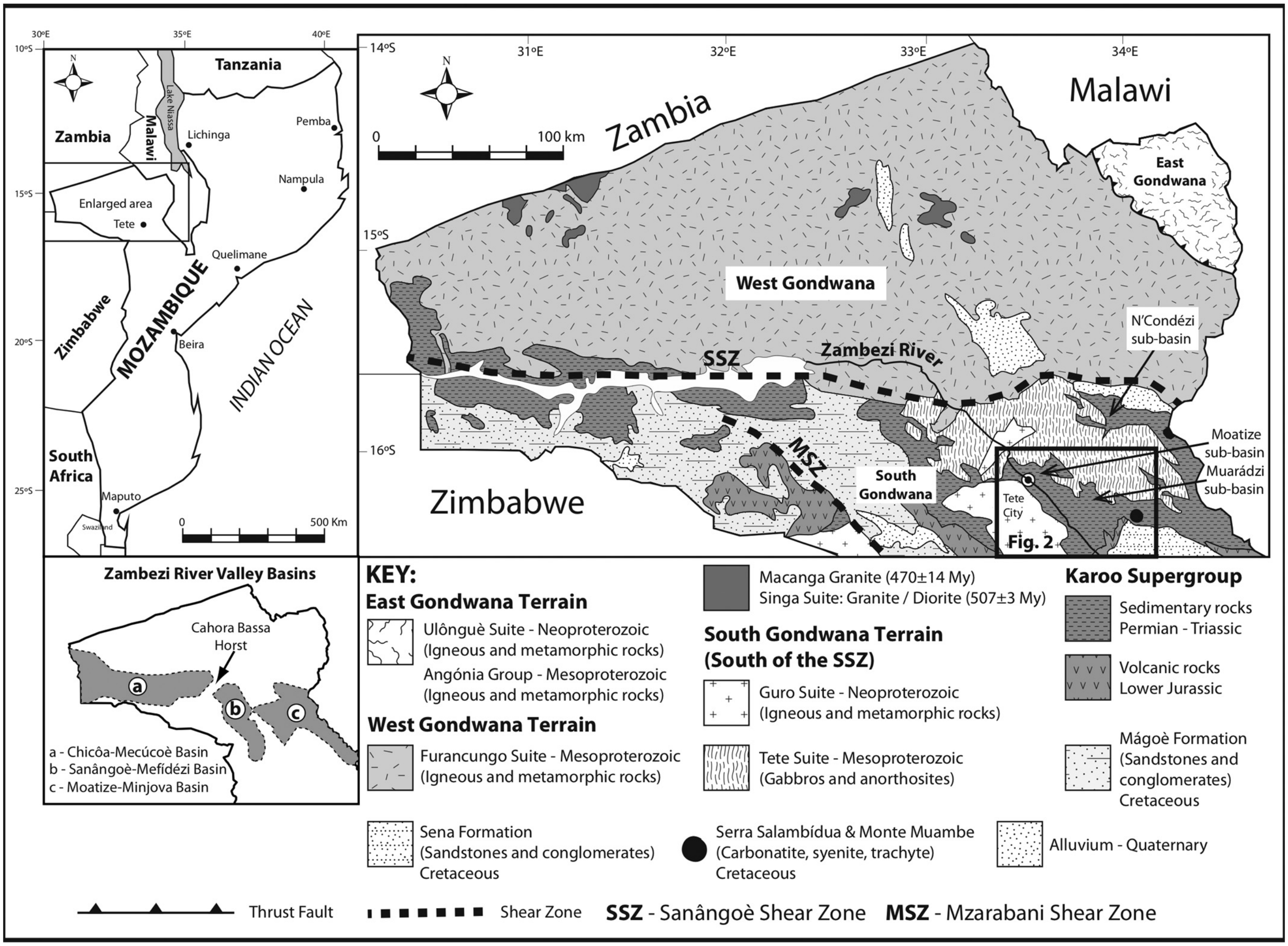

Fig. 1. Simplified geology of the Province of Tete, Mozambique, with the location of the Karoo rocks and basins. Adapted from Carta Geológica República de Moçambique, Escala 1/1 000 000 (2008) and Galasso et al. (2019)

most needed chronological framework to the continental stratigraphic successions studied herein, as well as a better understanding of the tectono-stratigraphy and geological history of the area in the late Paleozoic/early Mesozoic (Lopes et al., 2014; Pereira et al., 2016; Barbolini et al., 2016a, 2016c, 2018; Götz et al., 2018).

In this work, a detailed account of the palynological content of four cores drilled for coal exploration is presented. The cores were drilled in the Muarádzi sub-basin of the main Moatize-Minjova Coal Basin (MMCB), close to the northern contact with the basement rocks (Figs. 2 and 3). This study allowed the assignment of relative ages to the different stratigraphic units of the MMCB based on correlation with other Karoo basins, and helped to constrain the paleogeography of this basin within the supercontinent Gondwana.

2. Geological setting of the Moatize-Minjova Coal Basin and the Muarádzi sub-basin

The boreholes studied in this work were drilled in the Muarádzi sub-basin of the MMCB. In Mozambique, the Karoo sedimentary outcrops extend along the Zambezi River valley, in the Tete Province (Fig. 1). Differences in the stratigraphy, tectonics and geographic position of these outcrops, allow their division into three different coal-bearing basins which are, from west to east, the Chicôa-Mecúcoè, the Sanângoè-Mefidézi, and the Moatize-Minjova basins, respectively (Lächelt, 2004; GTK Consortium, 2006) (Fig. 1). These basins are part of a network of rift related basins that formed north of the main Karoo Basin, during Permian to Lower Jurassic. The brittle reactivation of high strain zones (e.g. the Sanângoé Shear Zone) of the Zambezi Belt during the Pan-African Orogeny (620–530 Ma), promoted the development of these basins (Carvalho, 1977; Afonso, 1975; Afonso, 1984; Pinna et al., 1993; Jamal, 2005; GTK Consortium, 2006; Norconsult Consortium, 2007; Grantham et al., 2008; Viola et al., 2008) (Fig. 1). The tectonic fault-related reactivation started in the early Permian by the initiation of strike-slip faulting under a transtensional stress regime that formed extensional basins with graben to half graben geometry (Carvalho, 1977; Hankel, 1994; Lächelt, 2004; Catuneanu et al., 2005; GTK Consortium, 2006).

The MMCB has a predominantly NW–SE trend, extending from the region of Tete city to the border with Malawi (Fig. 1). The basin is further divided into five sub-basins or areas based on different lithological and geographical characteristics: Moatize-Benga (abbreviated hereafter by Moatize sub-basin), Muarádzi, Minjova, N'Condédzi and Mutarara sub-basins (Fig. 1). In the Moatize and Muarádzi sub-basins (Fig. 2) siliciclastic successions are fault-bounded with basement rocks to the NE and the SW of the basin. The stratigraphic succession of the latter sub-basin unconformably overlies gabbro and anorthosite rocks of Mesoproterozoic age belonging to the Tete Suite in the NE, whereas the Mesoproterozoic Chacocoma and Mungári granites and Neoproterozoic metamorphic rocks of the Guro Suite underlye the siliciclastic succession to the SW (GTK Consortium, 2006) (Fig. 2).

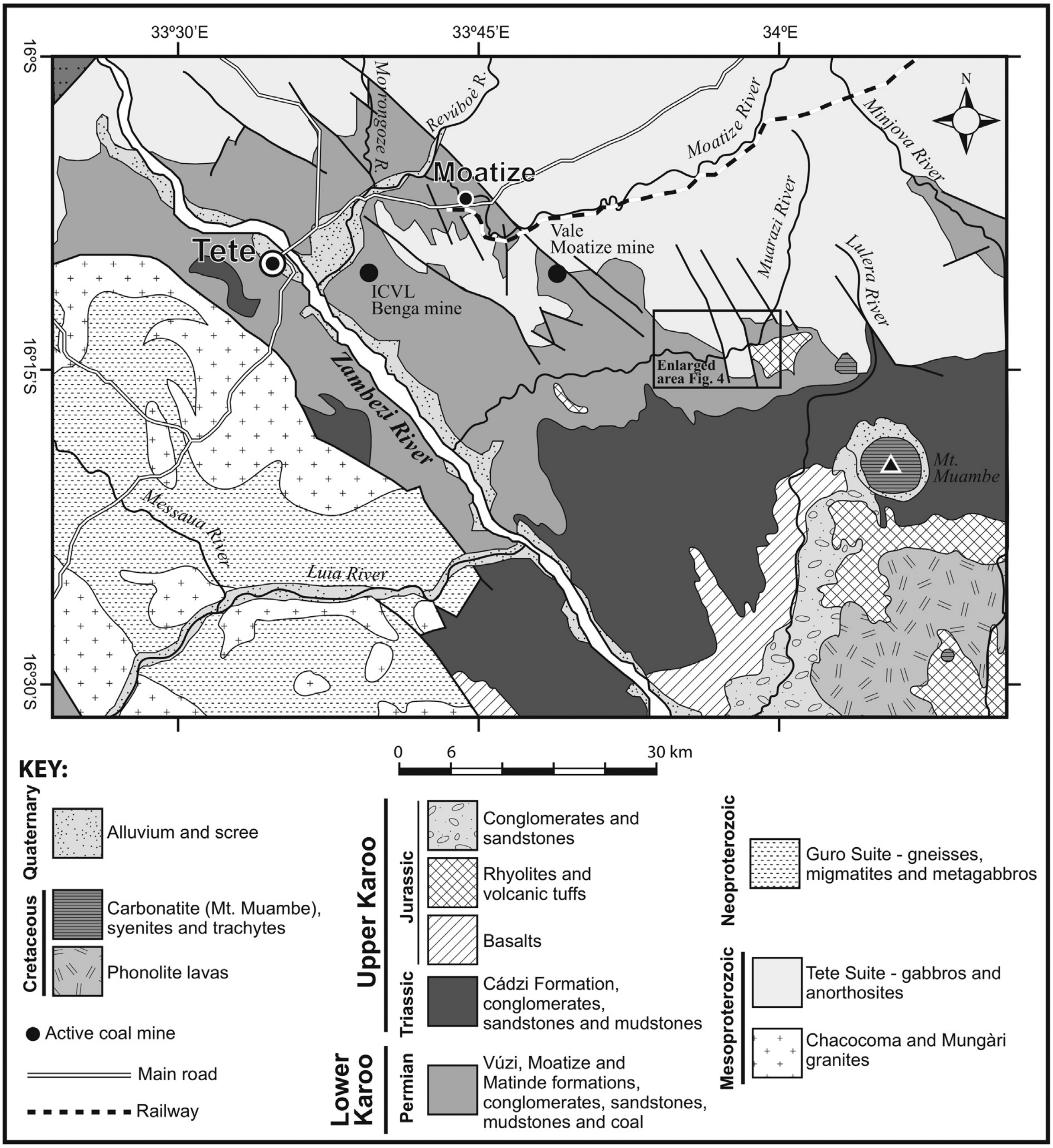

Fig. 2. Geology of the Moatize – Minjova Coal basin in the region of Tete, with the location of the two actives coal mines (Vale Moatize and ICVL Benga) and the location of the studied area. Adapted from Geological Map of Mozambique, sheet no. 1633, Tete, Geological Series 1/250,000, Direcção Nacional de Geologia, Maputo (2006).

The geology of the Moatize sub-basin is well known due to its importance in coal exploitation, and the type-sections defined in this sub-basin are historically labeled as the type coal sections of the Karoo Basins in Mozambique. Therefore, the geology of the Moatize sub-basin will be summarized here and the possible correlations with the Muarádzi sub-basin will be highlighted. The Karoo Supergroup in the Moatize sub-basin, following upwards, comprises four stratigraphic units: the Vúzi, Moatize, Matinde and Cádzi formations (GTK, 2006; Paulino et al., 2010) (Fig. 3). The Vúzi Formation rests unconformably on igneous and metamorphic Precambrian basement rocks, and consists of unsorted clast to matrix-supported conglomerates interbedded with sandstones and thin siltstones–mudstones beds deposited in glacial to periglacial environments. The thickness of this formation is variable throughout the Moatize sub-basin. Based on previous lithostratigraphic studies (GTK Consortium, 2006; Achimo et al., 2014), the Vúzi Formation was correlated to the upper part of the Dwyka Group in the main Karoo Basin of South Africa, and a late Pennsylvanian to early Permian age was attributed to this formation (GTK Consortium, 2006; Paulino et al., 2010; Achimo et al., 2014). Recently, Pereira et al. (2014) and Lopes et al. (2014) disputed this assumed age for the Vúzi Formation, and a Kungurian–Roadian age was recognized in the top of this formation based on palynology. This age was obtained from the study of two coal exploration boreholes. These boreholes were located in the Muarádzi sub-basin, and suggested a younger age for the final phase of the late Paleozoic Gondwana glacial deposition in Mozambique or alternatively, the conglomerates of these two boreholes are not glacial deposits, but sediments that accumulated in coarse alluvium fans related to fault activity, that occurred during the episodes of the basin formation (Carvalho, 1977).

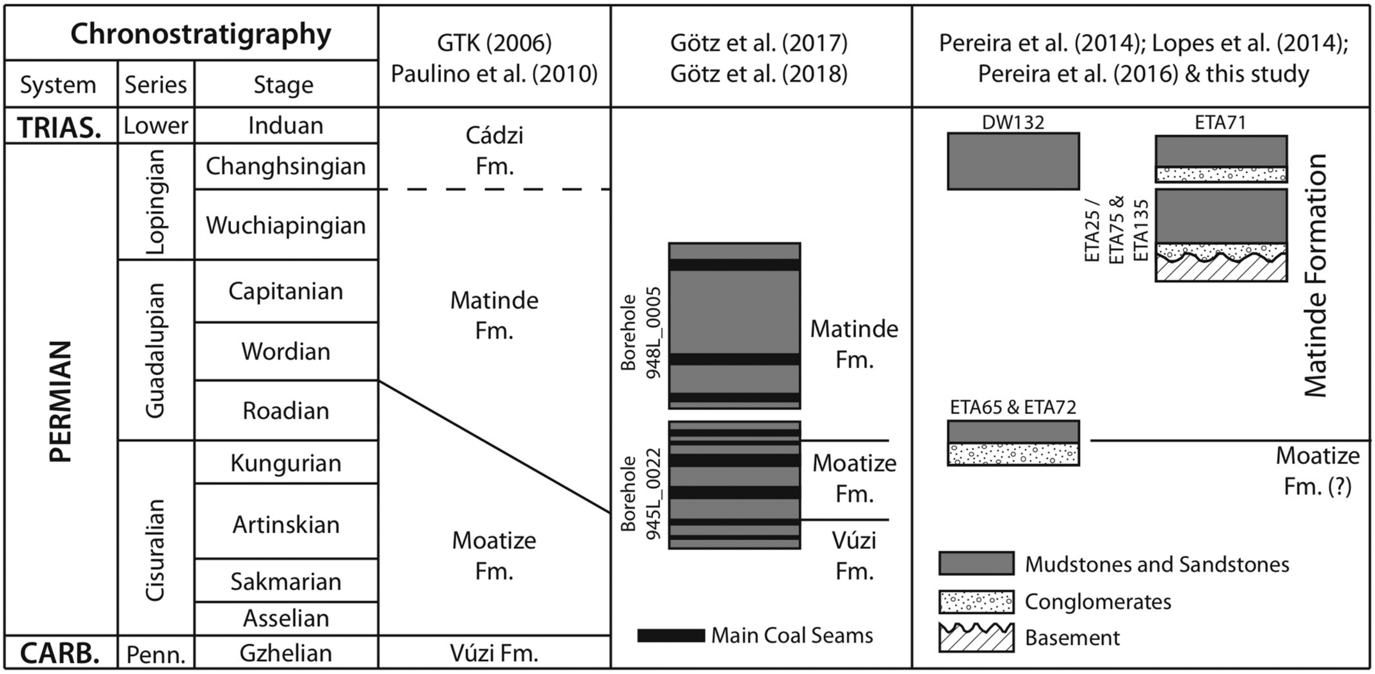

Fig. 3. Stratigraphic chart of the Moatize – Minjova Coal Basin (GTK, 2006 & Paulino et al., 2010), its comparison and re-interpretation according to recent palynological studies (Pereira et al., 2014; Lopes et al., 2014; Pereira et al., 2016; Götz et al., 2017; Götz et al., 2018) including the results of this study.

Following upwards, the Moatize Formation was conformably deposited above the Vúzi Formation. All the important and economic coal seams are part of the Moatize Formation, which consists of six coal zones that are intercalated with sandstone dominated sequences. The coal zones or "*Carbonaceous Complexes*" are in ascending stratigraphic order: Sousa Pinto, Chipanga, Bananeiras, Intermédia, Grande Falésia and André. These zones consist of alternating coal beds, carbonaceous mudstones, siltstones and fine-grained sandstones. All these lithologies have variable thicknesses throughout the basin; for instance, the coal seams can attain thicknesses ranging from over 2 m to few centimeters (barcode coal). The sandstone-dominated sequences occur intercalated with the coal zones and consist of coarse to medium grained sandstones showing erosive bases, graded-bedding and cross-stratification at different scales. The Moatize Formation beds are interpreted as being deposited in fluvial, deltaic and lacustrine environments (GTK, 2006; Bicca et al., 2017; Götz et al., 2018). Paleobotanic and palynomorph studies suggest a Cisuralian to Guadalupian age for this formation, which is correlated with the Middle to Upper Ecca Group of the Main Karoo Basin of South Africa (Teixeira, 1943; 1946; 1947; 1951; 1952; Daber, 1984; Mugabe, 1999). The Matinde Formation conformably overlays the Moatize Formation and consists of a thick fluvial deposited succession, ca. 2 km thick, of alternating conglomerates, sandstones, siltstones and mudstones, with some coal beds mostly concentrated near the base of its succession (GTK, 2006). Based only on the stratigraphic position, a Guadalupian to Lopingian age is assumed for the Matinde Formation (GTK, 2006; Paulino et al., 2010). This unit is correlated with the Middle - Upper Ecca Group of the main Karoo Basin (GTK, 2006; Paulino et al., 2010).

In the Muarádzi sub-basin, palynological studies revealed the presence of thick Lopingian (ca. 500 m) successions, and the Permian–Triassic transition is thought to be found in two of the studied boreholes based on stratigraphic and palynological data (Pereira et al., 2016) (Figs. 3 and 4). This new palynological evidence indicates that the upper part of the Matinde Formation seems to be Lopingian in age. The coal deposits were accumulated until the latest Permian, extending the age of the coal deposition in Mozambique. This inference shows that the coal deposits and coal depositional environments are not limited to the Moatize Formation. Furthermore, the lower three stratigraphic formations of the Karoo Supergroup in the Moatize and Muarádzi sub-basins encompass all the Permian interval (Lopes et al., 2014; Pereira et al., 2014, 2016).

The stratigraphic succession of the Karoo Supergroup in the Moatize sub-basin ends with the deposition of the Cádzi Formation, which consists mainly of red beds (conglomerates, sandstones, variegated mudstones with minor marls and limestone beds) (GTK, 2006). The Cádzi Formation lithologies were deposited in fluvial environments, in hot and arid conditions (GTK, 2006). Once more, based solely on stratigraphic relations, a Lopingian to early Triassic age was attributed to this formation, which was correlated with the Beaufort Group of the main Karoo Basin (GTK, 2006; Paulino et al., 2010). According to more recent palynological studies (Galasso et al., 2019) a Lower to Upper Triassic age was attributed to the Cádzi Formation in the N'Condezi sub-basin.

3. Material and methods

Sixty-four core samples were collected for palynostratigraphic studies from four coal exploration boreholes (ETA 25, ETA 71, ETA 75, and ETA 135) drilled in the Muarádzi sub-basin, Moatize-Minjova Coal Basin, southeast of Moatize. Fig. 4 shows the location of the boreholes discussed in this work. In this study, 35 samples proved productive, containing moderately preserved palynomorphs. A minimum of 200 palynomorphs was counted per slide (Tables 1–4), and the following terminology was used to describe the relative abundances: Abundant (>50%); Common (10–50%) and Rare (<10%).

The palynological samples presented in this paper were treated with standard palynological laboratory procedures to extract and concentrate the organic residues. These were oxidized using fuming nitric acid for about 1 min (Wood et al., 1996; Riding and Warny, 2008). All samples, residues, and slides are held in the Collection of the Geological Survey of Portugal, LNEG, S. Mamede de Infesta, Portugal, and the University of the Algarve, Portugal.

4. Borehole description

Two of the four studied coal exploration boreholes (ETA 25 and ETA 135) penetrated the basement rocks at its base, whereas the other two

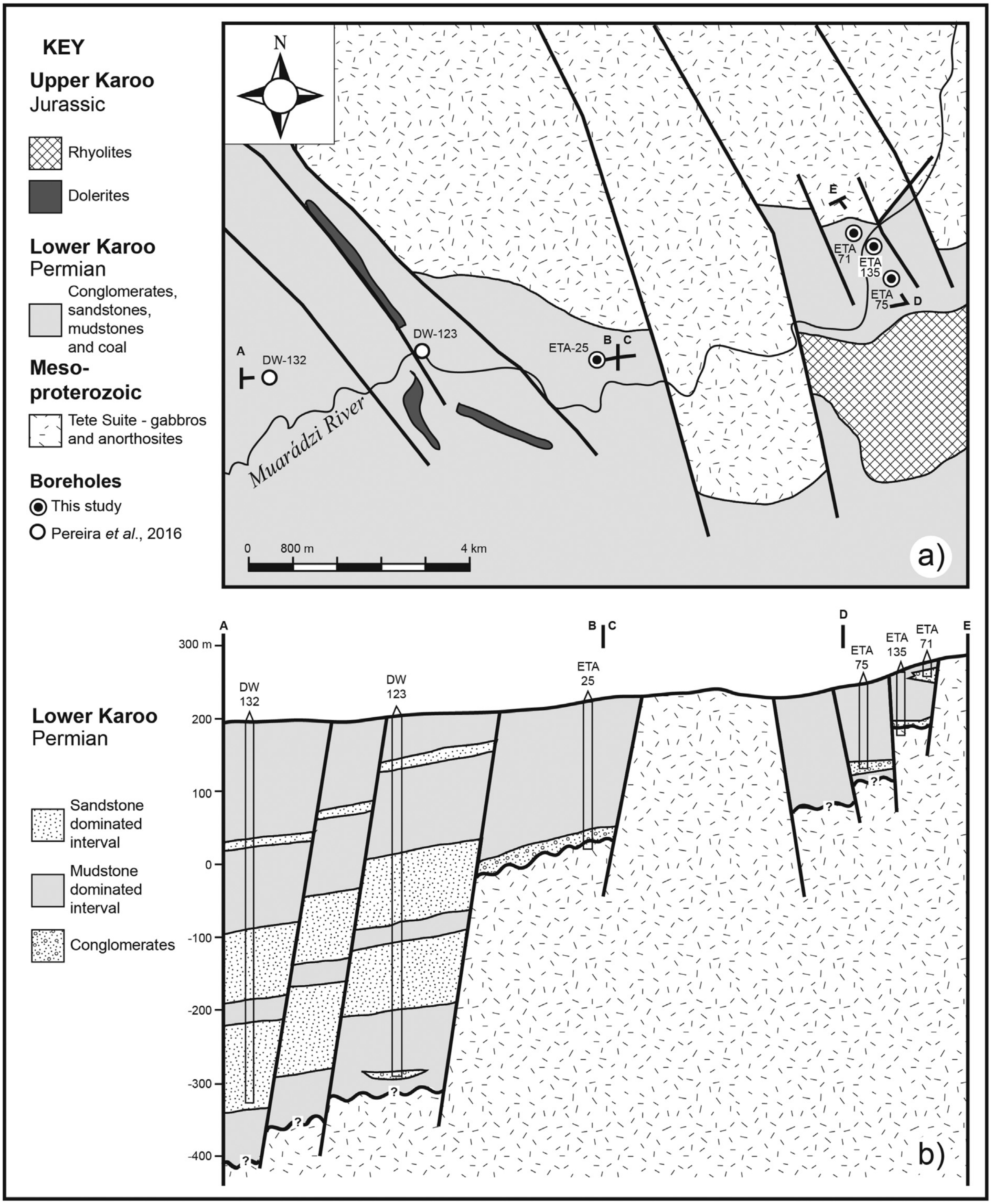

Fig. 4. (a) Detailed geology of the studied region with the location of the boreholes. (b) Interpretative cross-section of the boreholes studied and including boreholes DW123 and DW132 described in Pereira et al. (2016). Adapted from Geological Map of Mozambique, sheet no. 1633, Tete, Geological Series 1/250,000, Direcção Nacional de Geologia, Maputo (2006).

(ETA 71 and 75) were drilled until conglomerate beds of variable thicknesses were encountered (see Fig. 5).

With a total depth of ca. 201 m (Fig. 5), borehole ETA 25 is the deepest and was drilled between the Muarádzi River to the South, and the gabbros–anorthosites of the Tete Suite to the North (Fig. 4). This borehole penetrated, at its base, 5 m of crystalline basement rocks (anorthosites) belonging to the Tete Suite. The basement rocks are unconformably overlain by a 10 m thick fining-upward sequence comprising a matrix-supported conglomerate (diamictites) that passes upwards to centimetric beds of siltstones interbedded with black mudstones. Overlying this sequence there is a 40 m thick mudstone dominated interval interbedded with a 2 m thick coal seam and several centimetric thick coal lenses (barcode coal). The interval between 149 and 115 m, in depth, is characterized by medium to thick sandstone beds interbedded with centimetric thick siltstones and mudstones. This is followed by a 7 m thick mudstone interval, that passes upwards to a dominantly siltstone–mudstone interval (106–76 m depth). From 76 m depth to the top of the borehole, the succession consists of black

Table 1
Borehole ETA 25 palynomorph assemblages, Muarátzi sub-basin, Moatize-Minjova Coal Basin, Mozambique. The numbers represent the group percentages of the respective taxon within the overall palynoflora. A. Abundant (>50%); C. Common (10–50%) and R. Rare (<10%). A = Algae and *incertae sedis*.

			Spores														Pollen																		A	
Borehole ETA 25	**Sample ref.**	Assemblage	*Apicularisporites sp.*	*Calamospora rugosa*	*Calamospora* sp.	*Horriditriletes tereteangulatus*	*Horriditriletes* sp.	*Laevigatosporites colliensis*	*Laevigatosporites vulgaris*	*Laevgatosporites sp.*	*Leiotriletes* sp.	*Polypodiisporites mutabilis*	*Polypodiisporites* sp.	*Punctatisporites* sp.	*Thymospora pseudothiessenii*	*Verrucosisporites* sp.	*Alisporites landianus*	*Alisporites maximus*	*Alisporites ovatus*	*Alisporites plicatus*	*Alisporites* sp.	*Cannanoropollis janakii*	*Corisaccites alutas*	*Cycadopites cymbatus*	*Gnetaceaepollenites sinuosus*	*Guttulapollenites hannonicus*	*Guttulapollenites* sp.	*Platysaccus papilionis*	*Striatopodocarpites cancellatus*	*Striatopodocarpites fusus*	*Striatopodocarpites* sp.	*Striomonosaccites* sp.	*Vittatina* sp.	*Weylandites lucifer*	*Leiospaheridia* sp.	Chlorophycean algae
	MZ 154	L2					R	A	A	A					R						R									R						
	MZ 166		C	C	C	R	R			R	R	C	C		C	A					R			R	R	A	A				C		R	C	R	C
	MZ 160		C	C	C			R	R	R		C	C	C	C	A	C	C	C	C	C	R	R	C	C	A	A	R	C	C	C		C	C		R
	MZ 161	L1						R	R	R						R					R					A	A	R	C	C	C	R	C	C		R
	MZ 162															C			C	C	C			C									A		R	C

Table 2
Borehole ETA 75 palynomorph assemblages, Muarátzi sub-basin, Moatize-Minjova Coal Basin, Mozambique. The numbers represent the group percentages of the respective taxon within the overall palynoflora. A. Abundant (>50%); C. Common (10–50%) and R. Rare (<10%). A = Algae and *incertae sedis*.

			Spores																											Pollen																																															A			
Borehole ETA 75	**Sample nº/taxa**	**Assemblage**	*Apiculatisporis* sp.	*Baculatisporites bharadwaji*	*Baculatisporites* sp.	*Brevitriletes cornutus*	*Brevitriletes* sp.	*Calamospora rugosa*	*Calamospora* sp.	*Columinisporites* sp.	*Cyclogranisporites* sp.	*Fabasporites* sp.	*Horriditriletes curbibaculosus*	*Horriditriletes ramosus*	*Horriditriletes tereteangulatus*	*Horriditriletes* sp.	*Indotriradites niger*	*Kraeuselisporites* sp.	*Laevigatosporites colliensis*	*Laevigatosporites vulgaris*	*Laevigatosporites sp.*	*Leiotriletes sp.*	*Microbaculispora trisina*	*Microbaculispora sp.*	*Polypoodisporites sp.*	*Procoronaspora spinosa*	*Punctatisporites* sp.	*Retusotriletes* sp.	*Thymospora pseudothiessenii*	*Verrucosisporites andersonii*	*Verrucosisporites* sp.	*Alisporites maximus*	*Alisporites plicatus*	*Alisporites landianus*	*Alisporites potoniei*	*Alisporites ovatus*	*Alisporites* sp.	*Cahenniasaccites ovatus*	*Cannanoropolis janakii*	*Cannanoropolis* sp.	*Corisaccites* sp.	*Cycadopites cymbatus*	*Cycadopites* sp.	*Gnetaceaepollenites sinuosus*	*Florinites* sp.	*Guttulapollenites hannonicus*	*Hamiapollenites fusiformes*	*Hamiapollenites insolitus*	*Hamiapollenites* sp.	*Limitisporites* sp.	*Lueckisporites virkkiae*	*Lunatisporites variesectus*	*Lunatisporites* sp.	*Platysaccus papilionis*	*Platysaccus* sp.	*Plicatipollenites gondwanensis*	*Plicatipollenites* sp.	*Protohaploxypinus amplus*	*Protohaploxypinus goraiensis*	*Protohaploxypinus hartii*	*Protohaploxypinus limpidus*	*Protohaploxypinus* sp.	*Marsupipollenites striatus*	*Marsupipollenites triradiatus*	*Striatoabieites multistriatus*	*Striatopodocarpites cancellatus*	*Striatopodocarpites fusus*	*Striatopodocarpites gondwanensis*	*Striatopodocarpites* sp.	*Striomonosaccites ovatus*	*Striomonosaccites* sp.	*Vittatina costabilis*	*Vittatina fasciolata*	*Vittatina foveolata*	*Vittatina scutata*	*Vittatina* sp.	*Weylandites lucifer*	*Weylandites magmus*	*Leiosphaeridia sp.*	*Peltacystia venosa*	*Tetraporina horologia*	*Reduviasporonites chalastus*
	MZ 21	L2																																		C	R				R																												C		R											
	MZ 22		R	R	R				R		R	R				R			R		R	R					R	R	R					R	R		R						R		R								R							R		R				R			R			R		R	R	R	C		C			
	MZ 23		R								C		R		R	R	R					R	R	R	R	R	R		C	R	R	R			R	R	R				R			R						R			R		R							R			R	R	R		R		R	R	R			R	R		R			
	24					R	R							R	C	R			R													R	R	R	R	R	R				R		R	R										R	R			R			R	R				R	R		R	R	R						R		R			
	25		R								R			R		R		R					R	R	C	R		R	R	R	R	R	R			R	R	R	R		R		R	R		C				R	R	R		R	R		R		R		R	R				R	R	R	C		R					R	R	R				
	26	L1																						R								R	R	R	R	R	R		R		R					C					R			R								R	R	R	R				C			R			R		R					
	27		R			R	R								R	R				R	R						R					R			R	R	R					R												R	R			R	R		R	R				R	R		R	R						R	R		R			
	28					C	R		R						R				R	C	C			R			R					R					R		R	R		R	R	R																	R	R											R				R		R	R	R	
	29																			R	R	C					C									C																									C	R			R														C			
	30				R				R		R								R	R	R	R	R	R			C				R											R		R												R					R	R	R						R					R		R	C	R	R			
	33		R		R				R											R	R	R					R	R					R			R	R		C			R		R				R	R							R					R	R	R	R		R	R		R			R			R	R	R		C			
	34		R	R	R			R	R	C		R							R	R	R	R		R			R				R		R				R						R			R	R	R	C				R			R						R	R		R				R		R					R		R	R			R
	35									C					R	C					C															C	R																																	R									R			

Table 3

Borehole ETA 135 palynomorph assemblages Borehole, Muarátzi sub-basin, Moatize-Minjova Coal Basin, Mozambique. The numbers represent the group percentages of the respective taxon within the overall palynoflora. A. Abundant (>50%); C. Common (10–50%) and R. Rare (<10%). A = Algae and *incertae sedis*.

			Spores																	Pollen																										A			
Borehole ETA 135	Sample ref.	Assemblage	*Calamospora rugosa*	*Calamospora* sp.	*Horriditriletes brevis*	*Horriditriletes curvibaculosus*	*Horriditriletes ramuosus*	*Horriditriletes tereteangulatus*	*Horriditriletes uruguaiensis*	*Horriditriletes* sp.	*Laevigatosporites colliensis*	*Laevigatosporites vulgaris*	*Laevigatosporites* sp.	*Microbaculispora tentula*	*Microbaculispora trisina*	*Microbaculispora* sp.	*Polypodiiporites mutabilis*	*Punctatisporites* sp.	*Thymospora pseudothiessenii*	*Alisporites landianus*	*Alisporites potoniei*	*Alisporites ovatus*	*Alisporites plicatus*	*Alisporites* sp.	*Cannanoropollis janakii*	*Corisaccites alutas*	*Cycadopites cymbatus*	*Gnetaceaepollenites sinuosus*	*Guttulapollenites hannonicus*	*Guttulapollenites* sp.	*Limitrisorites* sp.	*Pakhapites* sp.	*Platysaccus papilionis*	*Plicatipollenites gondwanensis*	*Plicatipollenites* sp.	*Protohaploxypinus limpidus*	*Protohaploxypinus goraiensis*	*Protohaploxypinus* sp.	*Striatopodocarpites cancellatus*	*Striatopodocarpites fusus*	*Striatopodocarpites* sp.	*Striomonosaccites ovatus*	*Striomonosaccites* sp.	*Vittatina fasciolata*	*Weylandites lucifer*	Chlorophycean algae	*Leiospaheridia* sp.	*Peltcystia venosa*	*Peltacystia* sp.
	MZ 167	L2	R	R		R				R		R						R	C		C	C	C	C					R	R	R								A	A	A	R					R		
	MZ 168																		R						R		R	R	C	C		C	R				R		A	A	A	C	C			R			
	MZ 169				C						R	R	R				C		C	C	C	C	C	C	R	R		R	A	A		C	A				C		A	A	A				C	C			C
	MZ 170	L1					R		R	R	R	R	R							C	C	C	C	C		R			A	A		C	C					C	C	C	C		C		R	R			
	MZ 171				R	R		C	R	C				C	C	C						C	C	C	R		R		R	R		C	C	C	C	C		C	A	A	A			C	C			R	C
	MZ 172											R												C												C		C								A		R	
	MZ 176										R	R	R								A	A		A	C				R	R		R	C	R	R	C	R	C	C	C	C	C	C	C		C			
	MZ 177																							A	R															R		R							
	MZ 182		A	A							A	A	A												A										R							R							

Table 4

Borehole ETA 71 palynomorph assemblages, Muarátzi sub-basin, Moatize-Minjova Coal Basin, Mozambique. The numbers represent the group percentages of the respective taxon within the overall palynoflora. A. Abundant (>50%); C. Common (10–50%) and R. Rare (<10%). A = Algae and *incertae sedis*.

			Spores																								Pollen																																												A			
Borehole ETA 71	Sample ref.	Assemblage	*Apiculatisporis unicus*	*Calamospora* sp.	*Cyclogranisporites* spp.	*Cristatisporites* sp.	*Horriditriletes curvibaculosus*	*Horiditriletes tereteangulatus*	*Horriditriletes ramosus*	*Horriditriletes* sp.	*Indotriradites niger*	*Indotriradites* sp.	*Laevigatosporites vulgaris*	*Laevigatosporites colliensis*	*Laevigatosporites* sp.	*Leotriletes* sp.	*Lophotriletes* sp.	*Microbaculatispora tentula*	*Microbaculatispora* sp.	*Osmundacidites senectus*	*Osmundacidites* sp.	*Polypodiisporites mutabilis*	*Polypodiidites* sp.	*Puctatisporites* sp.	*Thymospora pseudothiessenii*	*Verrucosisporites* sp.	*Alisporites landianus*	*Alisporites ovatus*	*Alisporites plicatus*	*Alisporites potoniei*	*Alisporites* sp.	*Cannanoropollis janakii*	*Corisaccites alutas*	*Cycadopites cymbatus*	*Cycadopites follicularis*	*Cycadopites* sp.	*Florinites* sp.	*Gnetaceaepollenites sinuosus*	*Gnetaceaepollenites* sp.	*Guttulapollenites hannonicus*	*Guttulapollenites* sp.	*Hamiapollenites* sp.	*Limitisporites* sp.	*Lueckisporites virkkiae*	*Lunatisporites variesectus*	*Lunatisporites* sp.	*Marsupipollenites striatus*	*Marsupipollenites triradiatus*	*Pakhapites* sp.	*Platysaccus papillionis*	*Platysaccus* sp.	*Plicatipollenites* cf. *gondwanensis*	*Plicatipollenites* sp.	*Potonieisporites novicus*	*Potonieisporites* sp.	*Protohaploxypinus diagonalis*	*Protohaploxypinus goraiensis*	*Protohaploxypinus limpidus*	*Protohaploxypinus microcorpus*	*Protohaploxypinus* sp.	*Striatoabieites multistriatus*	*Striatopodocarpites cancellatus*	*Striatopodocarpites fusus*	*Striatopodocarpites pantii*	*Striatopodocarpites* sp.	*Striomonosaccites* sp.	*Vittatina fasciolata*	*Vittatina scutata*	*Vittatina* sp.	*Weylandites lucifer*	*Weylandites magmus*	Chlorophycean algae	*Leosphaeridia* sp.	*Peltacystia venosa*	*Tetraporina gigantea*
	MZ 44	L3		R				C		C			R		C	C			R	R	C			R		R		R	R		C	R	C			R		C	R	C		R		R			C		R	C	R				R	R	R	C		C	R	C	C		A	R				C	C	C	C		
	MZ 45			C	C		C	C	R	C			C	C	A	C			C	C	R			C		C		C	R	C	C			R		C			R							R			R								R		R	R			C	R	C					C	R	R	C	R	R
	MZ 46			R	P		R	R			C	C	C			A	R		C	R	C	R	C	C		C	R	C	R	C	R	R																	R	C							R	C				C	C		C				R	C	R	R	C	R	
	MZ 47		C	C	R			C	R	C			R	C	A	C		R	C		R			R		C		C		C	C																R			R						R	R	R	R	C		C	R		C					R	R	A	C		
	MZ 48			R	C			C		R						R			C	C	C	C	R		C	C																																							C							C	C		
	MZ 49			C				A	R	A			R	C	C	C	C							R													R														R						R	R	R	C		R	C		R		R					C	C	R	
	MZ 51				R		R				C			C	R	C				R	R			R	R			C		R	R	C	R		R						C	R		R		R		A	A	R	R		R	R	R		R	C	R		C		C	C	C	C			R	R	C	R	R	C		
	MZ 52			R	C	R	C	C		R	R		R	C	R	C				C	C	C		R	A			C	R	C	C	R	R	R		R		C		C	C			R						R		R		R		R		R	R			R	C	C		C		R		R	C	C	R	C		

mudstones that alternate with black carbonaceous mudstones and thin beds of coal (barcode coal). Sixteen samples were collected for palynology, yet only five samples yielded moderately to well-preserved palynomorphs (Fig. 5).

With a total depth of 33.4 m, ETA 71 is the shallowest of the studied boreholes (Fig. 5). At its base, the succession starts with ca. 9 m of a thick sequence of matrix-supported conglomerates interbedded with cm-thick lenses of siltstones and black mudstones. These lithologies are followed upwards by a 27.4 m thick sequence of dominantly black carbonaceous mudstones, siltstones and thin (cm-thick) coal beds. Nine samples, located in the lower-half part of the borehole were collected, and only one was barren of palynomorphs (Fig. 5).

Borehole ETA 75 has a total depth of 111.42 m (Figs. 5). At a depth of approximately 95 m to total depth, the succession consists of matrix-supported conglomerates interbedded with thin beds of gray siltstones and mudstones.

The sequence is followed upwards by a 45 m thick sequence (from 95 to 50 m depth) of fine-grained lithologies consisting of black carbonaceous mudstones interbedded with gray mudstones, siltstones and thin coal beds. Between ca. 75 and 80 m depth, two doleritic sills are intruded in the succession. From 50 m depth to the top of the borehole, the succession is characterized by coarse to medium grained sandstone beds interbedded with rare and thin beds of gray siltstones. Fifteen samples were processed for palynological studies, and only two were barren (Fig. 5).

Borehole ETA 135 has a total depth of 81.3 m and penetrated, at its base, a 3 m thick sequence of basement rocks consisting of anorthosites belonging to the Tete Suite (Fig. 5). The basement rocks are unconformably overlain by ca. 8 m of clast to matrix-supported conglomerates interbedded with thin beds of siltstones and black mudstones. A fine-grained interval consisting of siltstones interbedded with black carbonaceous mudstones and minor coal beds was deposited between approximately 70 and 35 m depth. From 35 to 28 m depth the succession consists of black carbonaceous mudstones interbedded with thin beds (<30 cm) of coal. The top 28 m of the succession consists of siltstones interbedded with black carbonaceous mudstones. Twenty-four samples were collected and processed for palynology, but only nine were positive for palynomorphs (Fig. 5).

In the studied boreholes, it was not possible to recognize the stratigraphic succession of the Moatize Formation defined in the Moatize sub-basin, namely, the several Coal Seams (*Carbonaceous Complexes*). According to the standard stratigraphy of the KSG in Mozambique, the conglomerate beds that unconformably overlay the basement rocks belong to the Vúzi Formation, while the mudstones and black carbonaceous mudstones that are located stratigraphically above them, are the oldest beds of the Moatize Formation that include the oldest Coal Seam (Sousa Pinto).According to a recent study by Götz et al. (2018), the palynology of borehole 945L_002 located in the ICVL Benga mine (Fig. 2), indicates an Artinskian age (Fig. 3). Borehole (948L_0005; Fig. 3) also drilled in the same area, intersected a succession with three coal seams, attributed to the Matinde Formation (Götz et al., 2017). Mudstone samples from this borehole yielded palynomorph assemblages indicating an early Guadalupian to early Lopingian age for the entire succession.

5. Palynological results

The quantitative and qualitative distribution of the palynomorph assemblages in the four studied boreholes enabled the identification of three diverse assemblages (Costa, 2015; Correia, 2016; Vaz, 2017). These are characterized by the first occurrence (FO) of particular taxa and the relative abundance of prominent taxa (Tables 1–4). Stratigraphically important taxa are illustrated in Plates I–IV. Following the stratigraphic order, the assemblages are:

Assemblage L1: The oldest assemblage is characterized by a clear dominance of non-taeniate and taeniate bisaccate pollen grains. Characteristic components of the assemblage are *Alisporites* spp., *Protohaploxypinus* spp. (e.g., *P. diagonalis, P. goraiensis,* and *P. limpidus*), and *Striatopodocarpites* spp., as well as rare to common *Cycadopites cymbatus*, *Hamiapollenites* sp., *Lueckisporites virkkiae*, *Marsupipollenites striatu*s, *M. triradiatus.* and *Vittatina* spp. Common to abundant *Guttulapollenites hannonicus*, *Weylandites lucifer*, *W. magnus*, and *Pakhapites* sp. (of large dimensions, 50–60 μm), and very rare monossacates assigned to the taxa *Cannanoropollis janakii, Plicatipollenites gondwanensis, Plicatipollenites* sp., and *Striomonosaccites* sp. are also present in the assemblage.

Spores are common to abundant and include *Apiculatisporis* sp., *Brevitriletes cornutus*, *Calamospora* spp., *Horriditriletes* spp., *Laevigatisporites* spp., and rare *Baculatisporites bharadwaji*, *Baculatisporites* sp., *Cyclogranisporites* sp., *Granulatisporites austroamericanus*, *Granulatisporites trisinus*, *Granulatisporites* sp. *Punctatisporites* sp., *Striatosporites* sp., and *Verrucosisporites* sp. (see Tables 2 and 3).

Occurrence: Borehole ETA 135, sample interval MZ182 to MZ170; Borehole ETA 75, sample interval MZ35 to MZ26; Borehole ETA 25, samples MZ162 to MZ161 (Fig. 5).

Assemblage L2: This assemblage contains abundant *Alisporites* spp. (e.g., *A. landianus, A. maximus, A. ovatus*, *A. plicatus,* and *A. potoniei*), *Protohaploxypinus* spp. (e.g., *Protohaploxypinus amplus, P. diagonalis*, *P. goraiensis*, *P. hartii,* and *P. limpidus*), and *Striatopodocarpites* spp. (*Striatopodocarpites cancellatus*, *S. fusus,* and *S. pantii*), as well as common *Guttulapollenites hannonicus*, *Pakhapites* sp. (of large dimensions), *Vittatina fasciolata*, *V. scutata*, *Weylandites lucifer,* and *W. magnus*.

Other rare to common pollen taxa occurring in this assemblage are: *Cycadopites follicularis*, *Corisaccites alutas*, *Lueckisporites virkkiae,* and *Gnetaceaepollenites sinuosus.* The latter occurs for the first time in borehole ETA 25 within this assemblage. In addition, rare to common *Hamiapollenites* spp., *Marsupipollenites striatu*s, *M. triradiatus* and *Striatoabieites multistriatus* are also observed.

Spores are rare to common and include *Baculatisporites* sp., *Brevitriletes cornutus*, *Calamospora* spp., *Deltoidospora* sp., *Horriditriletes filiformis*, *H. tereteangulatus*, *H. ramosus*, *Horriditriletes* sp., *Lophotriletes* sp., *Punctatisporites* sp., and *Retusotriletes* sp. The trilete spore taxa *Baculatisporites bharadwaji*, *Baculatisporites* sp., *Cyclogranisporites* sp., *Granulatisporites trisinus*, *Granulatisporites* sp., *Indotriradites niger*, *Kraeuselisporites* sp. *Procoronaspora spinose*, *Verrucosisporites andersonii*, and common to abundant monolete spore taxa including *Polypodiisporites mutabilis*, *Polypodiidites* sp., and *Thymospora pseudothiessenii* (~*Reticuloidosporites warchianus*), occur for the first time in this assemblage.

Occurrence: Borehole ETA 25, sample interval MZ160 to MZ154; Borehole ETA 75, samples MZ25 to MZ21; borehole ETA 135, sample interval MZ169 to MZ167 (Fig. 5).

Assemblage L3: The youngest of the three assemblages is characterized by a dominance of spores, which are better preserved than the pollen grains. The more common spore taxa in this assemblage include *Apiculatisporis unicus, Calamospora* sp., *Deltoidospora* sp., *Indotriradites niger*, *Horriditriletes* spp. (common to abundant *H. tereteangulatus*, and rare *H. curvibaculosus,* and *H. ramosus*), *Lophotriletes* sp., *Osmundidacites senectus,* and the monolete taxa *Laevigatosporites* spp. (*L. colliensis* and *L. vulgaris*), *Thymospora pseudothiessenii,* and *Polypodiisporites* sp.

The assemblage is complemented with common to abundant non-taeniate and taeniate bisaccate pollen grains containing *Protohaploxypinus* spp. (e.g.,*P. diagonalis*, *P. goraiensis*, *P. limpidus,* and *P. microcorpus*), *Striatopodocarpites* spp. (*S. cancellatus*, *S. fusus*, *S. gondwanensis,* and *S. pantii*), and *Alisporites* spp. (e.g., *A. landianus*, *A. ovatus, A. plicatus,* and *A. potoniei*), as well as rare to common *Guttulapollenites hannonicus*, *Corisaccites alutas,* and *Lueckisporites virkkiae.* More scarcely, *Hamiapollenites* sp., *Limitisporites* sp., and *Lunatisporites variesectus* are also identified. The most common colpate pollen grains are *Pakhapites* sp., *Gnetaceaepollenites sinuosus*, *Vittatina* spp., *Weylandites lucifer*, and *Weylandites magmus*. Rare monosacate

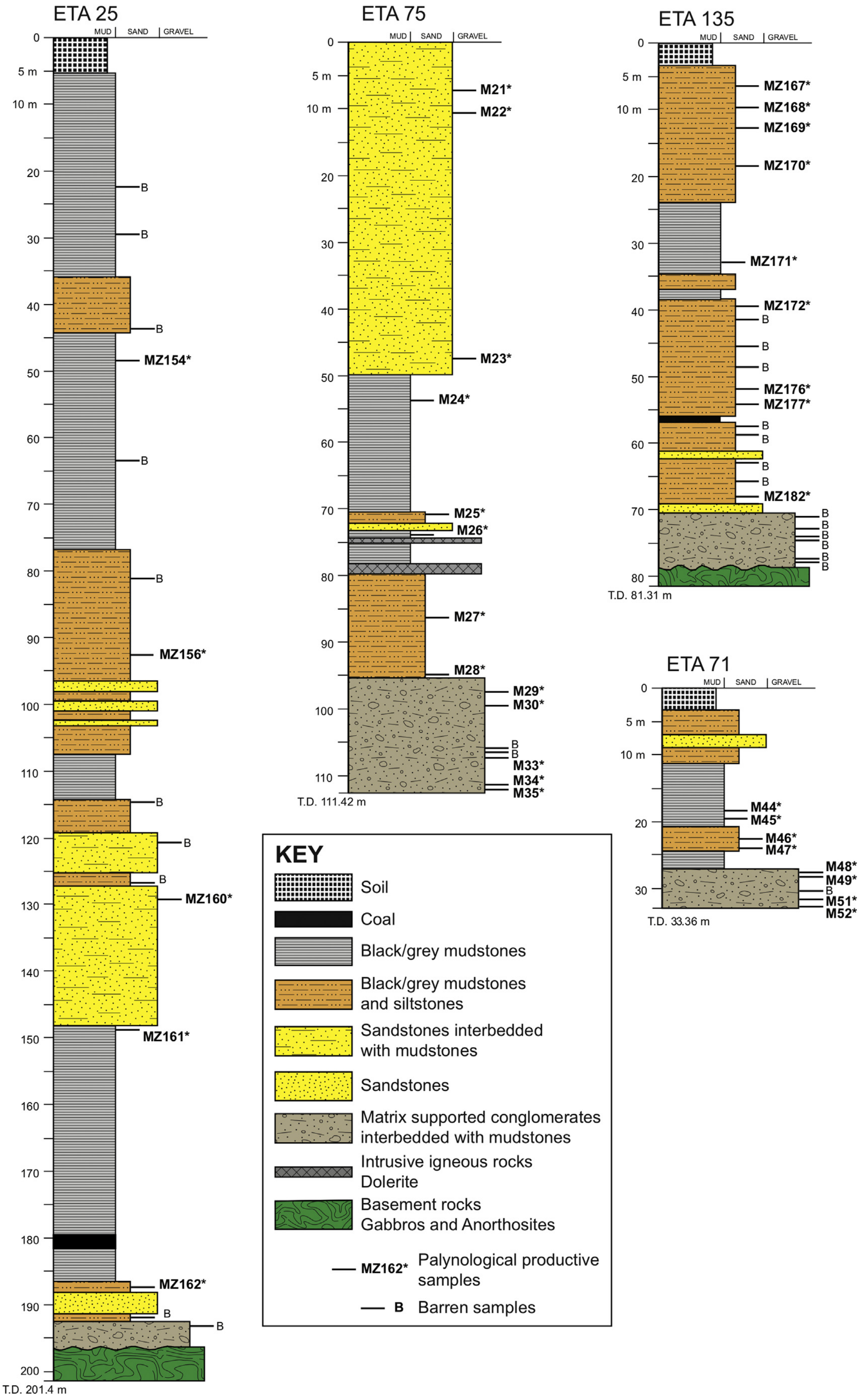

Fig. 5. Lithological logs of the boreholes with the position of the samples studied.

pollen grains are also present (*Cannanoropollis janakii*, *Plicatipollenites* cf. *P. gondwanensis* and *Potonieisporites novicus*).

Osmundacidites senectus occurs in assemblage L3 for the first time, sometimes occurring together with *Protohaploxypinus microcorpus*, and is common in the assemblage (see Table 4).

Occurrence: Borehole ETA 71, sample interval MZ 52 to MZ 44 (Fig. 5).

Specimens of algae and *incertae sedis* were also identified in all boreholes (assemblages L1 and L2), as for instance, *Peltacystia venosa*, *Peltacystia* sp., *Tetraporina horologia* (Zygnemataceae algae), and the genus *Leiosphaeridia* (Prasinophyceae algae). Common to abundant *incertae sedis* chlorophycean algae remains were recognized (spheromorph cluster of 2 to more than 20 spherical individuals), *Reduviasporonites* spp., and also some fungal hyphae remains and root hairs were identified.

Assemblage L3 is marked by the presence of *Peltacystia venosa*, *Tetraporina gigantea* (Zygnemataceae algae) and *Leiosphaeridia* sp. (Prasinophyceae), as well as abundant chlorophycean algae *incertae sedis* remains in clusters. These clusters, indicating the existence of colonial forms of apparent algal origin, were reported in several southern hemisphere Permian successions (Balme and Hennelly, 1956; Balme and Segroves, 1966; Segroves, 1967; Zavattieri et al., 2017).

The rare to common occurrence of algae and phytoplankton may be an indicator of the presence of a fluvial-lacustrine depositional environment. The palynodebris are dominated by brown and black wood and common well-preserved cuticle fragments.

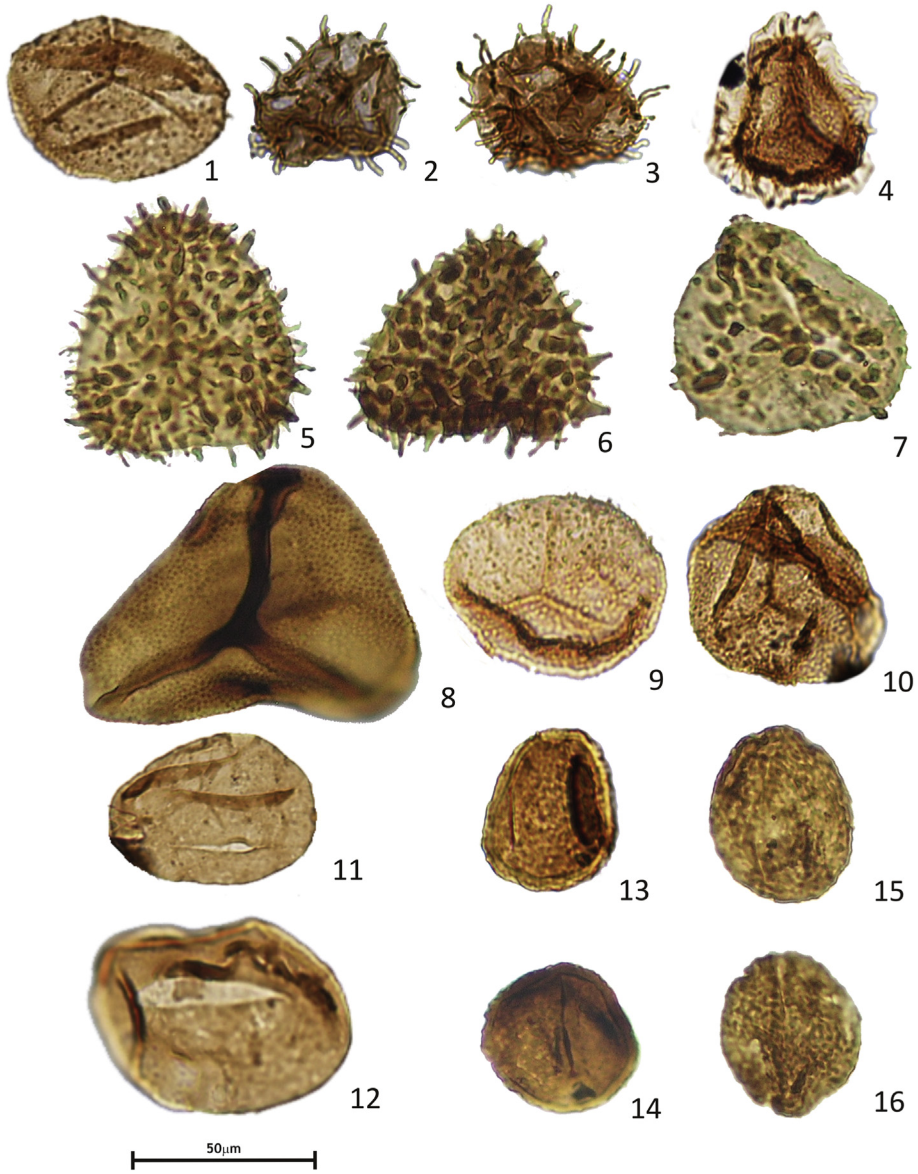

Plate I. Selected palynomorph specimens from the Muaradzi sub-basin, MMCB, Mozambique. Plate captions give the taxonomic name of the figured specimen, followed by borehole reference, sample number, slide number, and microscope coordinates (MC). Scale bars: 50 μm. 1. *Baculatisporites* sp., ETA 75, MZ 30, 30-1-1, MC 1008-457. 2. *Horriditriletes curvibaculosus* Bharadwaj and Salujha, 1964; ETA 71, MZ 52, 1, MC 182-1080. 3. *Horriditriletes curvibaculosus* Bharadwaj and Salujha, 1964, ETA 71, MZ 52, 1, MC 226-1005. 4. *Indotriradites niger* (Segroves) Backhouse, 1991, ETA 71; MZ 51, 1, MC 390-1071. 5. *Horriditriletes tereteangulatus* (Balme and Hennelly) Backhouse, 1991, ETA 135, MZ 171, 2, MC 73-1110. 6. *Horriditriletes tereteangulatus* (Balme and Hennelly) Backhouse, 1991, ETA 135, MZ 171, 2, MC 131-1498. 7. *Horriditriletes uruguaiensis* (Marques-Toigo) Archangelsky and Gamerro 1979, ETA 135, MZ 170, 1, MC 83-1423. 8. *Granulatisporites austroamericanus* Tiwari 1965, ETA 135, MZ 171, 1, MC 111-1147. 9. *Osmundacidites senectus* Balme, 1970, ETA 71, MZ 52, 1, MC 383-1065. 10. *Osmundacidites senectus* Balme, 1970, ETA 71, MZ 52, 1, MC 182-1039. 11. *Laevigatosporites colliensis* (Bharadwaj and Hennelly) Venkatachala and Kar, 1968, ETA 75, MZ 34, 34-1-1, MC 1100-660. 12. *Laevigatosporites vulgaris* (Ibrahim) Ibrahim 1933, ETA 75, MZ 28, 28-1-1, MC 1025-501. 13. *Polypodiisporites mutabilis* Balme, 1970, ETA 71; MZ 52; Slide 1 MC 275-1014. 14. *Polypodiisporites* sp. Balme, 1970, ETA 25, MZ 160, 1, MC 147-1235. 15. *Thymospora pseudothiessenii* (Kosanke) Wilson and Venkatachala 1963, ETA 25, MZ 166, 1, MC 180-1397. 16. *Thymospora pseudothiessenii* (Kosanke) Wilson and Venkatachala 1963, ETA 25, MZ 166, 1, MC 223-1405.

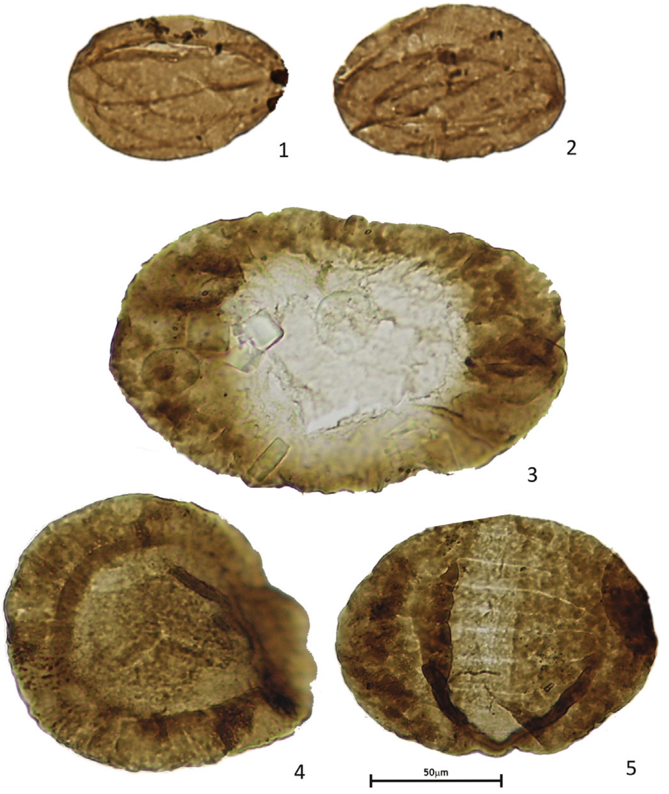

Plate II. Selected palynomorph specimens from the Muaradzi sub-basin, MMCB, Mozambique. Plate captions give the taxonomic name of the figured specimen, followed by borehole reference, sample number, slide number, and microscope coordinates (MC). Scale bars: 50 μm. 1. *Striatosporites heyleri (Doubinger)* Playford and Dino 2000 ETA-75, MZ 34, 34-1-1, MC 1033-601. 2. *Striatosporites* sp., ETA-75, MZ 34, 34-1-1, MC 955-577. 3. *Cannanoropollis janakii* Potonié and Sah 1960, ETA 135, MZ 171, 1, MC 175-1100. 4. *Plicatipollenites gondwanensis* (Balme and Hennelly) Lele 1964, ETA 135, MZ 171, 2, MC 110-1132. 5. *Striomonosaccites ovatus* Bharadwaj 1962, ETA 135, MZ 176, 1, MC 190-1200.

6. Age discussion, palynostratigraphic and paleophytogeographic correlations across the Gondwana

The absence of independent age constrains in these continental succession's hampers correlation of the Muarádzi sub-basin with other Karoo basins, as well as with other regions of the Gondwana paleophytogeographical province. However, in a more local context, the Karoo basins in the paleogeographical regions close to Mozambique, provide important palynostratigraphic correlations that indicate relative age intervals for the established assemblages: Tanzania (Msaky and Srivastava, 1997), Zambia (Utting, 1979; Nyambe and Utting, 1997; Barbolini et al., 2016b), Zimbabwe (Falcon, 1975, 1978) and South Africa (Falcon et al., 1984; Steiner et al., 2003; Prevec et al., 2010; MacRae, 1988; Aitken, 1998). Fig. 6 presents the palynological correlation of the Permo-Triassic transition across the Gondwana Basins, showing close palynological affinity with the MMCB of Mozambique, as for instance Tanzania, Zambia and South Africa.

The proposed assemblages are informal and established only for Mozambique. The correlation is based mainly in first occurrences (FO) of selected taxa and abundance of characteristic species. Assemblage L1 is characterized by the rich occurrence of *Guttulapollenites* and *Weylandites*. Whereas Assemblage L2 is characterized by the first occurrence of abundant *Thymospora pseudothiessenii* together with *Indotriradites niger*, *Kraeuselisporites* spp., *Polypodiisporites mutabilis* and *Polypodiidites* sp., that also occurs for the first time in this assemblage, as well as most of the taxa of the preceding assemblage. Assemblage L3 is characterized by the first occurrence of *Osmundacidites senectus* together with the taxa described from the previous assemblages.

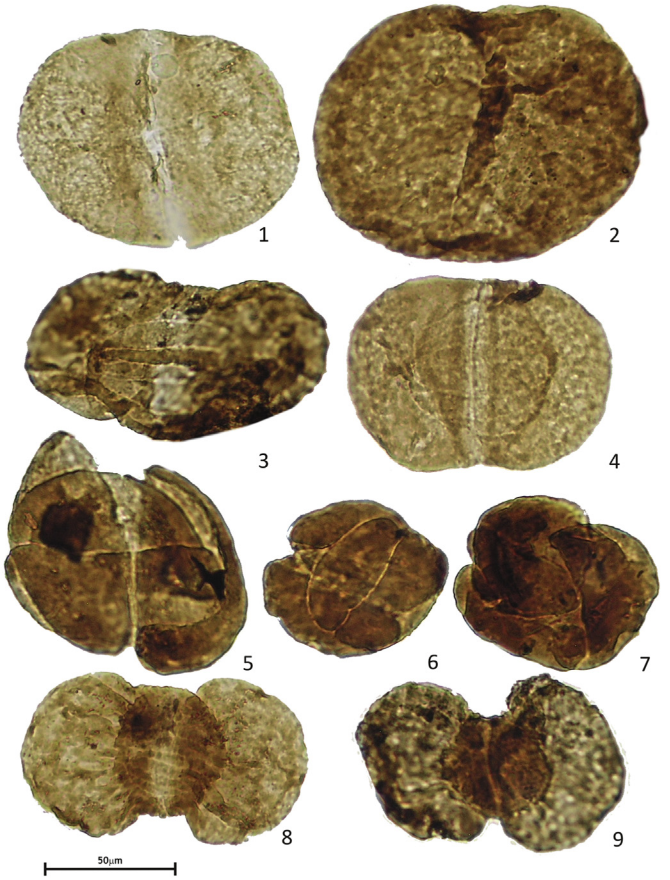

Plate III. Selected palynomorph specimens from the Muaradzi sub-basin, MMCB, Mozambique. Plate captions give the taxonomic name of the figured specimen, followed by borehole reference, sample number, slide number, and microscope coordinates (MC). Scale bars: 50 μm. 1. *Scheuringipollenites ovatus* (Balme and Hennely) Jansonius 1962, ETA 135, MZ 171, 2, MC 183-1396. 2. *Alisporites potoniei* (Lakhanpal, Sah and Dube) Somers 1968, ETA 135, MZ 176, 1, MC 156-1370. 3. *Protohaploxypinus goraiensis* Potonié and Lele 1961, ETA 135, MZ 169, 1, MC 64-1384. 4. *Protohaploxypinus limpidus* (Balme and Hennelly) Balme and Playford 1967, ETA 135, MZ 176, 1, MC 69-1280. 5. *Corisaccites alutas* Venkatachala and Kar 1966, ETA 135, MZ 170, 1, MC 56-1281. 6. *Guttulapollenites hannonicus* Goubin 1965, ETA 135, MZ 169, 1, MC 73-1289. 7. *Guttulapollenites hannonicus* Goubin 1965, ETA 135, MZ 168, 1, MC 122-1098. 8. *Striatopodocarpites cancellatus* (Balme and Hennelly) Hart 1963, ETA 135, MZ 171, 1, MC 158-1314. 9. *Striatopodocarpites fusus* (Balme and Hennelly) Potonié 1956, ETA 135, MZ 167, 1, MC 110-1390.

6.1. Local and regional correlations

On a local scale, and based on previous palynostratigraphic studies of the Muarádzi and the N'Condédzi sub-basins (Pereira et al., 2016; Götz et al., 2017, 2018; Galasso et al., 2019), a good palynological resolution within the Mozambican sub-basins could be achieved for the studied boreholes, and a Lopingian age was assigned to these assemblages (Fig. 3). Recent studies of Borehole 948L_0005 located in the Moatize sub-basin (Götz et al., 2017) allowed the identification of the key taxa *Guttulapollenites hannonicus* and *Lueckisporites virkkiae,* in sample 9 at ca. 70 m depth, which were correlated to the H′ zone of Falcon et al. (1984), yielding a late Guadalupian to early Lopingian age. Assemblage L1 (this work) is tentatively correlated with the upper part of Borehole 948L-0005, which includes the Coal Seams VU and XU.

In Tanzania, the Karoo Selous Basin (Hatambulo Formation, Pangani and Sumbadzi members) presents a Lopingian age palynological assemblage, based on the common presence of *Alisporites* app., *Striatopodocarpites* spp., and *Protohaploxypinus* spp., together with the biostratigraphic significant taxa *Guttulapollenites hannonicus*, *Limitisporites* sp., *Lueckisporites* sp., *Platysaccus* spp. and *Weylandites* spp. (Msaky and Srivastava, 1997). This assemblage can be correlated with Assemblage L1 (this work) (see Fig. 6).

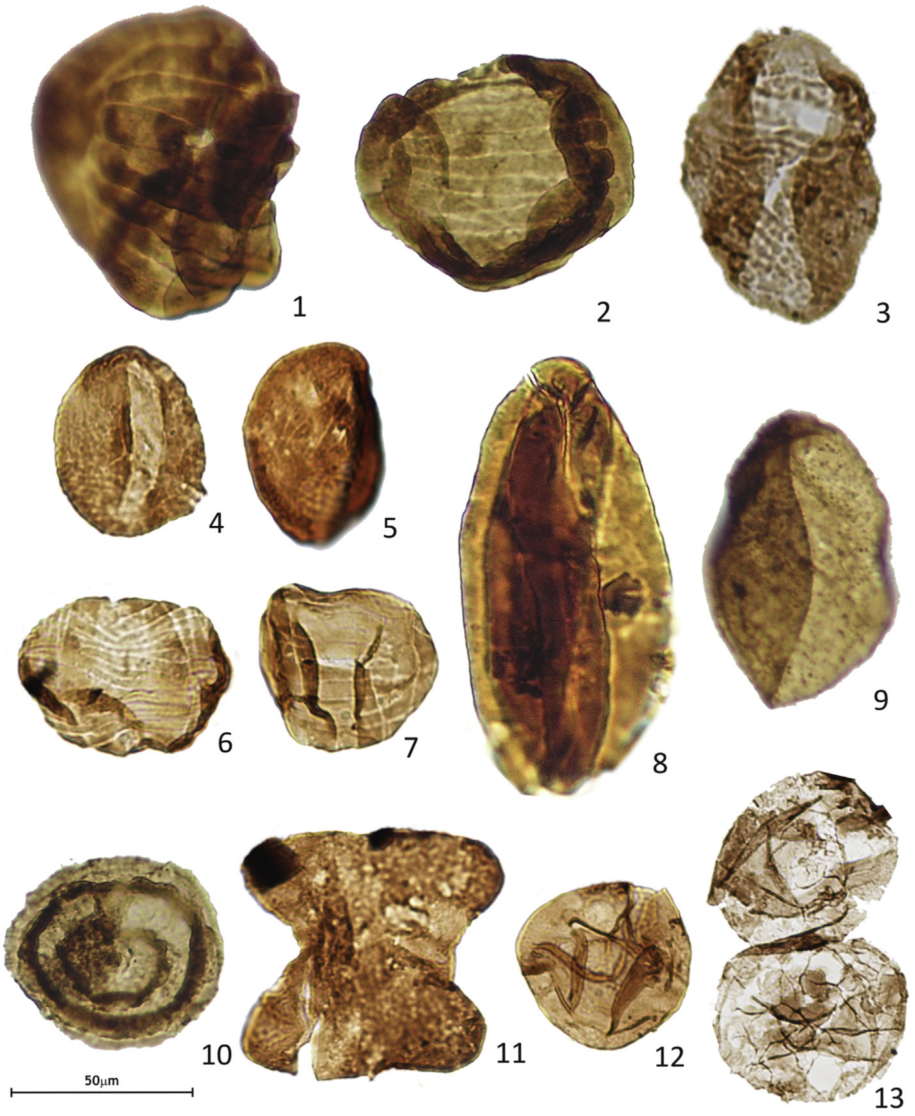

Plate IV. Selected palynomorph specimens from the Muaradzi sub-basin, MMCB, Mozambique. Plate captions give the taxonomic name of the figured specimen, followed by borehole reference, sample number, slide number, and microscope coordinates (MC). Scale bars: 50 μm. 1. *Pakhapites* sp., ETA 135, MZ 171, 1, MC 42-1384. 2. *Vittatina fasciolata* (Balme and Hennelly) Bharadwaj 1962, ETA 135, MZ 171, 2, MC 170-1473. 3. *Vittatina scutata* (Balme and Hennelly) Bharadwaj 1962, ETA-75, MZ 33, 33-1-1, MC 1044-457. 4. *Marsupipollenites triradiatus* Balme and Hennelly, 1956, ETA 71, MZ 51, 1, MC 320-1115. 5. *Marsupipollenites striatus* (Balme and Hennelly) Foster 1979, ETA 71, MZ 51, 1, MC 203-1042. 6. *Weylandites lucifer* (Bharadwaj and Salujha) Foster 1975, ETA 71, MZ 44, 1 MC 325-0969. 7. *Weylandites magmus* (Bose and Kar) Backhouse, 1991, ETA 71, MZ 44, 1, MC 292-1001. 8. *Gnetaceaepollenites sinuosus* (Balme and Hennelly) Bharadwaj and Srivastava 1969, ETA 135, MZ 168, 1, MC 135-1204. 9. *Cycadopites cymbatus* (Balme and Hennelly) Hart 1965, ETA 25, MZ 160, 1, MC 217-1193. 10. *Peltacystia venosa* Balme and Segroves, 1966, ETA 135, MZ 171, 2, MC 145-1430. 11. *Tetraporina gigantea* (Bose and Maheshwari) Backhouse, 1991, ETA 71, MZ 45, 1, MC 340-1014. 12. *Leiosphaeridia* sp., ETA 71; MZ 47, 1, MC 267-1002. 13. Chlorophycean algae *incertae sedis* (sphaeromorph cluster of two individuals) showing inner chloroplast bodies, ETA 71, MZ 47, 1, MC 325-1081.

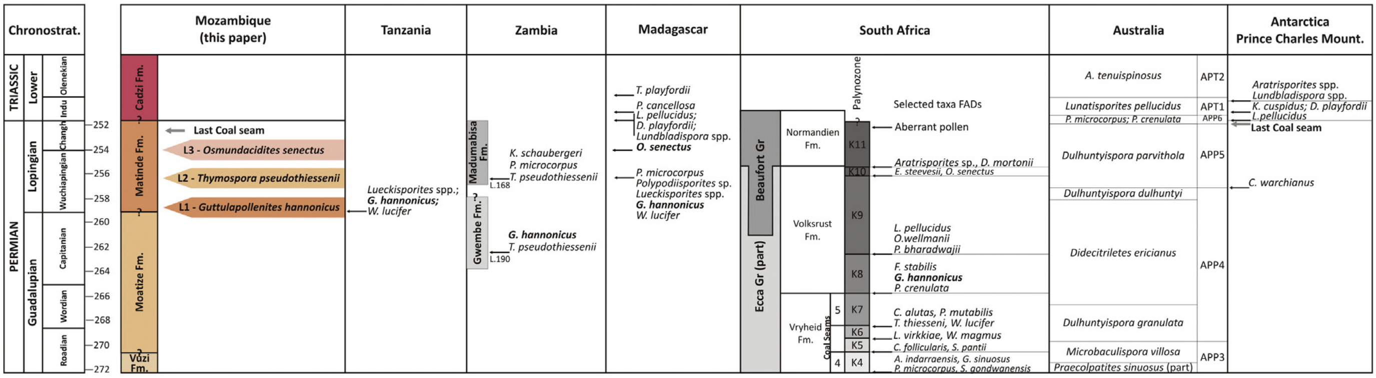

Fig. 6. Palynological correlation of the Permo-Triassic boundary across the Gondwana Basins that show close affinity with the MMCB of Mozambique.

In the upper part of the Gwembe Formation, in the lowermost unit of the Zambezi Basin, the studied palynoassemblage is correlated with the *D. ericianus* Zone of Backhouse (1991), the *G. hannonicus–P. rugatus* Zone (Zone VI) of Aitken (1998), Zone K8 (Barbolini et al., 2018), Assemblage Zone III of the mid-Zambezi Basin, Zimbabwe, and Biozone KK 3 in the Kalahari Karoo Basin, Botswana, suggesting a Guadalupian (Wordian-Capitanian) age (Barbolini et al., 2016c, Table 4). All these assemblages have common distinctive species as *G. hannonicus* and *T. pseudothiensenii* (with exception of Biozone KK 3 in the Kalahari Karoo Basin, Botswana, where both taxa are absent and therefore cannot be correlated), which suggests a correlation with Assemblage L2 (this work) (see Fig. 6).

In southern Zambia (Zambezi Basin), two different assemblages were identified (see Barbolini et al., 2016a). A Lopingian age assemblage comprising *Corisaccites alutas*, *Falcisporites australis*, *Guttulapollenites hannonicus*, *Klausipollenites schaubergeri*, *Polypodiisporites mutabilis*, *Protohaploxypinus goraiensis P. limpidus*, *P. microcorpus*, *Striatopodocarpites* spp., *Reticuloidosporites warchianus* (= *T. pseudothiessenii*), *Vittatina* spp., and *Weylandites lucifer* was identified in the upper Madumabisa Formation. The assemblage is correlated with the *Dulhuntyispora parvithola* Zone of Backhouse (1991) and the APP5 Zone of Price (1997), both dated as mid Wuchiapingian to late Changhsingian (Laurie et al., 2016). Also, it is indicated as correlating with the palynoflora of the *Daptocephalus* Assemblage Zone of the lower and middle Balfour Formation in the main Karoo Basin in South Africa (REF). The presence of *P. microcorpus* and *Klausipollenites schaubergeri* correlates this assemblage with Assemblage L3 (this study).

Assemblage L1 (this work), is also tentatively correlated with Zone H established in South Africa (Witbank Coal Fields/Northern Karoo South African region) and Zimbabwe (Falcon, 1975, 1978; Falcon et al., 1984). The first occurrence of *Guttulapollenites hannonicus* in the Main Karoo Basin of South Africa is assigned at the base of Zone H (Falcon et al., 1984), and it is suggested to be Guadalupian in age (Götz et al., 2017; Barbolini et al., 2018; Jha et al., 2018). Barbolini et al. (2018) proposed a palynozonation for the Main Karoo of South Africa, which presents the first occurrence of *G. hannonicus* as the key event that determines the base of palynozone K8, which is assigned a Capitanian age (see Fig. 6). This palynozonation incorporates data from the several basins (northern, southern and western) of Main Karoo Basin in South Africa. In the present study study, it cannot be excluded an older first appearance of *Guttulapollenites hannonicus* in the MMCB, as the succession is truncated at its base.

6.2. Paleophytogeography and events correlations

During the Lopingian, three phytogeographic provinces have been documented in the Gondwana Supercontinent, *Lueckisporites* in the west (South America), *Dulhuntyispora* in the east (Australia, Antarctica), and *Guttulapollenites* in the central part of the continent (Madagascar, Pakistan and India) (Jha, 2006; Lindström and McLoughlin, 2007; Stephenson, 2016; Jha et al., 2018). The palynological signatures and main events are substantially different from one province to the other (Backhouse, 1991; Lindström, 1996), which hinders the establishment of paleogeographic correlations.

The palynological data analyzed in this study locates Mozambique in the Central Gondwana *Guttulapollenites* paleophytogeographical province, during the Lopingian, within the *Glossopteris* dominated Gondwana megafloral province (Jha, 2006; Stephenson, 2016; Pereira et al., 2016; Jha et al., 2018). This province seems to extends across the Salt Range (Pakistan), the Morondava Basin (Madagascar), the Selous Basin (Tanzania), and Moatize-Minjova Basin (Mozambique), to the north, mid-Zambesi Basin (Zambia) to the west, Godavari Basin (South India) to the east, and Zimbabwe, South Africa and most probably Amery Basin (Antarctica) to the south (Balme, 1970; Hermann et al., 2012; Srivastava and Jha, 1990; Jha, 2006; Vijaya, 2011; Jha et al., 2018; Wright and Askin, 1987) (see Fig. 6).

Assemblages of the Morondava Basin, Madagascar (Lower Sakamena Group), of Lopingian age, are dominated by common *Alisporites* spp., *Protohaploxypinus* spp., *Striatopodocarpites* spp., *Guttulapollenites hannonicus*, *Klausipollenites schaubergeri*, *Lueckisporites virkkiae*, *Osmundacidites senectus*, *Protohaploxypinus microcorpus*, *Polypodiisporites* sp., *Weylandites* spp. On top of the succession rare *L. pellucidus* occur (Wright and Askin, 1987). This assemblage can be correlated with Assemblage L3 (this study).

In Pakistan, the occurrence of abundant *Alisporites* spp., *Guttulapollenites hannonicus*, *Kraeuselisporites* spp., *Lueckisporites* spp., *Playfordiaspora* sp., *Protohaploxypinus* spp., *Striatopodocarpites* spp. and *Weylandites lucifer* characterizes Lopingian age assemblages (Balme, 1970; Hermann et al., 2012), which can be correlated with Assemblage L1 (this study).

Recently, in a synthesis of the palynological data from the Gondavari Graben, south India (Kar and Srivastava, 2003; Jha et al., 2007; Murthy et al., 2010; Vijaya et al., 2012; Aggarwal and Jha, 2013; Tewari et al., 2015; Jha et al., 2018), a Changhsingian age (latest Lopingian) palynological assemblage (Assemblage IX) is described. This palynoassemblage is characterized by the dominance of striate bisaccates (*Striatopodocarpites*, *Faunipollenites*) and taeniates (*Guttulapollenites*, *Lunatisporites*, *Corisaccites*) along with some stratigraphically significant taxa such as, *Alisporites* spp., *Densipollenites magnicorpus*, *Klausipollenites* spp., *Falcisporites* spp., *Striatisulcites ovatus*, *Tiwarisporites* sp., *Osmundacidites* sp. and *Weylandites* spp. These data indicate a possible correlation with Assemblage L3 (this study).

In Prince Charles Mountain, Antarctica, latest Lopingian age assemblages include common *Alisporites* (including *A. splendens* and *A. tenuicorpus*), *Ephedripites* sp., *Protohaploxypinus* spp., and *Striatopodocarpites* spp. Spores assigned to the genera *Osmundacidites*, *Horriditriletes*, *Lophotriletes,* and *Laevigatosporites* increase in abundance towards the top of the sequence (Lindström and McLoughlin, 2007). This assemblage is tentatively correlated with the Assemblage L3 of late Lopingian age (this study).

As we compare the palynological events through the Karoo basins, distinct palynostratigraphic events occur based on the FO and abundance of key taxa (as for instance, FO of *G. hannonicus*, *T. pseudothiensenii* and *O. senectus*). A close palynological correlation between Madagascar, Tanzania (Selous Basin), Zambia (mid Zambezi Basin), and Mozambique (Moatize-Minjova Coal Basin) can be identified (see Fig. 6). This major region can be allocated to the northern Karoo-aged basins of south-central Africa (Catuneanu et al., 2005). The northern Karoo-aged basins palynoevents also show many similarities with the Lopingian assemblages of Pakistan, India and some basins of East Antarctica. However, the southern Karoo-aged basins, which include South Africa and Zimbabwe, show a completely different distribution of the palynoevents through the Permian successions, and a direct correlation is difficult to establish. A possible explanation for this feature may be differences in the latitudes or the presence of a phytogeographic barrier between the main Karoo Basin and the other Karoo basins located north of it. This topographic barrier could have been the Cargonian Highlands that extended further north occupying the majority of the Zimbabwe Craton (Isbell et al., 2008). This prominent highland region could have persisted during the Permian, preventing the fully exchange of floras between these two regions (see Fig. 6). More studies are needed to ascertain this last point.

The palynological data obtained in this study also opens new perspectives for coal exploration in the MMCB. This study indicates that the coal deposits of the basin have a wider stratigraphic distribution, reaching the latest Lopingian, and are not restricted to the Cisuralian-Guadalupian age, as it is commonly accepted (Falcon et al., 1984; GTK, 2006) (Fig. 3). In general, and concerning the coal deposits stratigraphy, the coal-bearing age deposits of the northern Karoo-aged basins of south-central Africa seems to have a wider stratigraphic range when compared with the southern Karoo-aged basins, suggesting a paleolatitude, climatic/tectonic controlled location within Gondwana.

7. Conclusions

The main results of this study are summarized below:

Three palynological assemblages were identified and studied in detailed, and are assigned to the Lopingian. Assemblage L1 is characterized by the common occurrence of *Guttulapollenites* and *Weylandites*. Assemblage L2 is defined on the first occurrence of abundant *Thymospora pseudothiessenii* together with *Indotriradites niger*, *Kraeuselisporites* spp., *Polypodiisporites mutabilis,* and *Polypodiidites* sp. Assemblage L3 is characterized by the first occurrence of *Osmundacidites senectus* together with the taxa described from the previous assemblages.

A close palynological correlation between Mozambique (Moatize-Minjova Basin), Tanzania (Selous Basin), Zambia (mid-Zambezi Basin), and Madagascar palynoevents is established. This major region can be assigned to the northern Karoo-aged basins of south-central Africa, and the palynoevents can be correlated with Lopingian assemblages of Pakistan, India, and some basins of Antarctica (East). Southern Karoo-age basins that include South Africa and Zimbabwe show distinct Lopingian palynoevents, and a direct correlation is difficult to achieve.

The recently obtained palynological data opens new perspectives for coal exploration in the MMCB as the coal deposits show a wider stratigraphic distribution, reaching until the latest Lopingian.

8. List of taxa

8.1. Spores

?*Cristatisporites* sp.
Acanthotriletes sp.
Apiculatisporis sp.
Apiculatisporis unicus (Tiwari) Bharadwaj and Srivastava 1969
Baculatisporites bharadwaji Hart 1963
Baculatisporites sp.
Brevitriletes cornutus (Balme and Hennelly) Backhouse, 1991
Brevitriletes sp.
Calamospora microrugosa (Ibrahim) Schopf, Wilson and Bentall 1944
Calamospora obscura Kosanke 1950
Calamospora plicata Hart 1065
Calamospora rugosa (Ibrahim) Schopf, Wilson and Bentall, 1944
Calamospora sp.
Striatosporites heyleri (Doubinger) Playford and Dino 2000
Striatosporites sp.*Cyclogranisporites* sp.
Fabasporites sp.
Horriditriletes curvibaculosus Bharadwaj and Salujha 1964
Horriditriletes ramosus (Balme and Hennelly) Bharadwaj and Salujha 1964
Horriditriletes tereteangulatus (Balme and Hennelly) Backhouse, 1991
Horriditriletes uruguaiensis (Marques-Toigo) Archangelsky and Gamerro 1979
Horriditriletes sp.
Indotriradites niger (Segroves) Backhouse, 1991
Kraeuselisporites cf. *K. enormis* Segroves 1970
Kraeuselisporites sp.
Laevigatosporites colliensis (Bharadwaj and Hennelly) Venkatachala and Kar, 1968
Laevigatosporites vulgaris (Ibrahim) Ibrahim 1933
Laevigatosporites sp.
Deltoidospora directa (Balme and Hennelly) Norris 1965
Deltoidospora sp.
Lophotriletes sp.
Granulatisporites austroamericanus Archangelsky and Gamerro 1979
Granulatisporites trisinus Balme and Hennelly, 1956 *Granulatisporites* sp.
Osmundacidites senectus Balme, 1970
Polypodiidites sp. sensu Balme, 1970
Polypodiisporites mutabilis Balme, 1970
Procoronaspora spinosa (Anderson) Backhouse, 1991
Punctatisporites sp.
Retusotriletes sp.
Thymospora pseudothiessenii (Kosanke) Wilson and Venkatachala 1963
Verrucosisporites andersonii Backhouse 1988
Verrucosisporites sp.

8.2. Pollen

Alisporites landianus Balme, 1970
Alisporites maximus (Hart) Tiwari 1973
Scheuringipollenites ovatus (Balme and Hennelly) Foster 1975
Alisporites plicatus Jizba 1962
Alisporites potoniei (Lakhanpal, Sah and Dube) Somers 1968
Alisporites sp.
Cannanoropollis janakii Potonie and Sah 1960
Cannanoropolis sp.
Corisaccites alutas Venkatachala and Kar 1966
Cycadopites cymbatus (Balme and Hennelly) Hart 1965
Cycadopites sp.
Florinites sp.
Gnetaceaepollenites sinuosus (Balme and Hennelly) Bharadwaj and Srivastava 1969
Gnetaceaepollenites sp.
Guttulapollenites hannonicus Goubin 1965
Guttulapollenites sp.
Illinites sp.
Limitisporites sp.
Lueckisporites virkkiae Potonié and Klaus 1954
Lueckisporites sp.
Lunatisporites variesectus Archangelsky and Gamerro 1979
Lunatisporites sp.
Marsupipollenites striatus (Balme and Hennelly) Foster 1979
Marsupipollenites triradiatus Balme and Hennelly, 1956
Pakhapites sp.
Platysaccus papilionis Potonié and Klaus 1954
Platysaccus sp.
Plicatipollenites gondwanensis (Balme and Hennelly) Lele 1964
Plicatipollenites cf. *gondwanensis* (Balme and Hennelly) Lele 1964
Plicatipollenites sp.
Potonieisporites novicus Bharadwaj 1954
Potonieisporites cf. *P. novicus* Bhardwaj 1954
Potonieisporites sp.
Protohaploxypinus diagonalis Balme, 1970
Protohaploxypinus goraiensis (Potonié and Lele) Hart 1964
Protohaploxypinus limpidus (Balme and Hennelly) Balme and Playford 1967
Protohaploxypinus microcorpus (Schaarschmidt) Clarke 1965
Protohaploxypinus sp.
Striatoabieites multistriatus (Balme and Hennelly 1955) Hart 1964
Striatomonosaccites sp.
Striatopodocarpites cancellatus (Balme and Hennelly) Hart 1963
Striatopodocarpites fusus (Balme and Hennelly) Potonie 1956
Striatopodocarpites gondwanensis Hart 1964
Striatopodocarpites pantii (Jansonius) Balme, 1970
Striatopodocarpites sp.
Striomonosaccites ovatus Bharadwaj 1962
Striomonosaccites sp.
Vittatina costabilis Wilson 1962
Vittatina fasciolata (Balme and Hennelly) Bharadwaj 1962

Vittatina scutata (Balme and Hennelly) Bharadwaj 1962
Vittatina sp.
Weylandites lucifer (Bharadwaj and Salujha) Foster 1975
Weylandites magmus (Base and Kar) Backhouse, 1991

8.3. Algae and incertae sedis

Chlorophycean algae *incertae sedis* (sphaeromorph clusters)
Horoginella sp.
Leiosphaeridia sp.
Peltacystia sp.
Peltacystia venosa Balme and Segroves, 1966
Tetraporina gigantea (Bose and Maheshwari) Backhouse, 1991
Tetraporina horologia (Staplin) Playford 1963
Reduviasporonites chalastus (Foster) Elsik, 1999

Acknowledgments

The research was supported by the project PALEOCLIMOZ (PTDC/CTA-GEO/30082/2017). The authors would like to thank ETA STAR Moçambique, S.A. and Gondwana Empreendimentos e Consultorias, Limitada, for borehole access and complementary information; LNEG's technicians Fernando Oliveira and Irene Sousa, for laboratory support and sample preparation. Editor M. Stephenson, anonymous reviewer and Annette Götz are gratefully acknowledged for valuable comments that improved the article.

References

Achimo, M., Vasconcelos, L., Marques, J., Ferrara, M., 2014. Sedimentologia dos depósitos tilíticos do vale do rio Murrongódzi, Bacia Carbonífera de Moatize – Minjova, Tete, Moçambique. 2° Congresso Nacional de Geologia e 12° Congresso de Geoquímica dos Países de Língua Portuguesa, maputo, Moçambique, pp. 57–61.

Afonso, R.S., 1975. Contribuição para o conhecimento da area de Tambara-Dôa (Folha Sul-E-36, grau quadrado 1634). Boletim Serviços de Geologia e Minas, Lourenço Marques 38, 51–53.

Afonso, R.S., 1984. Ambiente geológico dos carvões gonduânicos de Moçambique - uma síntese. In: Lemos de Sousa, M.J. (Ed.), Symposium on Gondwana Coals, Lisbon, 1983. Proceedings and Papers. Comunicações dos Serviços Geológicos de Portugal 70. vol. 2, pp. 205–214.

Aggarwal, N., Jha, N., 2013. Permian palynostratigraphy and palaeoclimate of Lingala-Koyagudem Coalbelt, Godavari Graben, Andhra Pradesh, India. J. Asian Earth Sci. 64, 38–57.

Aitken, G., 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, South Africa.

Backhouse, J., 1991. Permian palynostratigraphy of the Collie Basin, Western Australia. Rev. Palaeobot. Palynol. 67, 237–314.

Balme, B.E., 1970. Palynology of Permian and Triassic strata in the Salt Range and Surghar Range, West Pakistan. In: Kummel, B., Teichert, C. (Eds.), Stratigraphic Boundary Problems: Permian and Triassic of West Pakistan. The University Press of Kansas, Lawrence, KS, pp. 305–453.

Balme, B.E., Hennelly, J.P.F., 1956. Monolete, monocolpate, and alete sporomorphs from Australian Permian sediments. Aust. J. Bot. 4, 54–67.

Balme, B., Segroves, K., 1966. *Peltacystia* gen. nov.: a microfossil of uncertain affinities from the Permian of Western Australia. J. R. Soc. West. Aust. 49, 26–31.

Barbolini, N., Bamford, M.K., Tolan, S.C., 2016a. Permo-Triassic palynology and palaeobotany of Zambia: a review. Palaeontol. Afr. 50, 18–30.

Barbolini, N., Smith, R.M.H., Tabor, N., Sidor, C.A., Angielczyk, K., 2016b. Resolving the age of Madumabisa vertebrates: palynological evidence from the mid-Zambezi Basin of Zambia. Palaeoecol. Palaeoclimatol. Palaeogeogr. 457, 117–128.

Barbolini, N., Bamford, M.K., Rubidge, B., 2016c. Radiometric dating demonstrates that Permian spore-pollen zones of Australia and South Africa are diachronous. Gondwana Res. 37, 241–251.

Barbolini, N., Rubidge, B., Bamford, M.K., 2018. A new approach to biostratigraphy in the Karoo retroarc foreland system: utilising restricted-range palynomorphs and their first appearance datums for correlation. J. Afr. Earth Sci. 140, 114–133.

Bicca, M.M., Philip, R.P., Jelinek, A. Ritter, Ketzer, J.M.M., Scherer, C.M.S., Jamal, D.L., Reis, A.R., 2017. Permian-Early Triassic tectonics and stratigraphy of the Karoo Supergroup in northwestern Mozambique. J. Afr. Earth Sci. 130, 8–27.

Cairncross, B., 2001. An overview of the Permian (Karoo) coal deposits of Southern Africa. J. Afr. Earth Sci. 33, 529–562.

Carta Geológica República de Moçambique, Escala 1/1 000 000, 2008. Compiled by F.J. Hartzer. Collaboration by V.J. Manhiça, J.M. Marques, G. Grantham, G.R. Cune, P. Feitio, E.X.F. Daudi. Direcção Nacional de Geologia, Maputo.

Carvalho, L.H.B., 1977. Formações vulcânicas de Carinde, Tete-Moçambique. Instituto Superior Técnico, Lisboa. Unpublished PhD Thesis. p. 213.

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. Afr. Earth Sci. 43, 211–253.

Correia, J., 2016. Palinologia, palinofácies e maturação orgânica dos sedimentos da Bacia de Moatize – Minjova, Karoo Inferior, Moçambique. Faculdade de Ciências e Tecnologia. Universidade Nova de Lisboa, p. 166 Unpublished MSc Thesis.

Costa, M., 2015. Palinoestratigrafia e maturação orgânica do Karoo Inferior da Bacia de Moatize-Minjiova, Moçambique. Faculdade de Ciências e Tecnologia. Universidade Nova de Lisboa, p. 149 Unpublished MSc Thesis.

Daber, R., 1984. Plantas fósseis de Moçambique. Ciênc. Tecnol. Maputo 9, 77–81.

Falcon, R.M.S., 1975. Palyno-stratigraphy of the Lower Karroo sequence in the central Sebungwe District, Mid-Zambezi Basin, Rhodesia. Palaeontol. Afr. 18, 1–29.

Falcon, R.M.S., 1978. A palynological comparison of Karoo sediments on opposite sides of the Rhodesian Watershed with stratigraphic application. Unpublished Ph.D. Thesis. University of the Witwatersrand, Johannesburg, p. 480.

Falcon, R.M.S., Pinheiro, H., Sheperd, P., 1984. The palynobiostratigraphy of the major coal seams in the Witbank Basin with lithostratigraphic, chronostratigraphic and palaeoclimatic implications. Comunicações dos Serviços Geológicos de Portugal 70, 215–243.

Galasso, F., Fernandes, P., Montesi, G., Pereira, Z., Spina, A., Marques, J., 2019. Thermal history and basin evolution of the Moatize - Minjova Coal Basin (N'Condédzi sub-basin, Mozambique) constrained by organic maturation levels. J. Afr. Earth Sci. 153, 219–238.

Gastaldo, R.A., DiMichele, W.A., Pfefferkorn, H.W., 1996. Out of the icehouse into the greenhouse: a late Paleozoic analogue for modern global vegetational change. Geol. Soc. Am. Today 10 (10), 1–7.

Götz, A., Ruckwied, K., 2014. Palynological record of the Early Permian Postglacial climate amelioration (Karoo Basin, South Africa). Palebio. Paleoenv. 94, 229–235.

Götz, A., Hancox, P.J., Lloyd, A., 2017. Permian climate change recorded in palynomorph assemblages of Mozambique (Moatize Basin, eastern Tete Province). Acta Paleobot. 57 (1), 3–11.

Götz, A., Hancox, P.J., Lloyd, A., 2018. Southwestern Gondwana's Permian climate amelioration recorded in coal-bearing deposits of the Moatize sub-basin (Mozambique). Paleoworld https://doi.org/10.1016/j.palwor.2018.08.004.

Grantham, G.H., Macey, P.H., Ingram, B.A., Roberts, M.P., Armstrong, R.A., Hokada, T., Shiraishi, K., Jackson, C., Bisnath, A., Manhiça, V., 2008. Terrane correlation between Antarctica, Mozambique and Sri Lanka; comparisons of geochronology, lithology, structure and metamorphism and possible implications for the geology of southern Africa and Antarctica. In: Satish-Kumar, M., Motoyoshi, Y., Osanoi, Y., Hiroi, Y., Shiraishi, K. (Eds.), Geodynamic Evolution of East Antarctica: a Key to the East-west Gondwana Connection. 308. Geol. Soc. London, Special Publication, pp. 91–119.

GTK Consortium, 2006. Map explanation. Sheets 1631 - 1934. Geology of Degree Sheets, Mecumbura, Chioco, Tete, Tambara, Guro, Chemba, Manica, Catandica, Gorongosa, Rotanda, Chimoio and Beira, Mozambique. Vol 2. Ministério dos Recursos Minerais, Direcção Nacional de Geologia, Maputo.

Hancox, P.J., 2016. The coalfields of South-Central Africa: a current perspective. Episodes 39 (2), 407–428.

Hankel, O., 1994. Early Permian to Middle Jurassic rifting and sedimentation in East Africa and Madagascar. Geol. Rundsch. 83, 703–710.

Hermann, E., Hochuli, P.A., Bucher, H., Roohi, G., 2012. Uppermost Permian to Middle Triassic palynology of the Salt Range and Sugar Range, Pakistan. Ver. Palaeobot. Palynol. 169, 61–95.

Isbell, J.L., Cole, D.I., Catuneanu, O., 2008. Carboniferous-Permian glaciation in the main Karoo Basin, South Africa: stratigraphy, depositional controls, and glacial dynamics. In: Fielding, C.R., Frank, T.D., Isbell, J.L. (Eds.), Resolving the Late Paleozoic Ice Age in Time and Space. Geological Society of America, Special Paper 441, pp. 71–82.

Jamal, D.L., 2005. Crustal Studies across Selected Geotransects in NE Mozambique: Differentiating between Mozambican (Kibaran) and Pan African Events, with Implications for Gondwana Studies. Unpublished PhD Thesis. University of Cape Town, Cape Town, South Africa.

Jha, N., 2006. Permian palynology from India and Africa – a phytogeographic paradigm. J. Palaeontol. Soc. India 51, 43–55.

Jha, N., Tewari, R., Rajnikanth, A., 2007. Palynology of Permian Gondwana Sequence of Umrer Coalfield, Maharashtra. J. Geol. Soc. India 69, 851–857.

Jha, N., Aggarwal, N., Mishra, S., 2018. A review of the palynostratigraphy of Gondwana sediments from the Godavari Graben, India: global comparison and correlation of the Permian-Triassic palynoflora. J. Asian Earth Sci. 163, 1–21.

Kar, R., Srivastava, S.C., 2003. Palynological delimitation of the coal bearing Lower Gondwana sediments in the southern part of Tatapani-Ramkola Coalfield, Chhattisgarh, India. J. Geol. Soc. India 61, 557–564.

Lächelt, S., 2004. Geology and Mineral Resources of Mozambique. Direcção Nacional de Geologia, Maputo, p. 515.

Laurie, J.R., Bodorkos, S., Nicoll, R.S., Crowley, J., Mantle, J.D., Mory, A.J., Wood, G.R., Backhouse, J., Holmes, E.K., Smith, T.E., Champion, D.C., 2016. Calibrating the middle and late Permian palynostratigraphy of Australia to the geologic timescale via U-Pb zircon CA-IDTIMS dating. Aust. J. Earth Sci. 63 (6), 701–730.

Lindström, S., 1996. Late Permian palynology of Fossilryggen, Vestfjella, Dronning Maund Land, Antarctica. Palynology 20, 15–48.

Lindström, S., McLoughlin, S., 2007. Synchronous palynofloristic extinction and recovery after the end-Permian event in the Prince Charles Mountains, Antarctica: implications for palynofloristic turnover across Gondwana. Rev. Palaeobot. Palynol. 145, 89–122.

Lopes, G., Pereira, Z., Fernandes, P., Marques, J., 2014. Datação Palinológica dos Sedimentos Glaciogénicos da Formação (Tilítica) de Vúzi, sondagem ETA 65, Bacia Carbonífera de Moatize–Minjova, Moçambique-Resultados Preliminares. Actas do IX Congresso Nacional de Geologia. 2° Congresso de Geologia dos Países de Língua Portuguesa, Porto, Portugal, p. 7.

MacRae, C.S., 1988. Palynostratigraphic correlation between the lower Karoo sequence of the Waterberg and Pafuri coal-bearing basins and the Hammanskraal plant macrofossil locality, Republic of South Africa. Memoirs Geol. Surv. S. Afr 1–217.

Msaky, E., Srivastava, V., 1997. Lower Karoo (K5-K6) Palynological assemblage from Tanzania. Abstract 3rd Symposium of African Palynology. Johannesburg South Africa, p. 31.

Mugabe, J.A., 1999. Karoo Deposits of Zambezi Graben - Moatize and Tete City Mozambique; Sedimentary Facies Distribution and Palynological Approach. Tese Univ, Utrecht, p. 297 unpublished.

Murthy, S., Chakraborti, B., Roy, M.D., 2010. Palynodating of subsurface sediments, Raniganj Coalfield, Damodar Basin. West Bengal. J. Earth Syst. Sci. 119, 701–710.

Norconsult Consortium, 2007. Notícia Explicativa: Folhas 1039 Muidine, 1040 Palma, 1134 Ponta Messuli, 1135 Lupilichi, 1136 Milepa, 1137 Macalange, 1138, Negomano, 1139 Mueda, 1140 Mocímboa da Praia, 1234 Metangula, 1235 Macaloge-Chiconono, 1236 Mavago, 1237 Mecula, 1238 Xixano, 1239 Meluco, 1240 Quissanga-Pemba, 1334 Meponda, 1335 Lichinga, 1336 Majune, 1337 Marrupa, 1338 Namuno, 1339 Montepuez, 1340 Mecúfi, 1435 Mandimba, 1436 Cuamba, 1437 Malema, 1438 Ribáuè-Mecubúri, 1535 Insaca, 1536.

Nyambe, I.A., Utting, J., 1997. Stratigraphy and palynostratigraphy, Karoo Supergroup (Permian and Triassic), mid-Zambesi Valley, southern Zambia. J. Afr. Earth Sci. 24, 563–583.

Paulino, F., Vasconcelos, L., Marques, J., 2010. Estratigrafia do karoo em Moçambique. Novas unidades. 10° Congresso de Geoquímica dos Países de Língua Portuguesa e 16ª Semana da Geoquímica. In: Flores, M., Marques, M. (Eds.), Memórias no 14. Faculdade de Ciências da Universidade do Porto, Portugal, pp. 1285–1294.

Pereira, Z., Lopes, G., Fernandes, P., Marques, J., 2014. Estudo palinoestratigráfico da sondagem ETA 72 do Karoo Inferior da Bacia de Moatize, Moçambique - Resultados Preliminares. Actas do IX Congresso Nacional de Geologia/2° Congresso de Geologia dos Países de Língua Portuguesa, Porto, Portugal, p. 6.

Pereira, Z., Fernandes, P., Lopes, G., Marques, J., Vasconcelos, L., 2016. The Permian-Triassic transition in the Moatize-Minjova Basin, Karoo Supergroup, Mozambique: a Palynological perspective. Rev. Palaeobot. Palynol. 226, 1–19.

Pinna, P., Jourde, G., Calvez, J.Y., Mroz, J.P., Marques, J.M., 1993. The Mozambique Belt in northern Mozambique: Neoproterozoic (1100-850 Ma) crustal growth and tectogenesis, and superimposed Pan-African (800-550 Ma) tectonism. Precambrian Res. 62, 1–59.

Prevec, R., Gastaldo, R.A., Neveling, J., Reid, S.B., Looy, C.V., 2010. An autochthonous glossopterid flora with latest Permian palynomorphs and its depositional setting in the Dicynodon Assemblage Zone of the southern Karoo Basin, South Africa. Palaeogeogr. Palaeoclimatol. Palaeoecol. 292, 391–408.

Price, P.L., 1997. Permian to Jurassic palynostratigraphic nomenclature. In: Green, P.M. (Ed.), The Surat and Bowen Basins, South-east Queensland. Queensland Department of Mines and Energy, Brisbane, pp. 137–178.

Retallack, G.J., 1995. Permian-Triassic life crisis on land. Sci. New Ser. 267 (5194), 77–80.

Retallack, G.J., 2013. Permian and Triassic greenhouse crises. Gondwana Res. 24, 90–103.

Retallack, G.J., Veevers, J.J., Morante, R., 1996. Global early Triassic coal gap between Late Permian extinction and Middle Triassic recovery of peat-forming plants. Geol. Soc. Am. Bull. 108, 195–207.

Riding, J., and S. Warny, eds., 2008. Palynological techniques by C.A. Brown (second edition): AASP Foundation, The Palynological Society, 146 p.

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. Palaeoclimatol. Palaeoecol. 413, 167–172.

Segroves, K.L., 1967. Cutinized microfossils of probable nonvascular origin from the Permian of Western Australia. Micropaleontology 13, 289–305.

Srivastava, S.C., Jha, N., 1990. Permian–Triassic palynofloral transition in Godavari Graben, Andra Pradesh. Palaeobotanist 38, 92–97.

Steiner, M.B., Eshet, Y., Rampino, M.R., Schwindt, D.M., 2003. Fungal abundance spike and the Permian–Triassic boundary in theKaroo Supergroup (South Africa). Palaeogeogr. Palaeoclimatol. Palaeoecol. 194, 405–414.

Stephenson, M.H., 2016. Permian palynostratigraphy: a global overview. In: Lucas, S.G., Shen, S.Z. (Eds.), The Permian Timescale. vol. 450. Geological Society, London. Special Publications.

Teixeira, C., 1943. Notas para o estudo do "Karroo" da região de Tete, na África Oriental Portuguesa. Bol. Soc. Geol. Portg., Porto 2 (1), 41–46.

Teixeira, C., 1946. Sur la flore fossile du Karroo de Zambésie (Mozambique). C.R. Somm. et. Bull. Soc. Géol. France 16 (13), 252–254.

Teixeira, C., 1947. Contribuição para o conhecimento geológico do Karroo da África Portuguesa. I - Sobre a flora fóssil do Karroo da região de Tete (Moçambique). Na. Junta Missões Geogr. Invest. Colon. 2 (2), 9–28.

Teixeira, C., 1951. Present state of our knowledge concerning the palaeobotany of the Karroo of Portuguese Africa. Rep. Intern. Geol. Congr., 18th, Great Britain (London), 1948. Part 14. Proc. Association des Services Géologiques Africains 214–217.

Teixeira, C., 1952. La flore fossile du Karroo de la Zambesie et la notion de Continent du Gondwana. C.R. Confr. avanc. et. Stratigr. Géol Carbonif.. 3. Heerlen, Ernst van Aelst, Maastricht, pp. 627–630.

Tewari, R., Ram-Awatar, Pandita S.K., McLoughlin, S., Agnihotri, D., Pillai, S.S.K., Singh, V., Kumar, K., Bhat, G.D., 2015. The Permian-Triassic palynological transition in the Guryul Ravine Section, Kashmir, India: implications for Tethyan-Gondwanan correlations. Earth Sci. Rev. 149, 53–66.

Utting, J., 1979. Pollen and spore assemblages from the Upper Permian of the North Luangwa Valley, Zambia. IV International Palynological Conference, Lucknow (1976–77). vol. 2, pp. 165–174.

Vasconcelos, L., 2013. Coal Deposits in Mozambique an Overview. Presentation at FFF Mozambique Coald Conference, October 2013- Johannesburg, South Africa.

Vaz, M., 2017. Palinologia como ferramenta para a reconstituição da história geológica da Bacia Carbonífera de Moatize-Minjova (Karoo, Moçambique). Faculdade de Ciências, Universidade do Porto. Unpublished MSc Thesis. p. 140.

Vijaya, S.M., 2011. Palynostratigraphy of subsurface Upper Permian and Mesozoic Succession, Rakshitpur area, Raniganj Coalfield, West Bengal. Palaeoworld 20, 61–74.

Vijaya, S.M., Tripathi, A., Roy, A., Mitra, S., 2012. Palynostratigraphy and age correlation of subsurface strata within the sub-basins in Singrauli Gondwana Basin, India. J. Earth Sys. Sci. 121, 1071–1092.

Viola, G., Henderson, I.H.C., Bingen, B., Thomas, R.J., Smethurst, M.A., Azevedo, S., 2008. Growth and collapse of a deeply eroded orogen: Insights from structural and geochronological constraints on the Pan-African evolution of NE Mozambique. Tectonics 27, TC5009.

Wheeler, A., Götz, A.E., 2016. Palynofacies patterns of the Highveld coal deposits (Karoo Basin, South Africa): Clues to reconstruction of palaeoenvironment and palaeoclimate. Acta Palaeobot 56, 3–15.

Wignall, P.B., 2007. The End-Permian mass extinction - how bad did it get? Geobiology 5, 303–309.

Wood, G.D., Gabriel, A.M., Lawson, J.C., 1996. Palynological techniques-processing and microscopy. In: Jansonius, J., Mcgregor, D.C. (Eds.), Palynology: Principles and Applications. vol. 1. American Association of Stratigraphic Palynologists Foundation, pp. 29–50.

Wright, R.P., Askin, R.A., 1987. The Permian–Triassic boundary in the southern-Morondava basin of Madagascar as defined by plant microfossils. In: McKenzie, G.D. (Ed.), Gondwana Six: Stratigraphy, Sedimentology, and Paleontology. Geophysical Monograph Series, Washington, pp. 157–166.

Zavattieri, A.M., Gutiérrez, P.R., Ezpeleta, M., 2017. *Syndesmorion stellatum* (Fijałkowska) Foster et Afonin chlorophycean algae and associated microphytoplankton from lacustrine successions of the La Veteada Formation (late Permian), Paganzo Basin, Argentina. Paleoenvironmental interpretations and stratigraphic implications. Rev. Palaeobot. Palynol. 242, 1–20.