Permian climate change recorded in palynomorph assemblages of Mozambique (Moatize Basin, eastern Tete Province)

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ABSTRACT. Knowledge of Late Permian biodiversity patterns, following the end-Guadalupian crisis, is still in its infancy, since most recent studies have focused on the end-Permian biotic crisis. The palynological record of southern Africa, however, reveals major climatic changes during the Late Permian. Here we report new palynological data from eastern Tete Province of Mozambique, documenting the change from cool to warm temperate climates during the Lopingian. This prominent climate signal was also detected recently in other depositional environments elsewhere in southern Africa, and thus enables interregional temporal correlations.

KEYWORDS: palaeoclimate, palynology, coal, Permian, Moatize Basin, Mozambique

INTRODUCTION

During the late Palaeozoic, Gondwana underwent a major climate amelioration following the Carboniferous glaciation. Coal deposits are unique climate archives and Permian postglacial Gondwanan coals are widespread in Karoo basins of sub-Saharan Africa (Cairncross 2001). Although recent studies have focused on climate signatures recorded in palynomorph assemblages from coals of the Main Karoo Basin in South Africa (Götz & Ruckwied 2014, Ruckwied et al. 2014, Wheeler & Götz 2016, 2017), palynological studies on Mozambique's coal with regard to Gondwana's climate history lag behind. The coal-bearing basins of Tete Province, however, provide excellent climate archives, and recent coal exploration in the eastern part of the province has made new core material available for research (Pereira et al. 2016). Recent studies of Mozambican coal deposits have focused on the palynology of the Permian-Triassic transition (Pereira et al. 2016) and the thermal history of the Moatize and Minjova basins (Fernandes et al. 2015, Costa et al. 2016). Here, we report palynological data of interregional importance for deep-time climate reconstruction from Late Permian coals of the Moatize Basin located in eastern Tete Province (Fig. 1). To date, the stratigraphic position and range of the Moatize coals is under discussion and the interest in new palynological data thus enormous.

GEOLOGICAL SETTING

The Permian–Triassic basins of Mozambique form part of a network of rift-related basins of south-central Africa (Cairncross 2001, Catuneanu et al. 2005). Most of the
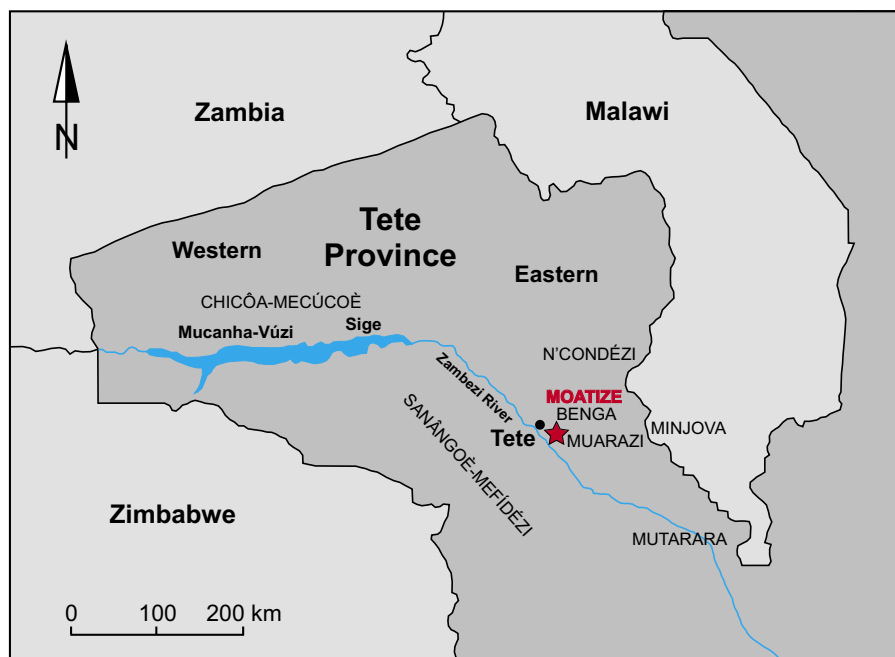
Fig. 1. Study area and sub-basins of the main Zambezi Basin. Falcon et al. (1984b) investigated boreholes from the Mucanha-Vúzi region in western Tete Province. Borehole 948L_0005 (this study, marked by star) is located in the Moatize Basin, eastern Tete Province

coal-bearing Karoo Supergroup equivalent deposits of Mozambique were laid down in an east-west trending, tectonically controlled basin, collectively ascribed to the main Zambezi Basin. The basin axis follows the fabric of the underlying Sanângoè Shear Zone in the Precambrian basement. The main Zambezi Basin may be further divided into several sub-basins (mostly fault-bounded grabens and half-grabens) that are now disconnected due to Jurassic and Cretaceous extensional tectonics and subsequent erosion. From west to east these are variously termed the Chicôa-Mecúcoè (including the Mucanha-Vuzi sector), Sanângoè-Mefídézi, Moatize (or Moatize-Benga), Muarazi and Minjova sub-basins, with northwest and southeast extensions to the Ncondézi (N'condézi) and Mutarara sub-basins (Vasconcelos 2012; Fig. 1).

The borehole utilized in this study penetrated the Moatize sub-basin. Here four main stratigraphic units are present within the Karoo Supergroup, designated, in ascending order, the Vúzi, Moatize, Matinde and Cádzi formations (Fig. 2). Both the Moatize and Matinde formations host coal seams. Traditionally, six main coal zones have been distinguished in the Moatize Formation, which are variously given names, letters or numbers as codes (Neto 1976, Cairncross 2001; Fig. 2). These have been referred to in ascending order as the Sousa Pinto, Chipanga, Bananeiras,

Intermédia, Grande Falésia and André coal seams (Fig. 2). Due to the historic dominance of the Moatize mining area, this seam stratigraphy has become the standard to which coal successions in other sub-basins are compared and correlated.

The Matinde Formation disconformably overlies the Moatize Formation and is the uppermost Karoo unit preserved over much of the Moatize sub-basin (Vasconcelos 2009). The formation generally consists of coarse-grained cross-stratified sandstone, siltstone and mudstone, with variously developed coal seams, which in the lower part are interpreted as having been deposited in fluvial sedimentary environments. It is reported to reach a thickness of 600 m in some areas of Mozambique (Vasconcelos 2009), and Lloyd (2015) sub-divided the succession into a lower and upper unit.

MATERIALS AND METHODS

Borehole 948L_0005 was collared on International Coal Ventures Limited's (ICVL) 948L licence. Here the surface geology is formed mainly by lithologies belonging to the lower and upper levels of the Matinde Formation. Borehole 948L_005 intersected six main coal zones of the Moatize Formation, which are referred to by ICVL, from the base upwards, as the SU, T, VL, VU, XL, XU and MS1 seams (Fig. 3). For palynological analysis, eight samples of organic-rich siltstones were taken from the roof and floor of the XU, VU and VL seams. Siltstones related to coal
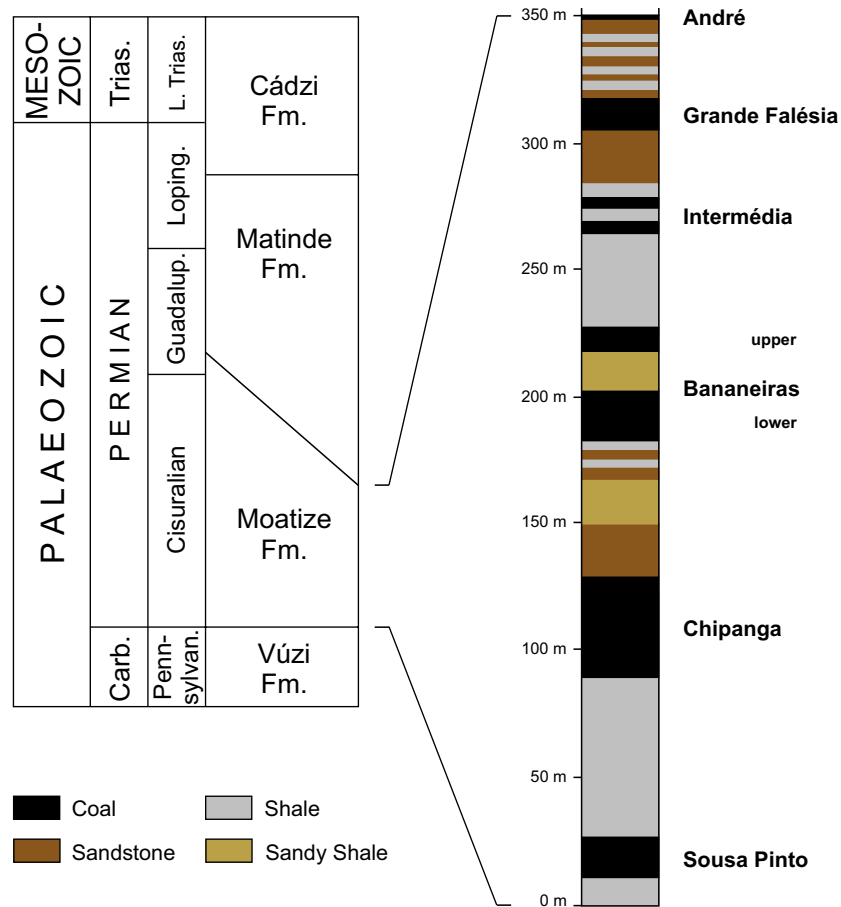
Fig. 2. Coal zones of the Moatize Formation (Sousa Pinto, Chipanga, Bananeiras, Intermédia, Grande Falésia and André), Moatize Basin, eastern Tete Province, and their stratigraphic position (Cisuralian) based on the relation to the underlying glaciofluvial deposits of the Vúzi Formation, which is to date correlated with the Pennsylvanian Dwyka Group of the Main Karoo Basin, South Africa (Vasconcelos 2009). However, palynological data from borehole 948L_0005 reveal a younger (late Guadalupian–Lopingian) age of the Moatize coals. Furthermore, the top of the Vúzi Formation and base of the Moatize Formation was recently dated as Kungurian/Roadian, i.e. late Cisuralian–early Guadalupian (Lopes et al. 2014), and Pereira et al. (2016) identified the Permian-Triassic boundary within the overlying Matinde Formation

seams are most suitable for palaeoenvironmental and palaeoclimate analyses since they contain auto- and allochthonous fractions of organic particles, thus documenting both the local depositional environment as well as climate-related changes within a stratigraphic succession.

Stratigraphically, the borehole is dominated by four thick (usually over 100 m) stacked packages. The basal unit (391.04–514.30 m) is incomplete, and preserves only the top carbonaceous mudrock-dominated package, which has thin coals at various levels. The top part of this succession was targeted by samples 7 and 8 (395.57–395.81 m, 399.84–400.05 m). This basal succession is overlain by an overall fining-upward succession (391.04–305.28 m), which has a medium- to coarse-grained, cross-stratified sandstone-dominated lower half, which is interpreted as the product of bedload-dominated braided rivers (Fig. 3a), and an upper half dominated by the VU Seam. Both the floor (sample 6; 343.57–343.79 m) and roof (samples 3, 4, 5; 309.33–309.55 m, 315.16–315.39 m, 317.25–317.50 m) of this seam were targeted. The third unit (305.28–136.48 m) also forms an overall fining-upward succession, but is significantly thicker than the underlying unit. It also has a basal sandstone-dominated unit, but one that is finer, with a greater percentage of carbonaceous sandstone (Fig. 3b). This unit is interpreted to have been deposited in a lower energy fluvial setting than that for the VL-VU interburden package, in a more distal, lacustrine braid-delta setting. The upper part is formed by the XL, XU and MS1 seams, which are all genetically related. The XU and MS1 seams are separated by a coarsening-upward sandstone-dominated unit. Samples 1 and 2 (201.17–201.40 m, 222.34–222.54 m) targeted the floor and roof of the XU Seam. Above the MS1 Seam, the uppermost unit (136.48 m – surface) is also formed by a thick sandstone-dominated succession, but unlike the lower units this one generally coarsens, then fines upwards.

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

Sedimentary organic matter is grouped into phytoclasts, sporomorphs (pollen grains and spores), freshwater algae, and degraded and amorphous organic matter (DOM/AOM) for palynofacies analysis. The relative percentages of these components are based on counting at least 300 particles per slide.
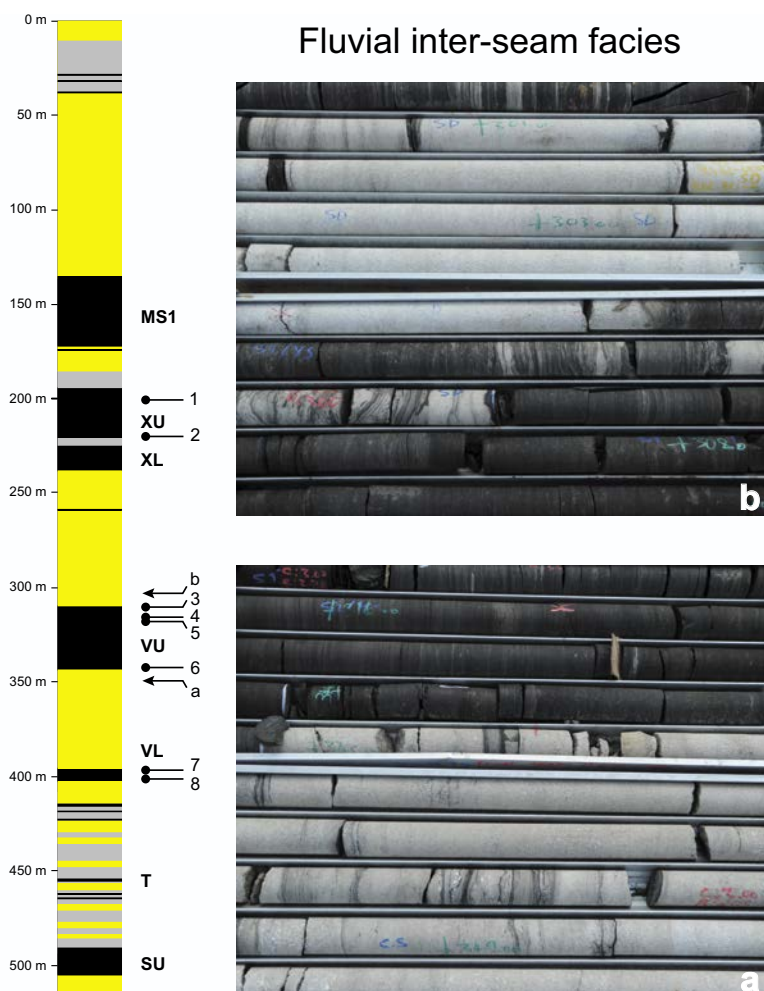
Fig. 3. Stratigraphic log of borehole 948L_005 showing the main seams intersected (SU, T, VL, VU, XL, XU, MS1), position of the palynological samples (1–8), and fluvial inter-seam facies. **3a**: Top of VL-VU interburden (341.00–350.00 m) showing the abandonment phase of the braided river system and the gradational changeover to a swamp setting (VU); **3b**: Contact between the VU and VU-XL interburden (300.00–309.00 m) showing the development of the river channel takeover. Arrows mark position of the illustrated intervals (a, b) within the succession

PALYNOSTRATIGRAPHY

A detailed palynostratigraphic zonation of coal-bearing Permian successions of the South African Karoo Basin was established by Falcon et al. (1984a) and applied to the Mucanha-Vúzi Basin of western Tete Province, Mozambique, for coal seam identification and correlation (Falcon et al. 1984b). Biozones III (sub-zone F) and IV (sub-zones G and H), representing a Middle to early Late Permian (Guadalupian/Lopingian) age, were identified within the two boreholes studied from western Tete Province by Falcon et al. (1984b) and comprise the *Sulcatisporites-Protohaploxypinus* Sub-Assemblage, *Protohaploxypinus-Vittatina-Striatopodocarpites* Sub-Assemblage, and *Protohaploxypinus-Vittatina-Guttulapollenites-Lueckisporites* Sub-Assemblage (Fig. 4).

Palynomorph assemblages of borehole 948L_0005 from eastern Tete Province reveal a slightly younger age (Fig. 4). The lowermost samples from seams VL and VU (399.84–400.05 m, 395.57–395.81 m, 343.57–343.79 m, 317.25–317.50 m, 315.16–315.39 m, 309.33–309.55 m) represent subzone H (*Protohaploxypinus-Vittatina-Guttulapollenites-Lueckisporites* Sub-Assemblage), and the topmost samples from seam XU (222.34–222.54 m, 201.17–201.40 m) represent subzone H[1] (*Protohaploxypinus* Sub-Assemblage). The presence of *Lueckisporites virkkiae* suggests correlation with the *Lueckisporites virkkiae* Interval Zone of the Brazilian Paraná Basin (Souza & Marques-Toigo 2005), which is interpreted to be Guadalupian in age. Thus, we place the entire succession chronostratigraphically into the uppermost Guadalupian and Lopingian. Similar palynomorph assemblages

were recently described from two coal exploration boreholes of the Moatize Basin (Pereira et al. 2016), which were interpreted as Lopingian. These assemblages are also dominated by glossopterid pollen grains, cavate trilete spores (*Kraeuselisporites* spp.), associated with conifer and pteridosperm pollen grains (*Lueckisporites virkkiae*, *Guttulapollenites hannonicus* and *Weylandites lucifer*). Late Permian palynomorph assemblages previously reported from other parts of Gondwana that were geographically close to Mozambique before the Gondwanan breakup, including data from Zimbabwe (Falcon 1975, 1978), Zambia (Nyambe & Utting 1997), Kenya (Hankel 1992), Madagascar (Wright & Askin 1987), India (Srivastava & Jha 1990, Jha 2006, Vijaya 2011) and Pakistan (Balme 1970, Hermann et al. 2012), show compositions similar to our findings from borehole 948L_0005 of the Moatize Basin, with

key genera including *Kraeuselisporites*, *Lueckisporites*, *Protohaploxypinus*, *Striatopodocarpites* and *Weylandites*. However, one has to consider that Late Permian assemblages vary across Gondwana (e.g., Backhouse 1991, Lindström 1996), which make precise correlation between the eastern, central and western parts of the supercontinent difficult.

The palynomorph assemblage encountered from the Moatize Basin is most comparable with assemblages described from outside of southern Africa in Madagascar, India, and Pakistan. Late Permian assemblages in Madagascar are dominated by *Guttulapollenites hannonicus*, *Weylandites* spp. and *Lueckisporites virkkiae*, with *Protohaploxypinus* spp. and *Striatopodocarpites* spp. also common. In Pakistan, the occurrence of abundant *Alisporites* spp., *Guttulapollenites hannonicus*, *Kraeuselisporites* spp., *Lueckisporites* spp., *Playfordiaspora* sp.,
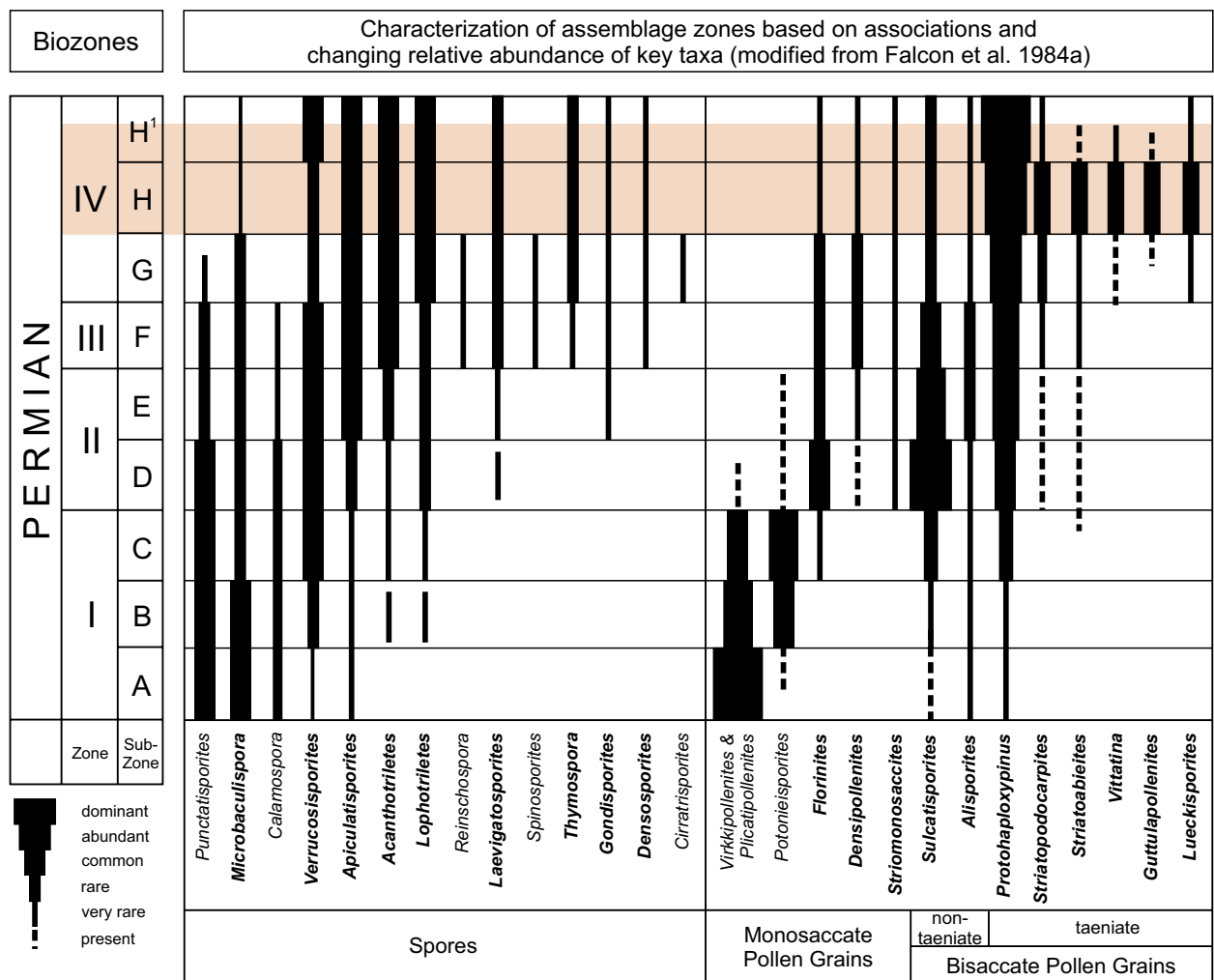

Fig. 4. Palynostratigraphic position of strata intersected in borehole 948L_0005 (highlighted in red) and identified taxa (highlighted in bold) in relation to the stratigraphic position of the coal-bearing series of the Main Karoo Basin (Falcon et al. 1984a). Relative abundances of palynomorphs are indicated as present (1 count), very rare (< 1%), rare (1–4%), common (5–10%), abundant (11–25%), dominant (> 25%)
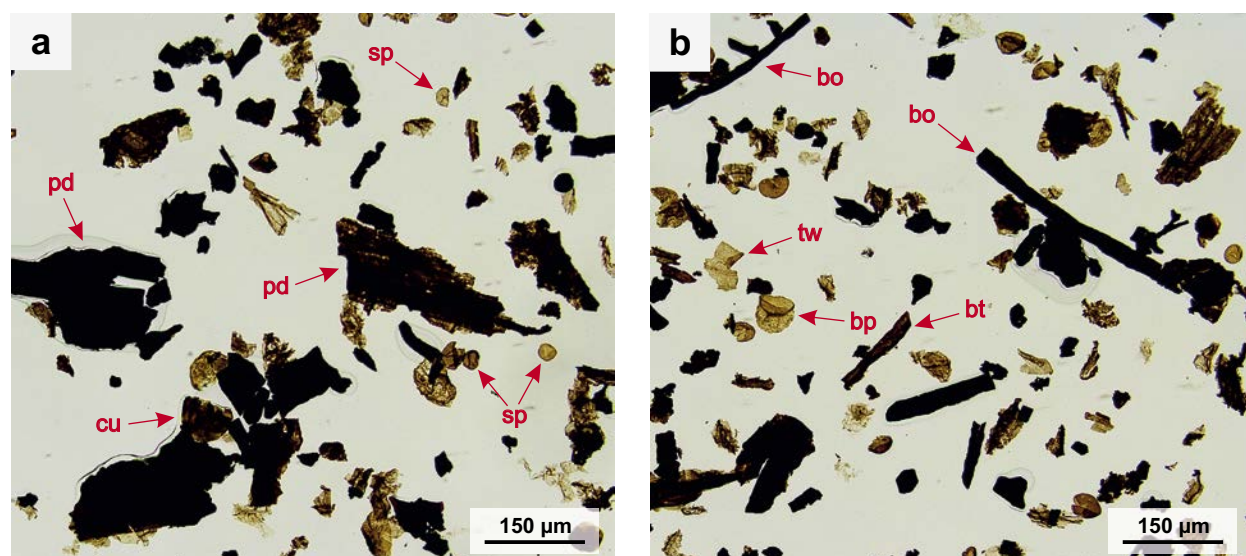
Fig. 5. Palynofacies of borehole 948L_0005. **5a**: Swamp setting characterized by large plant debris (pd), cuticles (cu) and trilete spores (sp) (seam VU); **5b**: Lacustrine setting with bisaccate pollen grains (bp), translucent wood remains (tw), blade-shaped translucent (bt) and blade-shaped opaque phytoclasts (bo) of different sizes (seam XU)

Protohaploxypinus spp., *Striatopodocarpites* spp. and *Weylandites lucifer* is characteristic of Late Permian assemblages. In India, *Protohaploxypinus* spp., *Striatopodocarpites* spp. and *Faunipollenites* spp. are the dominant elements. Other common taxa are *Alisporites* spp., *Densipollenites magnicorpus*, *Striatisulcites ovatus*, *Tiwarisporites* sp., *Osmundacidites* sp. and *Weylandites* spp., while *Guttulapollenites* are rare elements of the assemblage. In contrast, Late Permian assemblages described from Antarctica (Lindström 1996, Lindström & McLoughlin 2007) including *Alisporites* spp., *Ephedripites* sp., *Marsupipollenites* spp., *Praecolpatites sinousus*, *Protohaploxypinus* spp. and *Striatopodocarpites* spp., as well as assemblages from Australia (Backhouse 1991, Mory & Backhouse 1997, Price 1997) with *Dulhuntyispora parvithola*, which has never been found outside Australia, differ clearly from the Mozambican assemblages.

Previously, the coals of the Moatize Formation of the Tete Province were interpreted as Lower Permian deposits of Artinskian–Kungurian age (Cairncross 2001). However, the here-presented data from borehole 948L_0005 reveal a younger (late Guadalupian–Lopingian) age, and correspond to the findings of Mugabe (1999) who described a Late Permian palynomorph assemblage at the top of the Moatize Formation. Thus, the coal-bearing successions might be much thicker than previously assumed, which has implications for future coal mining in eastern Tete Province. In a fully preserved Moatize-Matinde succession possibly more than

50 coal-bearing units are expected, as inferred from the current sedimentological model (Lloyd 2015). Palynological data from the Matinde Formation revealing a Late Permian/Early Triassic age (Pereira et al. 2016) support the sedimentological interpretation of stratigraphically younger coals. Radiometric dates, as recently published from Late Permian successions in the Main Karoo Basin of South Africa (Rubidge et al. 2013, Gastaldo et al. 2015, McKay et al. 2015), are not yet available for the coal-bearing Moatize-Matinde succession to calibrate the available palynological data in a chronostratigraphic context.

PALAEOENVIRONMENT AND PALAEOCLIMATE

Palynofacies of the lower part of the studied succession (seams VL and VU; samples 399.84–400.05 m, 395.57–395.81 m, 343.57–343.79 m, 317.25–317.50 m, 315.16–315.39 m, 309.33–309.55 m) are dominated by opaque phytoclasts of various sizes and shapes, large cuticle fragments and plant debris together with trilete spores (Fig. 5a). Sedimentary organic matter in the upper part of the section (seam XU; samples 222.34–222.54 m and 201.17–201.40 m) is characterized by a higher amount of translucent and blade-shaped opaque phytoclasts, bisaccate pollen grains (Fig. 5b) and freshwater algae (*Tetraporina* sp., *Botryococcus* sp.). This change in palynofacies is interpreted to document a local change

in palaeoenvironment from swamp-dominated to lacustrine-dominated settings (Fig. 6). The higher amount of freshwater algae and the preservation of amorphous organic matter (AOM) in the upper part of the succession may point to hydrologically closed and stratified lake basins that developed from broad swamp areas rich in fern and horsetail vegetation. Fluvial deposits intercalating the organic-rich shales, siltstones and coals record river-dominated phases (Figs 3, 6) with low preservation of organic material, reworking and oxidation.

The palynomorph assemblages studied show striking changes within the succession (Figs 4, 6): the lower part is dominated by trilete spores (*Acanthotriletes* spp., *Apiculatisporites* spp., *Lophotriletes* spp.), monolete elements (*Laevigatosporites* sp., *Thymospora* sp.) being present (seam VL; samples 399.84–400.05 m and 395.57–395.81 m). The middle part of the section (seam VU; samples 343.57–343.79 m, 317.25–317.50 m, 315.16–315.39 m, 309.33–309.55 m) clearly shows a relative increase in pollen grains, monosaccate (*Florinites* spp., *Densipollenites* sp.) and bissacate non-taeniate elements (*Sulcatisporites* spp., *Alisporites* spp.) dominating the assemblage, bisaccate taeniate pollen grains (*Guttulapollenites hannonicus*, *Vittatina* spp.) being present. Up section (seam XU; samples 222.34–222.54 m and 201.17–201.40 m), bisaccate taeniate pollen grains (*Protohaploxypinus* spp., *Lueckisporites*

spp.) form the dominant group. The dominance of taeniate bisaccate pollen grains was also reported by Falcon et al. (1984b) from coeval strata of the Mucanha-Vúzi Basin of western Tete Province.

The recorded stratigraphic change of a fern and horsetail lowland community and an upland conifer community characterized by monosaccate- and non-taeniate bisaccate-producers to a gymnospermous flora of taeniate bisaccate-producers is interpreted to reflect the transition from cool to warm temperate climate conditions in the Lopingian, as also inferred from oxygen isotope data (Veizer & Prokoph 2015). Even though data from one borehole provide only limited information to distinguish between changes that are a response to local or regional shifts in the depositional setting (biome structure and taphonomy) and changes that are related to global-scale climatic shifts, differences in the composition of palynomorph assemblages within the succession studied allow for palaeoclimate interpretation. In particular, the change in the pollen-producing upland vegetation, not reflecting local changes within lowland swamp and lake settings, most likely records a climatic signature. In a global context, this shift in vegetation is assumed to document the final switch to warming greenhouse conditions in sub-Saharan Africa, persisting during the Lopingian and preceding Triassic hothouse conditions (Sun et al. 2012).
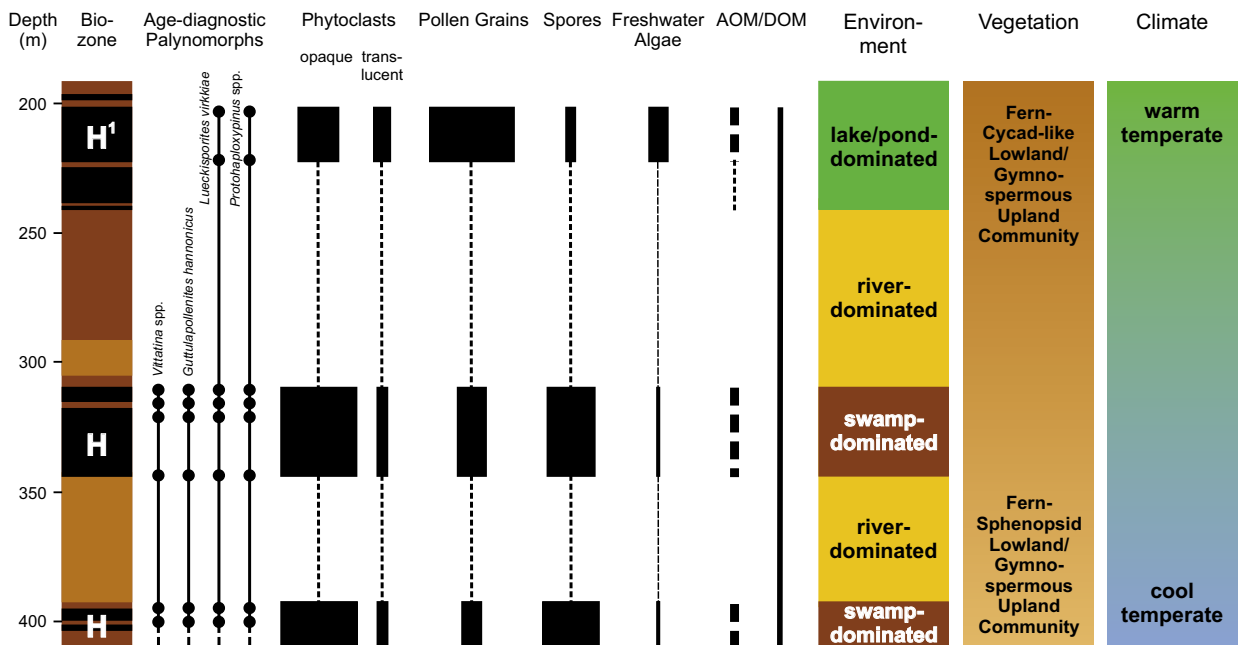

Fig. 6. Palynofacies patterns of borehole 948L_0005 (seams VL, VU, XU) and interpretation of palaeoenvironment, vegetation and climate. Biozones after Falcon et al. (1984a): H = *Protohaploxypinus-Vittatina-Guttulapollenites-Lueckisporites* Sub-Assemblage, H¹ = *Protohaploxypinus* Sub-Assemblage with distribution of age-diagnostic palynomorphs identified

The recently published updated global temperature curve for the Phanerozoic (Scotese 2016), showing drastic warming during the Lopingian, supports this interpretation. However, from the here presented Moatize dataset, superimposition of climatic and environmental signals has to be taken into account. Future studies integrating sedimentological, geochemical, and palynological data from Mozambican coals will serve to develop a more robust climate model for central Gondwana during Lopingian times.

CONCLUSIONS

Palynological data from the Moatize Basin located in eastern Tete Province of Mozambique reveal changes in palaeoenvironment and palaeoclimate during the Late Permian. The transition from cool to warm temperate climates during the Lopingian is recorded in palynomorph assemblages from the studied borehole. This prominent climate signal is seen as a powerful stratigraphic tool for interregional correlations of Gondwanan coals. Thus, it adds to coalfield exploration and development, coal seam identification and correlation. Furthermore, the palynological record of Gondwanan coals facilitates climate reconstruction in deep time and at high time resolution. Ongoing studies aim to establish a high-resolution palynostratigraphic framework of the Moatize Basin, including climatic signatures, to further develop intra-Gondwanan correlation schemes. The here presented palynological data show the potential for future application to Mozambican cross-basin and intra-basinal correlation.

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