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2021

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Fossil woods from the Permian and Triassic of Mozambique: taxonomy, palaeocology and geoconservation



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A dissertation submitted to the Faculty of Science, University of the Witwatersrand, in fulfilment of the requirements for the degree of Master of Science

Johannesburg, May of 2021

DECLARATION

I declare that this Dissertation is my own, unaided work. It is being submitted for the Degree of Master of Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.



(Signature of candidate)

28th day of May 2021

ABSTRACT

Despite the discovery of immense fossil forests in Mozambique over 150 years ago, meager palaeontological research has been directed to this unique legacy of Earth's history. As a consequence, only one outdated genus was known to date in Mozambique. To change this scenario, fossil woods from Permian and Triassic formations from the Tete and Niassa Provinces, Centre and Northern of Mozambique, were collected during three consecutive field campaigns in 2017, 2018 and 2019. Over 300 samples were sectioned and studied microscopically. As a result, important insights on the taxonomy, palaeoecology, palaeoclimates and geoconservation are provided and improve significantly our knowledge on one of the largest fossil forests in the world. Taxonomically, six genera and seven species are now identified, consisting of *Agathoxylon africanum*, *Agathoxylon karooensis*, *Australoxylon teixeirae*, *Prototaxoxylon uniseriale, Taxodioxylon* sp., *Cupressinoxylon* sp. nov, *Protaxodioxylon* sp. nov. 1 and *Protaxodioxylon* sp. nov. 2. The latter three taxa are assigned to new species but only the latter two have been submitted for publication. *Agathoxylon africanum* and *Australoxylon teixeirae* seem to be endemic to Gondwana, sustaining the idea of species-level provincialism based on Glossopteris leaf fossils. With the addition of the Mozambican occurrence, *Australoxylon teixeirae* represents the most widespread taxon in Gondwana. Based on growth ring analysis, it is found that the trees sampled show well-marked, wide, growth rings suggesting well-defined seasons. Most of the woods studied present rings belonging to D-type and S-type. S-type growth rings indicate extreme conditions dominated by very wet and hot climate with the possible occurrence of disease or post-depositional compression. Four fossil forests were also analyzed qualitatively and quantitatively. These forests, subdivided into Nhambando, Mapembera, Cadzewe and Carangache, are interesting for geotourism. In Mozambique, however, more straightforward decisions are needed to ensure the full legal protection of such sites and the implementation of safe geotourism. Although the number of specimens with good preservation is relatively low, this study represents an important contribution to fill gaps in the understanding of the Gondwana palaeoflora in the Southern Hemisphere as a whole.

Key words: Fossil woods, *Mozambican Karoo*, palaeoclimate, geoconservation, taxonomy

ACKNOWLEDGEMENTS

My entire gratitude and thanks go to my Supervisors Prof. Marion Bamford and Dr. Ricardo Araújo for all support, expert guidance, and wisdom that allowed me to carry on in order to overcome the hurdles and foster my amazement in the wonderful field of Palaeobotany. Thanks go out to the many people who assisted with sample collection, particularly Zanildo Macungo, Stephen Tolani, Roger Smith, Salimo Murrula, Issaia Macaneta, Nevas Gimo, and the local guides either in Tete and Niassa are also acknowledged. Fossil wood samples were prepared by Prosper Bande. Many thanks to Mariza Amaral and Sheila Zunguza for assistance with Adobe Illustrator and ArcGIS which has greatly aided in the preparation of this work and the paper submitted based on some data of this dissertation. Other acknowledgement goes to Al Robb (Exxon Mobil Mozambique Ltd.) for providing literature, inputs on research process, and friendship during this journey. Daúd Jamal (Eduardo Mondlane University, Geology Department) and Fátima Chauque (Instituto Nacional de Minas) for allowing me to have access to the Microscopy when I could not travel to South Africa because of Covid restrictions are also acknowledged.

This dissertation is dedicated to my mother Rita Gonçalves Canda who taught me the values of education and gave everything to educate us (my brothers and myself). Also, the dedication extends to my father Ernesto Nhamutole. For my father I simply say Rest in Peace and I hope to never disappoint you because you have been an inspiration through this journey. Additional thanks go to the direction of the Museu Nacional de Geologia (MNG) namely: Dino Milisse (Director), Estela Cuambe (Chief of the Financial department), Lino José (ex-Chief of the Technical Department at the MNG), and Marcelino Moiana (current Chief of the Technical department at MNG). In addition, this is research would not be possible without the funding provided by PAST (Palaeontological Scientific Trust), Centre of Excellence in Palaeosciences (CoE-Pal), Fundo Nacional de Investigação de Moçambique (FNI), FCT/Aga Khan Foundation and National Geographic Society (NGS).

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CHAPTER ONE – INTRODUCTION

1.1 Introduction

Palaeoxylotomy, which is the emphasis on silicified woods, is an important branch of Palaeobotany. Its applications include reconstruction of palaeoenviroments, palaeoclimates, identification and correlation of rock sequences based on the same plant assemblages, and indication of past vegetation. Some basins of the Karoo across southern Africa have almost a continuous sedimentation from the Carboniferous to the Jurassic, and as such the field of Palaeobotany has only received multiple continued contributions from South Africa. The Main Karoo Basin (MKB) has been extensively studied for a long period of time, yielding as a consequence interesting discoveries (Plumstead, 1956; Bamford, 1999; Prevec *et al*., 2009; Kock, 2018; Barbolini *et al*., 2019; Bamford, 2016, Bamford *et al*., 2020 and others). The MKB and other smaller basins across southern Africa are better known for their fossil record of vertebrates from Permian and Triassic ages. Indeed, vertebrates have been mostly used for their correlation with the MKB (Castanhinha et al., 2013; Sidor *et al*., 2015; Araújo *et al*., 2020).

The fossil wood record of Permian and Triassic basins in Mozambique (Tete and Niassa Provinces) are addressed in this present dissertation. However, it should be noted that several authors have studied the palaeoflora in Niassa and Tete, but more focused on fossil leaves, pollen and spores (Zeiller, 1883; Teixeira, 1950; Teixeira and Gonçalves, 1959; Verniers *et al.,* 1989; Hancox, 2015; Pereira *et al*., 2016, 2019; Gotz *et al*., 2017; Galasso *et al*., 2019, Lopes *et al.,* 2020), perhaps due to the lack of local expertise. However, the PaleoMoz project has dedicated the last decade to change this scenario. Some important contributions are from Silva *et al*. (1967), Marguerier (1973), and Verniers *et al*. (1989). This dissertation represents an expansion to the study of fossil woods from Mozambique. The research here presented focuses on four different aspects: Taxonomy, Palaeoclimatology, Palaeogeography and Geoconservation. Determining the alpha taxonomy present in the various basins herein studied is the first step towards further analytical approaches. Furthermore, the taxonomy was in serious need of revision because old generic synonyms have not been revised for more than three decades. As a matter of fact, all the fossil trunks found in Mozambique were assigned to the genus

Dadoxylon (Silva *et al*., 1967; Verniers *et al*., 1989), which is currently considered a nomen dubium (Rößler *et al*., 2014). Therefore, in the light of recent taxonomic revisions of Austral fossil wood (Philippe and Bamford, 2008), a taxonomic revision of Mozambican material was warranted. The Permian and Triassic palaeoclimatology in Mozambique is still insufficiently known, and is mostly focused on the lithostratigraphy and palynological proxies (Vasconcelos, 2009, Verniers et al., 1989), despite recent advances (Araújo *et al.* 2020). However, knowledge and understanding of the Mozambican Permian and Triassic landscape is now starting to be built up with contributions of the wood paleoflora.

The Magoé fossil forest in Mozambique is the most extensive in Africa (Araújo *et al*., 2017), thus new taxa are expected to contribute to the paleodiversity of the Southern Hemisphere ecosystems. Furthermore, Mozambican fossil forests have the potential for tourism. This is important for regional socio-economical development. Without research, it would be impossible to know the potential that exists. Briefly, this dissertation will contribute to a better understanding of the plant palaeodiversity, and their implications for palaeoecology and palaeoclimatology in the Permian and Triassic formations of Mozambique. It will, therefore, serve as an aid for future geoconservation management plans mainly in the Tete fossil forest areas. Also, given the paleoposition of Mozambique during the transition between Palaeozoic and Mesozoic, this research will fill the gap needed for the understanding of the Karoo floral ecosystem.

1.2 Anatomical features observed in the studied fossil woods

1.2.1 Bordered radial pitting

In most paleoxylological studies of softwoods (gymnosperms or tracheidoxyls), bordered radial pitting is attributed to araucarian, abietinean or mixed type (Bamford and Philippe, 2008).

Araucarian type: woods where more than 90% of pits on the radial wall of tracheids are contiguous with neighbouring pits.The araucarian radial pitting is biseriate, triseriate or rarely quadriseriate or uniseriate, and always alternate, rarely opposite to

sub-opposite. (Fig 1.1left). They are often somewhat flattened with recognised absence of Bars of Sanio (IAWA, 2004; Bamford and Philippe, 2008; Philippe *et al*., 2014).

Abietinian type

Woods with abietinean radial pitting are usually opposite, somewhat flattened when contiguous, and separated by Crassulae (Figure 1.1). The Crassulae or Bars of Sanio is not always present (IAWA, 2004; Bamford and Philippe, 2008;).

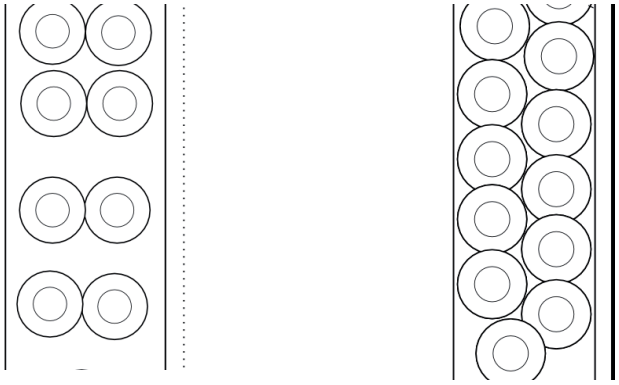


Figure 1.1: Different types of radial pitting adapted from Pujana *et al*., 2016, Left: Abietinian, Right: Araucarian.

1.2.3 Cross-Field pitting

Cross-field pitting is the most used feature for softwood identification (Gerrards *et al*., 2007). They are the pits between the vertical tracheids and horizontal ray parenchyma cells. The cross-field pitting is crucial to the identification of coniferous woods. Cross-field pit features include frequency, arrangement, form, size and/or position of the apertures relative to the border of the pits. There are several types of cross-field pitting that can be listed in categories (Barefoot and Hankins, 1982; Vogel, 1995), however, attention will be given for those that are found in Mozambique woods.

1.2.4 Types of Cross-field

Cupressoid

Cupressoid pits have elliptical and ovoid apertures included within the limits of the pit border, and the apertures are conspicuously narrower than the border. The long axis of the apertures varies in position from vertical to horizontal even within a single specimen. This type of pitting is characteristic of most Cupressaceae and is also observed in some Podocarpaceae and Taxaceae (Kukachica, 1960; IAWA, 2004).



Figure 1.2: Cupressoid cross-field pitting, modified from Philippe, 1995.

Taxodioid

Taxodioid pits have a large, ovoid-to-circular included aperture that is wider than the space on either side between the aperture and the border. Taxodioid pitting can be found in most taxa of Cupressaceae, but also in several species of Podocarpaceae. In certain Cupressaceae, particularly *Sequoia*, the cross-field pits are commonly arranged in rows of two to three pits per cross-field (Kukachica, 1960; IAWA, 2004).

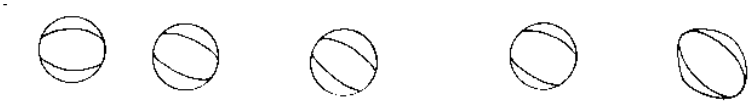


Figure 1.3: Taxodioid cross-field pitting, modified from Philippe, 1995.

Araucarioid

The individual pits display an elliptical aperture and are narrower than the border, (Barefoot and Hankins 1982; Ilic, 1995). The pits are arranged in alternate rows of usually three or more with a tendency for crowding; individual pits often have a polygonal outline similar to the alternate pitting in Araucariaceae. This type of pitting is restricted to Araucariaceae (*Agathis, Araucaria*).

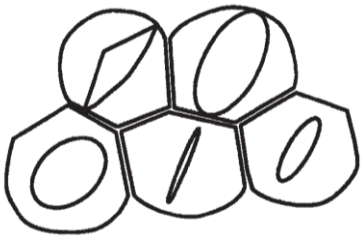


Figure 1.4: Araucarioid cross-field pitting modified from IAWA, 2004.

Spiral Thickening

Spiral thickening represents the ridges on the inner face of the tracheids with a tendency to extent over the entire body of the respective cell. The presence of the spiral thickenings, their relative size is used to to differentiating some species. For instance, *Sequoia* and *Taxodium* are readily separated anatomically on this basis.

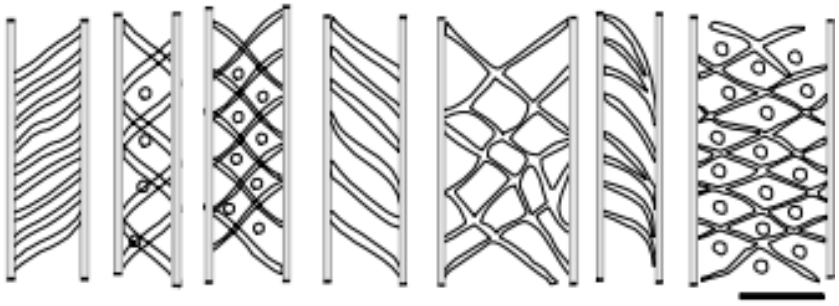


Figure 1.5: Microscopic images showing different arrangement of spiral thickening adapted from IAWA, 2004.

1.2.5 Various tissues in softwoods

Tracheids

Tracheids are the bigger components of softwoods being basically long cells, sometimes 100 times longer than wide. The tracheids are associated with conductive and mechanical aspects on woods. In the transverse section (e.g., Figure 1.6), tracheids seems to square or rectangular cells in radial rows. Within one growth ring, they can be thin-walled in the earlywood and thicker-walled in the latewood.

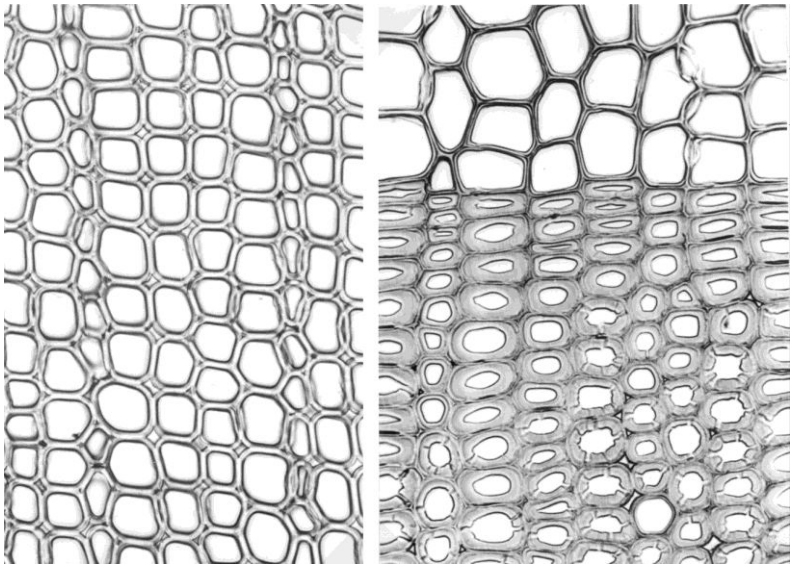


Figure 1.6: Intercelular spaces between tracheids, Scale bar = 50 µm.

Axial Parenchyma

The axial parenchyma is easily observed because their dark contents. The dark contents of vertical parenchyma are shown in Fig. 1.7 below. In some taxa, the axial parenchyma can be restricted to the growth ring boundary or interspersed throughout it (IAWA, 2004).

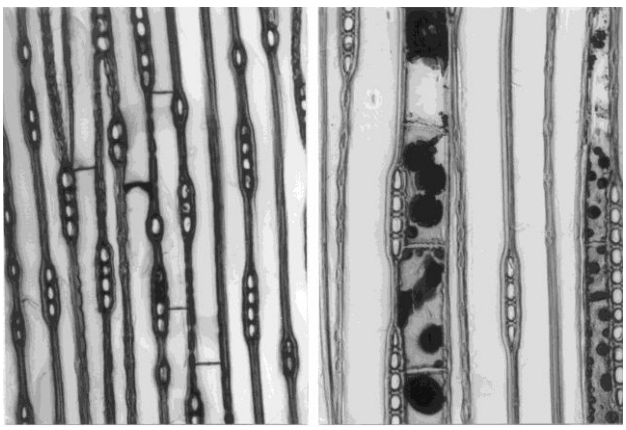


Figure 1.7: Transverse end walls of axial parenchyma cells obtained from IAWA, 2004.

1.2.6 Growth rings

Growth rings represent the dimension of wood expansion, thus influencing its width in a given season growth. The ring formation is a result of combination of the small, thick-walled cells, termed latewood formed at the end of the growing season, and the larger, thin-walled ones formed at beginning of the next growing season (Creber, 1984).

The growth ring studies in fossil wood offer a variety of approaches that can be used as proxy climate records (Creber and Francis, 1999; Parrish, 1999). These parameters include the presence or absence of growth rings (indicative of seasonal or non-seasonal climates respectively), or ring width as an indicator of growing conditions (Fritts, 1976, Schweingruber, 1988). For instance, wider rings, especially on larger trunks, are formed when growing conditions are favourable, with higher temperatures and adequate rainfall, such as in a warm temperate to tropical climate at the present day. In an arid or very cold climate the rings are narrow, sometimes only a few cells wide. If there is little or no year to year variation in climate, a series of very similar ring widths will result and these being termed 'complacent' (KocK, 2018). Conversely, a variable sequence is termed 'sensitive' (Kock, 2018).

Although can be found limitations to the use of fossil growth ring analysis for climate study, some information can be determined from fossil tree rings (Parrish and Spicer, 1988; Kumagai *et al*., 1995; Keller and Hendrix, 1997).

Growth rings can be divided into six groups, based on the relative width of the earlywood and latewood bands and the transition from earlywood to latewood (Figure 1.8 and Table 1.1). Each of the six groups is associated with a specific climate attribute and can therefore be used to supplement the palaeoclimate interpretation (Table 1.2) (Brison *et al*., 2001; Butterfield, 2003; Bamford, 2016). The earlywood and latewood transition is defined by the changes either in tracheid wall thickness or radial diameter. The transition can be gradual or abrupt. The type of transition is mainly controlled by growth conditions and weather (Krausel and Eckstein, 1992). Other factors that can influence the type of transition are compression wood, false growth rings, and flood-induced wood structure. Woods

can display one type of transition and then change to another type gradually, particularly in the wide rings of fast grown trees.

Narrow growth rings resulting from slow radial growth usually do not allow a reliable differentiation of gradual vs. abrupt transition between early- and latewood. This is particularly evident in *Sequoia sempervirens* and *Thuja plicata* (Cupressaceae), *Tsuga heterophylla* (Pinaceae) and *Pseudotsuga menziesii* (Pinaceae) from old growth stands.

Table 1.1: Six types of growth rings adapted from Creber and Chaloner (1984), Bamford (2016), Bamford *et al*. (2020).

Ring type	**Description**	**Climate interpretation**
A	Sharp earlywood–latewood transition, usually with narrow latewood	Good water supply
B	Gradual earlywood–latewood transition, usually with wide latewood	Long growing season with adequate water supply
C	Very gradual earlywood–latewood transition	Little change throughout the growing season
D	Uniform growth but terminal event to retard or stop growth, ring boundary is visible	Uniform growing season
E	Same as D but the ring boundary is very difficult to see	Uniform growing season
O	No growth rings	Uniform climate, no seasonality
S	Shear zones present and usually associated with narrow latewood	favourable climate

Table 1.2: Anatomical features of growth rings (Chaloner and Creber, 1990, Falcon-Lang 2000a, Kock, 2018).

Anatomical Feature	Climate Interpretation
Presence or absence of growth rings	**Present growth rings** = distinct, regular climate seasonality **Absent growth rings** = non-seasonal climate
Width of each growth ring	**Narrow growth rings** = arid or cold climate **Wide growth rings** = favourable growing conditions i.e. warm temperatures and sufficient rainfall
Mean sensitivity (mean variability in ring width)	**Little/no ring width variation** = favourable, uniform climate with 'complacent' trees **High ring width variation** = climate with fluctuating conditions and 'sensitive' trees
Presence of false rings or frost rings	**False rings** = occurrence of a drought, fire or insect attack event **Frost rings** = occurrence of extreme frost event
Percentage of latewood	**Low percentage** = unfavourable conditions towards end of growing season **High percentage** = favourable conditions towards end of growing Season
Deviation of cell diameter from mean cell diameter	**Deviation (CSDM curve) is symmetrical or skews left** = deciduous tree (sheds leaves annually) **Deviation (CSDM curve) skews right** = evergreen tree (retains leaves throughout year)

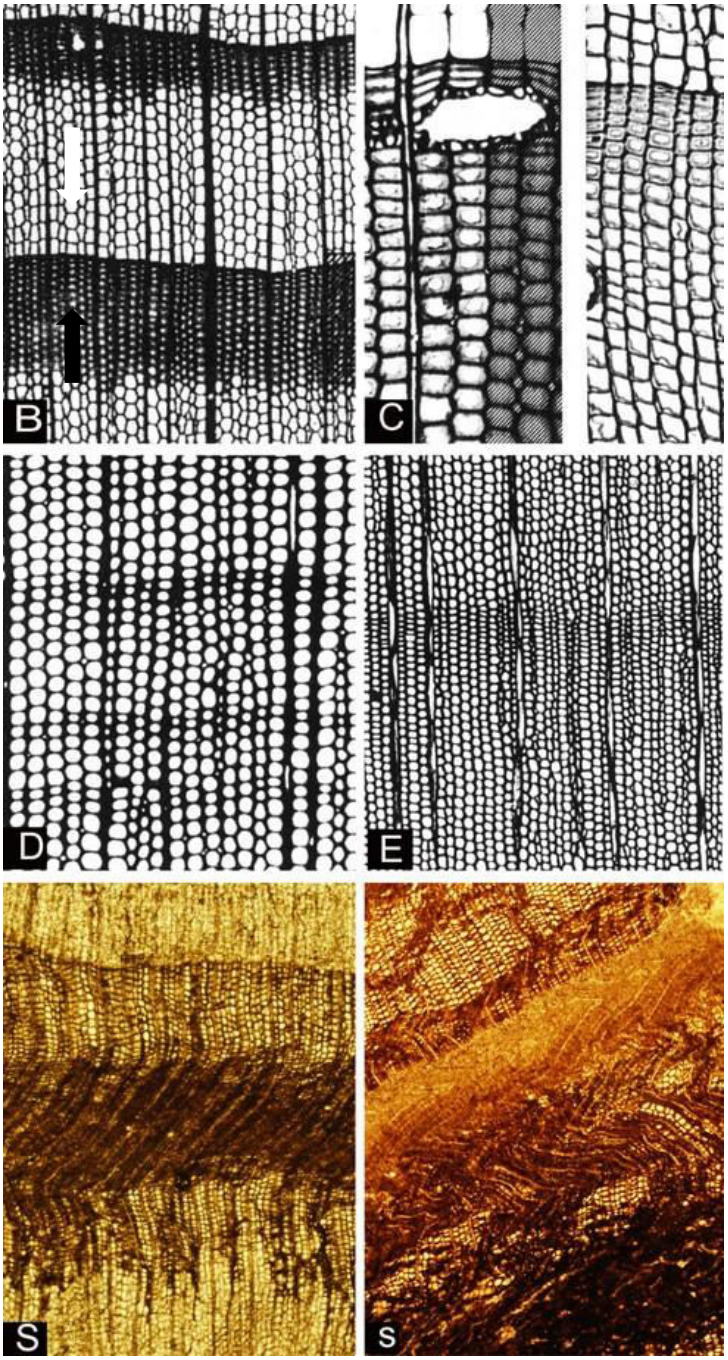


Figure 1.8: Types of growth rings based on Creber and Chaloner (1984) and Karoo woods (Bamford, 2016). B-Type has distinct growth rings with abrupt transition from earlywood (indicated by the white arrows) to latewood (Black arrows). C-type shows a gradual transition from earlywood to latewood; canal visible in *left* of the picture. D-type has indistinct growth rings seen as three bands where the cell walls are marginally thicker. E-type has indistinct growth rings with one band of slightly foreshortened cells. S-type has shear zones typical of Southern Africa Karoo woods. S-Type has shear zones in growth rings.

1.3 Preservation of the Palaeontological Heritage

1.3.1 Concepts used in Geoheritage

Geosite

A geosite is a physical space that has a particular importance for the understanding of the geological history of the earth. Geoheritage can also be defined as the occurrence of one or more elements of geodiversity resulting from either human or natural actions and must be of exceptional value from a cultural, touristic, scientific, or educational standpoint (Brilha, 2005; Cumbe, 2007). Each geosite can have one or more elements of interest, petrological, mineralogical, paleontological, stratigraphic, and geomorphological (Brilha, 2005).

Geoheritage

Geoheritage can be understood as a set of geological occurrences that are regarded as representative of a given region, with known scientific, pedagogical, cultural, touristic, or other values. Regarding the set of geological elements that the heritage can encompass, the geological heritage can be subdivided into paleontological heritage.

Geoconservation

The geological heritage is a non-renewable natural resource. Its destruction constitutes an irreversible process. For that aim actions or activities aiming at safeguarding this geological heritage are developed. In this regard, all activities that aimed at the conservation, sustainable management of the geological heritage and the associated natural processes are called geoconservation (Brilha, 2005). The objective of the geoconservation is not necessarily to protect all geosites inventoried, but those that have exceptional relevance compared to others (e.g, dimension, visibility, state of conservation).

1.3.2 Legislation applied for Geoheritage in Mozambique

The geological heritage of Mozambique can be protected through national legislation. Although there are no any strict legislation that is devoted to the protection of Mozambican geoheritage. Thus, the geological heritage of Mozambique can be protected by the Law of Forests and Wildlife (Law No. 10/99 of 07 July), through its Chapter II, Article 11, intended for national parks, which, in addition for the protection of the total vegetation and wild animals, also includes the protection of sites, geological formations of a given scientific, aesthetic value and for public recreation, representative of the national heritage. Other legal instruments that can also be applied to protect the Mozambican Geological Heritage are:

• The Constitution of the Republic (2004);

• Environmental framework law (Law No. 20/97 of 1 October);

• Mozambique's Cultural Policy and Implementation Strategy

(Resolution No. 12/97 of June 10).

1.3.3 Inventory, evaluation and classification

An inventory consists on the systematic survey and registration of geosites that occur in a given area, after prior reconnaissance of the area. The inventory process is then followed by the evaluation of each geosite (Brilha, 2005). The evaluation process consists of calculating the value that each geosite has, according to criteria such as: integrity (if the object is complete or not), representativeness (the extent to which geosite is representative of the geology of a given region), rarity (number of similar occurrences in the space in reference), observation condition (if the geosite is easy to observe), accessibility (if the location is easily accessible), vulnerability (ease of destruction), aesthetic value, social / economic value and cultural / historical (Reynard, 2009; Brilha, 2005). Other relevant aspects in the study of the geoheritage is the classification of a given geosite. The classification is the step that aims to endow the geological heritage with a legal statute for its protection and management.

1.4 Remarks on fossil wood studies across some sites in Gondwana

Mozambique

The first geological works in the Tete area are related to the studies of the coal occurrences and were executed by Guyot (1882), Zeiller (1883) and Kuss (1884). However, fossil woods and coal were first described by Livingstone (1865). These authors mainly describe in a broad manner the lithologies of the coal-bearing Karoo or occasional occurrences of *Glossopteris* fossil leaves in the Moatize Basin.

At the beginning of the XX Century, the German explorer C. Peters (1902) referred to the fossilized trees in the Tete Province. Strictly geological works had been focused on the local and regional stratigraphy of the carbonaceous Karoo sediments (Gerard, 1924; Andrade, 1929; and Dixey, 1929). The Zumbo area was described by Freitas (1932), and later on surveyed by Bebiano (1934).

The coal-bearing basins were further studied by Borges (1935), Teixeira (1943, 1946 and 1947), Borges (1946) and Gaspar (1948).

After the 1950s until the 1980s, various publications, and technical reports were done as a result of the fieldwork of a vast effort to improve the knowledge on the geology and economic value of the mineral resources of the Tete Province. These works are the ones of Teixeira (1950 and 1951), Borges (1952), Silva *et al.,* (1967),

and more recently the GONDWANA Enterprise Ltd, and Museu Nacional de Geologia (Marques and Ferrar, 2004). On the work undertaken by Museu Nacional de Geologia and the GONDWANA Enterprise Ltd the collected fossil trunks were noted as belonging to *Dadoxylon nicoli Seward*, 1917 and others to *Dadoxylon* sp. with varied dimensions, despite no thin-sections being performed. It should be noted that *Dadoxylon* is well-known genus from Late Paleozoic woods displaying distinctive araucarian tracheidal pitting ranging from alternate and contiguous, however, it is now an invalid name (Philippe, 1993 and Bamford and Philippe, 2001). Marguerier (1973) was an important contribution to the study of woods collected along the route from Carinde to Mágoè in Tete. This study gave rise to new fossil wood species, *Australoxylon teixeirae*. Later on Maithy (1977) named *Zalesskioxylon zambesiensis* from the Lower Gondwana *Glossopteris* beds of Mozambique. In its turn,

Zalesskioxylon zambesiensis was emended as *Australoxylon zambesiensis* by Bajpai and Maheshwari (1986).

In the Niassa Province (northern Mozambique), silicified woods have only been reported from the Lu-ulucia Formation, K4 Formation (Lower Permian), Mount Lilonga Formation [(Late Permian-Early Triassic) (Borges and Freitas, 1953, Verniers *et al*., 1989)]. These woods were assigned to *Dadoxylon* sp., despite no thin-sections being performed.

Brazil

The earliest reports of the fossil woods in Brazil date back from the XIX century. The first described specimens were placed into the morphogenus *Dadoxylon*, which is considered now to be an invalid name (see chapter three). Zeiller (1895) described *Dadoxylon pedroi* from the Rio Bonito Formation. Maniero (1944) described the first morphospecies from the Iráti, which was assigned to *Dadoxylon whitei*, a specimen that was later transferred to *Polysolenoxylon* (Krausel and Dolianiti, 1958). Between 1975 and 1978, in the State of Rio Grande do Sul (Southern Brazil) and São Paulo, were described *Polysolenoxylon*, *Brasilestiloxylon* and *Solenobrasilioxylon* (Mussa, 1978). Mussa (1878) was an important contribution of the field of fossil woods, which resulted in a small atlas compiled with data for the Iráti Formation. Mussa (1978) described several species and genera, many of them were regarded as invalid according to the International Code of Nomenclature for Algae, Fungi and Plants (McNeil *et al*., 2012), because they were not published in scientific journals. Recent publications including Merlotti and Kurzawe (2006), Merloti (2009), Kurzawe and Merlotti (2010), Merlotti and Kurzawe (2011) represent an attempt to revise and validate specimens erected by Mussa (1978). Some well-known species from the Karoo formations such as *Australoxylon teixeirae* from Late Permian deposits of Teresina and Rio do Rasto Formation, *Agathoxylon africanum* from the Late Triassic conifer woods of the Caturrita Formation have been recently reported as occurring in some Brazil formations (Merlotti and Kurzawe, 2011; Crisafulli *et al*., 2016 and others).

Namibia

Krausel and Range (1928) studied silified woods from the Lower Permian of Namibia. These woods were identified as *Medullopitys*, *Abietopitys*, *Phyllocladopitys* and *Taxopitys*, revised by Lepekhina (1972). Krausel (1956a, b) described more woods with pith from the Dwyka-equivalent strata from Kaokoveld. The woods were assigned to *Solenoxylon*, *Lobatoxylon*, *Megaporoxylon* and *Kaokoxylon*. All these genera are restricted to Permian deposits from Gondwana, however more works need to be done as no correlation at species level have yet been performed (e.g., Antartica: Mahehswari, 1972; Guerra-Sommer, 1977; India: Prasad, 1982; South America: Krausel and Dolianiti, 1958; Krausel and Dolianiti, 1958; Guerra-Sommer, 1977 and others). More recently Bamford (2000), carried out a systematic study uncovering the fossil wood diversity of Namibia. In this study, identified *Prototaxoxylon africanum*, *Agathoxylon africanum* and *Agathoxylon karooensis* for the Tsarabis Formation (Permian). In the Huab Formation which supposedly has the Permo-Triassic boundary, the occurrence of *Protopodocarpoxylon* sp*., and Agathoxylon africanum*. Lastly, *Protopodocarpoxylon* cf*. lamthari*, Protopinaceae, and *Agathoxylon africanum* were identified from the Gai As Formation which is Permo-Triassic-Jurassic? in age (Bamford 2000). This study added more insights regarding the biostratigraphical correlation amongst Namibian formations and the formations from the MKB in South Africa (Bamford, 2000).

Zambia

The first reports of fossil wood in Zambia are from the earliest years of the XX century. Silicified woods from Mlembo and Lukasashi valleys were first reported by L. A. Wallace (1907). Two years later, 1909, J.C. Molyneux reports silicified woods in fragments, or in prostrated trunks. The Lufua River in the mid-Zambezi valley and Lusangashi river were identified due to their abundance of silicified woods in the Upper Shales by F.P. Mennell (1930). Moreover, in 1931, G.R. Downs confirmed the abundance of silicified woods in the Lukasashi valley in the areas north and northwest of Manchiti.

Dixey (1937) described large masses of fossil wood in three different localities: Grey Shales, Red Pebbly Grits and Grey Grits of the Upper Luangwa Valley. These woods were taxonomically assigned to *Dadoxylon sclerosum* (Walton) and *Dadoxylon arberi*. Another fossil wood material was reported by Dixey (1937) in the Red Sandstones of the Upper Luangwa Valley, which is correlated with the Forest Sandstone Formation of other sites (Lacey, 1961).

In 1941, T.D. Guersey mentions in his report based on prospection and mapping data undertaken by several geologists in Zambia the occurrence of fossil wood (e.g., up to 7ft in diameter and 100ft long). Gair (1959) reported fossil woods belonging to *Dadoxylon* sp. and *Rhexoxylon africanum* from the Madumabisa Mudstone. Taverer-Smith (1960) described abundant silicified tree trunks in the Grift Formation.

The latest studies were undertaken by Lacey (1974) in the Kafue Valley resulting on the identification of *Rhexoxylon africanum*. The other study reported by Lacey and Lucas (1984) yielded *Dadoxylon* cf. *sclerosum* from Triassic deposits of the Luangwa valley. Additionally, unpublished reports from the Evolutionary Studies Institute indicate the occurrence of *Australoxylon* and *Agathoxylon* genera in the Upper Luangwa Valley. More works are underway aiming at updating the palaoebotany of Zambia. The field work of this latter study was carried out by N. Barbolini, S. Kock, M.Bamford and S.Tolani.

Botswana

A. Campbell found a piece of silicified woods in the bed of the Boteti River in 1994. Later, more woods have been found by A. Campbell in the north bank of the Boteti River. In 1996, a team formed by A. Campbell, M. Bamford, M. Main, R. Bousfield visited the site, however, no fossil woods have been found in the Boteti river. More fossil woods were collected by R. Bousfield in the top of the hill at Tshaitshe (archaeological site). The fossil woods collected by A. Campbell at Boteti river were assigned to *Dadoxylon* sp. (Late Permian), *Araucarioxylon* sp. (Permian-Triassic). In its turn, the fossil woods from Tshaitshe were named as *Dadoxylon parenchymatosum* (Triassic age).

In june 2018, M. Wit, M. Bamford and V. Warden collected fossil woods from Mosolotsane Formation (equivalent to the Molteno Formation in South Africa) have been collected and identified. Interestingly, this study based on the tracheid pits arrangement reported the first occurrence of *Agathoxylon africanum* in Botsawana. The latter study, has been undertaken in the Toutswemogala Hill, Lower Karoo Supergroup, central Botswana (Dietrich, *et al*., 2019). *Megaporoxylon kaokense* was the taxonomic assignment given to these fossil wood following the key developed by Bamford and Philippe (2008).

Paraguay

Picnoxylic woods has been described in Paraguay but they were all referred to *Dadoxylon* (Harrington, 1950; Eckel, 1959). A more detailed description was undertaken by Crisafulli (2000, 2004). In particular, the Tacuary Formation has received attention and several woods have been identified. Crisafulli and Herbst (2009), determined gymnospermous woods with affinities to Ginkgoales (*Baieroxylon cicatricum*, *Podocarpoxylon paralatifolium*, *Australoxylon teixeirae*, *Prototaxoxylon brasilianum*). Specimens of *Agathoxylon biseriatum*, *Kaokoxylon rioclarense*, *Polysolenoxylon whitei*, *Chapmanoxylon jamuriense*, *Baieroxylon cicatrum* have also been confirmed by Leiva *et al*., (2012). According to palynological correlations, the Tacuary Formation is considered Late Permian in age (Vergel, 1993 and Perez *et al*., 2010).

India

Extensive palaeobotanical research has been carried out in India both for Mesozoic and Palaeozoic formations. Some of the contributions aiming at studying the fossil woods in India are those Sahni (1925), Moonje (1945), Surange and Sahni (1958), Maheswahri (1964), Prasad and Chandra (1980) and others. Fossil woods are mostly restricted to the Raniganj and Khamti Formation, which are considered to the Late Permian (Chandra, 1992, Singh *et al*., 2006). There are 28 genera belonging to 68 species from the Palaeozoic of India (Prasad, 1982). On the other side the Mesozoic fossil woods in India are well-studied and as a result over 51 species

assigned to 14 genera have been described (Chinnappa and Rajanikanth, 2017). For both Palaeozoic and Mesozoic era, the coniferals represents the most dominant fossil wood group and is represented by the occurrence of some the following genera: *Agathoxylon*, *Circoporoxylon*, *Cupressinoxylon*, *Podocarpoxylon*, *Prototaxoxylon*, *Taxaceoxylon*, *Australoxylon* and others (Sahni, 1931; Bose and Sah, 1954; Bonde, 2010; Chinnappa, and Rajanikanth, 2016).

Uruguay

Fossil woods in Uruguay have been studied from three formations: Tres Islas Formation, Melo Formation and Yaguari Formation (Ferrando and Andreis, 1990). The Tres Islas Formation (Lower Permian) palaeozoic woods described consist in the following taxa: *Agathoxylon allani*, *Agathoxylon kurmarpurensis*, *Australoxylon teixeirae* and *Prototaxoylon brasilianum* (Crisafulli *et al*., 2009). The Melo Formation (Lower Permian) has also been researched and gymnosperms identified. According to Crisafulli and Lutz (2000), these gymnosperms have affinities to Cordaitales, Coniferales and Taxales. A detailed study from the Yaguari Formation (Late Permian) was undertaken by Crisafulli (2001) resulting in identification of three species: *Araucarioxylon roxoi*, *Barakaroxylon jhariense* and *Baieroxylon cicatrum*. Other taxa were added later and include *Australoxylon teixeirae*, *Zalesskioxylon uniseriatum*, *Zalesskioxylon sahnii* and *Araucarioxylon nummularium* (Crisafulli, 2002).

1.5 Geographic Location

Mozambique is a country located in the Southern region of Africa (Figure 1.9). The samples were collected from two diferent provinces in Mozambique: Niassa and Tete. The Niassa province is situated in the Northwest of Mozambique and the samples were collected from the Metangula Graben. The Metangula Graben is limited in the North by Tanzania, South by Lichinga district, East by Sanga district and West by Lago Niassa (Figure 1.9). The province of Tete is located in the central-west region of Mozambique and is bordered by Malawi in the Northeast, Northwest by Zambia, Southeast by Zimbabwe and in its south part is bordered by three Mozambican provinces, namely, Manica, Sofala and Zambézia.

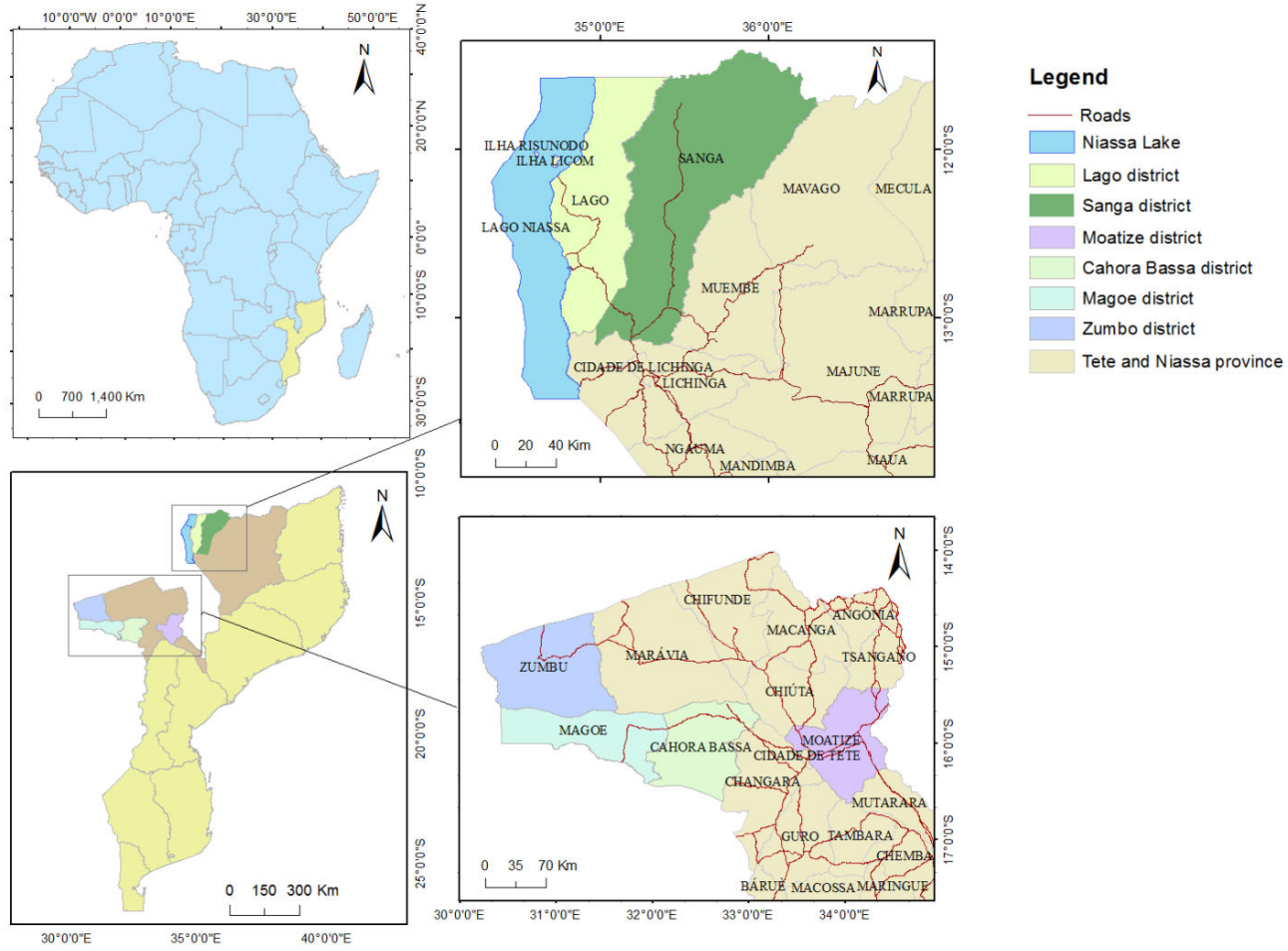


Figure 1.9: Geographical map of the studied area.

1.6 Geological Background

Various southern Africa countries have formations penecontemporaneous to the Karoo Supergroup (KSG). In Mozambique, the KSG consists of sedimentary and igneous rocks overlying the Precambrian basement consisting of igneous and metamorphic rocks, which are in turn unconformably overlain by Middle Jurassic or younger rocks (Norconsult Consortium 2007). The KSG succession comprises, in general, the change from glaciogenic to temperate deltaic facies at the base, that develop into fluvial/lacustrine clastic sediments, and finally more arid and continental facies at the top of the succession (Verniers *et al*., 1989, Norconsult Consortium 2007). The occurrence of the KSG succession in Mozambique is restricted to intracontinental extensional sedimentary basins (Figure 1.10). The origin of these Mozambican sedimentary basins was associated with regions of old crustal sutures, where high-strain structures formed during the Pan-African Orogeny (620–530 Ma). The reactivation of these sutures during a period of lithospheric extension (Lower Permian to Lower Jurassic times), has driven subsidence and formed linear extensional basins with morphology similar to half-graben to graben (GTK Consortium, 2006a; Norconsult Consortium 2007). In this dissertation the description of the Karoo basins from Mozambique is focused on the Tete province (black circle) and the Metangula graben (black rectangle) as it follows:

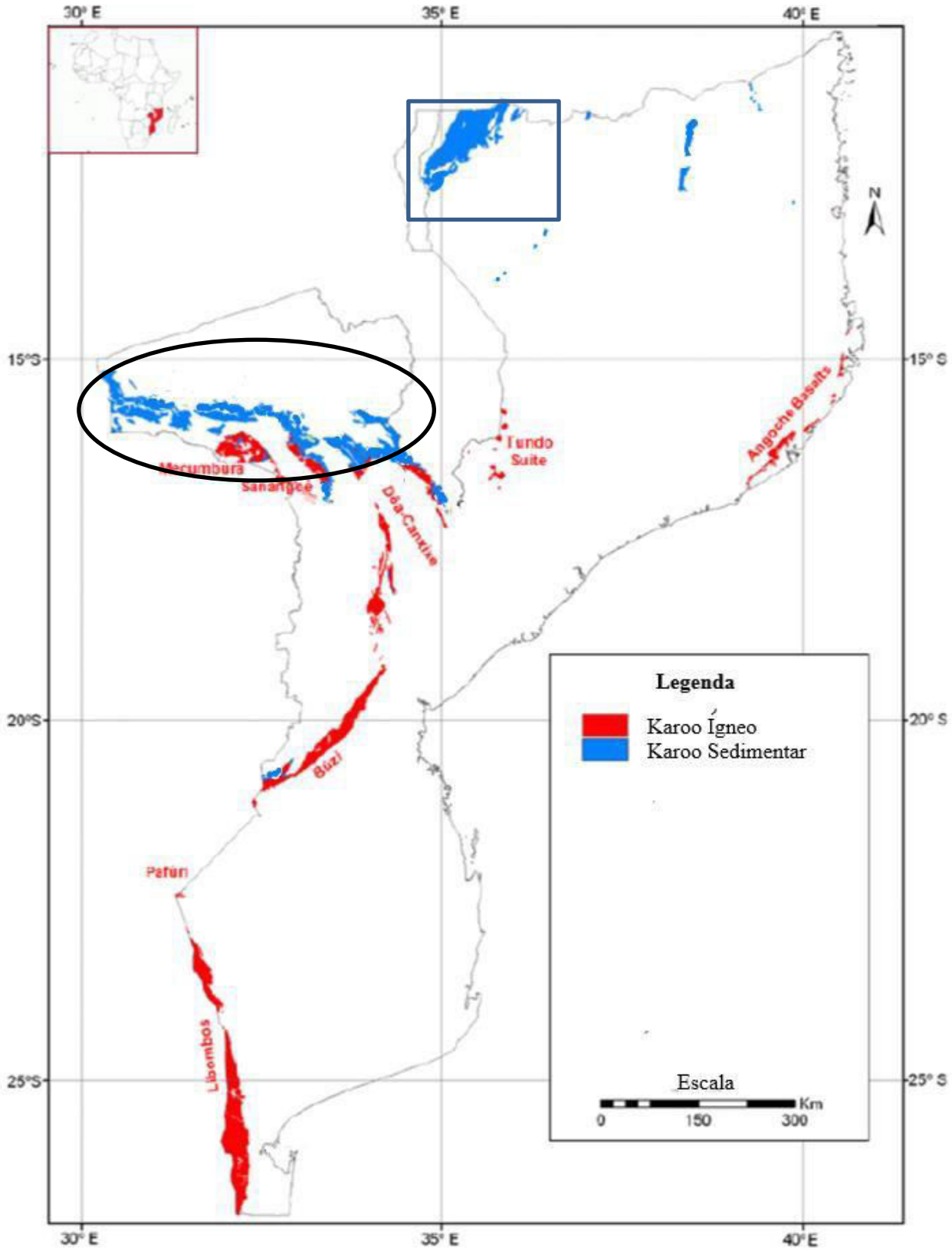


Figure 1.10: Map of Karoo distribution in Mozambique (Adapted from Paulino *et al*., 2010).

1.6.1 Geology of Tete

The geology of the Tete Province is mainly controlled by the Zambezi River. Along the Zambezi River three sedimentary basins exist and are namely Chicôa-Mecúcoe Sanângoé-Mefidezi and Moatize-Minjova Basins. The Chicôa-Mecúcoe Basin with an E-W trending is now in partly submerged by the water of the Cahora Bassa Dam, which probably obscured some fossil forests in the northern margin of the Zambezi River discovered by Livingstone (1865). Most of the samples here analysed from Tete area were collected from this Basin. The other two Basins are the NW-SE trending Sanângoé-Mefidezi and Moatize-Minjova Basins (Figure 1.11). These basins were originated as a consequence of successive phases of tectonics of the extensional type (Catuneanu *et al*., 2015).

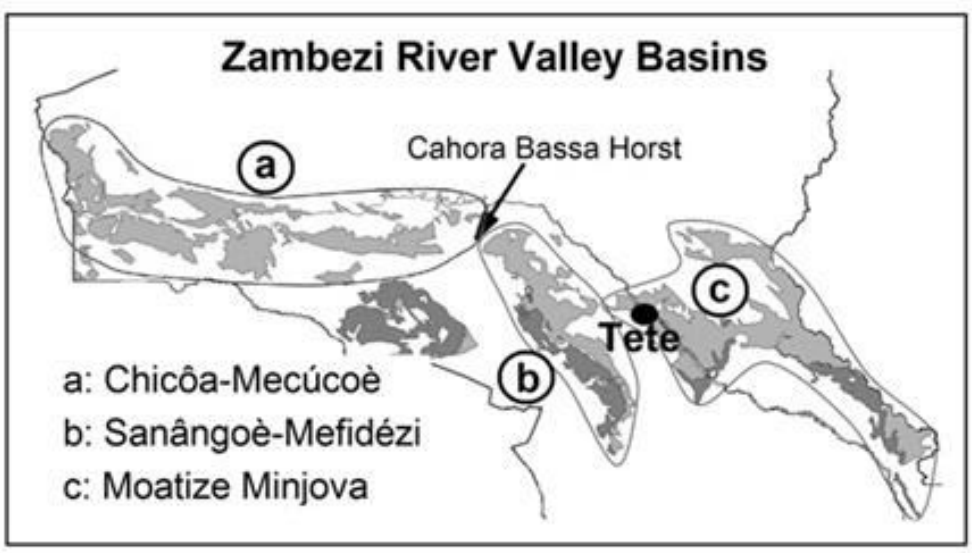


Figure 1.11: Simplified Map illustrating the Basins of the Tete area (adapted from Pereira *et al.*, 2016).

The geology of the basins in the Tete Province is dominated by the deposits of glacial origin at the base (Vasconcelos, 2009) and fluvio-lacustrine formations completing the stratigraphic sequence (Vasconcelos, 2009). The Tete stratigraphic sequence is very often correlated with the formations of the MKB and comprises the Tillite series (Vúzi Formation), the Moatize Formation, Matinde Formation, Cádzi Formation, Zumbo Formation, Lualádzi Formation and other recent formations (GTK, 2006; Paulino *et al*., 2009; Hancox, 2016).

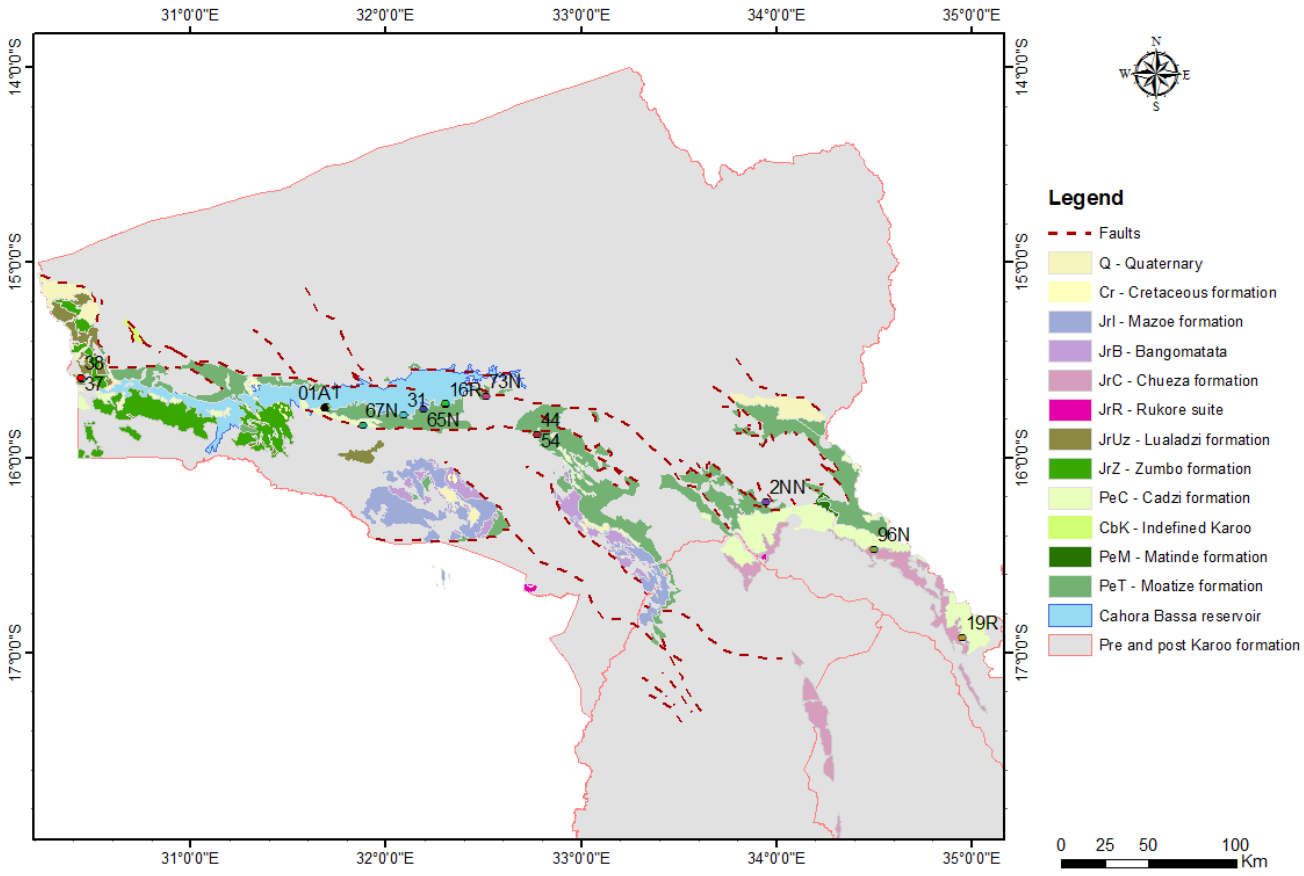


Figure 1.12: Geology Map of the study area with the main searched areas searched (Adapted from Paulino *et al.*, 2010).

Vúzi Formation

The Vúzi Formation is the lowermost unit of the Karoo Supergroup in Mozambique (KSG), indicated thus the onset of Karoo sedimentation (Vasconcelos, 2009). The rocks of Vúzi Formation consist of diamictites interbedded sandstones, siltstones basal conglomerates, and carbonaceous shales which were deposited in fluvial and glacial environments (Vasconcelos, 2009). The Vúzi Formation varies in thickness from a few meters to some ca. 200m. This variability is related to faulting associated with the basin formation process, palaeovalleys and weathering (Hancox, 2016). Based on the correlation with the MKB, the Vúzi Formation is considered to be equivalent to the Dwyka Group in the KSG in South Africa and therefore dated as Late Carboniferous to Lower Permian (GTK Consortium, 2006). The Vúzi Formation

is conformably overlain by the coal-bearing Moatize Formation (Pereira *et al*., 2016). No fossil wood samples were collected from this formation.

Moatize Formation

The Moatize Formation overlies unconformably the Vúzi Formation. The maximum thickness observed for the Moatize Formation is about ca. 340m. The Moatize Formation consist of carbonaceous shales, siltstones, interbedded sandstones, and coal seams. The productive coal seams within the formation differ in thickness and they are the "Souza" "Pinto", "Chipanga" (mostly hosted in thick mudstones and siltstones), "Intermédia", "Grande Falésia" and "André" coal seams (bounded either above or below by sandstones) (Hancox, 2016). The deposition of the formations occurred under wet temperate conditions (Mugabe, 1999). The Moatize Formation is suggested to be equivalent to the Middle-Late Ecca Group of MKB. The correlation assumption is based on palynomorphs and macrofossil studies (Mugabe, 1999). Several materials were collected from the Moatize Formation, but their poor state of preservation have hindered their taxonomic study.

Matinde Formation

The climatic conditions of the deposition of the Matinde Formation are fluvial and the transition from wet temperate to hot arid can be interpreted (Vasconcelos, 2009, Lopes *et al*., 2020). Disconformably, the Matinde Formation overlies the Moatize Formation. The rocks are mostly cross-stratified sandstone, siltstone, mudstone with occasional coal seams (Hancox, 2016; GTK Consortium, 2006). In regard to the age, the Matinde Formation is now inferred to be Late Permian-Lower Triassic. This assumption is based on the palynological evidences recently found (Pereira *et al*., 2016, 2019; Galasso *et al*., 2019; Lopes *et al*., 2020). Most of the studied material for this dissertation was collected in this formation and represents the most productive formation in regards to fossil woods taxon (see Tables 3.4 and 4.5). Earlier reports of fossil trunks by Teixeira (1950), Silva *et al*., (1967), Marguerier (1973) are from this formation. More than one hundred samples were prepared at the Palaeobotany

Laboratory in the Evolutionary Studies Institute, however, twenty samples have revealed to be well preserved.

Cádzi Formation

The rocks of the Cádzi Formation consist of limestones, conglomerates and marls. The depositional environment of the Cádzi Formation is interpreted to be fluvial and lacustrine under hot and arid conditions. Previously, the Cádzi Formation was correlated with the Beaufort Group in the MKB. However, new palynological evidence shows a younger age (Mid-to Late Triassic) (Pereira *et al*., 2016). Records of fossil trunks in the Cádzi Formation hae been assigned to *Rhexoxylon* cf. *priestleyi* and *Dadoxylon* sp. Some of the well-preserved material in this dissertation was collected in the Cádzi Formation, however none of them show affinities with the above taxon reported by GTK Consortium (2006). *Rhexoxylon* woods are typical of the Triassic in Gondwana (Anderson *et al*., 2020). Nine samples are derived from this formation with five allowing taxonomical identification.

1.6.2 Geology of the Metangula Graben

The Metangula Basin (Figure 1.13) is located in northwest Mozambique, in the province of Niassa. Overall, the Metangula Basin has a graben to half-graben structure, with the main growth faults located at the western boundary of the basin against Precambrian basement rocks. The KSG extends northwards from Maniamba to the Rovuma River, continuing on towards Tanzania. The Metangula Graben is the southern extension of the Tanzanian Ruhuhu Basin. The geology of the Metangula Graben is subdivided into different groups: Lower Karoo and Upper Karoo. This division is mainly based on the lithological differences (Verniers *et al*., 1989; GTK Consortium, 2006c; Paulino, 2009). The Upper Karoo Group occupies most of this basin, and the Lower Karoo Group rocks are restricted to the southern area of the graben (Fig. 3). The most comprehensive study of the Metangula sediments was done by Jacques Verniers and colleagues from the “Brigadas de Cartografia Geológica da Bacia carbonífera de Metangula” during 1977 to 1980 (Araújo *et al*.,

2018; Macungo *et al*., 2020; Nhamutole *et al*., submitted). The formations and members based on lithology proposed by Verniers *et al*., (1989) are followed in this dissertation, with recent additions by Araújo *et al.,* (2020). A brief description of the stratigraphy from base to top according Verniers *et al*., (1989) follows.

Lower Karoo

The Lower Karoo consists of Ecca and Beaufort groups. The Ecca-equivalent group consists of the K2, K3 and K4 Formations, whereas the Beaufort-equivalent group includes the K5 and K6 Formations (Verniers *et al*., 1989). This correlation is supported by updated taxa ranges of the macrofauna recovered from South Africa (e.g., Gastaldo *et al*., 2020). The K2 Formation unconformably overlies Precambrian rocks, and consists of basal conglomerate, fine siltstones, claystones, and carbonaceous fine sandstones. Despite our attempts to collect samples from this formation, its limited exposure and dense vegetational cover impossibilitated such endeavour. Occasional coal veins form the upper part of the K2 Formation. The thickness of the upper part varies between 14 to 45m. The lower part with a thickness between 22m to 29m, consists of coarse-grained sandstones displaying conglomerate levels.

K3 Formation

The K3 Formation consists of an overall fining-upward sequence made up by white sandstones, red siltstones and sandstones. Cyclical fluvial sequences are found in the lower part with more fine sandstones. The thickness varies from 70 and 90m in the NE of the Lunho valley and near the Messumba area, its thickness reaches 25m. No samples were collected from this Formation.

K4 Formation

This formation consists of coal seams, carbonaceous intercalations and green-grey sandy silt. The floral ecosystem is represented by *Glossopteris* leaves assigned to

three different species: *Glossopteris ampla*, *G.browniana* and *G. ampla*. (Teixeira and Gonçalves, 1959). In addition, silicified woods assigned to *Dadoxylon* sp. occur and display marked seasonal growth rings (Norconsult Consortium, 2007).Only five samples from this Formation provided identifiable anatomy. We prepared five samples from this formation. The thickness of this formation varies from 171m to 186m.

K5 Formation

The K5 Formation is 250 to 260 meters thick, and is subdivided into 3 members known as: K5a at the base, K5b in the middle, and then K5c on the top (Verniers *et al*., 1989; Araújo *et al*., 2020). The K5a member consists of dark grey, massive siltstones, minor tabular fine-grained sandstone.The depositional environment is suggested to be formed by well-drained and fully-vegetated river floodplains associated with generally high water tables (Araújo *et al*., 2020). In turn, the K5b member, is mostly composed of siltstones with fine to medium grain sizes, either dark or greenish grey. Carbonaceous sediments are, however, also present in this member. Here, due to the good preservation of siliceous wood material collected and analysed, it therefore seems to be the most productive formation in Niassa (see the Metangula Graben map in the appendix and the Tables 3.4 and 4.5). The K5c member contains rocks such as reddish grey, compact siltstone and claystone. According to the recent radiometric data the K5c has a maximum depositional age of 258.85 ± 0.41 Ma and is thus older than previously thought, and falls closer to the boundary between the *Lycosuchus-Eunotosaurus* and *Tropidostoma-Gorgonops* subzones of the *Endothiodon* Assemblage Zone (Day and Smith, 2020; Smith *et al*., 2020), rather than being coeval with the *Cistecephalus* Assemblage Zone (Araujo *et al*., 2020).This geochronological age compares in favour with the biostratigraphic age of Middle Beaufort postulated by Verniers *et al*., (1989) and obtained later by Norconsult Consortium, 2007). Vertebrate fossils are found in the K5c member and include *Endothiodon* skull and skeletal elements, small and medium-sized dicynodonts such as *Niassodon mfumukasi*, a partial gorgonopsian skull, non-marine bivalves, and silicified woods (Verniers *et al*., 1989; Castanhinha *et al*., 2013; Macungo *et al*., 2020; Verniers *et a*l., 1989; Araújo *et al*., 2020). We selected 26

samples for laboratory analysis of which twenty have allowed taxonomical identification (Appendix F).

K6 Formation

Four members compose the K6 Formation and are on a stratigraphical sequence as it follows: K6a1, K6a2, K6a3, and K6b from base to top. A Beaufort equivalent age of the K6 Formation can be interpreted because all their members contain *Glossopteris* leaves and vertebrate fossils (synapsid bones). These fossil bones consist of fragmented skeletal and cranial elements of therapsids with a black colour (Araújo *et al*., 2020). According to macroscopic aspects of the fossil woods in the K6 Formation, only five samples have been processed because show well-preserved features despite over fifteen were collected (appendix 6).

K6a1 member

The rocks of the K6a1 are greyish, fine grained, siltstones and claystones. Occasional calcilutite of a red colour is present. The depositional environment setting consists of floodplain and lacustrine-dominated environments (Araújo *et al*., 2020).

K6a2 member

This member consists of red or reddish fine siltstones, red siltstones conglomerates and a horizon displaying reptile bones. The deposition environment is interpreted as an axial braided channel and wet overbank environments (Araújo *et al*., 2020). The fossil content of this member includes *Glossopteris* impressions in carbonaceous seams as well *Daptocephalus*-like medium to large dicynodont skulls and their isolated postcranial elements with distinctive black bone colour (Araújo *et al*., 2020).

K6a3 member

The K6a3 member shows a compact sedimentation consisting of light greenish grey, with occasional fine siltstones (Verniers *et al*., 1989). The siltstones display structures with a laminated spheroidal shape. The palaeoenvironments are interpreted as being a part of a more distal braidplain consisting of a drier and better-drained floodplains with replaced gypsum desert-rose structures similar to those referred from the Balfour Formation of the MKB (Araújo *et al*., 2020). Based on these structures an indication of temporary alkaline lakes on the floodplains (Smith, 1990) is inferred. Fossils comprise silicified wood fragments and a few black bone fragments. The spheroidal laminated shape is associated with recent events such as weathering and dewatering. Silicified trunks are sometimes observed.

K6b member

The rocks of the uppermost member (K6b) are grey or reddish grey fine siltstones. Vertebrate fossils are found in the bottom, middle and almost in the top. The environment of deposition is a broad, shallow, low-sinuosity channel belt which is associated with seasonally dry floodplain environments (Araújo *et al*., 2020). Here isolated fragments of black bone and pieces of silicified wood have recently been recovered. The thickness of the K6 Formation varies between 52 and 75m (Verniers *et al*., 1989).

Upper Karoo (KSa, KSb, KSc, KSd, KSe)

The Upper Karoo Group in the Metangula Basin occupies large areas in the central and northern regions (Lopes *et al*., 2020). The Upper Karoo includes the Lipirichi Formation (KSe), Tende Formation (KSd), Mecondece Formation (KSc), Fúbué Formation (KSb), Mount Lilonga Formation (KSa).

Mount Lilonga (KSa) Formation

This formation conformably overlies the K6b member with a laterally-continuous, cliff-forming, coarse-grained trough cross-bedded conglomeratic arkosic wackestone

The Mount Lilonga Formation consists of a fluvial sequence and is lithologically made up of coloured fine-grained rocks (greenish grey) and 10-50% of sandy section. Coarse sandstones are found at the base of the formation and are separated by greenish, fine-grained siltstone. The depositional setting of the Mt Lilonga Formation consists of a mid-fan braided river system (Araújo *et al*., 2020). Some parts of the Mount Lilonga Formation have been correlated with the Cádzi Formation in Tete and the Beaufort Group in the MKB (Marques and Ferrara, 2009). The thickness of the Mount Lilonga is between 51 to 141m. Similar to the below Fúbué Formation some of the tree trunks were collected for the first time in this formation. Four samples with well-preserved features were studied from the Mount Lilonga Formation.

Fubué (KSb) Formation

The Fubué Formation overlies conformably the Mount Lilonga Formation (Araújo *et al*., 2020). The lithology of the Fubué Formation consists of coarse-grained conglomeratic sandstones. The deposition of the formation seems to have occurred under braided river system (Verniers *et al*., 1989). Typically, the thickness of the formation is up to 200m, however, it decreases in thickness farther east to 35m. A single well-preserved fossil wood fragment that allow their identification to species level have been collected and interpreted in this dissertation. In addition, isolated dicynodont cranial and postcranial fragments also occur (Araújo *et al*., 2020).

In the remaining upper karoo formations, Lipirichi Formation (KSe), Tende Formation (KSd), Mecondece Formation (KSc) no fossil woods have been studied, however the upcoming studies will attempt to cover all the stratigraphic sequence. It should be highlighted that there was an attempt to process fossil woods from the Lipirichi Formation, however no anatomical features was observed in the microscope.

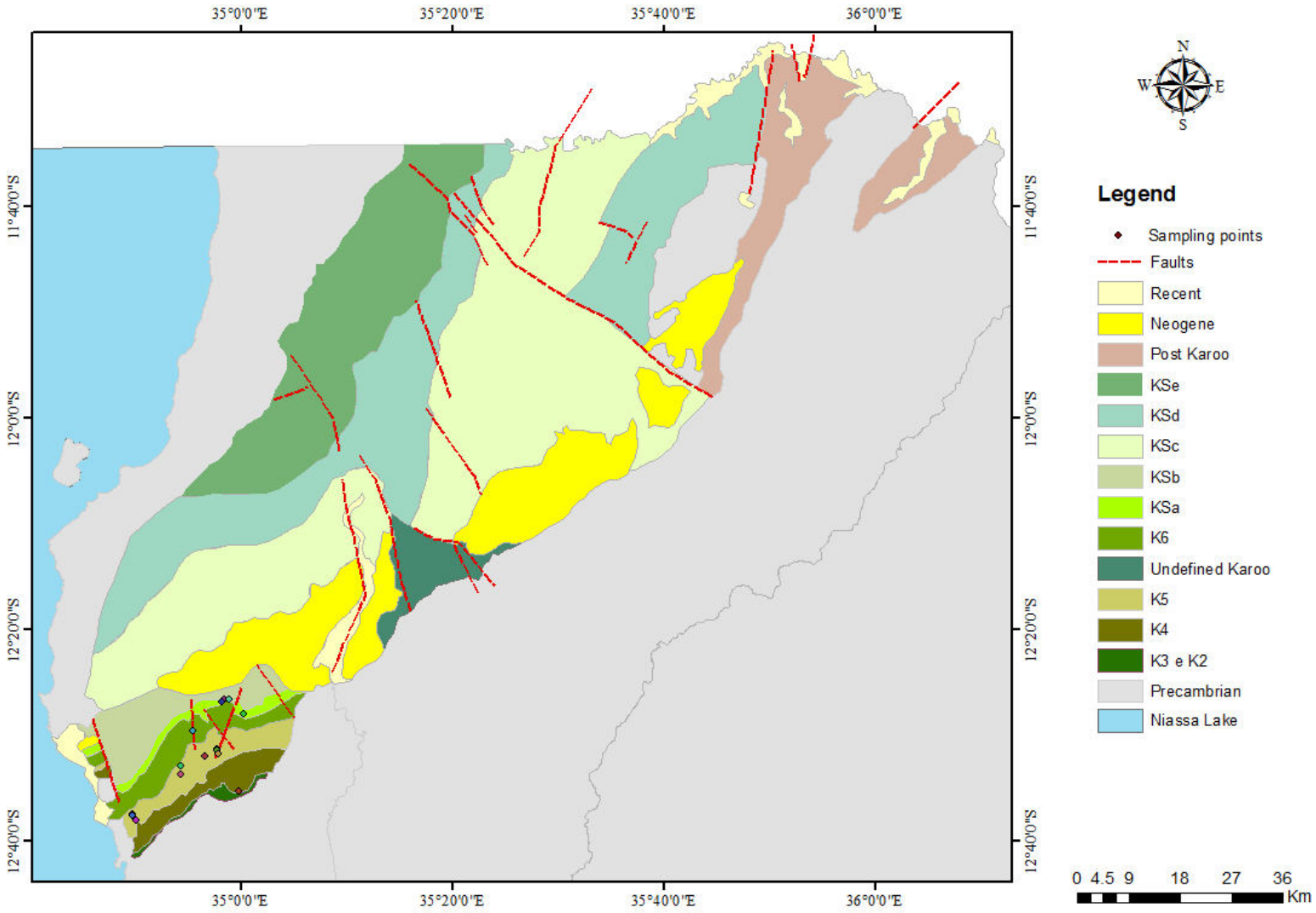


Figure 1.13: Geology Map of the Metangula Graben adapted from Verniers *et al*., (1989).

CHAPTER TWO-MATERIALS AND METHODS

2.1 Materials

The fossil woods herein studied were collected from different formations in the Tete and Niassa Provinces, Mozambique. The choice to sample in these provinces was based on the available reports (Borges *et al*., 1952; Teixeira, 1967; Verniers *et al*., 1989; Marques and Ferrara, 2004). However, due to extensive fieldwork under the PaleoMoz project, multiple fossil woods were collected from formations that there were not previously reported (e.g., K5 Formation, K6 Formation and Mount Lilonga Formation in Niassa). The selection of the fossil wood samples with seemingly suitable preservation for thin-sections was performed in the Laboratory of Palaeontology in Mozambique and then sent to the Evolutionary Studies Institute in South Africa. The samples are now temporarily housed in the fossil collection of the Evolutionary Studies Institute (ESI) and will be returned in due course. Over 300 samples have been prepared for this study. Only the fossil wood displaying moderate to good preservation as observed with the naked eye was chosen to be studied.

2.2 Methods

2.2.1 Thin sections

The thin sections were prepared in the Evolutionary Studies Institute, Faculty of Science, University of the Witwatersrand. This process consists of: 1) cutting a block of wood from each sample in three orthogonal planes required for study: transverse, radial longitudinal and radial longitudinal; 2) polishing the surfaces and gluing them onto petrographic slides; 3) cutting the remaining wood block with a discoplan and then the newly cut surface was ground and polished (Bamford, 1999; Kock, 2018). Ideal polishing thickness is between 25 to 80 µm. However, variation of the thickness can occur depending on the dimension of the cells (Bamford, 1999). All thin sections were identified according IAWA Softwood Committee (2004).

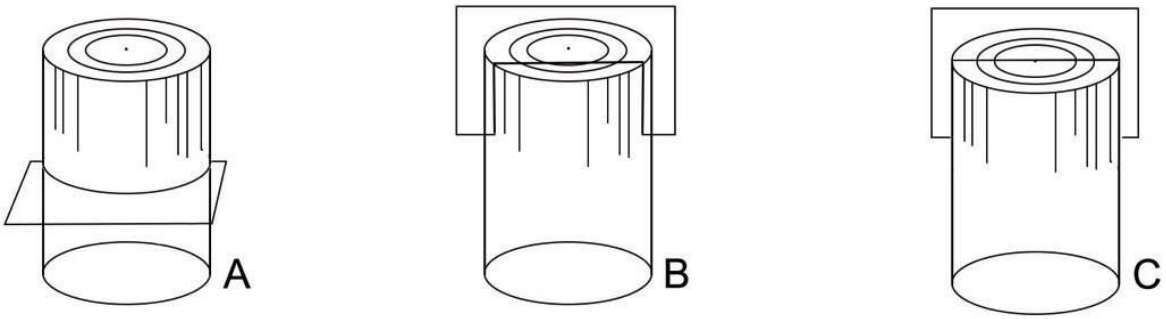


Figure 2.1: Three sections of the wood (modified from Xiao, 2016). A. Transverse section B. Tangential section C. Radial section.

A-Transverse Section (TS)

Typical features recognized in transverse section are: shape and size of the pits, presence of growth rings and resin canals, distribution and size of the tracheids, radial and tangential diameters of both earlywood and latewood.

B-Radial Longitudinal Section (RLS)

In radial section, interesting aspects for species identification include the arrangement and shape of the bordered pits on the radial walls of the tracheids (e.g., arrangement, contiguity, separation). The measurements undertaken include: the radial and tangential diameter of bordered pits, and pit aperture when possible. The number of pits in the cross-field can be assessed in radial section and is the most relevant character for species identification (Bamford and Philippe, 2008.).

C-Tangential Longitudinal Section (TLS)

In tangential section, anatomical features such as rays (height, density, form and size of ray cells) and the arrangement of the axial parenchyma are the important features for wood study.

All thin sections were analyzed and studied under a Zeiss Axioskop transmitted light microscope, with a magnification varying from 40-400x. The photomicrographs were taken with Olympus DP72 digital camera and Streams Essentials® software for

photography and measurement. Subsequently, they were assembled into photographic plates with the aid of Illustrator CS4 software. Image quality improvement was made with the use of the software ImageJ2, FIJI and FastStone Image Viewer version 7.5. The key developed by Bamford and Philippe (2001), and Philippe and Bamford (2008), aided in species identification of the studied fossil woods. Also for species-level identification, a broad anatomical comparison was made based on articles describing fossil woods of the same or similar taxa (e.g., Vaudois and Privé 1971; Bamford 1999; Crisafulli, 2016, and other articles cited on the taxonomy chapter). Regarding the quantitative characters, 25 measurements were performed per attribute. The measurements are represented by the mean values before the brackets and the minimum with maximum values within it as suggested by many other authors (Vera and Césari 2011; Chinnappa and Rajanikanth, 2016).

2.2.2 Growth ring analyses

The analysis of growth rings was undertaken considering the following aspects: presence of growth rings, growth ring width, presence of shear zones within growth rings, presence of false rings, the type of transition observed from Earlywood and Latewood, and the type of growth rings produced by each wood according to the scheme of Chaloner and Creber (1984). The most used procedure to study growth rings is the calculation of mean sensitivity obtained through the mean ring width. However, due to the reduced number of samples displaying growth rings in the data, this procedure had to be discarded (Fritts, 1976; Francis, 1986; Francis and Poole, 2002; Falcon-Lang, 2005a, b).

The growth rings were measured in terms of their width, followed by the calculation of average ring width for each sample. For this purpose, two software programmes were needed. ImageJ 2 was used to measure growth rings width and cropping the most relevant features of a given sample. The ring value and the mean ring width were calculated using the traditional Excel software.

2.2.3 Qualitative and Quantitative analysis of fossil forests

The general methods applied in this study included inventory, classification, characterization, and numerical assessment of each geosite. The inventory consisted on field identification of large numbers of fossil logs, which was followed by the mapping of the selected forests. The selection process was based on some studies that analysed a similar type of material. In this regard, the main aspects analysed were: features that provide an opportunity for research (scientific value); features that can be used for educational purposes (ED) and features that can offer opportunities for the development of geotourism activities (TV). The characterization was undertaken based on field observations, descriptions of the site with help from available information in the literature. During the characterization process, relevant features were taken into account such as: a) name of the geosite; b) geographic information; c) accessibility; d) geological description; e) protection aspects; f) vulnerability and fragility (Brilha, 2016). Moreover, to complement the qualitative assessment, analyses were carried out with a quantitative approach.

The quantitative analysis aimed at assessing the sites in order to score and thus, rank the geosites. For the quantitative assessment the criteria based and adapted by Cortés *et al*., (2018) for the Spanish inventory of Geoheritage was used. This criterion was also adapted by Cumbe (2007) for the first inventory of Geoheritage of Mozambique. The criteria adapted by Cortés *et al*., (2018) were recently used in the study of geosites of the African continent during the Geoheritage training course funded by the European Union in collaboration with the African Geological Survey (PanAfGeo Project). However, for the geoheritage quantitative assessment several criteria can also be used (Brilha, 2005; Bruschi and Cendrero, 2005).

CHAPTER THREE-SYSTEMATICS

3.1 Systematic

In this chapter fossil wood specimens collected from the 2017, 2018 and 2019 PaleoMoz expeditions are described and their taxonomic affinities determined. Each described taxon is preceded by a short history of the genus, and comparisons with closely related species and their distribution across Gondwana are provided.

3.1.1 *Agathoxylon*

History of the genus

Various fossil woods described from Mozambique have been assigned to *Dadoxylon nicoli* and *Dadoxylon* sp. over time (Silva *et al*., 1967; Verniers *et al*., 1989; Marques and Ferrara., 2004). However, this genus has been reviewed in recent years.

Dadoxylon is a well-known genus of Late Palaeozoic woods. The main features displayed by this genus of pycnoxylic secondary wood are: (1) the tracheid pitting of the araucarian type (alternate and compressed) and, (2) oculipores in the cross-fields (Bamford, 2000; Prevec *et al*., 2009; and others). However, the validity of the *Dadoxylon* genus has received criticism. *Dadoxylon* Endlicher 1843 was a genus erected for Late Palaeozoic woods with the features above described and *Araucarioxylon* Kraus 1870 for Mesozoic woods displaying the same features. However, this attribution based on geological age is not diagnostic. The set of features described above can be referred to the genus *Agathoxylon* Hartig 1848, as proposed by Bamford and Philippe (2001) for homoxylous gymnospermous woods. Up to 400 species attributable to the *Dadoxylon-Araucarioxylon-Agathoxylon* complex have been identified worldwide, extending from the Carboniferous to the Cretaceous (Philippe, 2011). Bamford (1999) erected two species of *Agathoxylon* from South Africa, namely: *Agathoxylon africanum* and *Agathoxylon karooensis*. *Agathoxylon africanum* is characterized by biseriate to rarely uniseriate arrangement of the tracheid pits, compressed, alternate and contiguous, which characterizes an araucarian type of tracheid pitting. On the other hand, *Agathoxylon karooensis*

displays biseriate to triseriate bordered pitting and alternate, contiguous to slightly compressed (araucarian pitting).

Genus: *Araucarioxylon* Kraus 1870

Agathoxylon africanum

Specimen Number: PPM 2019-61NN.

Other Mozambican specimens referable to this species: PPM 2018-19R, PPM 2018-67N, PPM 2018-5N, PPM 2018-28N, PPM 2019-8Z, PPM 2019-15NN, PPM 2019-5R, PPM 2017-44, PPM 2017-54, PPM 2018-56, PPM 2019-86NN, PPM 2019-43NN, PPM 2019-44NN, PPM 2019-52R, PPM 2019-102NN, PPM 2019-82NN, PPM 2019-44Z, PPM 2019-83NN, PPM 2019-85NN, PPM 2019-61NN (see Table 3.4 for information regarding the Formation and locality of each sample).

Locality: Nhamago, Niassa.

Horizon and age: K4 Formation (Lower Permian).

Description: Silicified wood, pycnoxylic secondary wood with well-marked and slightly compressed growth rings associated with a likely shear zone (Figure 3.1). Latewood is 3-5 cells wide (Figure 3.1). The shape of the tracheids in the transverse section is square. The earlywood tracheid mean tangential diameter is 14 µm ranging from 8 to 20 µm and, the mean radial diameter is 14 µm ranging from 8 to 18 µm. The longitudinal radial section pits are circular, alternate, and contiguous with an average diameter of 9 µm (Figure 3.1B-F). The cross-field pits are araucarioid characterized by narrow borders, with 4-5 pits per field, however, other fields are likely to be hidden or difficult to discern due to the preservation. The cross-field pits are round to oval. In the tangential longitudinal section, the radial system is homogenous with homocellular rays, uniseriate, very low with 1-12 cells high. There are at least 5 rays per horizontal (Fig. 3.1H). Resin canals or axial parenchyma were not observed in the wood.

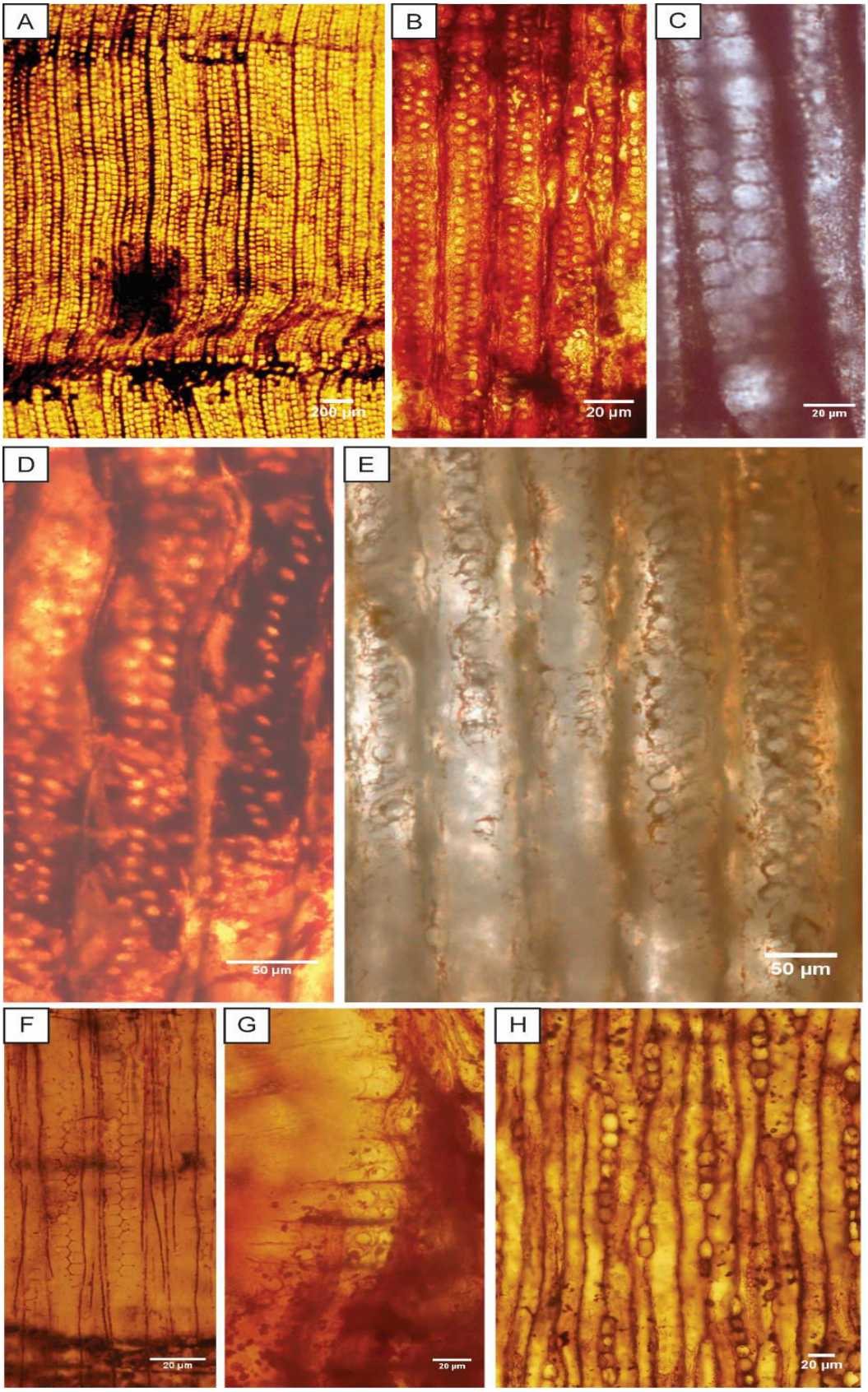


Figure 3.1: ***Agathoxylon africanum*** A. TS (thin-section) showing square tracheids and distinct growth rings. B-F. RLS (radial longitudinal section) displaying uniseriate

and biseriate alternate bordered pitting. G. RLS exhibiting 4-5 narrow bordered pits per field. H. TLS (tangential longitudinal section) showing uniseriate rays.

Comparisons: The specimen described above and others listed in the table below are characterized by the presence of araucarian tracheid pitting and araucarioid cross-field pits in the radial walls, which is assignable to *Agathoxylon africanum* (Bamford, 1999).

According to Bamford (1999) and personal observations, *Agathoxylon africanum* resembles the Cretaceous Chadian specimen assigned to *Dadoxylon* (*Araucarioxylon*) *dalloni* (Duperon Laudoueneix, 1976). The Chadian specimen differs from *Agathoxylon africanun* for its large bordered pits and the number of pits in the cross-fields. In addition, two more species show similarities with *Agathoxylon africanum* as described by Bamford (1999). The two specimens are *Dadoxylon kiliani* reported from the Cretaceous of Morocco and *Dadoxylon* sp. 1 from the Permian of Saudi Arabia. The more uniseriate nature of the tracheid pitting distinguished these species from *A. africanum*, given the information provided by the recent large numbers of specimens from Mozambique.

Distribution in other Gondwana sites and Mozambique

This species is well-known from the Normandien Formation, South Africa (Late Permian; Bamford, 1999). Although the Beaufort Group is unlikely to be present in Namibian formations (Smith *et al.,* 1993), woods of *Agathoxylon africanum* are recorded in Namibia (see above the section on Namibian fossil wood studies). In the Namibian formations the time range of these species is Permian to possibly Jurassic (Bamford, 1999). Also, two more occurrences of *Agathoxylon africanum* are reported from Triassic formations of both Mosolotsane (Late Triassic, Botswana; De Wit *et al*., 2018) and Caturrita (Late Triassic, Brazil; Crisafulli, 2016). Beyond its occurrence in some Gondwana formations, *Agathoxylon africanum* is also now found in Mozambique within the following formations: Cádzi Formation (Late Permian-Lower Triassic), Matinde Formation (Late Permian), KSb, Fubué Formation (Lower Triassic-

Middle Triassic?), K5 Formation (Middle Permian) and K4 Formation (Lower Permian).

Agathoxylon karooensis

History of the genus is given in the section above.

Specimen number: PPM 2018-65N.

Other Mozambican specimens referable to this species: PPM 2017-13 (see Table 3.4 for information regarding the Formation and locality of the sample).

Locality: Bungué, Tete.

Horizon and age: Matinde Formation (Late Permian).

Description: Silicified homoxylous wood with araucarian tracheid pitting on the radial walls. The bordered pits are biseriate to triseriate. The pits are alternate, contiguous to slightly compressed (Figure 3.2B). Some of them are biseriate, alternate to sub-opposite (short portions). The pit diameters range from 3 to 4 µm. There are at least 5-7 circular to oval taxodioid pits per cross-field (Figure 3.2C). Due to the preservation of the wood in the tangential section no details can be described.

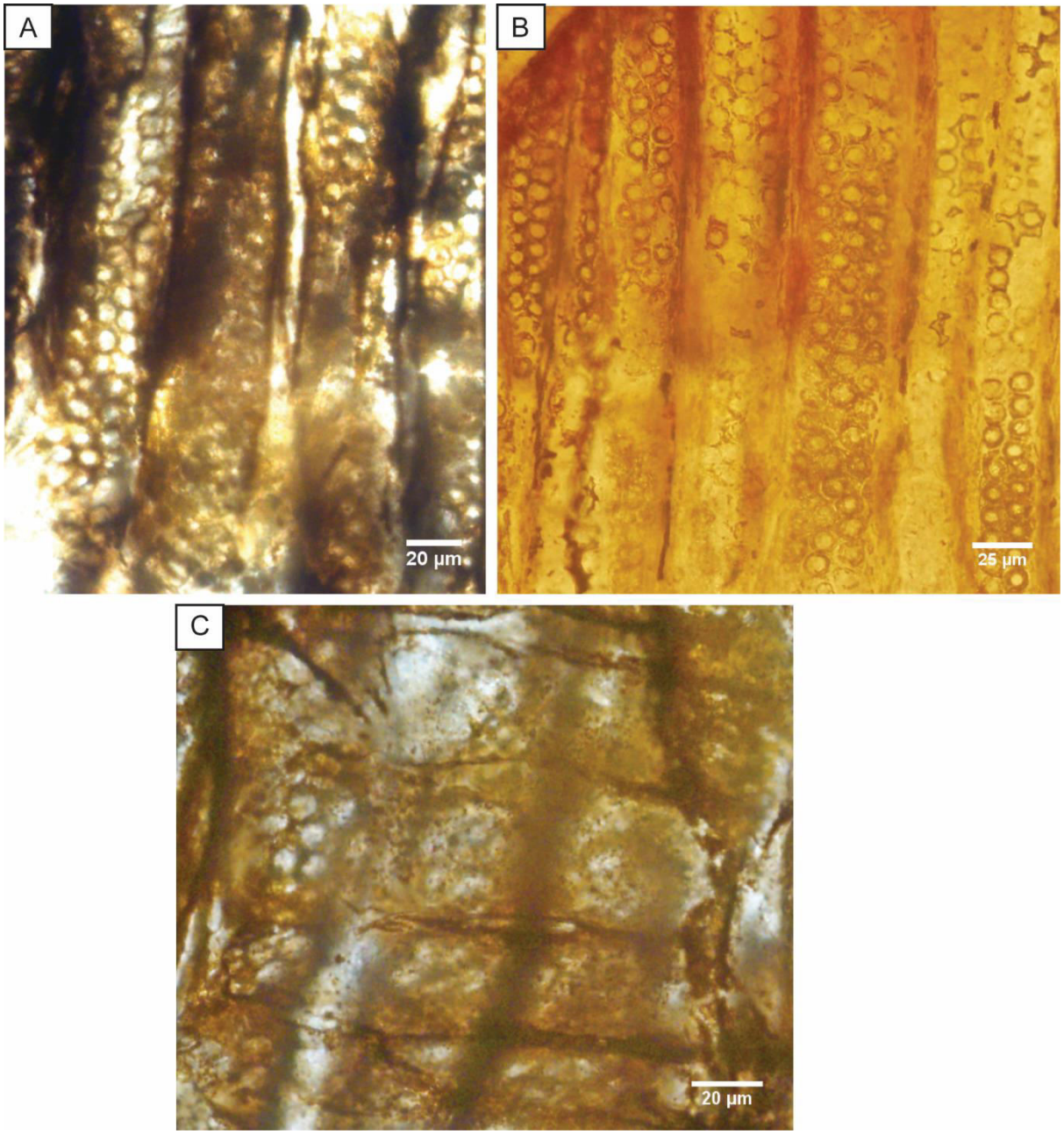


Figure 3.2: ***Agathoxylon karooensis***. A and B. RLS showing biseriate to triseriate alternate pitting. C. RLS Cross field with narrow borders.

Comparisons with other known species of genus

The two specimens display in the radial tracheid walls biseriate to triseriate pits. According to personal observations and Bamford (1999), *Agathoxylon karooensis* is similar to *Agathoxylon agathiodes*. However, in *Agathoxylon agathioides* the pits in the radial walls are larger compared to *Agathoxylon karooensis*. Other woods referred by Bamford (1999) as close to *Agathoxylon karooensis* are: *Araucarioxylon*

kharkhariense (Maithy, 1965) from Permian formations in India and, *Araucarioxylon amraparense* (Sah and Jain, 1963) from Jurassic deposits in India, previously both referred as *Dadoxylon*. However, these taxa possess a random arrangement of tracheid pitting and the observation of abietinian type of tracheid differentiate them from *Agathoxylon karooensis.*

Distribution in other Gondwana sites and Mozambique

Agathoxylon karooensis has been restricted to some sites in South Africa and Namibia thus far. In South Africa, it occurs in the Normandien Formation (Upper Beaufort, Bamford 1999), while in Namibia they were found in the Tsarabis to the Etjo Formation (Permian to possible Jurassic, Bamford 1999). Now, *Agathoxylon karooensis* is also found in Mozambique at the Matinde Formation (Late Permian).

3.3.2 *Cupressinoxylon*

History of the genus

The genus was erected by Goppert (1850) based on the study of *Retinodendron. pityoides* (Krausel, 1919). Over 150 species of *Cupressinoxylon* have already been described (Ríos *et al*., 2020). The most comprehensive revision of the genus can be found in Vaudois and Privé (1971) and recent descriptions of the genus include Pujana *et al*., (2017) and Rios *et al*., (2020). Before the revision by Vaudois and Privé (1971), Krausel (1919) undertook a revision that resulted in 17 species. The genus *Cupressinoxylon* has been assigned to those specimens where the cross-field pits are cupressoid, the tracheid pitting is abietinian and the ray cell walls are smooth following the key of Philippe and Bamford (2008).

Genus: *Cupressinoxylon* Göppert, 1850.

Type species: *Cupressinoxylon gothanii* Kräusel in Jahrb (1920).

Specimen number: IPG-01B.

Location: Mapembera, Tete.

Other Mozambican specimens referable to this species: None.

Locality: Mapembera, Tete.

Horizon and age: Matinde Formation (Late Permian).

Description: The growth rings are distinct but there is a slight compression of the wood (Figure 3.3A). The transition from earlywood to latewood is abrupt (Figure 3.3A). In the transverse section the tracheids show subrectangular to square outlines (Figure 3.3A). The latewood bands are narrow and show three to four cells wide. The smallest bands are 16 µm, the largest maximum are 44 µm and on average are 31µm (Figure 3.3A). The earlywood diameter is 30 µm on average, ranging from 16 to 48 µm in tangential direction, and 33 µm in radial direction, ranging from 16 to 53 µm. Bordered pits on the radial walls of tracheids are circular, 1-2-3-seriate (Figure 3.3C). Uniseriate pits are spaced, sometimes showing contiguity (Figure 3.3D). Biseriate and triseriate pits and are mostly opposite to sub-opposite (Figure 3.3C). The pores of the pit are either elliptical and round with a diameter of 2.5 µm on average, ranging from 1.65 to 3.76 µm. Both biseriate and triseriate opposite pits are heavily surrounded by crassulae or Bars of Sanio (Figure 3.3C). The crassulae are frequent in the studied specimen with up to ten thin crassulae between adjacent pits can be seen in the radial walls (Figure 3.3C). The bordered tracheids pit is 5µm on average, ranging from 3 to 6 µm in tangential diameter and, 4 µm on average, but ranging from 2 to 6 µm in radial diameter. Cross-field pits borders are mostly wider than the aperture and therefore are of the cupressoid type with two to five, mean four spaced pits per cross-field (Figure 3.3D and E). Cross-field pits display a horizontal and vertical line arrangement with relatively large borders and the pits are elliptical and oriented obliquely (Figure 3.3D). The rays are mostly uniseriate sometimes biseriate, and 1-12 cells high (Figure 3.3F). The ray walls are slightly undulating but smooth. The average of ray cells height is ~75 µm. Both parenchyma and resin canals are absent.

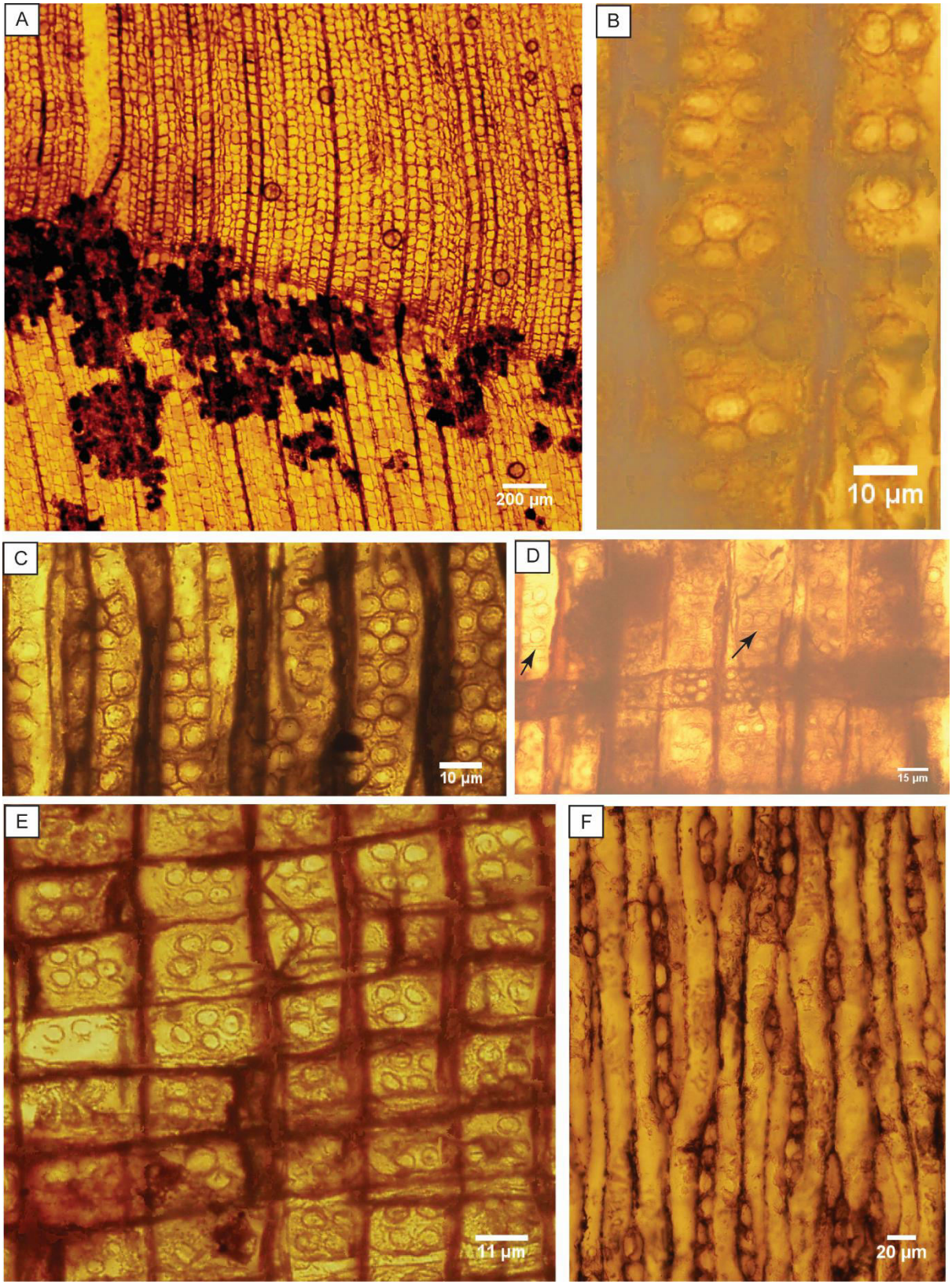


Figure 3.3: A. *Cupressinoxylon* sp. nov. A: TS showing the distinct growth rings and transition from earlywood to latewood. B, C and D. RLS showing details of bordered pits with arrows indicating the Bars of Sanio in D. E. RLS showing 2-5 pits per cross-field. F: TLS showing distribution of xylem rays.

Comparison with other *Cupressinoxylon* species

According to Philippe and Bamford (2008), *Cupressinoxylon* species are conifer woods with abietinian radial pitting, smooth ray cell walls, cupressoid cross-field pits. Typically the cupressoid cross-field pits are separate when there are two or more in a cross-field. The specimen found in Mozambique possesses these conditions, thus, here it is confidently assigned to *Cupressinoxylon*. Although there are some differences, the studied specimen is closely related to three previously described species, namely:

1. ***Cupressinoxylon canadense* (Schroter, 1880**) from the Miocene of North Canada. *C. canadense* differs from the studied specimen because it has a very high number of ray cells (2-45) and a low number of pits per cross-field. While there is 1-3 pits per cross-field in *C. canadense*, the Mozambican specimen has 2 to 5. Bordered pits on the radial walls of tracheids are 1- or 2-seriate in *C. canadense*, whereas for the studied specimen is 1-2-3seriate.

2. ***Cupressinoxylon jiayinense* (Wang *et al.*, 1996)** differs from the studied specimen because it: is uni- to biseriate, has pitted tangential section, has a much greater number of rays height 4-68 cells and, the number of pits per cross-field is two to three.

3. ***Cupressinoxylon megeeci* (Knowlton, 1889)** differs from the Mozambican species due to the following aspects: the simple pits in cross field, it has wider rays uni- to triseriate and, it has bi- or triseriate bordered pits on the radial walls.

Based on the differences within the published species of *Cupressinoxylon* as listed above it is proposed as a new species, *Cupressinoxylon* sp. nov.

Distribution in other Gondwana sites and Mozambique

Cupressinoxylon is a cosmopolitan genus that has been found in both hemispheres (e.g., Wang *et al*., 1996, Krausel 1949 and Pujana *et al*., 2017, Nishida, 1984). However, in Mozambique it is now recorded for the first in the Matinde Formation (Late Permian).

3.3.3 *Prototaxoxylon*

History of the genus

The genus *Prototaxoxylon* was established by Krausel and Dolianiti (1958). *Prototaxoxylon* was created to replace the generic name *Spiroxylon* which was first erected by Walton (1925), but had already been used by Hartig (1848) to assign other types of woods (Gnaedinger and Herbst, 2006). The woods assigned to *Prototaxoxylon* usually exhibit tracheid pitting of the araucarian type on the radial walls of the tracheids, cross-fields of the araucarioid type or cupressoid type and the presence of oblique spiral thickening.

Genus: *Prototaxoxylon* Kräusel et Dolianiti, 1958.

Type species: *Prototaxoxylon africanum* (Walton) Kräusel et Dolianiti, 1958.

Prototaxoxylon uniseriale Prasad, 1982.

Specimen number: PPM2019-32R.

Other Mozambican specimens referable to this species: PPM 2017-51, PPM 2019-66R (see Table 3.4 for information regarding the Formation and locality of each sample).

Locality: Matepué, Niassa Province.

Horizon and age: K5 Formation (Middle Permian).

Description: The wood is pycnoxylic without growth rings. The transverse section display earlywood tracheids with rectangular, circular and polygonal outlines (Figure 3.4A). The number of tracheids that separate the rays varies from one to five cells (Figure 3.4A). The earlywood tracheid mean tangential diameter is 12 µm, ranging from 8 to18 µm and, the average radial diameter is 12 µm, ranging from 8 to 20 µm. Bordered pits, which are typically present in the radial section, can also be noted in the transverse section in this wood (Figure 3.4B). In the radial walls, the tracheid pitting is of the araucarioid type, circular to oval. The arrangement of the tracheids is mostly uniseriate, contiguous but rarely separate, and sometimes biseriate and alternate. The spirals are of the clockwise and anticlockwise type, with an inclination of 45^{o} (Figure 3.4C and D). The mean diameter of the bordered pits is 25 µm, ranging from 16 to 36 µm. Cross-field pits are single or oblique and, each field has one pit but rarely two (Figure 3.4 E). In longitudinal section, the features are not well-preserved, though, the homogeneity of the rays can be observed (Figure 3.4F). Resin canals or axial parenchyma are absent.

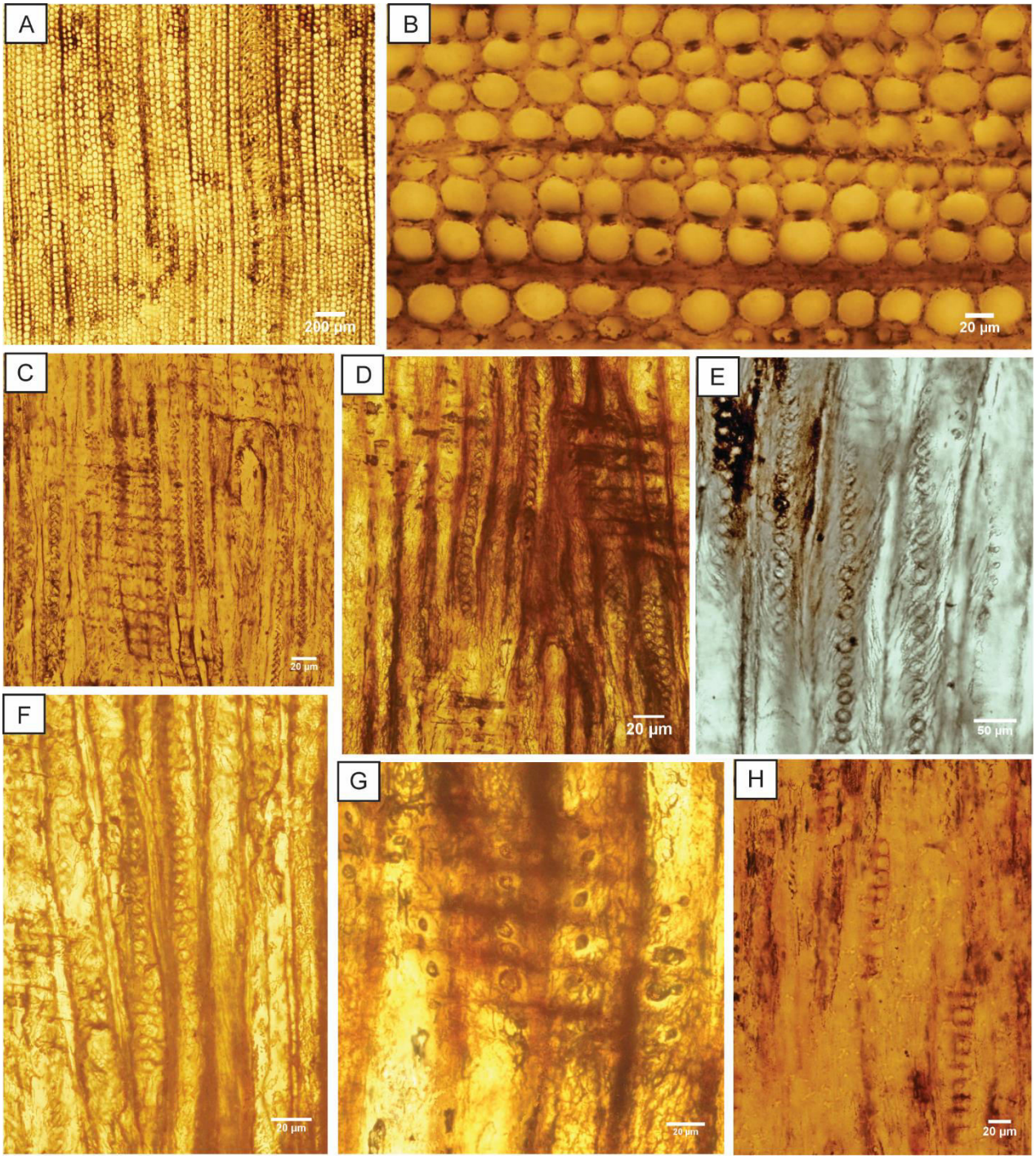


Figure 3.4: ***Prototaxoxylon uniseriale*****.** A and B. TS showing circular to rounded tracheids and bordered pits. C, D and F. RLS with uniseriate to biseriate bordered pits and spiral thickening. G. RLS Details of cross field pits. H. TLS showing uniseriate rays.

Comparisons with *Prototaxoxylon* species

The studied specimen and the other two listed in the table show tracheid bordered pits characterized by uniseriate and contiguous arrangement and spiral thickening at 45°, thus assigning them to *Prototaxoxylon uniseriale.* There are sixteen species of *Prototaxoxylon* described from Gondwana deposits (Shilkina, 1960; Gnaedinger, 2006). The relatively close species is *P. acevedoe* (Gnaedinger and Herbst, 2006), however, has triseriate radial pitting and the number of cross-fields differs from *P. uniseriale* (Prasad, 1982). The other species is *Prototaxoxylon maithy* Prasad, 1982, however, *P. uniseriale* differs from this due to its uni- to biseriate tracheid pitting on the tangential walls (Prasad, 1982, 1986). See below the comparison among *Prototaxoxylon* species described from Gondwana (partially adapted from Prakash and Srivastava, 1961; Prasad, 1986; Lutz *et al*., 1999; 2002; Gnaedinger and Herbst, 2006; Ming *et al*., 2015).

Distribution in other Gondwana sites and Mozambique

Prototaxoxylon uniseriale occurs in the Abrahamskraal Formation and the Waterford, Fort Brown Formations from the Lower Permian of South Africa (Bamford, 1999). The other two reports come from the Kamthi Formation (Late Permian in India, Prasad, 1982) and the Jurassic sediments in the Matilde Formation of Argentina (Gnaedinger, 2006). There are also recent findings of *Prototaxoxylon uniseriale* from Permian deposits in China (Ming-Li *et al*., 2015). *Prototaxodioxylon uniseriale* is now also recorded in Mozambique in both the Matinde Formation (Late Permian) and K5 Formation (Middle Permian).

3.3.4 *Protaxodioxylon*

History of the genus

The manuscript that described two new species of *Protaxodioxylon* from Metangula Graben has been submitted to the Journal of African Earth Sciences (Elsevier) for publication; however, it is still “under editor’s evaluation”.

The genus *Protaxodioxylon* was erected by Bamford and Philippe (2001) for woods with mixed radial pitting (araucarian and abietinian) and taxodioid pits within the cross-field. However, it should also be highlighted that there are earlier studies on related taxa. Vogellehner (1968), when analysing the holotype of *Prototaxodioxylon,* revealed a clear absence of taxodioid pits in the cross-fields. Later on, Bamford and Philippe (2001) suggested that the genus *Prototaxodioxylon* should be synonymized with either *Protocupressinoxylon* or *Brachyoxylon*. Thus, for those specimens showing mixed radial pitting and taxodioid pits in the cross-field, they proposed the taxon name *Protaxodioxylon* as the representative new genus.

Genus: *Protaxodioxylon* Bamford and Philippe, 2001.

Species: *Protaxodioxylon* sp. nov. 1 (Nhamutole *et al*., submitted) (Fig. 3.4A-F).

Specimen number: PPM2018-105N.

Other Mozambican specimens referable to this species: None.

Locality: Muchumua, Niassa.

Horizon and age: K5 Formation, Late Capitanian (Verniers *et al*., 1989).

Description: The growth rings in the transverse section are distinct (Fig. 3.5A). The rings vary from 640 µm to 1256 µm in width. The transition of tracheids from early wood to latewood is abrupt. Early wood is much broader than late woods. The early wood tracheids are mainly subquadrangular to subcircular in shape. Latewood consists of a few rows (three to six) of flattened, tangentially-elongated tracheids. The tracheids of late wood are subrectangular in shape. In the radial section, the bordered pits are uniseriate or biseriate (Figure 3.5B-E). The height of the pits varies from 4.0 µm to 9.0 µm and width varies from 5.0 µm to 10.0 µm. When uniseriate, the bordered pits are somewhat flattened, being separated or contiguous (Figure 3B). When biseriate, they are alternate, opposite and mostly contiguous, although some separation is observed in few cases (Figure 3.5C-E). The aperture is mostly rounded, with a mean diameter of 2 µm. The cross-field pits are taxodioid, with

narrow borders, and the aperture vertical to oblique. There are three to four pits in the cross-field, where two of them are almost arranged horizontally as a row (Figure 3.5F). In the tangential section, the rays are homogeneous, cells are circular and predominantly uniseriate, albeit some short biseriate portions are present occasionally (Fig. 3.5G). The ray height varies from 2-28 cells. Axial parenchyma was not observed; the dark deposits visible in the cross-section are in fact extraneous material because at higher magnification it is clear that the dark material covers more than one cell and does not follow the outline of any individual cells. In contrast with the other specimens described in this paper, the presence of pits on the tangential walls of the tracheids is noticed (Figure 3.5H).

Based on the xylological features, that characterize *Protaxodioxylon* (*sensu* Philippe and Bamford, 2001), which are taxodioid cross-field pits and mixed type of radial pitting on the tracheid radial walls, this specimen is assigned to *Protoxodioxylon*. However, a detailed comparison between published species is presented below.

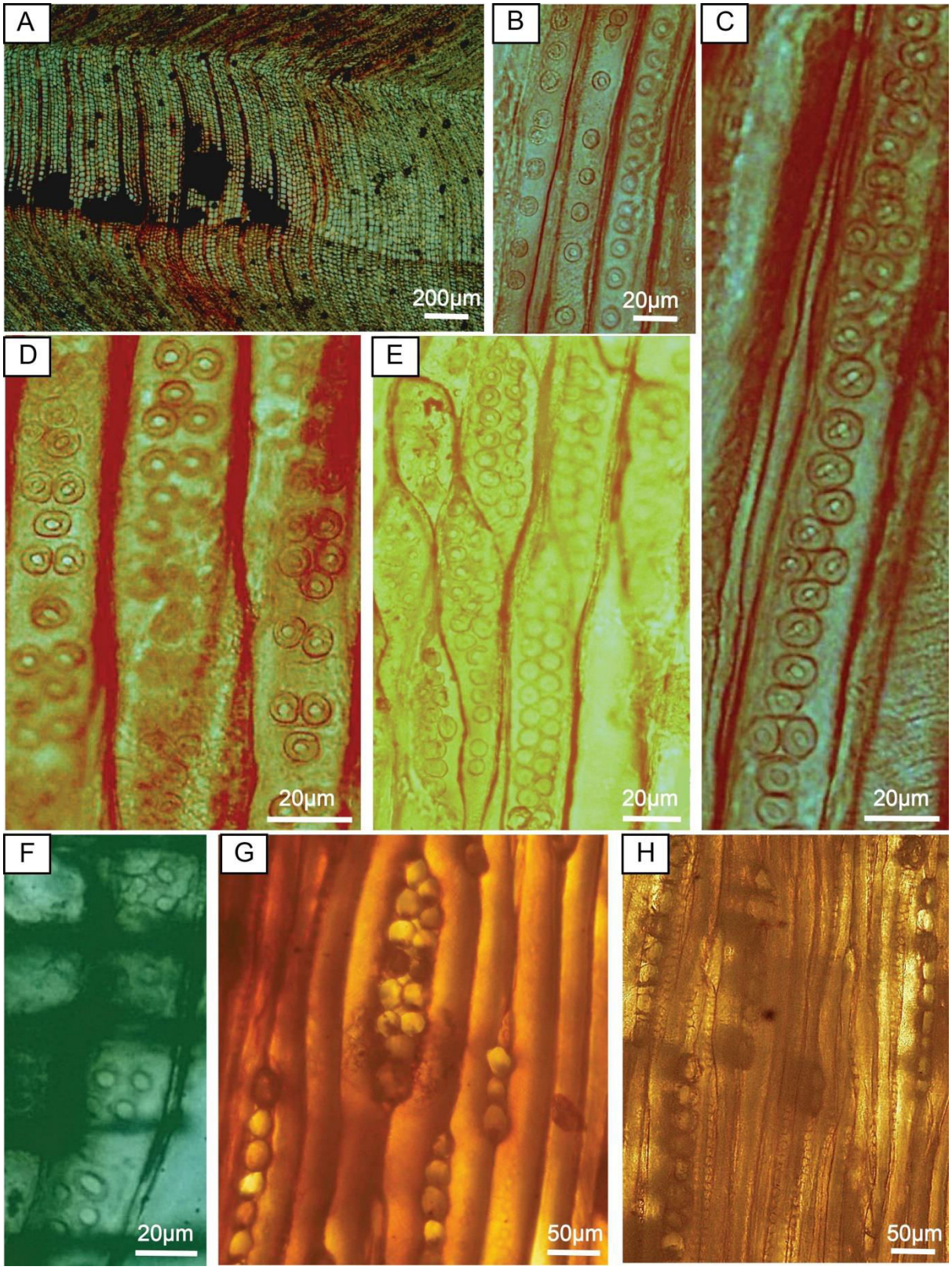


Figure 3.5: ***Protaxodioxylon*** **sp. nov 1**. Anatomical features of thin-section slides are in three directions. A. TS exhibiting tracheid shape and a distinct growth ring. B. RLS showing details of uniseriate radial pitting. C. RLS Bordered pits on tracheid radial walls are mostly uniseriate with biseriate opposite portions. D. RLS highlighting bordered pits

showing alternate and contiguous arrangement. E RLS showing distribution of taxodioid cross-field pits. F. TLS displaying uniseriate rays with some biseriate portions and bordered pits.

Genus: *Protaxodioxylon* Bamford and Philippe, 2001.

The history of the genus is the same as described above.

Species: *Protaxodioxylon* sp. nov. 2 (Nhamutole *et al*., submitted) (Fig. 3.6A-F).

Specimen number: PPM 2018-107N.

Other Mozambican specimens referable to this species: None.

Locality: Mechumua, Niassa.

Horizon and age: K5 Formation, Late Capitanian (Verniers *et al*., 1989; Araújo *et al*. 2020).

Description: In the transverse section, the growth rings are distinct (Figure 3.6A). The rings vary from 382 µm to 554 µm in width. The transition between tracheids from early wood to late wood is abrupt. Earlywood cells are wider than latewood cells (24 µm on average). The tracheids of early wood are mainly square to hexagonal in shape (Figure 3.6A). Latewood consists of 2-3 rows of radially flattened tracheids (Fig 4A). The latewood tracheids are rectangular in shape (23 µm on average). Bordered pits seen on the radial section are uniseriate, biseriate to triseriate, both with araucarioid and abietioid affinity (Figure 3.6B-D). The height of pits varies from 4.7 µm to 7.9 µm and their widths vary from 4.2 µm to 7.9 µm. The uniseriate rounded pits are contiguous (Figure 3.6C). The biseriate pits, when opposite and spaced, are separated by crassulae, also known as Bars of Sanio (Figure 3.6B). However, the biseriate pits are either alternate separate or alternate contiguous (Figure 3.6C). The triseriate pits are opposite and alternate, yet they tend to be biseriate in the terminal part of the tracheid (Figure 3.6D). The aperture is mostly rounded to oblique with a 3 µm mean diameter. The cross-field pits are mostly taxodioid type with two (most cases) to three pits per field (Figure 3.6E). When there

are two pits per field, they are contiguous and horizontally-arranged (Figure 3.6E). In the tangential section, the cell rays are mostly rounded to longitudinally elliptical, uniseriate, despite some biseriate portions (Figure 3.6F). The variation of ray height is 2-21 cells. The axial parenchyma is not observed and there are no bordered pits on tangential walls of the tracheids. Following the determination key to morphogenera of Mesozoic conifer-like woods by Philippe and Bamford (2008), the Mozambican wood is assigned to the genus *Protaxodioxylon* Bamford and Philippe (2001) characterized by mixed radial tracheid pitting and taxodioid cross-field pits.

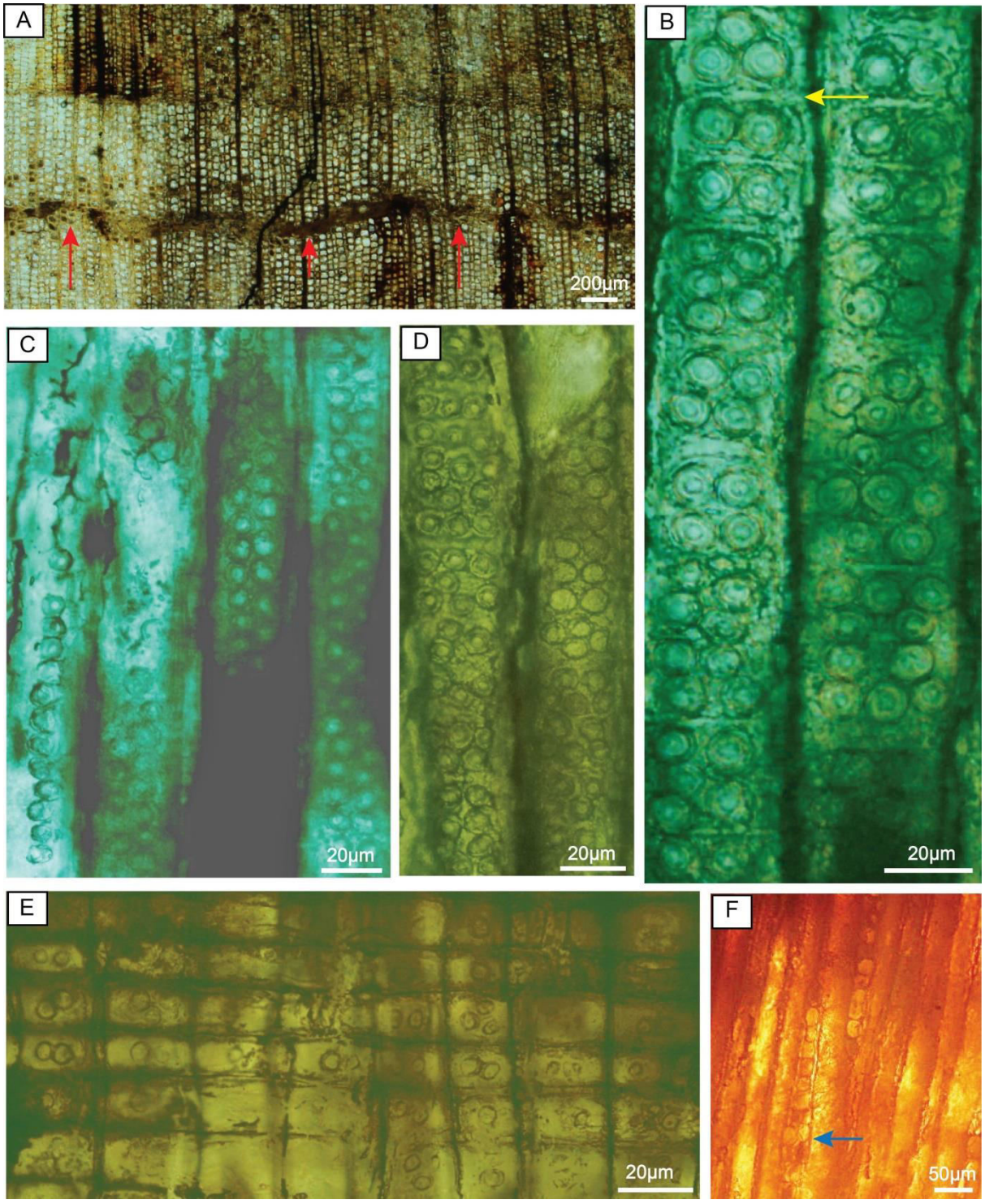


Figure 3.6: *Protaxodioxylon* sp. nov.*2*. Anatomical features of thin-section slides are in three directions. A. TS showing distinct growth rings and radial sections (red arrows). B. RLS abietioid bordered pits on the radial walls of the tracheids surrounded by crassulae or Bars of Sanio (yellow arrow). C. RLS Araucarioid uniseriate and biseriate radial pitting. D. RLS triseriate bordered pits mostly in opposite arrangement with biseriate portions. E. RLS with details of the distribution of taxodioid cross-field pits. F. TLS showing details of uniseriate rays with occasional biseriate portions (blue arrow).

Comparisons with other *Protaxodioxylon* species

The two specimens (PPM 2018-105N and PPM 2018-107N) from Metangula Graben all have mixed radial pitting and taxodioid pits in the cross-field. For these two new species described, comparisons between both can be specified. *Protaxodioxylon* sp. nov. 1, differs from the *P.* sp. nov. 2, due to the presence of tangential bordered pits, higher number of pits per cross-field, and the arrangement of pits on the radial walls, which is uniseriate to biseriate in *P.* sp. nov. 1. In turn, *P.* sp. nov. 2, lacks bordered pits on the tangential walls, shows a lower number of pits per cross-field, exhibits Bars of Sanio, and the arrangement of pits on the radial walls ranges from uniseriate to triseriate. However, the most obvious features that differentiate both new species from the known *Protaxodioxylon* species are the absence of parenchyma, and the numbers of both ray cells and taxodioid pits in the cross-field (Table 3.1).

The new species from Mozambique can be differentiated from *P. romanensis* (Bamford and Philippe, 2001) mainly due to the presence of false growth rings (although not necessarily of taxonomic value), presence of axial parenchyma, and lower rays (1-5 cells high) in *P. romanensis*. Unlike the studied new species, *P. turolense* lacks growth rings and shows higher rays, which is 7 to 42 cells high. *P. mongolense* has spiral thickenings on the tracheid radial walls accompanied by higher ray cells (1-57 cells high), thus distinguishable from both new species from Mozambique. The new species are distinguished from *P. jiachangense* because it shows spiral thickenings on the radial tracheid walls and relatively lower rays, which is 1 to 16 cells high and, has mostly one pit in the cross-field (Tian *et al*., 2015). *P. patagonicum* is distinctive from both new species because of the presence of growth rings, presence of axial parenchyma and septate tracheids on the radial walls (Bodnar and Espada, 2016). Finally, *P. sahnii* (Chinnappa *et al*., 2019) differs from both new species due to its lower xylem rays (1-7 cells high) and the higher number of pits in the cross-field. Following the differences stated above, is then ruled out their ascription to one of the known species, thus proposing new specific taxa for newly collected species.

Table 3.1: Comparison of the anatomical features from known species of *Protaxodioxylon* (modified from Tian N, *et al.,* 2015 and Chinnapa *et al*., 2019).

Species	Growth rings	Bordered Pits on the radial walls			Tangential Pits	Axial Parenchyma	Rays	Pits per cross-field	Geological range	References
Protaxodioxylon jianchangense	Present	Contiguous, occasionally separated	Uniseriate		Simple holes	Present	Uniseriate; 1–16, mostly 2–7 cells high	1 pit per field; taxodioid, occasionally cupressoid	Middle Jurassic	Tian *et al*., 2015
P. romanensis	Present	Contiguous or separated	Uniseriate or biseriate	Opposite or alternate	Present, simple or bordered	Present	Uniseriate or biseri- ate; mean 5 cells high	1–5 pits per field; mixed type and taxodioid	Lower Jurassic	Bamford and Philippe, 2001
P. mongolense	Present	Contiguous	Uniseriate or biseriate	Opposite or alter-nate	Absent	Present	Uniseriate, locally biseriate to triseri- ate; 1–57, mostly 8–26 cells high, uniseriate or completely	1–2 pits per field; taxodioid and cupressoid	Late Jurassic to Lower Cretaceous	Ding *et al*., 2010

							or partially biseriate;			
P. turolense	Absent	Contiguous or separated	Mostly uniseriate	Opposite	Absent	Present	7–26, mostly 12 and 22 cells high	1 or 2, occa-sionally 3 pits per field; tax- odioid	Lower Cretaceous	Vozenin-Serra *et al*., 2011
P. patagonicum	Poor and abrup	Contiguous ou spaced	Uniseriate to biseriate	Opposite to sub-opposite	Absent	Present	1-26 cells high uniseriate and partially biseriate	1-4 per field, taxodioid and cupressoid	Lower Jurassic	Bodnar and Escapada, 2016)
P. sahnii	Distinct	Spaced or contiguous	Uniseriate to biseriate	Opposite to sub-opposite	Absent	Absent	1-5-7 cells high	2-6 per field, taxodioid	Middle Jurassic-Lower Jurassic	Chinappa *et al*., 2019
***P.* sp. nov. 1 (PPM 2018-105N)**	Present	Contiguous or separated	Uniseriate or biseriate	Opposite or alternate	Present	Absent	Uniseriate or biseriate , 2-28 cells high, mean cells high 10	4 pits per cross-field; taxodioid	Middle Permian	This thesis
***P.* sp. nov. 2**	Present	Contiguous	Uni, bi-	Opposite	Absent	Absent	Mostly	2 or 3 pits	Middle	This thesis

(PPM 2018-107N)		or separated	triseriate	or alternate			uniseriate, occasionally biseriate, 2-21 cells high, mean cells high 12	cross-field, taxodioid	Permian	

Distribution in other Gondwana sites and Mozambique

Over the past two decades six species have been assigned to *Protaxodioxylon*, even though the generic diversity remains low (Table 3.1 above). The known species ascribed to *Protaxodioxylon* are: *P. romanensis* known from Lower Jurassic of Doubs and Bas-Rhin, France (Bamford and Philippe, 2001), *P. turolense* from the Lower Cretaceous of the Iberian Range , Spain (Vozenin-Serra *et al*., 2011), *P. mongolense* from the Late Jurassic to Lower Cretaceous of Southeast Mongolia (Ding *et al*., 2011), *P. Jianchangense* from the Middle-Upper Jurassic of Liaoning, China (Tian *et al*., 2015), *P. patagonicum* known from the Lower Jurassic of Cerro Bayo, Chubut Province, Argentina (Bodnar and Espada, 2016), and *P. sahnii* from the Middle Jurassic to Lower Cretaceous of India (Chinnappa *et al*., 2019) for further details, see Table 3.1. Both new species of *Protaxodioxylon* in Mozambique are from the same geological unit, which is the K5 Formation (Middle Permian) and represents the first occurrence of this genus in the Karoo sequence (Nhamutole *et al*., submitted).

3.3.5 *Australoxylon*

History of the genus

Australoxylon was erected by Marguerier (1973). The type species is *Australoxylon teixeirae* described from the samples collected in the Karoo deposits of Mozambique (Lower Permian). *Australoxylon natalense*, from KwaZulu Natal in South Africa was described at the same time (Marguerier, 1973). *Australoxylon teixeirae* is different from *Australoxylon natalense* because the latter, displays Bars of Sanio. *Australoxylon natalense* exhibit the following characters: 1) tracheid pitting of araucarian type, characterized by alternate and compressed tracheids; 2) abietinian tracheid pitting, with uni- to multiseriate opposite tracheids in radial walls and 3) different clusters of pits (Marguerier, 1973).

Genus: *Australoxylon* Marguerier, 1973.

Type Species: *Australoxylon teixeirae*, Marguerier, 1973.

Specimen number: PPM 2019-39R.

Other Mozambican specimens referable to this species: PPM 2017-37, PPM 2017-37, PPM 2017-38, PPM 2017-38, PPM 2018-2N, PPM 2019-40NN, PPM 2019-6R, PPM 2019-16R, IPG-01A, IPG-07, IPG-02, PPM 2018-2N, PPM 2019-2NN, PPM 2019-45NN, PPM 2019-56NN, PPM 2019-39R (see Table 3.4 for information regarding the Formation and locality of each sample).

Locality: Matepué, Niassa Province.

Horizon and age: K5 Formation (Middle Permian).

Description: Secondary xylem wood with well-marked growth rings and insect damage due to fungal activity (Figure 3.7A). The transition from early to latewood is gradual according to IAWA 2004.Tracheids are square to rectangular in transverse section. The range of the radial diameter of the tracheids is 13 (10-16) µm and 14 (10-22) µm tangentially. The tracheids in some areas are arranged in "s-shaped linear rows" or zig-zag configuration *sensu* Maheshwari (1972) and in “shearing zones” *sensu* Erasmus (1976). Bordered pits are seen on the radial walls characterized by several clusters that make the pitting arrangement very irregular. They are uniseriate, separate, circular, and contiguous representing an araucarian type of pitting (Figure 3.7B and E). In addition, most of the pits are biseriate, circular, opposite to sub-opposite, and separate, alternate, contiguous, but are always arranged in distinct clusters and with no compression characteristic of araucarian pitting (Figure 3.7B, C, and D). When contiguous, the pits are round and some distortion is observed when separation occurs. The average of the tracheid radial diameter in the radial walls is 13 µm, but ranging from 6 to 18 µm, whereas the tracheid tangential diameter is 12 µm, ranging from 8 to 18 µm. The rays are homogeneous, uniseriate and, 2-20 cells high exhibiting thin and very smooth cells (Figure 3.7G). No resin canals or axial parenchyma were observed.

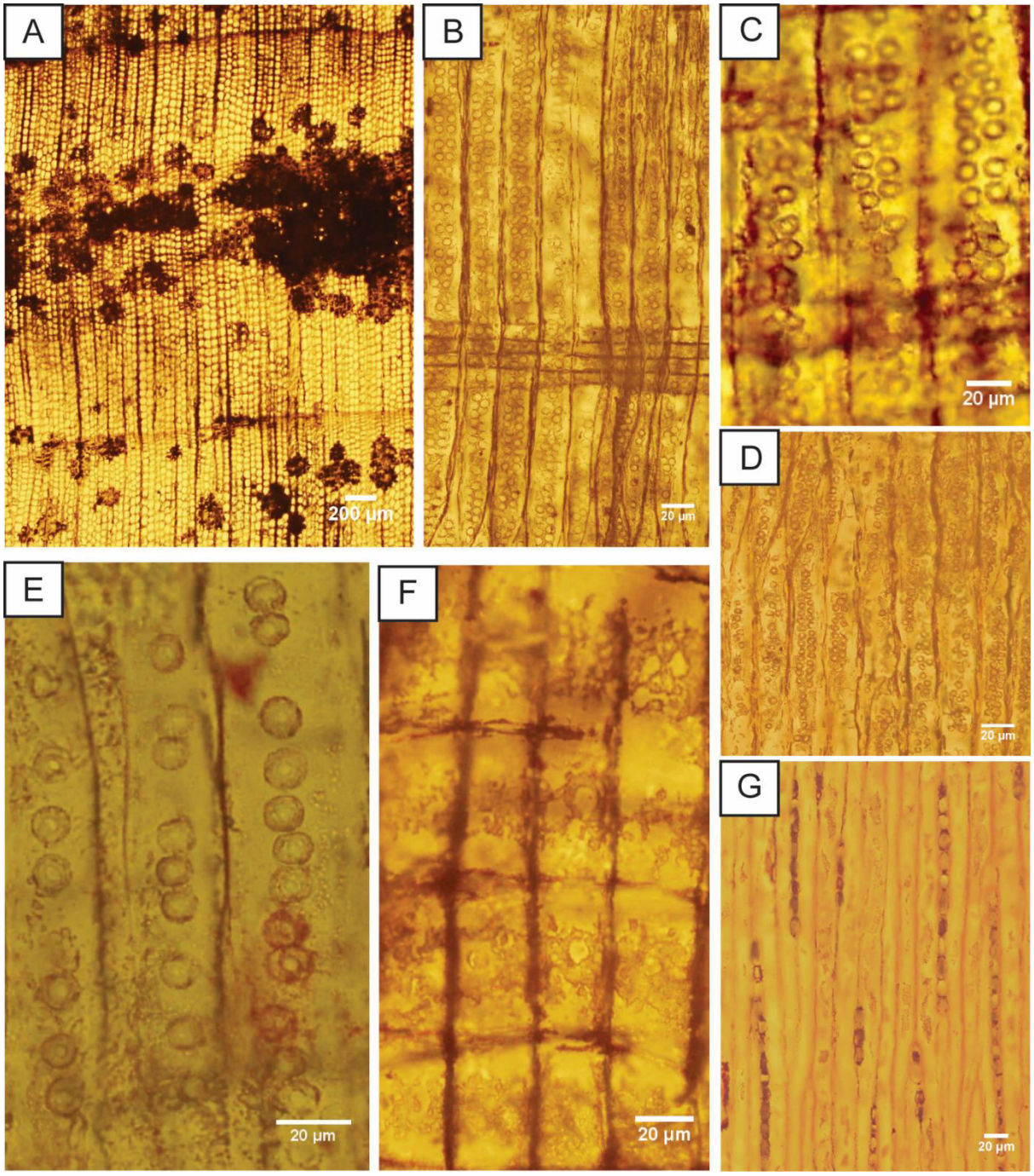


Figure 3.7: ***Australoxylon teixeirae***. A: TS displaying well-marked growth rings with possible insect or fungal damage (dark patches). B, C and D. RLS showing biseriate pits on the tracheidal walls. D. Details of uniseriate pits in the radial walls. F. RLS bordered pits in the cross-field. G. TLS showing homogeneous and uniseriate rays.

Comparison with other *Australoxylon* species

The material from Tete and Niassa, assigned to *Australoxylon teixeirae* show in the radial walls very irregular tracheid pitting with several clusters of pits, uniseriate to biseriate, opposite and alternate arrangement in the radial walls.

Over the last years, the *Australoxylon* genus has been associated with Vertebraria roots, which are glossopteridalean roots (Neish *et al*., 1993; Decombeix *et al*., 2009). This association is supported because both share similar anatomy (e.g., presence of several clusters of bordered pits on the tracheid walls). Twenty-one species of *Australoxylon are* already described. The main distinctive features among some *Australoxylon* species can be easily understood in the Table 3.2.

Distribution in other Gondwana sites and Mozambique

Australoxylon teixeirae is well-known from the Late Permian from the following sites: Collingham, Middleton and Normandien Formations from South African Permian deposits (Bamford, 1999; Bamford *et al.*, 2020), Raniganj and Khamthi Formations in India (Prasad, *et al*., 2003), Teresina and Rio do Rasto Formation from Brazil (Schneider *et al*., 1974), Shale Group in Malawi (Crisafulli, 2002), and Yaguary and Tacuary Formations from Uruguay and Paraguay (Crisafulli, 2002). According to this master research, in Mozambique, *A. teixeirae* is found in Matinde Formation (Late Permian), Cádzi Formation (Late Permian-Lower Triassic), K5 Formation (Middle Permian), and in Mount Lilonga Formation (Lower Triassic).

Table 3.2: Anatomical features of diferent *Australoxylon* species adapted from Merloti and Kurzawe (2006).

Species	Horizons	Age	Bordered pits	Cross-field pits	Tangential pits	Ray Cells
A. catarinensis	Rio Bonito Formation	Lower Permian	1-3seriate, clusters	2-6 per field	Absent	2-6 cells high
A. ningahense	Raniganj Formation	Late Permian	1-4seriate, clusters	1-6 per field	1-2seiate	1-11 cells high
A.barakense	Barakar Formation	Lower Permian	1-3seriate	2-5 per field	1seriate	1-22 cells high
A. natalense	Ecca Formation	Lower Permian	1-4seriate	1-7 per field	Absent	1-40 cells hig
A. nicoli	New South Wales	Permian	1seriate	2-6 per field	Absent	1 to rarely 2 cells high
A. allani	Allan Nunatak Formation	Permian	1-3seriate	1-6 per field	Absent	1-2 cells high
***A. teixeirae* (Mozambican specimens)**	Matinde Formation, Cádzi Formation, K5 Formation, KSa Mount Lilonga Formation	Middle Permian, Late Permian, Early Triassic	Clusters; uni- and bi- seriate, opposite and alternate	3-7 per field	Absent	2-20 cells high

3.3.6 *Taxodioxylon*

History of the genus

Taxodioxylon was erected by Hartig (1848), in which *Taxodioxylon goeppertii* was the first species described. Later on, a revision study of the genus was undertaken by Gothan (1905) and a new species was created, *Taxodioxylon taxodii* Gothan. In the same study, Gothan (1905) transferred *Cupressinoxylon sequoianum* Mercklin to *Taxodioxylon*. Seward (1910) treated *Taxodioxylon* as a synonym of *Cupressinoxylon*. Krausel (1949) synomized *Taxodioxylon sequoianum* with *Taxodioxylonn gyspsaceum* (Goppert) Krausel. The distinctive features of *Taxodioxylon* include distinct growth rings, absence of spiral thickening in the tracheids, uniseriate to occasionally biseriate rays, cross-field pits of taxodioid or cupressoid type and absence of normal resin canals (Gothan, 1905; Krausel, 1949).

Genus *Taxodioxylon* (Hartig) emend. Gothan, 1905.

Type species. *Taxodioxylon goeppertii* Hartig, 1848.

***Taxodioxylon* sp.**

Specimen number: PPM 2019-27Z (Figure 3.8 A-D).

Locality: Lisanga, Niassa Province.

Other Mozambican specimens referable to this species: None.

Horizon and age: KSa Formation, Mount Lilonga Formation (Lower Triassic).

Description: The woods show distinct growth rings in the transverse section (Figure 3.8A). The transition from earlywood to latewood is gradual (Figure 3.8A). Earlywood cells are very wide, rounded to polygonal, measuring 21 µm, ranging from 10 to 31 µm. For the mean tangential diameter and 12 µm, ranging from 8 to 18 µm and, for the mean radial diameter averages from 21 µm from to 15-31 µm. The latewood consists of 3 to 6 cells wide. The latewood tracheids are mostly quadrangular or

rounded in outline (Figure 3.8A). The radial walls show bordered pits with circular shape about 21 to 29 µm tangential diameter and 6 to 9 µm radial diameter. The bordered pits are in few numbers, uniseriate, and spaced. The pit aperture is oval and is about 6 to 9 µm of diameter. Spiral thickenings are not present in the radial walls. The cross-field pits are of the taxodioid type and some cases cupressoid. In each field one to three pits are present (Figure 3.8C). The poor preservation hinders more detailed observations of the exact numbers of pits preserved in each field. Finally, the tangential section displays homogeneous rays with low number of cells, varying from 1-10 cells wide (Figure 3.8D).

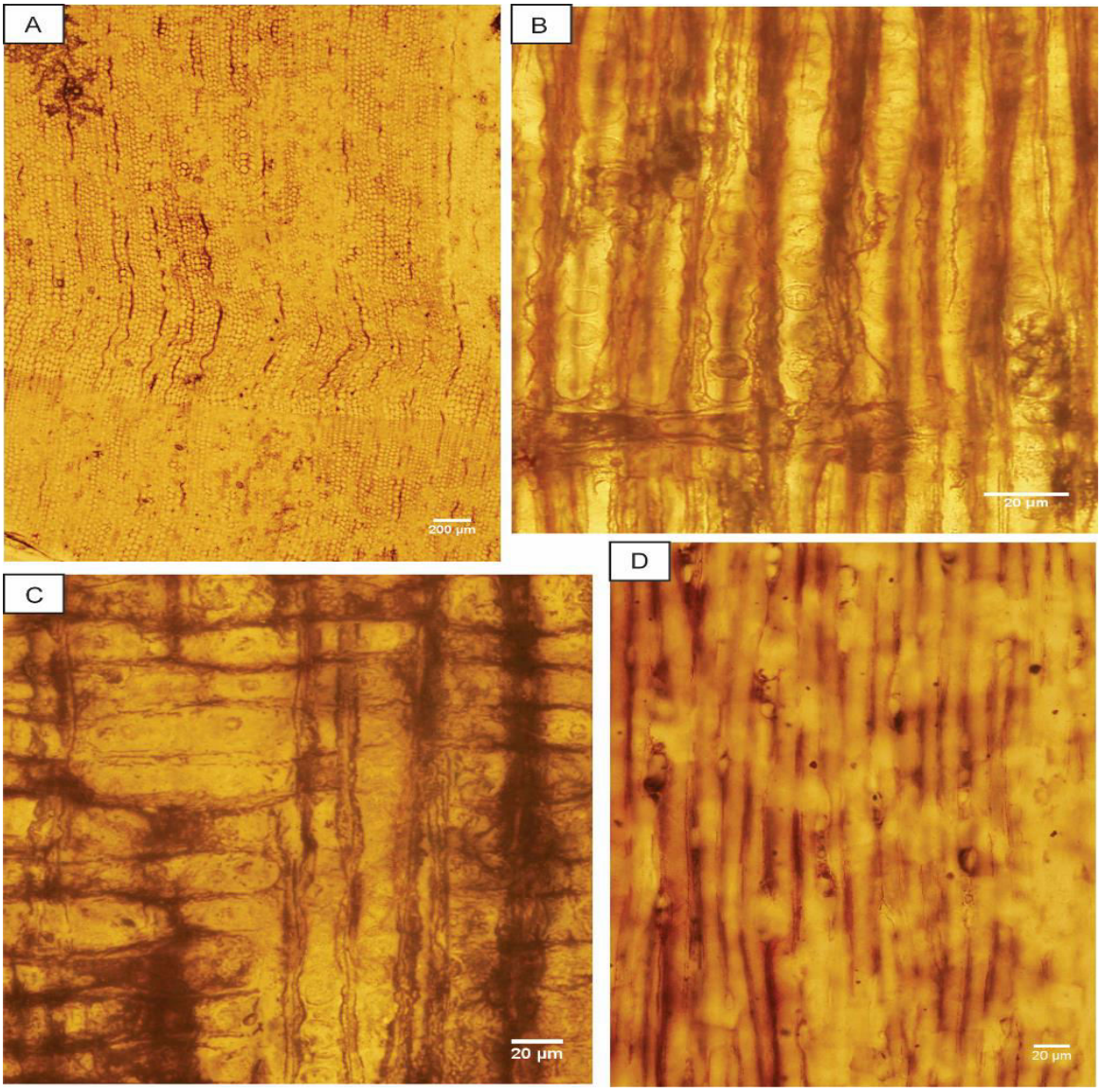


Figure 3.8: *Taxodioxylon* sp. A. transverse section, showing distinct growth rings. B. radial section, showing bordered pits of tracheids, uniseriate and spaced arranged in one row. C. radial section, showing 1–3 taxodioid-type per field. D. tangential section,

showing uniseriate rays.

Comparisons with other *Taxodioxylon* genus

The Mozambican material described above is characterized by distinct growth rings, uniseriate arrangement in the radial walls, taxodioid to cupressoid pits in the cross-field, lack of both resin canals, and spiral thickenings, and uniseriate smooth ray cells. These groups of features lead to the assignment of the new material to *Taxodioxylon* (Gothan, 1905; Krausel, 1949). The *Taxodioxylon* specimen from Mozambique can be differentiated from previously described material of this genus due to the presence of lower rays (1-10 cells high), as well as the absence of axial parenchyma and resin canals (Table 3.3). Nevertheless, because the poor preservation of the pits in the cross-field, this specimen is referred to *Taxodioxylon* sp. According to Yang and Zheng (2003), up to 14 species of *Taxodioxylon* exist worldwide.

Distribution in other Gondwana sites and Mozambique

This genus has been restricted to Lower Cretaceous to Cenozoic sediments of the Northern Hemisphere. Examples of some studies are those from the Late Cretaceous of Japan (Nishida, 1962), Jurassic of France (Phillipe, 1994), Late Cretaceous of China (Sze *et al*., 1963). The *Taxodioxylon* genus in Mozambique is found in the Mount Lilonga Formation (Late Permian-Lower Triassic) and represents its first appearance in the Karoo formations.

Table 3.3: Comparison with some described species of *Taxodioxylon (*Adapted from Yang *et al*., 2003*).*

Species	***T. albertense***	***T. compressum***	***T. nihongii***	***T. paranihongii***	***T. pseudoalbertense***	***T. sequoianum***	***T. taxodii* Cretaceous**	***T.* sp**
Geological age	*Cretaceous*	*Cretaceous*	*Cretaceous*	*Cretaceous*	*Cretaceous*	*Cretaceous-Cenozoic*	*Cretaceous*	*Lower Triassic*
References	Shimakura, 1937	Ogura, 1944	*Nishida et al., 1985*	*Nishida et al*.,1985	Nishida *et al*., 1985	Ogura, 1944	Nishida, 1962	This thesis
Growth ring/ Width	Distinct/ 0.5–10 mm	Distinct 2–3 mm	Distinct —	Indistinct —	Distinct —	Distinct ?	Distinct ?	Distinct _
Transition from early to late wood	Gradual	Gradual	Abrupt	Abrupt	Abrupt	Gradual	Abrupt	Gradual
Normal resin canals	Absent	Absent	Absent	Absent	Absent	Absent	Absent	Absent
Traumatic resin canal	Present	Absent	Present	Present	Present	Present	Absent	Absent
Height of ray	1–60 cells	1–12 cells	1–10 cells	1–11 cells	1–18 cells	1–25 cells	2–20 cells	1–10 cells
Seriation of rays	Uni-, bi-, rarely Triseriate	Uniseriate, rarely partly biseriate	Uniseriate	Uniseriate	Uniseriate, rarely partly biseriate	Uniseriate, rarely partly biseriate	Uniseriate	Uniseriate
Axial wood parenchyma cells	Abundant	Abundant	Abundant	Abundant	Abundant	Abundant	Abundant	Absent
Bordered pits on radial wall of tracheid	1–2 rows (opposite in 2 rows)	1–3 rows (opposite in 2 rows)	1 row	1 row	1–2 rows (opposite in 2 rows)	1–2 rows	1–2 rows (opposite in 2 rows)	1 row
Type and number of pits in cross field	Taxodioid, 1–4	Taxodioid, 2–4 in 1–2 rows	Taxodioid, 1–2	Taxodioid, 1, rarely 2	Taxodioid, 1–2	Taxodioid, 1–4	Taxodioid, 1–7 in 1–2 rows	Taxodioid, 1–3

Table 3.4: List of well-preserved specimen and their stratigraphic distribution.

Province	Samples	Localities	Taxa	Formation
Tete	PPM 2018-19R	Chimpundu	*Agathoxylon africanum*	Cádzi F.
	PPM 2017-38	Zumbo	*Australoxylon teixeirae*	Cádzi F.
	PPM 2017-38	Zumbo	*Australoxylon teixeirae*	Cádzi F.
	PPM 2018-67N	Nhangome	*Agathoxylon africanum*	Cádzi F.
	PPM 2017-13	Mapembera	*Agathoxylon karooensis*	Matinde F.
	PPM 2018-2N	Nhambando	*Australoxylon teixeirae*	Matinde F.
	PPM 2018-5N	Cadzewe	*Agathoxylon africanum*	Matinde F.
	PPM 2018-28N	Cadzewe	*Agathoxylon africanum*	Matinde F.
	PPM 2019-8Z	Nhambando	*Agathoxylon africanum*	Matinde F.
	PPM 2019-15NN	Nhambando	*Agathoxylon africanum*	Matinde F.
	PPM 2019-40NN	Nhambando	*Australoxylon teixeiare*	Matinde F.
	PPM 2019-5R	Nhambando	*Agathoxylon africanum*	Matinde F.
	PPM 2019-6R	Nhambando	*Australoxylon teixeiare*	Matinde F.
	PPM 2019-16R	Nhambando	*Australoxylon teixeirae*	Matinde F.
	IPG-01A	Mapembera	*Australoxylon teixeirae*	Matinde F.
	IPG-01B	**Mapembera**	***Cupressinoxylon* sp. nov***	**Matinde F.**
	IPG-07	Mapembera	*Australoxylon teixeirae*	Matinde F.
	IPG-02	Mapembera	*Australoxylon teixeirae*	Matinde F.
	PPM 2017-42	Carangache	*Australoxylon teixeirae*	Matinde F.
	PPM 2017-44	Carangache	*Agathoxyon africanum*	Matinde F.
	PPM 2017-51	Carangache	*Prototaxoxylon uniseriale*	Matinde F.
	PPM 2017-54	Carangache	*Agathoxylon africanum*	Matinde F.
	PPM 2018-56	Carangache	*Agathoxylon africanum*	Matinde F.
	PPM 2018-2N	Nhambando	*Australoxylon teixeirae*	Matinde F.
Niassa	PPM 2019-86NN	Luiga	*Agathoxylon africanum*	KSb (Fubué F.)
	PPM 2019-27Z	Lisanga	*Taxodioxylon* sp.	KSa (Mount Lilonga F.)
	PPM 2019-43NN	Monte Lilonga	*Agathoxylon africanum*	KSa (Mount Lilonga F.)
	PPM 2019-44NN	Monte Lilonga	*Agathoxylon africanum*	KSa (Mount Lilonga F.)
	PPM 2019-45NN	Monte Lilonga	*Australoxylon teixeirae*	KSa (Mount Lilonga F.)
	PPM 2019-56NN	Monte Lilonga	*Australoxylon teixeirae*	KSa (Mount Lilonga F.)
	PPM 2019-52R	Tulo	*Agathoxylon africanum*	K6 F.
	PPM 2019-66R	Tulo	*Prototaxoxylon uniseriale*	K5 F.
	PPM 2019-102NN	Michumua	*Agathoxylon africanum*	K5 F.
	PPM 2018-105N *	**Michumua**	***Protaxodixylon* sp. nov. 1**	**K5 F.**
	PPM 2018-107N *	**Michumua**	***Protaxodioxylon* sp. nov. 2**	**K5 F.**
	PPM 2019-32R	Matepue	*Prototaxoxylon uniseriale*	K5 F.
	PPM 2019-39R	Matepue	Austraoxylon teixeirae	K5 F.
	PPM 2019-82NN	Ngumbule	*Agathoxylon africanum*	K5 F.
	PPM 2019-44Z	Tulo	*Agathoxylon africanum*	K5 F.

	PPM 2019-83NN	Ngumbule	*Agathoxylon africanum*	K5 F.
	PPM 2019-85NN	Ngumbule	*Agathoxylon africanum*	K5 F.
	PPM 2019-61NN	Nhamago	*Agathoxylon africanum*	K4 F.

Table 3.5: Measurements of taxonomical features of the studied material. **Note:** The specimens are not in stratigraphical order (*=specimens not measured due to the preservation). -=difficult to measure such particular feature.

			Width of Radial pit (µm)			Height of Ray (µm)			Pit aperture (µm)		
Specimen number (PPM)	**Taxonomy**	**Locality**	**Minimum**	**Maximum**	**Average**	**Minimum**	**Maximum**	**Average**	**Minimum**	**Maximum**	**Average**
2019-40NN	*Australoxylon teixeirae*	Nhambando, Tete	2.11	4.17	3.78	1.7	3.9	3.27	-	-	-
2019-15NN	*Agathoxylon africanum*	Nhambando, Tete	10.3	22.03	15.5	5.51	15.3	9.58	3.61	8.25	6.3
2019-8Z	*Agathoxylon africanum*	Nhambando	*	*	*	*	*	*	*	*	*
2019-6R	*Australoxylon teixeirae*	Nhambando, Tete	5.65	13.7	9.2	4.12	9.93	6.74	-	-	-
2019-5R	*Agathoxylon africanum*	Nhambando, Tete	8.09	12.3	9.96	3.9	9.39	6.57	4.12	8.09	5.87
2019-5N (Niassa)	*Agathoxylon africanum*	Tulo, Niassa	7.67	12.4	9.72	5.77	10.23	7.75	-	-	-
2019-2NN	*Agathoxylon africanum*	Moatize	*	*	*	*	*	*	*	*	*
2017-13	*Agathoxylon karooensis*	Mapembera, Tete	6.14	12.32	8.04	3.61	8.19	5.93	-	-	-
2018-5N	*Agathoxyon africanun*	Cadzewe, Tete	2.25	5.48	3.87	2.97	4.13	3.47	-	-	-
2018-50	*Prototaxoxylon uniserale*	Cadzewe, Tete	6.86	11.42	9.05	5.64	9.704	7.61	-	-	-
2018-65N	*Agathoxylon karooensis*	Bungue, Tete	3.47	6.42	4.7	2.58	5.51	3.67	-	-	-
2018-73N	*Agathoxylon* sp.	Emboque, Tete	5.16	8.48	6.49	3.22	7.09	5.15	-	-	-
2019-40NN	*Australoxylon teixeirae*	Nhambando, Tete	3.67	7.42		3.22	6.12		-	-	-
2018-67N	*Agathoxylon africanum*	Nhangome, Tete	4.34	7.64	6.61	4.79	7.96	6.01	-	-	-
***2018-52R**	*Agathoxylon africanum*	Maluizo, Tete	24	34.5	-	15.7	28	-	-	-	-

***2018-19R**	*Agathoxylon africanum???*	Chimpundu,Tete	15.83	30.83	-	13.33	35.83	-	-	-	-
***2017-37**	*Austrloxylon* sp.	Zumbo, Tete	2.272	5.019	3.84	3.181	5.453	4.5	-	-	-
***2018-28N**	*Agathoxylon* sp.	Cadzewe, Tete	*	*	*	*	*	*	*	*	*
***2017-51**	*Prototaxoxylon uniserale*	Carangache, Tete	-	-	-	-	-	-	-	-	
***2017-54**	*Agathoxylon africanum*	Carangache, Tete	6.316	15.789	10.49	5.263	13.845	9.51	-	-	
***2018-56**	*Agathoxylon africanum*	Cadzewe, Tete	-	-	-	-	-	-	-	-	-
***2017-44**	*Agathoxylon africanum*	Carangache, Tete	-	-	-	-	-	-	-	-	-
***2019-16R**	*Australoxylon teixeirae*	Nhambando, Tete	9.187	15.312	11.89	6.125	10.719	8.88	-	-	
***2017-38**	*Australoxylon teixeirae*	Zumbo, Tete	25.23	43.1	35.58	18.97	30.59	25.07	-	-	-
***2018-2N**	*Australoxylon teixeirae*	Nhambando, Tete	*	*	*	*	*	*	*	*	*
IPG-01A	*Australoxylon teixeirae*	*	*	*	*	*	*	*	*	*	*
IPG01B	*Cupressinoxylon* sp.nov	Mapembera, Tete	3.65	6.86	5.15	27.68	179.94???	74.0	-	-	-
IPG-02	*Australoxylon teixeirae*	Mapembera, Tete	*	*	*	*	*	*	*	*	*
PPM 2019-86NN	*Agathoxylon africanum*	Luiga, Niassa	*	*	*	*	*	*	*	*	*
PPM 2019-27Z	*Taxodioxylon* sp.	KSa (Mount Lilonga F.), Niassa	10.49	18.52	14.69	6.15	10.30	8.13	5.82	8.49	6.69
PPM 2019-43NN	*Agathoxylon africanum*	KSa (Mount Lilonga F.), Niassa	1.52	4.57	3.40	6.13	14.56	9.85	-	-	-
PPM 2019-44NN	*Agathoxylon africanum*	KSa (Mount Lilonga F.), Niassa	2.54	5.59	4.07	6.99	13.99	11.41	-	-	-
PPM 2019-45NN	*Australoxylon teixeirae*	KSa (Mount Lilonga F.), Niassa	3.05	7.12	5.47	7.99	15.69	11.06	-	-	-
PPM 2019-56NN	*Australoxylon teixeirae*	KSa (Mount Lilonga F.), Niassa	2.54	5.08	3.67	9.66	16.79	13.32			
PPM 2019-	*Agathoxylon*	K5F., Niassa	*	*	*	*	*	*	*	*	*

52R	*africanum*										
PPM 2019-66R	*Prototaxoxylon uniseriale*	K5F., Niassa	10.17	16.28	13.71						
PPM 2019-102NN	*Agathoxylon africanum*	K5F., Niassa	29.41	51.78 *	43.52	-	-	-	11.40	21.63	16.46
PPM 2018-105N	*Protaxodioxylon* sp. nov. 1	K5F., Niassa	4.90	10.02	7.28				2.01	2.61	2.7
PPM 2018-107N	*Protaxodioxylon* sp. nov. 2	K5F., Niassa	2.48	4.72	3.38	-	-	-	2.28	4.27	3.08
PPM 2019-32R	*Prototaxoxylon uniseriale*	K5F., Niassa	12.21	20.35	16.50	-	-	-	-	-	-
PPM 2019-82NN	*Agathoxylon africanum*	K5F., Niassa	6.10	20.35	11.29	7.49	13.03	10.50	-	-	-
PPM 2019-44Z	*Agathoxylon africanum*	K5F., Niassa	8.51	18.02	11.97	-	-	-	-	-	-
PPM 2019-83NN	*Agathoxylon africanum*	K5F., Niassa	2.03	3.59	2.99	7.64	12.53	9.78	-	-	-
PPM 2019-85NN	*Agathoxylon africanum*	K5F., Niassa	3.56	5.59	4.69	4.99	14.99	10.20	-	-	-
PPM 2019-61NN	*Agathoxylon africanum*	K4F., Niassa	3.05	9.16	6.34	-	-	-	-	-	-

CHAPTER FOUR-RESULTS

4.1 Growth rings results

Growth rings were observed in 46 specimens and their width was measured when possible (n=13). Poor preservation of some specimens did not allow other calculations (e.g., mean sensitivity). For specimens that had growth rings preserved, the boundaries are well-defined and a sharp earlywood-latewood transition was noted (Figure 4.1). Latewood in the specimens is very narrow, consisting of 1-4 narrow cells with thick walls. Earlywood in the specimens is characterized by thin-walled cells and a much higher proportion compared to latewood. All the specimens have wide growth rings according to IAWA Committee (1989). Measured growth rings range from 0.3-2.7 mm wide (Table 4.1). Due to the limitations imposed by the rock cutting and polishing equipment, the thin sections are relatively small (~30 x 15mm), so the minimum number of growth rings observed for the specimens was one or two (Table 4.1).

Study found growth ring types O, S, and D (Creber and Chaloner 1984). Ring type O has no growth rings, and type S has shear zones associated with the earliest earlywood (Bamford, 2016; revised in Bamford *et al*., in press). Ring type D is characterized by a thin band of latewood and sharp but, sometimes gradual, earlywood-latewood transition (Brison *et al*., 2001).

Most of the specimens from Mozambique display type D, however, *Prototaxoxylon uniseriale* (n=1) exhibits only growth ring type O (Table 4.3 and Figure 4.2). Ring type O is found in three different genera: *Agathoxylon africanum*, *Australoxylon teixeirae and Prototaxoxylon uniseriale* (Figure 4.2). The ring type S is characterized by crushed and distorted tracheids in a zig-zag fashion (Figure 4.3). Type S rings are observed in *Agathoxylon africanum*, *Australoxylon teixeirae* and some unidentifiable specimens (Figure 4.3 and Table 4.2). *Agathoxylon africanum* and *Australoxylon teixeirae* produce more than two types of rings (Table 4.2). None of the specimens in our sample display growth rings of types A, B, and E (Creber and Chaloner, 1984). In our sample, there is no clear trend in ring width temporally, spatially, or stratigraphically (Table 4.1). Some false growth rings were found in the studied

material (Figure 4.1A and C indicated in arrow). False growth ring occurrence is linked to the final portion of the earlywood at the end of the growing season (Creber and Chaloner, 1984). False growth rings may be distinguished from seasonal growth rings, because they have a gradual transition to thick-walled narrow cells, then a gradual reversal to large thin-walled cells (Spicer 2003). Furthermore, false rings are marked by zones of small and dense tracheids (Pires *et al*., 2005). Interestingly, correlation between climate information provided by lithostratigraphy and growth rings is presented suggesting somewhat similar patterns (Table 4.3).

Table 4.1: Growth ring measurements in all specimens that had more than one complete ring. F. =Formation.

Basins	Formations	Samples	Taxonomy	Number of growth rings	Range of ring widths (mm)	Mean ring widths (mm)
Chicôa-Mecucoé Basin (Tete)	Cádzi F.	PPM 2018-67N	*A. africanum*	2	0.578-0.978	0.729
	Matinde F.	IPG-02	*A. teixeirae*	1	1.814-2.094	1.946
	Matinde F.	PPM 2017-13	*A. teixeirae*	2	0.336-0.436	0.396
Metangula Basin	Ksa (Mount Lilonga F.)	PPM 2019-44NN	*A. africanum*	1	2.051-2.162	2.106
	Ksa (Mount Lilonga F.)	PPM 2019-45NN	*A. teixeirae*	1	2.677-2.792	2.732
	K5 F.	PPM 2019-39R	*A. teixeirae*	1	0.967-1.007	0.982
	K5 F.	PPM 2019-82NN	*A. africanum*	2	0.701-1.083	0.900
	K4 F.	PPM 2019-61NN	*A.africanum*	1	0.928-1.002	0.969

Table 4.2: Wood species and number of specimens representing a particular growth ring type. * means that due to the poor preservation there is no measured growth rings.

Specimen	Type O	Type D	Type S	Type A, B, C
A. africanum	3	3	2	Absent
A. karooensis	*	*	*	*
A. texeirae	2	3	1	Absent
Proto. uniseriale	3	Absent	Absent	Absent
***P.* sp. nov. 1**	Absent	1	Absent	Absent
***P. sp.* nov. 2**	Absent	1	Absent	Absent
Cupressinoxylon* sp. *nov.	Absent	1	Absent	Absent
***Taxodioxylon* sp.**	Absent	1	Absent	Absent
Unidentified specimens	12	Absent	1	Absent

Table 4.3: Climates interpretation based in our material and from other sources indicated on the table.

Province	Age	Formations	Ring Type	Interpretation from growth rings of the studied material	Paleoenvironments (other authors)	Climate according to the lithostatigraph information of other sources
Tete	Late Permian-Early Triassic	Cádzi Formation	O+S+D	Variable climate (dry+humid and warm)	Fluvial and lacustrine environments (GTK Consortium, 2006)	Hot and dry (Vasconcelos, *et al*., 2014)
	Late Permian	Matinde Formation	O+S+D	Variable climate (humid+dry)	Fluvial environment (Vasconcelos et al., 2014; Hancox, 2016).	Wet temperate to hot arid climate (Vasconcelos *et al*., 2014; Hancox, 2016).
Niassa	Early Triassic-Middle Triassic?	KSb Formation	S	Variable climate (Wet+dry)	Cyclical fluvial sequences are not present and the sedimentological pattern indicates deposition by an anastomosing or braided river system (Verniers *et al*., 1989)	Wet to hot (Vasconcelos *et al*., 2014)
	Early Triassic	KSa Formation	D+S	Variable climate (dry)	Fluvial cyclical sequence (Verniers *et al*., 1989)	Humid (Verniers et al., 1989)
	Late Permian	K6 Formation	*	*	Fluvial and lacustrine (Verniers *et al*., 1989)	Dry and humid (Verniers *et al*., 1989)
	Middle Permian	K5 Formation	D+O	Variable climate (humid+warm)	Fluvial and lacustrine (Verniers et al., 1989)	Humid (Verniers et al., 1989)
	Early Permian	K4 Formation	D	Variable climate	Cyclical Fluvial sequences (Verniers *et al*., 1989)	Humid (Verniers *et al*., 1989)

*No available well-preserved fossil wood for study.

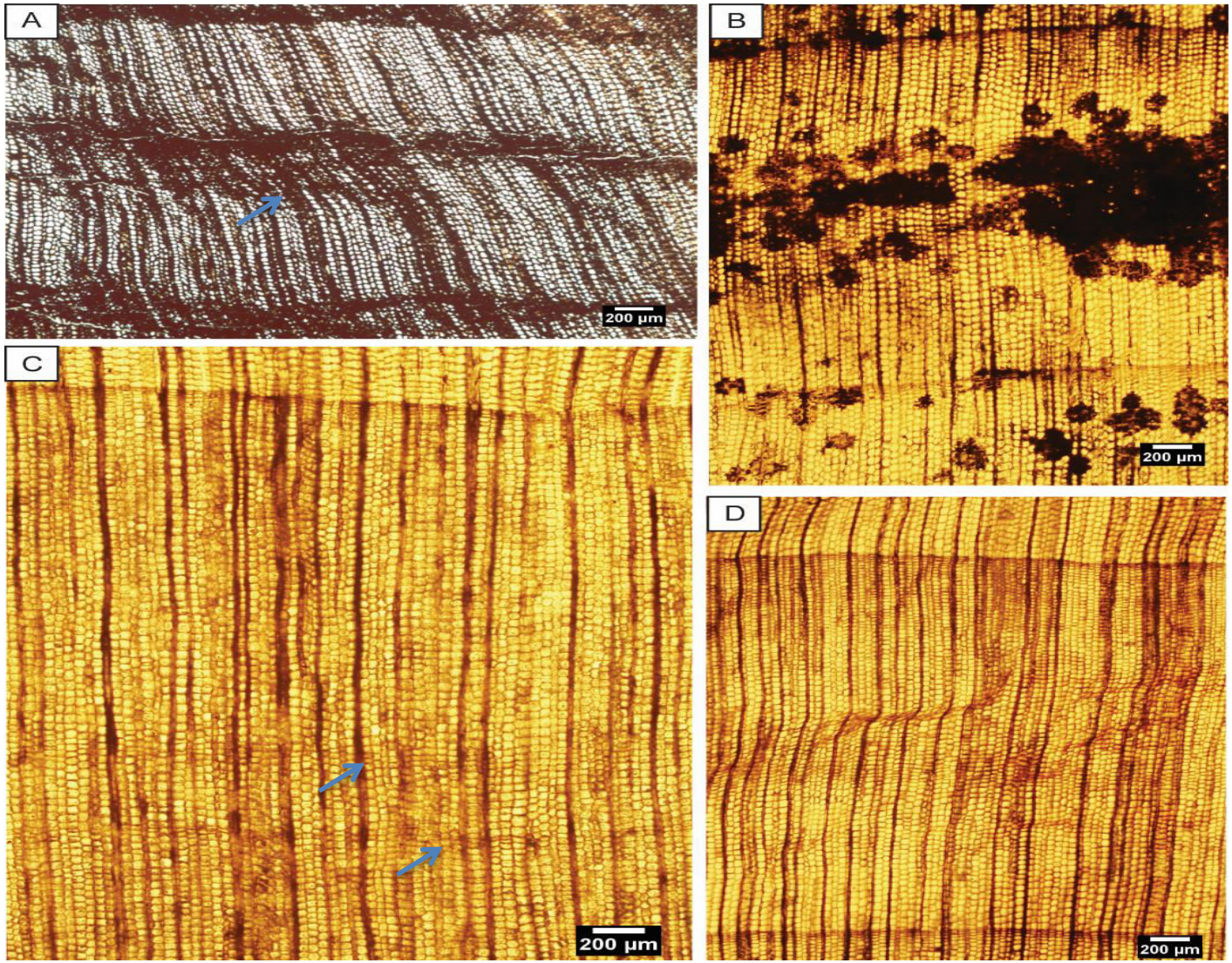


Figure 4.1: Examples of sections with distinct ring boundaries, sharp earlywood-latewood transition and narrow latewood and false rings indicated by the arrows.

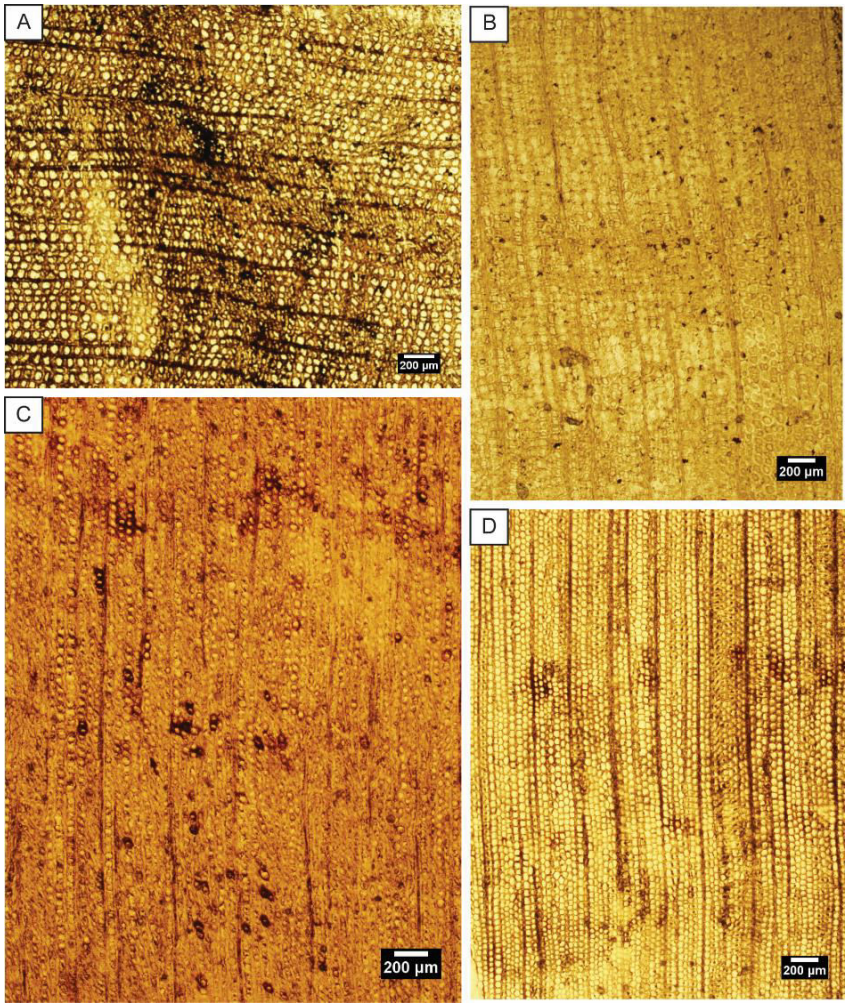


Figure 4.2: Type O growth rings present in some selected specimens.

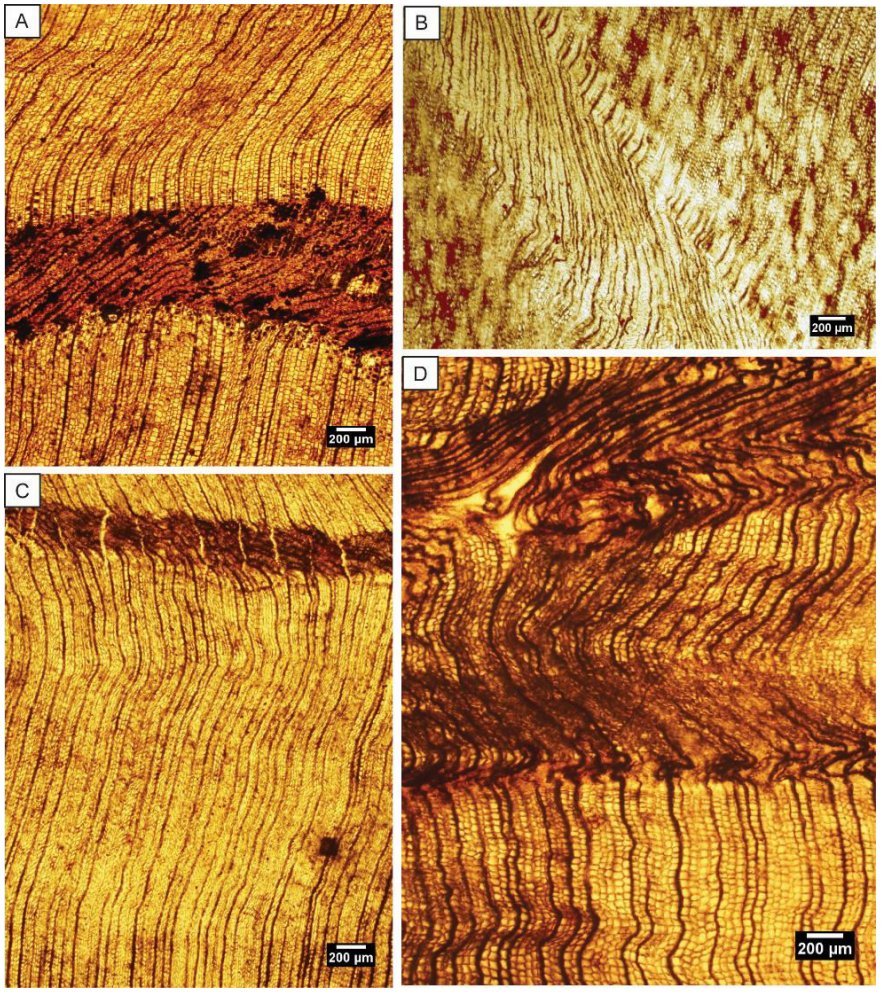


Figure 4.3: Growth ring type S in selected specimens.

Table 4.4:Growth Rings Anatomical Information in stratigraphical sequence.									
Province	**Samples**	**Localities**	**Taxa**	**Formation**	**Growth rings**	**Type of Growth rings**	**Transition (E-L)**	**Shear Zones**	**False rings**
Tete	PPM 2018-19R	Chimpundu	*Agathoxylon africanum*	Cádzi F.	Absent	O	Absent	Absent	Absent
	PPM 2017-57	Dôa	unidentified	Cádzi F.	Absent	O	Absent	Absent	Absent
	PPM 2018-96N	Dôa	unidentified	Cádzi F.	Present	O	Sharp Transition	Absent	Absent
	PPM 2017-37	Zumbo	unidentified	Cádzi F.	Present	S	Sharp Transition	Present	Absent
	PPM 2017-38	Zumbo	*Australoxylon teixeirae*	Cádzi F.	Absent	O	Absent	Present	Absent
	PPM 2018-67N	Nhangome	*Agathoxylon africanum*	Cádzi F.	Present	D	Sharp Transition	Absent	Present
	PPM 2017-1	Mapembera	unidentified	Matinde F.	Absent	O	Absent	Absent	Absent
	PPM 2017-18	Cadzewe	unidentified	Matinde F.	Absent	O	Absent	Absent	Present
	PPM 2017-19	Cadzewe	unidentified	Matinde F.	Absent	O	Absent	Absent	Absent
	PPM 2017-20	Cadzewe	unidentified	Matinde F.	Absent	O	Absent	Absent	Absent
	PPM 2017-21	Cadzewe	unidentified	Matinde F.	Absent	O	Absent	Absent	Absent
	PPM 2017-22	Cadzewe	unidentified	Matinde F.	Absent	O	Absent	Absent	Absent
	PPM 2017-25	Cadzewe	unidentified	Matinde F.	Absent	O	Absent	Absent	Absent
	PPM 2017-23	Cadzewe	unidentified	Matinde F.	Absent	O	Absent	Absent	Absent
	PPM 2017-24	Cadzewe	unidentified	Matinde F.	Absent	O	Absent	Absent	Absent
	PPM 2017-26	Cadzewe	unidentified	Matinde F.	Absent	O	Absent	Absent	Absent
	PPM 2017-29	Cadzewe	unidentified	Matinde F.	Absent	O	Absent	Absent	Absent
	PPM 2017-31	Cadzewe	unidentified	Matinde F.	Absent	O	Absent	Absent	Absent
	IPG-01B	Mapembera	*Cupressinoxylon* sp. nov.	Matinde F.	Present	D	Sharp Transition	Present	Absent
	IPG-07	Mapembera	*Australoxylon teixeirae*	Matinde F.	Present	S	Sharp-Transition	Present	Absent
	IPG-02	Mapembera	*Australoxylon teixeirae*	Matinde F.	Present	D	Sharp Transition	Present	Absent
	PPM 2017-42	Carangache	*Australoxylon teixeirae*	Matinde F.	Absent	O	Absent	Absent	Absent
	PPM 2017-44	Carangache	*Agathoxyon africanum*	Matinde F.	Present	O	Absent	Absent	Absent
	PPM 2017-47	Carangache	unidentified	Matinde F.	Absent	O	Absent	Present	Absent

	PPM 2017-50	Carangache	unidentified	Matinde F.	Absent	O	Absent	Absent	Absent
	PPM 2017-51	Carangache	*Prototaxoxylon uniseriale*	Matinde F.	Absent	O	Absent	Present	Absent
	PPM 2017-54	Carangache	*Agathoxylon africanum*	Matinde F.	Absent	O	Absent	Absent	Absent
	PPM 2017-55	Carangache	unidentified	Matinde F.	Present	O	Absent	Absent	Present
	PPM 2018-2N	Nhambando	*Australoxylon teixeirae*	Matinde F.	Present	D	Sharp Transition	Absent	Present
Niassa	PPM 2019-86NN	Luiga	*Agathoxylon africanum*	KSb (Fubué F.)	Present	S	Sharp-Transition	Present	Absent
	PPM 2019-27Z	Lisanga	*Taxodioxylon* sp.	KSa (Mount Lilonga F.)	Present	D	Abrupt-Transition	Absent	Absent
	PPM 2019-43NN	Monte Lilonga	*Agathoxylon africanum*	KSa (Mount Lilonga F.)	Present	S	Sharp-Transition	Present	Absent
	PPM 2019-44NN	Monte Lilonga	*Agathoxylon africanum*	KSa (Mount Lilonga F.)	Present	S	Sharp-Transition	Present	Absent
	PPM 2019-45NN	Monte Lilonga	*Australoxylon teixeirae*	KSa (Mount Lilonga F.)	Present	S	Sharp-Transition	Present	Absent
	PPM 2019-56NN	Monte Lilonga	*Australoxylon teixeirae*	KSa (Mount Lilonga F.)	Present	D	Abrupt	Absent	Absent
	PPM 2019-66R	Tulo	*Prototaxoxylon uniseriale*	K5F.	Absent	O	Absent	Absent	Absent
	PPM 2019-102NN	Michumua	*Agathoxylon africanum*	K5 F.	Present	D	Sharp Transition	Absent	Present
	PPM 2018-105N	Michumua	*Protaxodixylon* sp. nov. 1	K5 F.	Present	D	Sharp Transition	Present	Absent
	PPM 2018-107N	Michumua	*Protaxodioxylon* sp. nov. 2	K5 F.	Present	D	Sharp Transition	Absent	Absent
	PPM 2019-32R	Matepue	*Prototaxoxylon uniseriale*	K5F.	Absent	O	Absent	Absent	Absent
	PPM 2019-39R	Matepue	Austraoxylon teixeirae	K5F.	Present	D	Abrupt-Transition	Absent	Absent
	PPM 2019-67NN	Mechumua	unidentified	K5F.	Absent	O	Absent	Present	Absent
	PPM 2019-82NN	Ngumbule	*Agathoxylon africanum*	K5F.	Present	D	Sharp-Transition	Absent	Absent

	PPM 2019-44Z	Tulo	Agathoxylon africanum	K5F.	Absent	O	Absent	Absent	Absent
	PPM 2019-83NN	Ngumbule	*Agathoxylon africanum*	K5F.	Present	D	Sharp-Transition	Present	Absent
	PPM 2019-85NN	Ngumbule	*Agathoxylon africanum*	K5F.	Present	D	Sharp-Transition	Present	Absent
	PPM 2019-61NN	Nhamago	*Agathoxylon africanum*	K4F.	Present	D	Sharp-Transition	Present	Absent

4.2 Palaeogeography

The woods species identified in Mozambique are correlated to other occurrences across Gondwana. Subsequently, these records are correlated with known biozones within the main Karoo Basin. The seven genera and eight different species found in Mozambique (*Agathoxylon africanum, Agathoxylon karooensis, Australoxylon teixeirae, Prototaxoxylon uniseriale, Protaxodioxylon* sp. nov. 1, *Protaxodioxylon* sp. nov. 2, *Cupressinoxylon* sp. nov and *Taxodioxylon* sp.) are related under the form of tables (Tables 4.5, 4.6, and 4.7). The K5 Formation (Middle Permian) in Niassa and the Matinde Formation (Late Permian) in Tete with four genera and five species each are the most biodiverse formations within the studied areas (Table 4.5). This may be due to sampling bias as these formations were the most surveyed over the course of the various PaleoMoz expeditions.

Agathoxylon africanum and *Agathoxylon karoeensis* seem to be the most dominant species in southern Africa within the Karoo formations (Table 4.5). *Agathoxylon africanum* ranges from Lower Permian to the Jurassic, whereas *Agathoxylon karooensis* extends from Middle to the Late Permian (Table 4.6). *Australoxylon teixeirae* is the longest ranging species in Gondwana with a time range extending from Lower Permian to possibly Lower Triassic (Table 4.6). In Gondwana, *Prototaxoxylon uniseriale* seems to be restricted to Permian deposits from South Africa, India, Mozambique but also Jurassic deposits in Middle Argentina (Table 4.5). *Prototaxoxylon uniseriale* time range is longer in the Mozambican Karoo compared to the South African Karoo Basin (Table 4.6). Other species are only restricted to the Permian deposits of Mozambique, namely: *Protaxodioxylon* sp. nov. 1*, Protaxodioxylon* sp. nov. 2, *Cupressinoxylon* sp. nov, and *Taxodioxylon* sp. (Table 4.6). The new taxa here analyzed seem to indicate that the Mozambican Karoo is more diverse than its South African counterpart.

Table 4.5: Gymnosperm fossil woods identified from the Permian-Triassic of Mozambique and their records in other sites of Gondwana with data adapted from Crisafulli *et al*., 2009.

		Agathoxylon		***Australoxylon***	***Prototaxoxylon***	***Protaxodioxylon***		***Cupressino-xylon* sp.nov**	**Taxodioxylon Sp.**
Counrty	**Age**	***Africanum***	***karooensis***	***teixeirae***	***uniseriale***	**sp. nov. 1**	**sp. nov. 2**		
South Africa	Beaufort Group, Late Permian	**X**	**X**	***X***	**X**				
South Africa	Normandien Formation, Beaufort Group, Late Permian	**X**	**X**						
Namibia	Tsarabis to Gai As formations (Permian to Triassic?)	**X**	**X**						
	Tsarabis to Etjo formations (Permian to Jurassic)								
Malawi	Shale Group,			**X**					
Botswana	Mosolotsane Formation, Triassic	**X**		**X**					
Zambia	Bamford pers. com.	**X**	**X**						
Brazil	Teresina and Rio do Rasto Formaton, Late Permian			**X**					
	Caturrita Formation, Late Triassic	**X**							
Argentina	Solca Formation, Early Permian			**X**					
	Matilde Formation, Jurassic			**X**	**X**				
Paraguay	Tacuary Formation, Late Permian			**X**					
Uruguay	Yaguary Formation, Late Permian, Tres Islas Fm. Early Permian			**X**					
India	Raniganj Formation, Late Permian			**X**	**X**				
	Khamti Formation, Late Permian								
Mozambique	Cádzi Formation, Late Permian-Early Triassic	**X**							
	Matinde Formation	**X**	**X**	**X**	**X**				
	KSb Formation, Fubué Formation, Late-Permian-Early Triassic	**X**							

	KSa Formation, Mount Lilonga Formation, Late-Permian-Early Triassic			X					X
	K5 Formation, Middle Permian	X		X	X	X	X		
	K4 Formation, Early Permian	X							

Table 4.6: Stratigraphy of the Karoo Basin and the ranges of the fossil wood genera, modified from Bamford (2016). Abbreviations (St=Stormberg), (Mz=Mozambique).

			West of 24° Formations	East of 24° Formations	Vertebrate biozones from Rubidge (2005)	Main Karoo Basin wood taxa				Permian-Triassic wood taxa from Mozambique						
PERMAN	St			Molteno												
	BEAUFORT GROUP	Tarkasta		Burgersdorp	*Cynognathus*											
		Adelaide Subgroup		Katberg	*Lystrosaurus*		*Australoxylon teixeirae*	*Agathoxylon africanum*	*A. karooensis kkarooensis*							*Taxodioxylon*
			Teekloof	Balfour	*Daptocephalus*					*Prototaxoxylon uniseriale*	*Australoxyllon teixeirae*	*Agathoxylon africanum*	*A. karooensis*	*Cupressinoxylon*		
				Middleton	*Cistecephalus*											
					Tropidostoma											
					Pristerognathus											
			Abrahams kraal	Koonap	*Tapinocephalus*	*Prototax oxylon*									*Protaxo dioxylon*	
					Eodicynodon											
	ECCA GROUP		Waterford	Waterford												
			Tierberg/Fort Brown	Fort Brown												
			Lingsberg/Ripon	Ripon												
			Collingham	Collingham												
			Whitehill	Whitehill												
			Prince Albert	Prince Albert												

Table 4.7: Fossil woods occurrences in Mozambique and their correlation with the South African Main Karoo Basin. **PTF**=Permian and Triassic formations.

	Formations	Taxa (PTF of Mozambique)	Main Karoo Basin (MKB)
Tete	Cádzi Formation (Late Permian-Early Triassic)	*Agathoxylon africanum*	Late Permian
		Australoxylon teixeirae	Late Permian
	Matinde Formation (Late Permian)	*Agathoxylon africanum*	Late Permian
		Agathoxylon karooensis	
		Australoxylon teixeirae	
		Prototaxoxylon uniseriale	Early Permian
		Cupressinoxylon sp.nov	**Not found yet**
Niassa	KSb, Fubué Formation (Lower Triassic-Middle Triassic?)	*Agathoxylon africanum*	Late Permian
	KSa Mount Lilonga Formation (Lower Triassic)	*Australoxylon teixeirae* *Taxodioxylon* sp.	
	K5 Formation (Middle Permian)	*Agathoxylon africanum*	Late Permian-Triassic
		Protaxoxylon uniseriale	Late Permian
		Protaxodioxylon sp. nov. 1 *and Protaxodioxylon* sp.nov. 2	**Not found yet**
		Australoxylon teixeirae	Late Permian

	K4 Formation (Lower Permian)	*Agathoxylon africanum*	Late Permian

4.3 Geoconservation

4.3.1 Preservation of the fossil Forests in Mozambique

The Tete fossil forest offers a unique geoheritage of palaeontological interest, in addition to the quality of the landscape and the magnificent geological outcrops. Four exceptional geosites have been selected to fulfil the objective of this study (see criteria in the chapter two).

These four forests have almost similar values for the parameters assessed (see the Appendix A, B, c, and D). However, the Nhambando fossil forest presents low scientific value compared to the other studied forests. Although the Nhambando fossil forest shows lower scientific value when compared with the other areas, its scientific value is still high according to the ranges suggested by Cortés *et al*., (2019; table 4.8).

Table 4.8: Quantitative assessment results of the fossil forests (Cortés *et al*., 2019). Other detailed tables are found in the appendixes.

Geosites	SV	EV	TV	(VuN = F x AN x 30/9)	SDA	RDA
Mapembera	26	23.5	23.5	21	81	1860
Cadzewe	26	23.5	23.5	21	81	1860
Nhambando	22	23.5	23.5	21	81	1860
Carangache	26	23.5	23.5	21	81	1860

VuN=Vulnerability due to anthropic treats; SDA=susceptibility for anthropic degradation; RDA= Risk of degradation, SV=Scientific Value, EV=Educational Value, TV=Touristic Value.

This section also includes the characterization of the forest areas, based on field observations and some unpublished literature studies of the area (Marques and Ferrara, 2004; Cumbe, 2007). The taxonomic description, detailed geological setting

and stratigraphy are described in some of the previous chapters of this dissertation. The exact location and description of each of these palaeontological sites follows.

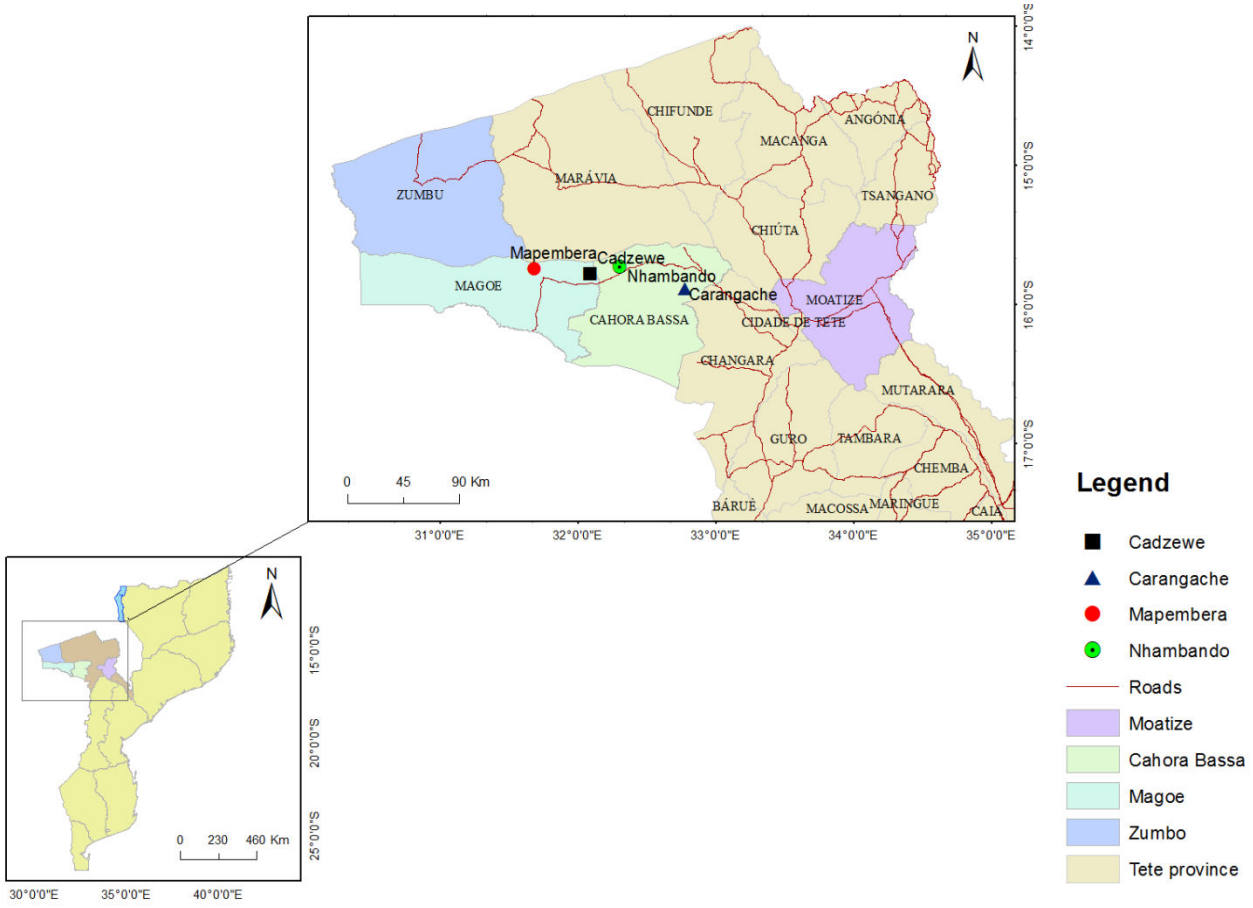


Figure 4.4: Map illustrating the exact location of the forests (Cadzewe, Mapembera and Nhambando and Carangache).

4.3.2 Carangache Fossil Forest

The Carangache fossil forest is located in the Cahora Bassa district (Tete Province), 17 km from Chitima. This site includes fossilized trees of the genus *Dadoxylon nicoli Seward* (Silva *et al*., 1967; Marques and Ferrara, 2004). *Dadoxylon nicoli* is a well-known genus and has been referred as restricted to the Permian period. However, this genus is now considered an illegitimate name (Bamford and Philippe, 2001). Fossilized woods are found scattered over an area of 500 km^2 accessed by unpaved roads, and can easily be visited. Among the four fossil forest sites herein assessed, this is the only one that is not found near the Zambezi River. The majority of tree

trunks are in the horizontal position, reaching up to 4 m long (Figure 4.5B). The diameter of the trunks ranges from 15 to 50 cm (Figure 4.5B). Tree trunks can be seen almost complete, with minimal fragmentation and reaching over 1.5 m (Figure 4.5C).

Tree trunks from Carangache are silicified, although other minerals can be observed, such as ankerite, calcite, and goethite. This study reveals that some logs collected from this area are most likely to be *Agathoxylon africanum* (this dissertation). Often, the identification of the genus and species of the fossilized plants in this area is impossible, since it relies on the preservation of the cellular structures of the wood. In addition, distinct growth rings can be seen which suggest a climate influenced by strong seasonal variations (Figure 4.5B; chapter four). Marques and Ferrara (2004) mention that some of the silicified trunks at the Carangache locality are used as stools for people to sit on. It has also been observed that these logs are used for trapping small mammals by the locals. The results of Carangache quantitative assessment are found in Table 4.9, and in the Appendix B.

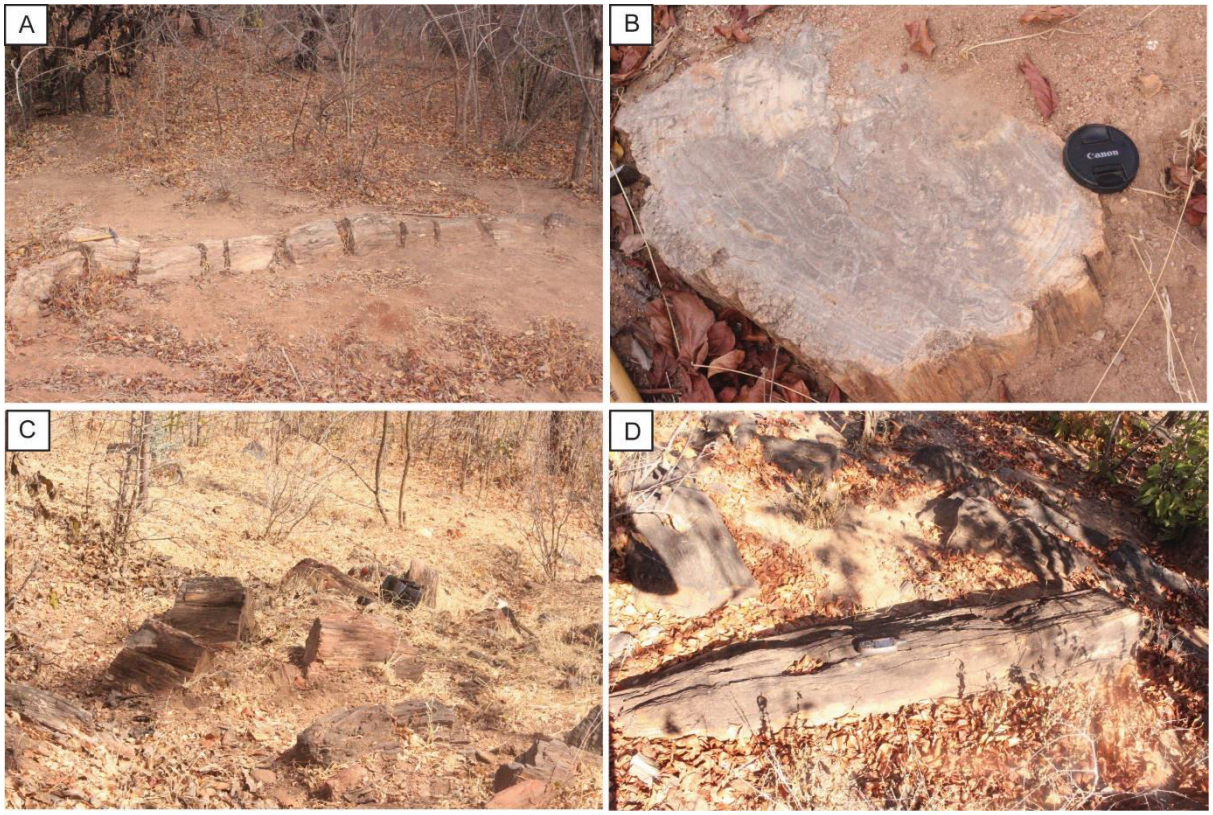


Figure 4.5: Selected aspects of the Carangache fossil forest: A. Fragmented fossil trunk; B. Fossil tree trunk showing seasonal growth rings; C. Tree trunks scattered over

the studied area; and D. Fossil tree trunk reaching 1.5 m without fragmentation.

Table 4.9: Geosite assessment-Carangache

Code of the Geosite: 7PG **Name of the Geosite:** **Carangache**

Person filling in the form: Nelson Nhamutole **Date:** **25.09.2020**

Nelson Nhamutole

TABLE FOR GEOSITE ASSESSMENT		Scientif Value (SV)		Educacional Value (EV)		Tourístic Value (TV)	
Parameters	Scores	Coeficient	Result	Coeficient	Result	Coeficient	Result
Representativity	4	2	8	0.5	2	0	0
Type of local	2	1	2	0.5	1	0	0
Level of scientific knowledge	2	2	4	0	0	0	0
State of conservation	3	1	3	1	3	0	0
Observation condition	4	1	4	1	4	0.5	2
Rareness	1	2	2	1	1	0	0
Geodiversity	3	1	3	1	3	0	0
Educative potential	2	0	0	2	4	0	0
Logistic infrastutures	3	0	0	1	3	1	3
Acessibility	2	0	0	1	2	1	2
Dimensions of the site	2	0	0	0.5	1	0.5	1
Beauty or spectacularity	3	0	0	0.5	1.5	2.5	4.5
Possibilities for outreach	3	0	0	0	0	2	6
Sumplementary touristic attractions	2	0	0	0	0	0.5	1
Resistence of the site	3	0	0	0	0	1	3
Socioeconomic level of the region	3	0	0	0	0	1	3
		SV	**26**	**EV**	**25.5**	**TV**	**25.5**

Values: $20 < V \leq 30$: very high ; $10 < V \leq 20$: high ; $4 < V \leq 10$: intermediate ; $4 \leq V \leq 0$: Low

ASSESSMENT OF THE RISK FOR DEGRADATION OF THE GEOSITE

Parameters	scores
Fragility (F)	2
Natural treats (AN)	3
Natural vulnerability(VuN)	20

(VuN = F x AN x 30/9)

		Coeficient	Result
Interests for mineral and water extraction	3	2	6
Possibility of looting	3	2	6
Proximity to infrastrutures or urban areas	1	2	2
Acessibility	2	2	4
Populacional density	1	1	1
Proximity to recreational area	2	1	2
Vulnerability to antropic treats			21

FDimension factor (FD) :

Susceptibility to natural degration (SDN = VuN x FD) : **20*40=80**

Susceptibility to antropic degration (SDA = VuA x FD) : **21*4=81**

SDA > 10: high ; 5 ≤ SDA ≤ 10 : intermediate ; 0 ≤ SDA < 5 : low

Risk of degration (RD = V × SD) : 21*80=1680

RDA > 200 : high ; 50 ≤ RDA < 200 : intermediate ; RDA < 50 : low

4.3.3 Cadzewe Fossilised Forest

The Cadzewe fossil forest is located 45.5 km from the Mágoe village and 8 km along the road Magoé-Chitima. The Magoé fossilized tree trunks occur over a wide area of approximately 4,000 m^2 (Figure 4.6A-H). The diameter of the logs varies from 1.5 to 2 m. Even if most of the trunks are in the horizontal position, reaching 3 m long in that position, trunks also occur in their upright vertical position, showing the autochthonous nature of the forest (Figure 4.6C). These logs in their original position can reach 1.75 m in diameter (Figure 4.6C). Some of the trunks are fragmented due to chemical weathering (Figure 4.6B). During the rainy season, some logs are flooded by the Zambezi River. However, the most spectacular exposures remain intact, visible and accessible (Figure 4.6B-H). Due to the excellent level of preservation of the Cadzewe fossil woods, the presence of the plant-insect interactions (insect borings) and fossil tree hollows are clearly visible (Araújo *et al*., 2018). Other features seen in situ are inclusions of minerals such as goethite, calcite, and silica in the secondary cell walls (Figure 4.6H). So far the fossil plant diversity in the area includes *Agathoxylon africanum* and *Prototaxoxylon uniseriale* (Chapter three). All these are conifer woods recorded in Gondwana formations (Bamford *et al*., 1999, Crisafulli, 2002). Mathematical calculation of the Cadzewe geosite is stated in Table 4.10 and in the Appendix A.



Figure 4.6: A, Fragmented fossilized trunk; B, Fossil tree trunk reaching 1.5 m, showing a slight fragmentation; C, D, E, Fossil tree trunk in its upright position, and scattered trunks in the studied area; G, Tree trunk showing marked growth; H, Mineral inclusions and boring traces in the tree trunks.

Table 4.10: Geosite assessment-Cadzewe

Code of the do Geosite: 1PG **Name of the Geosite: Cadzewe**

Person filling in the form: Nelson Nhamutole **Date: 25.09.2020**

Nelson Nhamutole

TABLE FOR GEOSITE ASSESSMENT		Scientif Value (SV)		Educacional Value (EV)		Tourístic Value (TV)	
Parameters	Scores	Coeficient	Result	Coeficient	Result	Coeficient	Result
Representativity	4	2	8	0.5	2	0	0
Type of local	2	1	2	0.5	1	0	0
Level of scientific knowledge	2	2	4	0	0	0	0
State of conservation	3	1	3	1	3	0	0
Observation condition	4	1	4	1	4	0.5	2
Rareness	1	2	2	1	1	0	0
Geodiversity	3	1	3	1	3	0	0
Educative potential	2	0	0	2	4	0	0
Logistic infrastutures	1	0	0	1	1	1	1
Acessibility	2	0	0	1	2	1	2
Dimensions of the site	2	0	0	0.5	1	0.5	1
Beauty or spectacularity	3	0	0	0.5	1.5	2.5	4.5
Possibilities for outreach	3	0	0	0	0	2	6
Sumplementary touristic attractions	2	0	0	0	0	0.5	1
Resistence of the site	3	0	0	0	0	1	3
Socioeconomic level of the region	3	0	0	0	0	1	3
		SV	**26**	**EV**	**23.5**	**TV**	**23.5**

Values: 20 < V ≤ 30: very high ; 10 < V ≤ 20 : high ; 4 < V ≤ 10 : intermediate ; 4 ≤ V ≤ 0 : Low

ASSESSMENT OF THE RISK FOR DEGRADATION OF THE GEOSITE

Parameters	scores
Fragility (F)	2
Natural treats (AN)	3
Natural vulnerability(VuN)	20

(VuN = F x AN x 30/9)

		Coeficient	Result
Interests for mineral and water extraction	3	2	6
Possibility of looting	3	2	6
Proximity to infrastrutures or urban areas	1	2	2
Acessibility	2	2	4
Populacional density	1	1	1
Proximity to recreational area	2	1	2
Vulnerability to antropic treats			21

FDimension factor (FD) :
Susceptibility to natural degration (SDN = VuN x FD) : 20*40=80
Susceptibility to antropic degration (SDA = VuA x FD) : 21*4=81
SDA > 10: high ; 5 ≤ SDA ≤ 10 : intermediate ; 0 ≤ SDA < 5 : low

Risk of degration (RD = V × SD) : 21*80=1680
RDA > 200 : high ; 50 ≤ RDA < 200 : intermediate ; RDA < 50 : low

4.3.4 Mapembera Fossilised Forest

The Mapembera site is located along the road Magoé-Carinde, 16 km from Magoé village. Here, the biggest logs of petrified tree trunks are frequently submersed in the Zambezi River (Figure 4.7C and D). Although a large part of the forest is mostly water-covered, some fossil trunks are seen lying on the ground and others embedded in sandstone outcrops. Some smaller pieces of tree trunks in this site seem to have been transported by the river. Palaeobotanical studies reveal that the petrified trunks in the Mapembera site correspond to *Agathoxylon karooensis* and *Cupressinoxylon* sp. nov. Once the latter is confirmed, it would add significant information to the Karoo system as a whole (Chapter three). *Agathoxylon karooensis* is an extinct genus of gymnosperms. These fossil woods have solely been recorded in southern Africa (Normandien Formation in South Africa, and Tsarabis-Etjo Formation in Namibia; Bamford, 1999). Furthermore, the first record of *Australoxylon teixeirae* (Marguerier, 1973) in Gondwana was collected and studied from this site, thus, similar woods were expected to be found, a fact that has been confirmed with this study.

The silicified woods analyzed from this site are mostly made up of silica (Araújo *et al.,* 2017). The panoramic view in this area is spectacular, however, access is difficult and this could potentially hinder its attractiveness for possible visitors (Figure 4.7A). Table 4.11 below represents the quantitative assessment of the Mapembera fossil forest.

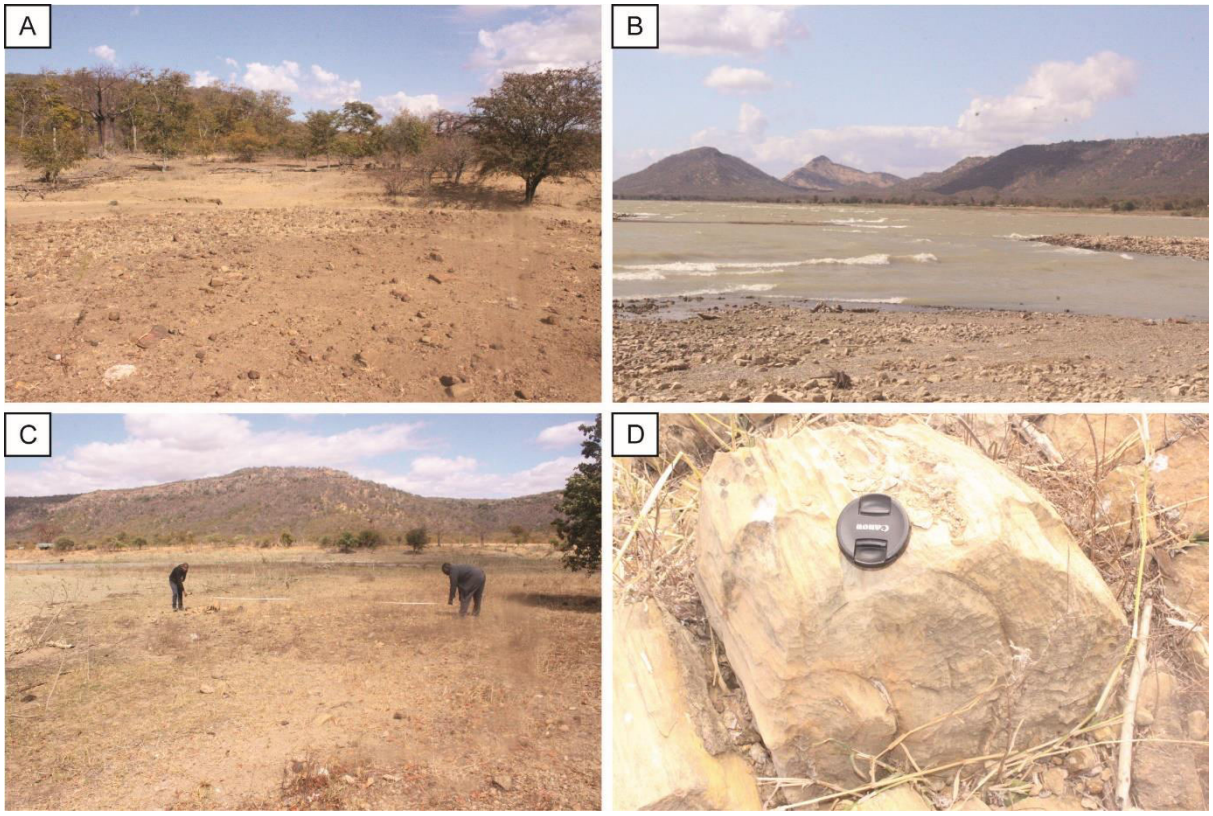


Figure 4.7: A and B, Panoramic view of the Mapembera fossilised trunks; C, Big piece of fossilised tree lying on the ground; and D, Tree trunks with growth rings.

Table 4.11:Geosite assessment-Mapembera

Code of the Geosite: 1PG **Name of the Geosite:** **Mapembera**

Person filling in the form: Nelson Nhamutole **Date:** **25.09.2020**

Nelson Nhamutole

TABLE FOR GEOSITE ASSESSMENT		Scientif Value (SV)		Educacional Value (EV)		Tourístic Value (TV)	
Parameters	Scores	Coeficient	Result	Coeficient	Result	Coeficient	Result
Representativity	4	2	8	0.5	2	0	0
Type of local	2	1	2	0.5	1	0	0
Level of scientific knowledge	2	2	4	0	0	0	0
State of conservation	3	1	3	1	3	0	0
Observation condition	4	1	4	1	4	0.5	2
Rareness	1	2	2	1	1	0	0
Geodiversity	3	1	3	1	3	0	0
Educative potential	2	0	0	2	4	0	0
Logistic infrastutures	1	0	0	1	1	1	1
Acessibility	2	0	0	1	2	1	2
Dimensions of the site	2	0	0	0.5	1	0.5	1
Beauty or spectacularity	3	0	0	0.5	1.5	2.5	4.5
Possibilities for outreach	3	0	0	0	0	2	6
Sumplementary touristic attractions	2	0	0	0	0	0.5	1
Resistence of the site	3	0	0	0	0	1	3
Socioeconomic level of the region	3	0	0	0	0	1	3
		SV	**26**	**EV**	**23.5**	**TV**	**23.5**

Values: 20 < V ≤ 30: very high ; 10 < V ≤ 20 : high ; 4 < V ≤ 10 : intermediate ; 4 ≤ V ≤ 0 : Low

ASSESSMENT OF THE RISK FOR DEGRADATION OF THE GEOSITE

Parameters	Scores
Fragility (F)	2
Natural treats (AN)	3
Natural vulnerability(VuN)	20

(VuN = F x AN x 30/9)

		Coeficient	Result
Interests for mineral and water extraction	3	2	6
Possibility of looting	3	2	6
Proximity to infrastrutures or urban areas	1	2	2
Acessibility	2	2	4
Populacional density	1	1	1
Proximity to recreational area	2	1	2
Vulnerability to antropic treats			21

FDimension factor (FD) :

Susceptibility to natural degration (SDN = VuN x FD) : **20*40=80**

Susceptibility to antropic degration (SDA = VuA x FD) : **21*4=81**

SDA > 10: high ; 5 ≤ SDA ≤ 10 : intermediate ; 0 ≤ SDA < 5 : low

Risk of degration (RD = V × SD) : 21*80=1680

RDA > 200 : high ; 50 ≤ RDA < 200 : intermediate ; RDA < 50 : low

4.3.5 Nhambando Fossilised Forest

The Nhambando fossil forest is located in the south margin of the Zambezi River, within a natural protected area. The site is 51 km from Chitima, and 3 km along the road from Chitima to Magóe. This fossilized forest is part of Tete's largest fossil forest, which extends over 75 km (Marques and Ferrara, 2004). This area displays a higher concentration of tree trunks lying on the ground with some following the same direction, mostly NW-SE (Figure 4.8A, D and G). The permineralized trees' length exceeds 13 m, and diameters range from 30 cm to 1.5 m (Figure 4A-B). The colour of the scattered trees is grey, yellow to red due to the process of fossilization (Figure 4A, B, D), during which the organic matter is replaced by minerals and the pore spaces are completely filled by silica. However, minerals such as hematite and goethite can eventually intergrow with the silica during the replacement process (Figure 4F). Taking into consideration ongoing studies (Chapter three), the palaeoflora of this area is dominated by *Australoxylon teixeirae* and *Agathoxylon africanum*. Both species are well known from Permian deposits of Gondwana (Bamford, 1999; Crisafulli, 2002). It can be noted that the extant vegetation of this area is covered by *Colophospermum mopane* (Bamford, personal observation) and other Miombo open woodland taxa (Burrows *et al*., 2018). The Nhambando quantitative assessment is represented in the Table 4.12.



Figure 4.8: A and B Panoramic view of the Nhambando fossil forest; C and D, Big pieces of fossilised tree trunks in Nhambando site; E and F, Piece of a silicified trunk with mineral inclusions.

Table 4.12:Geosite assessment-Nhambando

Name of the Geosite:

Code of the Geosite: 6PG

Nhambando

Person filling in the form: Nelson Nhamutole

Date: 25.09.2020

Nelson Nhamutole

TABLE FOR GEOSITE ASSESSMENT		Scientif Value (SV)		Educacional Value (EV)		Tourístic Value (TV)	
Parameters	Scores	Coeficient	Result	Coeficient	Result	Coeficient	Result
Representativity	4	2	8	0.5	2	0	0
Type of local	2	1	2	0.5	1	0	0
Level of scientific knowledge	0	2	0	0	0	0	0
State of conservation	3	1	3	1	3	0	0
Observation condition	4	1	4	1	4	0.5	2
Rareness	1	2	2	1	1	0	0
Geodiversity	3	1	3	1	3	0	0
Educative potential	2	0	0	2	4	0	0
Logistic infrastutures	1	0	0	1	1	1	1
Acessibility	2	0	0	1	2	1	2
Dimensions of the site	2	0	0	0.5	1	0.5	1
Beauty or spectacularity	3	0	0	0.5	1.5	2.5	4.5
Possibilities for outreach	3	0	0	0	0	2	6
Sumplementary touristic attractions	2	0	0	0	0	0.5	1
Resistence of the site	3	0	0	0	0	1	3
Socioeconomic level of the region	3	0	0	0	0	1	3
		SV	**22**	**EV**	**23.5**	**TV**	**23.5**

Values: $20 < V \leq 30$: very high ; $10 < V \leq 20$: high ; $4 < V \leq 10$: intermediate ; $4 \leq V \leq 0$: Low

ASSESSMENT OF THE RISK FOR DEGRADATION OF THE GEOSITE

Parameters	Scores
Fragility (F)	2
Natural treats (AN)	3
Natural vulnerability(VuN)	20

(VuN = F x AN x 30/9)

		Coeficient	Result
Interests for mineral and water extraction	3	2	6
Possibility of looting	3	2	6
Proximity to infrastrutures or urban areas	1	2	2
Acessibility	2	2	4
Populacional density	1	1	1
Proximity to recreational area	2	1	2
Vulnerability to antropic treats			21

FDimension factor (FD) :

Susceptibility to natural degration (SDN = VuN x FD) : **20*40=80**

Susceptibility to antropic degration (SDA = VuA x FD) : **21*4=81**

SDA > 10: high ; 5 ≤ SDA ≤ 10 : intermediate ; 0 ≤ SDA < 5 : low

RisK of degration (RD = V × SD) : 21*80=1680

RDA > 200 : high ; 50 ≤ RDA < 200 : intermediate ; RDA < 50 : low

CHAPTER FIVE-DISCUSSION

5.1 Growth rings

The growth rings were analyzed based on fossilized woods that belong to seven genera and eight different species from Permian and Triassic formations of Mozambique (see Table 4.2, 4.3, and others in the appendix). This study aimed to find patterns concerning growth rings in their variability, taxonomy, stratigraphic position, presence of shear zones, and false rings.

Latewood *versus* Earlywood. Independently of formation, age, and taxonomy, the presence of well-defined growth rings in many Mozambican fossil woods, indicates that their growth environment was dominated by well-defined seasons. The different cell dimensions over the ring widths suggest that conditions during the growing season were suitable for cell division and expansion (Creber and Chaloner, 1984b), thus resulting in the thick Earlywood zones. In contrast, the narrow Latewood zones are related to water shortage, low light levels, or shorter day length, mainly during the onset of the winter season which would cause hindrances to cell production (Creber and Chaloner, 1984b).

Taxonomy *versus* Type of Rings. *Cupressinoxylon* (n=1), *Taxodioxylon* (n=1), *Protaxodioxylon* (n=2) and *Prototaxoxylon* (n=3) have rings of only one type each. Thus, these woods are strongly genetically controlled in their growth so the ring type is not controlled by the environment, although there might be some influence (Pires and Sommer, 2009). The number of fossil woods studied, however, is not enough to make definitive conclusions. Furthermore, both *Cupressinoxylon* and *Taxodioxylon* show one type of rings (Type D), which corroborates with the studies performed by Brison *et al*., 2001 for the Mesozoic fossil woods at a global scale. Brison *et al*. (2001) concludes that, *Agathoxylon* trees do not have ability to produce latewood even if the trees grew in seasonal climate conditions. Thus, the presence of narrow latewood does not imply unfavourable conditions but a possible characteristic of the *Agathoxylon* trees. In contrast, specimens of *Australoxylon teixeirae* and *Agathoxylon africanum* show 2-3 ring types. Thus, growth rings are climatically and environmentally driven and not genetically determined (Pires and Sommer, 2009).

Furthermore, in *Agathoxyon africanum* and *Australoxylon teixeirae* there are S-type rings with shear zones, which seem to be characteristic of Karoo woods (Bamford, 2016). Dendrochronological studies undertaken by Kock (2018) and Bamford (2016 and 2020) in the Karoo Basin, supports the same ideas. This type of ring was added by Bamford (2016) on her study of a large collection of Karoo woods with similar taxonomy to the present dissertation. On another note, *Agathoxylon* does not produce rings of the A, B, or C type. Brison *et al*. (2001) suggested that this taxon possesses the inability to build rings of A, B or C type regardless of how seasonal the climate is. In fact, extant Araucariaceae, with *Agathoxylon* wood type, never show these types of rings either (Seitz and Kanninen, 1989). Therefore, this phenomenon according to Brison *et al*., 2001, seems to be indeed characteristic of *Agathoxylon*.This fact is also now being confirmed with the study of the Mozambican material because none of the studied Mozambican material presented rings type B, C and E. However, these types of rings have only been found in Lower Cretaceous deposits of both hemispheres (Creber and Chaloner, 1984).

Ring variability *versus* growth rings. The studied material presents variable ring widths, which suggests a fluctuating climate with annual variability (Chaloner and Creber, 1990). This suggests that the climate fluctuated from year to year, with some years having favourable growing conditions for a longer period, e.g., moderate temperatures and sufficient rainfall resulting in wide Earlywood (Fritts, 1976; Butterfield, 2003). Other years had less favourable growing conditions. However, based on ring variability, it is not possible to see with the very short sections. Furthermore, almost all materials show relatively wide growth rings (IAWA 2004), suggesting that tree growth was fast during a slightly shorter growing period.

Stratigraphy *versus* growth rings. The Tete region has a complex geological history controlled by the Zambezi rift (Lachelt, 2004). The Niassa region, on the other hand, has a continuous stratigraphic record from the Carboniferous to the Jurasasic (Verniers *et al*., 1989). We assume that the stratigraphic layers are correctly correlated temporally and spatially and that the environment has changed from fluvial to lacustrine to fluvial again over time (Table 4.3). We do not have the resolution in the fossil wood record to correlate any particular taxon or growth ring type with any sediment types (or depositional environment). However, despite the biotic crisis at the End-Permian and the low sampled record obtained, conclusively

Permian and Triassic woods from Mozambique seem to have been subjected to different environmental conditions. However, Pereira *et al*., 2019 showed a slightly similar story with a decrease of pollens and spores across the Permo-Triassic boundary. Recent studies that highlight the collapse of the palaeoflora based on vegetation turnover, carbon isotope shift have been undertaken worldwide in Permo-Triassic formations (Fielding *et al*., 2019, Nowak *et al*., 2019, and others).

Shear zones *versus* growth rings. There are at least two possible explanations for the shear zones: fungal infection and climate (Bamford, 2020, Kock, 2018). The presence of shear zones in the growth rings were observed in the fossil woods from Cádzi Formation, Matinde Formation, KSa Mount Lilonga Formation, KSb Fubúé Formation and suggest that the tracheid walls are thin and less robust, allowing the tracheids to collapse under the pressure of lateral forces and thus resulting in shear zones (Bamford *et al*., 2020). Presence of *Lasiodiplodia theobromae* and brown-rot fungi are responsible for the processes of decay and damage of the woods according to Cedeño *et al*. (1996) and Green *et al*., (1996). The damage and decay of the woods affect their internal structure thus weakening the cells (e.g., the walls of the tracheid cells). Dead trees or branches, once buried, would lead to the collapse of wood cells due to the weight of the overlying sediment. Subsequently, the wood cells become distorted leading to the formation of shear zones in the growth rings. Therefore, the presence of shear zones in the analyzed samples could be explained by post-burial decay.

Alternatively, according to Bamford *et al*., (2000), the shear zones might be associated with extreme conditions (e.g., very wet and/or hot), resulting in rapid growth and thin walls. The absence of shear zones in the older formations, K4 Formation and K5 Formation, could mean that the local Early Permian and Middle Permian conditions were mostly stable and have not been heavily affected by Olsonʾs extinction. This conclusion agrees with the findings obtained by Minana et al., (2015), where the seed plants seem to be unaffected by the Olsonʾs extinction. Studies have debated the impact of the Olson's extinction in flora and faunas and its relevant influence on the Permian ecosystems (Minana *et al*., 2015; Brocklehurst *et al*., 2017). In addition, the observed shear zones do not follow a given trend and display different thickness (See Fig 4.3 in the appendixes G), indicating that the forces that possibly originated the shear zones were not uniform and without a

widespread influence (Kock, 2018). Other interesting aspect has to deal with the fact that the shear zones are present in both earlywood and latewood suggesting that the forces than weaken the cell walls of earlwood tracheids affected the latewood in the same proportion (Kock, 2018).

False rings *versus* growth rings

The presence of false rings is observed in some growth rings in the Matinde, and Cádzi Formation in Niassa and K5 and KSa Mount Lilonga Formation in Niassa suggests that in some years the trees experienced water-stressed conditions characterized by less water availability. False rings (i.e., incomplete rings or very faint “latewood”) could possibly be a result of limited groundwater sources and/or the represented trees being a fair distance from their water source (Falcon-Lang, 2000a; Francis and Poole, 2002). Another possible cause for the appearance of false rings in the studied fossil woods is the potential occurrence of an event comprising fire, drought or insect attack during their growing season (Falcon-Lang, 2000a; Francis and Poole, 2002). Nevertheless, their absence in the K4 Formation, K5 Formation and in the formations does not imply that conditions were less arid/water-stressed. For that aim a large sample size would have to be considered for such a conclusion. These conclusions are similar to those obtained by Kock (2018) in the Ecca-Beaufort contact. Kock (2018), compiling information from Catuneanu *et al*., 1998; Bamford, 2004; Catuneanu *et al*., 2005; Barbolini *et al*., 2016), observed between the Ecca-Beafourt contact a seasonal climate, favourable and unfavourable conditions thus also suggesting more sampling to achieve a more precise interpretation

Based on research on wood types, wood quality and the effects of climate on woods; they can be broadly divided into three categories (Creber and Chaloner 1984). The first category is where the growth rings are very distinctive for the taxon and do not appear to differ even when the growth environment varies. The second category includes woods whose growth rings vary according to climate, for example wide and narrow rings for good and poor seasons respectively, as well as the development of frost rings and traumatic rings. The third category is what seems to be occurring amongst the Mozambican woods, where the ring type can vary within the same wood fragment and within the same taxon. This is the case of *Agathoxylon*

africanum, *Australoxylon teixeirae* and some unindenfied specimens (Table 4.4). However, this implies that the over-riding control for the development of the growth rings is the climate. This is also observed to the Antarctic conifers (Francis, 1986), albeit some of the araucarian and podocarpacean conifers from Antarctica are associated with cell production independent of climate influence (Creber and Chaloner, 1984b). Nevertheless, the interpretation of growth rings for palaeoclimate inferences should be taken with caution and also based on large diverse assemblages because studies undertaken with small sample size can give rise to problematic interpretations (Brison *et al*., 2001; Falcon-Lang, 2005a). In summary, the studied material show growth ring that reflect climate characterized by warm, dry and moderate temperatures associated with sufficient rainfail for the Middle to Lower Triassic at both Tete and Niassa formations. This conclusion was also sustained by attempt undertaken aimet at correlating the climate information provided by the lithostratigraph and the growth ring. From this correlation, is also obvious that the climate from the Middle to Lower Triassic in Niassa and Tete sites was variable with temperatures influenced by warm, hot and wet conditions. In addition, the occurrence of water stressed condition in these areas is also observed based on this two climate proxies (Table 4.3).

5.2 Palaeogeography

The palaeoflora of Mozambican Permian and Triassic formations were represented by plants belonging to the gymnosperms lineages comprising Cupressaceae, Taxodiaceae and the Glossopteridales. Cupressaceae and Taxodiaceae have been merged together into a single family (Cupressaceae), based on the phylogenetic studies carried out by Eckenwalder (1976) and since then, have been adopted in most classification schemes of gymnosperms (e.g., Farjón, 2001, 2005; Christenhusz *et al*., 2011) and supported by most non-molecular and molecular phylogenetic studies (e.g., Hart, 1987; Price and Lowenstein, 1989; Brunsfeld *et al*., 1994; Gadek *et al*., 2000; Yang *et al.,* 2012). On the other hand, although the inclusion of plants to the Glossopteridales order is somehow uncertain, there are studies performed in the Permian of Gondwana that associate *Araucarioxylon* plants with *Vertebraria* and *Vertebraria* with *Australoxylon* (Gould and Delevoryas 1977,

Neish *et al*., 1993; Decombeix *et al*., 2009; Harper *et al*., 2017). The association between *Vertebraria* and *Australoxylon* is based on the similarity of the clusters in the bordered pits between them, meanwhile, the affinity of *Vertebraria* and *Araucarioxylon* wood is based on the similarity of the tracheid anatomy between both. These studies, however, suggest close affinities amongst them (see above references). Considering such affinities we can then consider the order Glossopteridales as the most dominant in the Mozambican palaeoflora due to the presence of *Agathoxylon africanum* and *Australoxylon teixeirae* in almost all studied formations. This is also supported by the occurrence of leaves of *Glossopteris* in the K4 (Lower Permian) and K6 Formation (Late Permian), with different species of glossopterids, *Glossopteris ampla, G. browniana* and *G. Indica* (Teixeira and Gonçalves, 1959; Verniers *et al*., 1989). Some other *Glossopteris* leaves are also reported in the Karoo system of the Tete area such as, *Glossopteris browniana*, *G. angustofolia*, *G. retifera, G. indica, G. brancai,* and others (Zeiller, 1883).

Regarding the time range of the species, *Agathoxylon africanum*, *Australoxylon teixeirae* and *Prototaxoxylon* uniseriale indicates that these species have survived well the Permian extinction. In its turn, *Agathoxylon africanum* and *Australoxylon teixeirae* are endemic to Gondwana as no other similar occurrences were recorded elsewhere. This supports the concept that the floras of the Southern continents were broadly similar and that some species-level provincialism defined latitudinally is observed at almost all time in the floras of Gondwana based on studies of other plant groups too (Dettmann and Clifford, 1992; Srivastava, 1994, McLoughlin, 2001). Nevertheless, other genera recorded from the Mozambican Karoo formations; *Taxodioxylon, Protaxodioxylon,* and *Cupressinoxylon* do not seem to have survived well the Permian extinction across Gondwana, because to date they have not been found so far in younger Mesozoic formations. Therefore, the time ranges of the wood taxa should not be taken at face value for a number of reasons. The apparent range can also be considered as a matter of sampling, scarcity of fossil woods, poor preservation due to extreme climate conditions that preceded the Triassic age and perhaps competition with other plant groups (McLoughlin, 2001). Further, the scarcity of fossil woods could also be associated with the geological stability of the continent and due to the contribution of the fluctuating climate characterized by weathering profiles widespread across much of the landscape in Gondwana (Gale,

1992). *Protaxodioxylon, Cupressinoxylon, Taxodioxylon, and Prototaxoxylon* are examples of cosmopolitan genera because they have been found in both hemispheres at different time ranges. For instance, the coniferous family Cupressaceae s.l., although it is found in both hemispheres, does provide an excellent example for studying the break-up history of Pangea. This is because it diversified into seven subfamilies during the Late Triassic and Jurassic (Gadek *et al*., 2000; Mao *et al*., 2012), which coincides with the separation of Gondwana and Laurasia. Another argument is that the period of the divergence of its subfamily Callitroideae from Gondwanan deposits and its other subfamily Cupressoideae from the Northern Hemisphere which could be dated back to the Jurassic. This conclusion is drawn based on molecular clock analysis that provides strong evidence for the vicariance between the two subfamilies by the spilt of Laurasia and Gondwana (Li and Yang, 2002; Mao *et al*., 2012). The cosmopolitan distribution of *Protaxodioxylon, Cupressinoxylon, Taxodioxylon, and Prototaxoxylon* in both hemispheres could be seen *as a* representation of a likely floristic exchange between Gondwana and Laurasia as suggested by Wan *et al*., (2015) in the study of the *Prototaxoxylon uniseriale* from Wuchiapingian of Wutonggou Formation (Permian) in China. Interesting observations can be drawn from the fact that *Protaxodioxylon*, *Cupressinoxylon* and *Protaxodioxylon* are found in Mesozoic terrains, Jurassic to Cretaceous whereas *Taxodioxylon* is recorded in the Mesozoic and its occurrence continues to much younger strata into the Cenozoic (Yang and Zheng, 2003; Dolezych *et al*., 2011). According to herein reported data, all these genera are now recorded from much older strata, and it is likely that their earliest representatives have originated, dispersed and diversified during the Permian, a period of pronounced global warming and widespread aridity (Chumakov and Zharkov, 2000). This conclusion is also referred to the studies of other plant groups (Taylor *et al*., 2009). This also attests to the conservatism of fossil wood anatomy that can range the three most important phases of life on Earth.

The Permian period is, therefore, well-known as when most terrestrial plants broadly diversified (Anderson and Anderson, 1985). However, the analysis of diversification within plant groups is not a straightforward process, and should be taken with caution because the place of origin does not always represent the place of diversification (Wang and Ran, 2014). For instance, although *Protaxodioxylon,*

Cupressinoxylon and *Taxodioxylon* are found in Permian strata of the Southern Hemisphere, their diversification seem to have occurred in the Northern Hemisphere given the number of species that have been so far recorded in the Northern counterpart (Tian *et al*., 2015). Perhaps these plants originated during the Permian in the Southern Hemisphere then dispersed to the Northern Hemisphere and hereinafter they diversified. Therefore, biogeographical patterns and inferences should take into consideration relevant aspects such as vicariance scenarios and dispersal events (McLoughlin, 2001; Givnish and Renner, 2004; Sanmartin and Ronquist, 2004; Crisp *et al*., 2011). In addition, another relevant aspect that deserves attention in the data is the different diversity between the Mozambican Karoo and the South African main Basin. In this regard, the relatively higher diversity of the Mozambican Karoo, if compared to the South African main Basin, can perhaps indicate that the fossil record is incomplete or otherwise suggesting that in some cases the preservation of the material is poor. The latter scenario is unlikely to be the only reason. For instance, during the Beaufort times the enormous inland sea dried up and both braided rivers and flood plains decreased to meandering streams environments creating conditions for fossil wood preservation (Catuneanu *et al*., 1998).

5.3 Geoconservation

A quantitative assessment has been undertaken to give numerical parameters for each geosite and thus be able to rank them (Tables 4.8, 4.9, 4.10, 4.11, and Appendixes A to D, Table 1). The assessed geosites in order of inventory, characterization and evaluation are: Mapembera, Cadzewe, Nhambando and Carangache (see the table above). All these sites are important geological heritage sites. The Mapembera geosite is a unique area for which accessibility is quite difficult and the log exposures for the geotouristic point of view can be totally submerged by the waters of the Zambezi River. In this geosite, scientific activities would be prioritized over any touristic activities. The Nhambando fossil forest displays low scientific value, thus far. This value can be associated with the lack of scientific knowledge of this particular geosite, and this study represents the first effort for that aim. Nhambando, Cadzewe and Carangache fossil forests would be given top

priority for geotourism purposes because of their easy accessibility, spectacular views, the possibility of some outdoors activities, etc. In these fossilised forests, the visitors would be able to see impressive remains of Permian paleoflora. Regardind a more scientific point of view a lot can be learned about the fossilization processes, taphonomy, taxonomy, etc. In summary, all of the four forests show high scientific, educational, touristic, vulnerability and degradation values suggesting that conservation and protection based on local legislation is indeed needed, factors that would enhance their valorization and outreach. In addition, some urgent actions are needed to be undertaken including the following: 1) Cooperation among stakeholders for the development of geotourism, and enforcement of regulations for the protection of the site (e.g., against vandalism, theft.); 2) enforcing the designation of the area as a geological heritage site would help reduce possible exploitation of its geological resources as happens in other similar sites across the world (Dias-Brito *et al*. 2014; Won-In and Singtuen, 2018; Maksoud and Metwaly, 2020; Parker, 2005; Zouros, 2010 and others; and 3) Providing facilities for geotourism activities such as the placement of fences, and information panels to serve visitors, which would contain an explanation of the local geology, importance of the palaeontoogical heritage and other relevant aspects. Moreover, it is important to highlight that similar fossil forests occur across worldwide, such as Chirundu Hill in Zambia, Arizona Petrified Forest National Park in the United States of America, Lesvos Petrified Forest in Greece, Khorixas petrified forest in Namibia (see Appendix F). However, the diversity, amount of log exposures concentrated within it, and the dimension of the Tete fossil forest makes it the most spectacular, one of its kind worldwide and perhaps the largest fossil forest encountered across the entire continent (Appendix F).

CHAPTER SIX-CONCLUSIONS

Fossil woods in Mozambique have been sporadically reported as a result of geological cartography. However, no comprehensive analyses of these fossil woods from multiple sites and provinces has ever been reported. This dissertation has dedicated to study the fossil wood assemblages in Permian and Triassic formations in Mozambique. Based on the results of this study, the main conclusions are:

Taxonomy:

Five genera and seven species of fossil woods are described. Among them, three are new species to science: *Cupressinoxylon* sp. nov, *Protaxodioxylon* sp. nov. 1, *Protaxodioxylon* sp. nov. 2. The latter two have been accepted for publication (Nhamutole *et al*., submitted). The other identified taxa were: *Agathoxylon africanum*, *Agathoxylon karooensis*, *Prototaxoxylon uniseriale*, *Taxodioxylon* sp., *Australoxylon teixeirae*. All of these taxa are described for the first time in the Karoo system of Mozambique with *Australoxylon teixeirae* being the only exception. *Agathoxylon africanum* is the most dominant taxon in the Permian and Triassic formations in Mozambique similarly with the floral ecosystem of the MKB in South Africa.

Palaeoclimatology:

The presence of growth rings as a common feature in fossil woods from the Permian and Triassic formations in Mozambique indicates seasonal variation in tree growing conditions, characterized by the cyclical alternation of warm, dry and wet periods. These woods were not determined by environmental conditions alone.

A-Woods of studied *Cupressinoxyon*, *Taxodioxylon*, *Protaxodioxylon*, *Prototaxoxylon* are likely genetically controlled whereas woods of *Agathoxylon*, *Australoxylon* were climate and environment driven.

B-Most of the samples present rings of type D and S-type.

C- Woods with S-type underwent fungal infection and extreme conditions (very wet and /or hot). The S-type rings are only present in Triassic formations in the Niassa

province. This could possibly be a result of increased stress after the End-Permian Extinction.

D- Woods are wide in both Permian and Triassic formations indicating an environment with fluctuating climate, annual variability, and fast growth.

E- The Permian and Triassic formations in the Tete and Niassa provinces display false growth rings indicating that these trees experienced somewhat water stressed conditions during the growing season and/or arthropod damage during the life-cycle of the trees.

Results show that the growth analysis has to be based on even larger sampling and perhaps even more diverse assemblages in order to provide further inputs. To complement this analysis the impact of paleoposition in the growth rings would also add more strength to the conclusions presented here, as well as the calculation of Mean Sensitivity. In the future, further fieldwork is required to achieve a large sample enough to allow the calculation of these variables.

Palaeoecology:

A- *Australoxylon teixeirae* was found in the Matinde Formation (Late Permian), Mount Lilonga Formation (Lower Triassic) and K5 Formation (Middle Permian) in Mozambique. Australoxylon teixeirae is the most widespread taxon in Gondwana formations and is reported from the Beaufort Group (Late Permian in South Africa), Mosolotsane Formation, Upper Triassic (Botsawana), Teresina and Rio de Rasto Formation, Late Permian (Brazil), Solca Formation, Early Permian (Argentina), Tacuary Formation, Late Permian (Paraguay), Yaguari Formation and Tres Islas, Late and Lower Permian respectively (Uruguay), Raniganj Formation, Late Permian (India).

B- Occurences of *Cupressinoxylon*, *Taxodioxylon*, *Protaxodioxylon* in the Karoo formations in Mozambique provides the robust physical evidence for the first steps of dispersal and diversification of Cupressaceae, Taxodiceae in Gondwana.

C- *Taxodioxylon*, *Protaxodioxylon*, *Cupressinoxylon* are found in the Late Palaeozoic in the Karro of Mozambique, whereas *Agathoxylon*, *Australoxylon* have ranges extending further into Mesozoic.

D- Fossil woods studied reiterate also that *Agathoxylon africanum* and *Australoxylon teixeirae* are endemic to Gondwana and that *Agathoxylon karooensis* is to date endemic to Southern Africa.

E- So far, the K5 Formation in Niassa (Middle Permian) and the Matinde Formation in the Tete area (Late Permian) are the most taxonomically diverse formations in Mozambique Karoo system.

F- This study reveals that so far the Mozambican Karoo system is relatively more diverse with six genera compared to the four genera of the MKB in South Africa. More field work needs to be done in both basins to confirm that conclusion.

Geoconservation:

A - Except for the Mapembera fossil forest, the remainder of the fossil forests including the Nhambando, Cadzewe, and Carangache fossil forests, have the potentiality for geotourism activities to occur similar to the Arizona Petrified Forest in The USA, the Lesvos Petrified Forest in Greece, and the Khorixas Petrified Forest in Namibia.

B - These fossilized forests form autochthonous (life position trunks), and allochthonous assemblages.

C - Autochthonous assemblages are accumulated in the margins of the Zambezi River, occasionally affected by non-channelized, high energy fluvial systems.

D - All of the four studied fossil forests assemblages are stratigraphically placed at the Matinde Formation (Late Permian).

E - From a geoconservation viewpoint, however, the relative damage due to natural events currently taking place in these sites calls for urgent actions that must include outreach activities that engage local communities and enforcement of protective measures by the government.

These Petrified Forests are important geological heritage sites. Properly managing them as protected geosites and the establishment of a large museum should help mitigate the negative effects of their destruction by human and related natural influences on the unique geological heritage of the forest and its vicinity.

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APPENDIXES

APPENDIX A

Quantitative assessment of the Fossil Forests

Cadzewe Fossil Forest

GENERAL INFORMATION			
1. IDENTIFICATION			
Identification number or code : 4PG			
Name of the site : **Cadzewe**			
Physical description : See the Cadzewe description site in the section **4.3.2**			
Confidentiality :	☒ Public	☐ Confidential	
Source of collections :	☐ Yes	☐ No	
If yes, **location of collections :**			
2. LOCATION			
X : **S 15° 46' 47.1''**	Y : **032° 18' 14.9'' E**	UTM Zone : **36S**	Type of coordinates : **geográficas**
Altitude Max.	Min.	**Area** (estimate):	
Related 1:50.000 maps:			
Place locally known as : **Cadzewe**			
Province, municipality or county : **Tete, Magoé**			
Department or state :			
Region :**Cahora district**			
Description of the itinerary to access the site : **The Cadzewe fossil forest is located 45,5Km from Magoé district towards Chitima village.**			
Is permission required for visit ? (need for prior authorization) :	☐ Yes	☒ No	
3. GEOLOGICAL CONTEXT			
Geological domain : **Sedimentar domain**			
Description of geological processes and elements : (Include supplementary information in the Annex)			
Age of the processes : Late Permian	Lower age limit	Upper age limit	
Age of the elements :	Lower age limit	Upper age limit	

4. INTEREST				
Main type of geological interest (choose just ONE option)				
☐ Stratigraphical	☐ Sedimentological	☐ Geomorphological	☒ Paleontological	
☐ Tectonic	☐ Petrological-geochemical		☐ Metallogenetic	
☐ Mineralogical	☐ Hydrogeological	☐ History of geology	☐ Pedology, edaphology	
Justification :				
Secondary type(s) of geological interest (choose one or more options)				
☐ Stratigraphical	☐ Sedimentological	☐ Geomorphological	☐ Paleontological	
☐ Tectonic	☐ Petrological-geochemical		☐ Metallogenetic	

☒ Mineralogical	☐ Hydrogeological	☐ History of geology	☐ Pedology, edaphology	
Justification :				
NON-geological interest of the site (choose one or more options)				
☐ Mining-industrial	☐ Use of thermal-mineral water	☒ Biological (flora, fauna)	☒ Landscape	
☐ Architectural	☐ Archeological	☐ Ethnological (traditions)	☐ Historical and cultural	
Justification of the non-geological interest :				

Representativity (choose just one option). Coefficient : 2 for SV and 0.5 for EV	**Points**
☐ Somewhat useful as a model to represent, even if partially, a geological phenomenon	
☐ Useful as a model to partially represent a geological phenomenon	
☐ Useful as a model to fully represent a geological phenomenon	
☒ The best example, within the geological area under consideration, to fully represent a geological phenomenon	4.0
Type locality (choose just one option). Coefficient : 1 for SV and 0.5 for EV	
☐ The site does not comply by itself with any of the following criteria	
☒ Regional reference locality	2.0
☐ Reference locality (for stratigraphy, paleontology, petrology, mineralogy, geomorphology, etc.) used at international scale, or type locality of local fossils or biozones with a long history of scientific use	
☐ Stratotype accepted by the IUGS or mineral type locality of the IMA	
Level of scientific knowledge (choose just one option). Coefficient : 2 for SV	
☐ There are no scientific publications or theses on the site	
☒ There are scientific publications or theses on the site	2.0
☐ Studied by several scientific teams, with theses and scientific publications in national journals	
☐ Studied by several scientific teams, with theses and scientific publications in international journals	
State of conservation (choose just one option). Coefficient : 1 for SV and 1 for EV	
☐ Unfavourable bad: the site has major degradations or is virtually destroyed	
☐ Unfavourable inadequate: with degradations that prevent the appreciation of certain characteristics of interest	
☒ Favourable with modifications: there are certain degradations which do not affect decissively the value of the site	3.0
☐ Favourable**:** the site is well preserved, almost intact	
Observation conditions (choose just one option). Coefficient : 1 for SV, 1 for EV and 0.5 for TV	
☐ With elements that strongly hide the features of interest	
☐ With elements that obscure the site and prevent the appreciation of certain features of interest	
☐ With elements that do not prevent to observe the site in its integrity, although it is done with difficulty	
☒ Perfectly observable in its entirety and with ease	4.0
Rareness (choose just one option). Coefficient : 2 for SV and 1 for EV	
☒ There are several similar sites in the area	1.0
☐ The site is one of the few examples known at the regional level	
☐ The site is the only known example at the regional level	
☐ The site is the only known example at the national or international level	
Geodiversity (choose just one option). Coefficient : 1 for SV and 1 for EV	
☐ The site only has one main type of interest	
☐ The site presents another type of interest, in addition to the main one, but it is not remarkable	
☒ Two types of interest, in addition to the main one, or only one additional type, but remarkable	3.0
☐ Three or more types of interest, in addition to the main one, or just two, but the two outstanding	
Scientific value (add all SV) :	
> 20 : very high value **10 ≤ V ≤ 20 : high value** **4 ≤ V < 10 : intermediate value**	
Educational potential (choose just one option). Coefficient : 2 for EV	
☐ The site does not respond, by itself, to any of the following criteria	
☐ Useful to illustrate the contents of university programs	
☒ Useful to illustrate the contents of programs at any level of the educational system, or it is used in the educational	3.0

activities of universities	
☐ The site is used routinely in educational activities at any level of the education system	
Logistic infrastructures (choose just one option). Coefficient : 1 for EV and 1 for TV	
■ The site does not meet, by itself, any of the following criteria:	1.0
☐ Accommodation and restaurant for groups up to 20 people within 25 km	
☐ Accommodation and restaurant for groups up to 40 people within 25 km	
☐ Accommodation and restaurant for groups up to 40 people within 5 km	
Accessibility (choose just one option). Coefficient : 1 for EV and 1 for TV	
☐ The site does not meet, by itself, any of the following criteria (such as, for example, paved road without the possibility of parking, footpath, off-road track, boat, etc.):	
■ Direct access by unpaved road accessible by cars	2.0
☐ Direct access by asphalt road with possibility of parking for cars	
☐ Direct access by asphalt road with possibility of parking for buses	
Dimensions of the site (choose just one option). Coefficient : 0.5 for EV and 0.5 for TV	
☐ Metric-size elements (vulnerable to a simple visit)	
■ Decametric-size elements (not vulnerable to visits, but sensitive to more aggressive human activities)	2.0
☐ Hectometric-size elements (may be subject to some degradation by human activity)	
☐ Kilometric-size elements (not easily vulnerable by human activity)	
Beauty or spectacularity (choose just one option). Coefficient : 0.5 for EV and 2.5 TV	
☐ The site does not meet, by itself, any of the following criteria:	
☐ (1) Large amplitude relief, or 2) large courses or bodies of water (or ice), or 3) remarkable chromatic variety. Also, attractive fossils and/or minerals.	
■ Coincidence of two of the three preceding characteristics. Also, attractive fossils and/or minerals.	3.0
☐ Coincidence of the three preceding characteristics.	
Educational value (add all EV) :	
Possibilities for outreach (choose just one option). Coefficient : 2 for TV	
☐ The site does not meet, by itself, any of the following criteria:	
☐ The site is clearly understandable by people with a certain cultural level	
■ The site is clearly illustrative of the importance or usefulness of geology for people with any cultural level	3.0
☐ The site is frequently used for outreach activities	
Supplementary touristic attractions (choose just one option). Coefficient : 0.5 for TV	
☐ The site does not meet, by itself, any of the following criteria:	
■ 1) Possibility of outdoor activities, or 2) The site is less than 5 km from a recreational area, or 3) The site is within 5 km of another cultural or natural feature	2.0
☐ Meets two of the previous criteria	
☐ Meets three of the previous criteria	

Non-fragility (resistance) of the site (choose just one option). Coefficient : 1 for TV	**Points**
☐ Site with unconsolidated or consolidated lithologies, but soft and highly fractured and / or weathered	
☐ Site with soft but consolidated lithologies, with little fracturing and / or weathering	
■ Site with resistant or very resistant lithologies, but with strong fracturing and / or weathering	3.0
☐ Site with highly resistant lithologies (quartzites or similar), with little fracturing and no weathering	
Socioeconomic level of the region (choose just one option). Coefficient : 1 for TV	
☐ The site is in an area with higher income, education level and employment level than the regional average	
☐ The site is in an area with similar income, education level and employment level than the regional average	
■ The site is in an area with lower income, education level and employment level than the regional average	3.0
☐ The site is in an area under socio-economic decline	
Touristic value (add all TV) :	

5. PROTECTION AND SUSCEPTIBILITY OF DEGRADATION	
Is the site already included in a prior inventory? Yes ■ No ☐	
If yes, reference and date : Ferrara and Marques (2004), Cumbe (2007), Araújo and Nhamutole (2017)	
Legal instruments for protection : Yes ☐ No ■	

If yes, reference and date :			
URL address :			
Is there physical protection ? : Yes ☐ No ☐			
Soil property :	Public (%)	Private (%)	
Current use of the site : **The Locals use the surrounding area (Zambezi river) to extract water for their needs.In addition, fishing is also an activity to have in account.**			
Fragility F (choose just one option)			**Points**
☐ Highly resistant lithologies (quartzites or similar), with little fracturing and no weathering			
☐ Resistant or very resistant lithologies but with strong fracturing and / or weathering			2.0
☐ Soft but consolidated lithologies, with little fracturing and / or weathering			
☐ Unconsolidated or consolidated lithologies, but soft and highly fractured and / or weathered			
Natural threats T_N (choose just one option)			
☐ Site not significantly affected by natural processes (geological or biological)			
☐ Site affected by slightly active natural processes (geological or biological)			
☐ Site affected by moderately active natural processes (geological or biological)			3.0
☐ Site affected by intensively active natural processes (geological or biological)			
Natural vulnerability ($Vu_N = F \times T_N \times 30/9$) :			
Intrinsic vulnerability: Yes ☐ No ☐ Partially ☐			
Interest for mineral or water extraction (choose just one option). Coefficient : 2			
☐ Geosite without interest for mineral or water extraction			
☐ Geosite with intermediate interest for mineral or water extraction, but with alternative extraction areas			
☐ Geosite with intermediate interest for mineral or water extraction, and without alternative extraction areas			3.0
☐ Geosite with great interest for mineral or water extraction			
Possibility of looting (choose just one option). Coefficient : 2			
☐ There is no paleontological or mineralogical deposit, or it is difficult for looting			
☐ Paleontological or mineralogical site of low value and easy looting			
☐ Paleontological or mineralogical site of great value, with many specimens and easy looting			3.0
☐ Paleontological or mineralogical site of great value, with few specimens and easy looting			
Proximity to infrastructures or urban areas (choose just one option). Coefficient : 2			
☐ Geosite without threats			1.0
☐ Geosite located less than 100 m from a main road, less than 1 km from an industrial activity, or within 2 km of urban areas			
☐ Geosite nearby an industrial or urban area, or located less than 25 m from a main road			
☐ Geosite in an industrial or urban area, or located by a main road			
Accessibility (choose just one option). Coefficient : 2			
☐ The site does not meet, by itself, any of the following criteria (such as, for example, paved road without the possibility of parking, footpath, off-road track, boat, etc.):			
☐ Direct access to the site by unpaved road accessible by cars			2.0
☐ Direct access by asphalt road with possibility of parking for cars			
☐ Direct access by asphalt road with possibility of parking for buses			

Population density (choose just one option). Coefficient : 1	
☐ Less than 100,000 inhabitants in 50 km radius	1.0
☐ Between 100,001 and 200,000 inhabitants in 50 km radius	
☐ Between 200,001 and 1.000,000 inhabitants in 50 km radius	
☐ More than 1.000,000 inhabitants in 50 km radius	
Proximity to recreational areas (choose just one option). Coefficient : 1	
☐ Geosite located more than 5 km from a recreational area (camping, beach, etc.)	1.0
☐ Geosite located between 2 and than 5 km from a recreational area	
☐ Geosite located between 500 m and 2 km from a recreational area	
☐ Geosite located less than 500 m from a recreational area	
Vulnerability due to anthropic threats (add all Vu_A) :	

Dimension factor D_F (choose just one option)	
☐ Metric-size elements (vulnerable to a simple visit) (value : 1)	
☐ Decametric-size elements (not vulnerable to visits but sensitive to more aggressive human activities) (value : 1)	
☐ Hectometric-size elements (may be subject to some degradation by human activity) (value : 0.5)	
☒ Kilometric-size elements (not easily vulnerable by human activity) (value : 0.1)	4.0
Susceptibility to degradation ($S_D = V_{UN} \times D_F$) :	
S_D > 10: High susceptibility to degradation; 5 ≤ S_D ≤ 10 : intermediate ; 0 ≤ S_D < 5 : low	
Risk of degradation ($R_D = V \times S_D$) :	
R_{DA}>200 : high ; 50≤R_{DA}<200 : intermediate ; R_{DA}< 50 : low	

6. SUPPLEMENTARY DATA FOR GEOSITE MANAGEMENT			
Difficulty of the visit :	☒ Easy	☐ Intermediate	☐ Difficult
Is there a hazard threat for visitors? Yes ☒ No ☐			
If yes, explain : **The Cadzewe is integrated within the protected natural park (Magoé National park). The animals living in the park are the main treats for the potential visitors, however, visitation to the the park is made possible with the collaboration of local park security. Further, other dangerous animals such as crocodiles, hippopotamus are the main treats along the zambezi river located closer to the forest.**			
☐ Viewpoint, lookout	☐ Interpretive pannels, tables, etc.	☐ Itineraries	
Is there access for disabled persons : Yes ☐ No ☒ Comment :			
Distance to a paved road (in km) : 8km to the paved road Chitima-Magoé			
Duration of a normal visit (in min) :			
Date this form was first filled in : 25.07.2020	Date of the last update :		
Person filling in the form : Nelson Nhamutole	Person(s) updating the form :Nelson Nhamutole		

APPENDIX B

Carangache Fossil Forest

GENERAL INFORMATION			
1. IDENTIFICATION			
Identification number or code : 7PG			
Name of the site : **Carangache**			
Physical description : See the Physical decription of the Carangache Fossil Forest in the section 4.3.3			
Confidentiality :	☒ Public	☐ Confidential	
Source of collections :	☐ Yes	☐ No	
If yes, **location of collections :**			
2. LOCATION			
X : **S 15° 53' 02.6"**	Y : **032° 46' 28.2" E**	UTM Zone : **36S**	Type of coordinates : **geographic**
Altitude Max.	Min.	**Area** (estimate):	
Related 1:50.000 maps:			
Place locally known as : **Carangache**			
Province, municipality or county : **Tete, Cahora Bassa**			
Department or state :			
Region :**Centre of Mozambique**			
Description of the itinerary to access the site : **The Carangache fossil forest is located 17Km from the Chitima village.**			

Is permission required for visit ? (need for prior authorization) :	☐ Yes	☑ No

3. GEOLOGICAL CONTEXT		
Geological domain : **Sedimentar domain**		
Description of geological processes and elements : (Include supplementary information in the Annex)		
Age of the processes : Late Permian	Lower age limit	Upper age limit
Age of the elements :	Lower age limit	Upper age limit

4. INTEREST				
Main type of geological interest (choose just ONE option)				
☐ Stratigraphical	☐ Sedimentological	☐ Geomorphological	☑ Paleontological	
☐ Tectonic	☐ Petrological-geochemical		☐ Metallogenetic	
☐ Mineralogical	☐ Hydrogeological	☐ History of geology	☐ Pedology, edaphology	
Justification :				
Secondary type(s) of geological interest (choose one or more options)				
☐ Stratigraphical	☐ Sedimentological	☐ Geomorphological	☐ Paleontological	
☐ Tectonic	☐ Petrological-geochemical		☐ Metallogenetic	
☑ Mineralogical	☐ Hydrogeological	☐ History of geology	☐ Pedology, edaphology	
Justification :				
NON-geological interest of the site (choose one or more options)				
☐ Mining-industrial	☐ Use of thermal-mineral water	☑ Biological (flora, fauna)	☑ Landscape	
☐ Architectural	☐ Archeological	☐ Ethnological (traditions)	☐ Historical and cultural	
Justification of the non-geological interest :				

Representativity (choose just one option). Coefficient : 2 for SV and 0.5 for EV	**Points**
☐ Somewhat useful as a model to represent, even if partially, a geological phenomenon	
☐ Useful as a model to partially represent a geological phenomenon	
☐ Useful as a model to fully represent a geological phenomenon	
☑ The best example, within the geological area under consideration, to fully represent a geological phenomenon	4.0
Type locality (choose just one option). Coefficient : 1 for SV and 0.5 for EV	
☐ The site does not comply by itself with any of the following criteria	
☑ Regional reference locality	2.0
☐ Reference locality (for stratigraphy, paleontology, petrology, mineralogy, geomorphology, etc.) used at international scale, or type locality of local fossils or biozones with a long history of scientific use	
☐ Stratotype accepted by the IUGS or mineral type locality of the IMA	
Level of scientific knowledge (choose just one option). Coefficient : 2 for SV	
☐ There are no scientific publications or theses on the site	
☑ There are scientific publications or theses on the site	2.0
☐ Studied by several scientific teams, with theses and scientific publications in national journals	
☐ Studied by several scientific teams, with theses and scientific publications in international journals	
State of conservation (choose just one option). Coefficient : 1 for SV and 1 for EV	
☐ Unfavourable bad: the site has major degradations or is virtually destroyed	
☐ Unfavourable inadequate: with degradations that prevent the appreciation of certain characteristics of interest	
☑ Favourable with modifications: there are certain degradations which do not affect decissively the value of the site	3.0
☐ Favourable: the site is well preserved, almost intact	
Observation conditions (choose just one option). Coefficient : 1 for SV, 1 for EV and 0.5 for TV	
☐ With elements that strongly hide the features of interest	
☐ With elements that obscure the site and prevent the appreciation of certain features of interest	
☐ With elements that do not prevent to observe the site in its integrity, although it is done with difficulty	
☑ Perfectly observable in its entirety and with ease	4.0
Rareness (choose just one option). Coefficient : 2 for SV and 1 for EV	

■ There are several similar sites in the area	1.0
□ The site is one of the few examples known at the regional level	
□ The site is the only known example at the regional level	
□ The site is the only known example at the national or international level	
Geodiversity (choose just one option). Coefficient : 1 for SV and 1 for EV	
□ The site only has one main type of interest	
□ The site presents another type of interest, in addition to the main one, but it is not remarkable	
■ Two types of interest, in addition to the main one, or only one additional type, but remarkable	3.0
□ Three or more types of interest, in addition to the main one, or just two, but the two outstanding	
Scientific value (add all SV) :	
> 20 : very high value 10 ≤ V ≤ 20 : high value 4 ≤ V < 10 : intermediate value	
Educational potential (choose just one option). Coefficient : 2 for EV	
□ The site does not respond, by itself, to any of the following criteria	
□ Useful to illustrate the contents of university programs	
■ Useful to illustrate the contents of programs at any level of the educational system, or it is used in the educational activities of universities	3.0
□ The site is used routinely in educational activities at any level of the education system	
Logistic infrastructures (choose just one option). Coefficient : 1 for EV and 1 for TV	
□ The site does not meet, by itself, any of the following criteria:	
□ Accommodation and restaurant for groups up to 20 people within 25 km	
■ Accommodation and restaurant for groups up to 40 people within 25 km	3.0
□ Accommodation and restaurant for groups up to 40 people within 5 km	
Accessibility (choose just one option). Coefficient : 1 for EV and 1 for TV	
□ The site does not meet, by itself, any of the following criteria (such as, for example, paved road without the possibility of parking, footpath, off-road track, boat, etc.):	
■ Direct access by unpaved road accessible by cars	2.0
□ Direct access by asphalt road with possibility of parking for cars	
□ Direct access by asphalt road with possibility of parking for buses	
Dimensions of the site (choose just one option). Coefficient : 0.5 for EV and 0.5 for TV	
□ Metric-size elements (vulnerable to a simple visit)	
■ Decametric-size elements (not vulnerable to visits, but sensitive to more aggressive human activities)	2.0
□ Hectometric-size elements (may be subject to some degradation by human activity)	
□ Kilometric-size elements (not easily vulnerable by human activity)	
Beauty or spectacularity (choose just one option). Coefficient : 0.5 for EV and 2.5 TV	
□ The site does not meet, by itself, any of the following criteria:	
□ (1) Large amplitude relief, or 2) large courses or bodies of water (or ice), or 3) remarkable chromatic variety. Also, attractive fossils and/or minerals.	
■ Coincidence of two of the three preceding characteristics. Also, attractive fossils and/or minerals.	3.0
□ Coincidence of the three preceding characteristics.	
Educational value (add all EV) :	
Possibilities for outreach (choose just one option). Coefficient : 2 for TV	
□ The site does not meet, by itself, any of the following criteria:	
□ The site is clearly understandable by people with a certain cultural level	
■ The site is clearly illustrative of the importance or usefulness of geology for people with any cultural level	3.0
□ The site is frequently used for outreach activities	
Supplementary touristic attractions (choose just one option). Coefficient : 0.5 for TV	
□ The site does not meet, by itself, any of the following criteria:	
■ 1) Possibility of outdoor activities, or 2) The site is less than 5 km from a recreational area, or 3) The site is within 5 km of another cultural or natural feature	2.0
□ Meets two of the previous criteria	
□ Meets three of the previous criteria	

Non-fragility (resistance) of the site (choose just one option). Coefficient : 1 for TV	**Points**

☐ Site with unconsolidated or consolidated lithologies, but soft and highly fractured and / or weathered	
☐ Site with soft but consolidated lithologies, with little fracturing and / or weathering	
☐ Site with resistant or very resistant lithologies, but with strong fracturing and / or weathering	3.0
☐ Site with highly resistant lithologies (quartzites or similar), with little fracturing and no weathering	
Socioeconomic level of the region (choose just one option). Coefficient : 1 for TV	
☐ The site is in an area with higher income, education level and employment level than the regional average	
☐ The site is in an area with similar income, education level and employment level than the regional average	
☐ The site is in an area with lower income, education level and employment level than the regional average	3.0
☐ The site is in an area under socio-economic decline	
Touristic value (add all TV) :	

5. PROTECTION AND SUSCEPTIBILITY OF DEGRADATION			
Is the site already included in a prior inventory? Yes ☐ No ☐			
If yes, reference and date : Ferrara and Marques (2004), Cumbe (2007), Araújo and Nhamutole (2017)			
Legal instruments for protection : Yes ☐ No ☐			
If yes, reference and date :			
URL address :			
Is there physical protection ? : Yes ☐ No ☐			
Soil property :	Public (%)	Private (%)	
Current use of the site : **The Locals use the surrounding area (Zambezi river) to extract water for their needs.In addition, fishing is also an activity to have in account.**			
Fragility F (choose just one option)			**Points**
☐ Highly resistant lithologies (quartzites or similar), with little fracturing and no weathering			
☐ Resistant or very resistant lithologies but with strong fracturing and / or weathering			2.0
☐ Soft but consolidated lithologies, with little fracturing and / or weathering			
☐ Unconsolidated or consolidated lithologies, but soft and highly fractured and / or weathered			
Natural threats T_N (choose just one option)			
☐ Site not significantly affected by natural processes (geological or biological)			
☐ Site affected by slightly active natural processes (geological or biological)			
☐ Site affected by moderately active natural processes (geological or biological)			3.0
☐ Site affected by intensively active natural processes (geological or biological)			
Natural vulnerability ($Vu_N = F \times T_N \times 30/9$) :			
Intrinsic vulnerability: Yes ☐ No ☐ Partially ☐			
Interest for mineral or water extraction (choose just one option). Coefficient : 2			
☐ Geosite without interest for mineral or water extraction			
☐ Geosite with intermediate interest for mineral or water extraction, but with alternative extraction areas			
☐ Geosite with intermediate interest for mineral or water extraction, and without alternative extraction areas			3.0
☐ Geosite with great interest for mineral or water extraction			
Possibility of looting (choose just one option). Coefficient : 2			
☐ There is no paleontological or mineralogical deposit, or it is difficult for looting			
☐ Paleontological or mineralogical site of low value and easy looting			
☐ Paleontological or mineralogical site of great value, with many specimens and easy looting			3.0
☐ Paleontological or mineralogical site of great value, with few specimens and easy looting			
Proximity to infrastructures or urban areas (choose just one option). Coefficient : 2			
☐ Geosite without threats			1.0
☐ Geosite located less than 100 m from a main road, less than 1 km from an industrial activity, or within 2 km of urban areas			
☐ Geosite nearby an industrial or urban area, or located less than 25 m from a main road			
☐ Geosite in an industrial or urban area, or located by a main road			
Accessibility (choose just one option). Coefficient : 2			
☐ The site does not meet, by itself, any of the following criteria (such as, for example, paved road without the possibility of parking, footpath, off-road track, boat, etc.):			

☒ Direct access to the site by unpaved road accessible by cars	2.0
☐ Direct access by asphalt road with possibility of parking for cars	
☐ Direct access by asphalt road with possibility of parking for buses	

Population density (choose just one option). Coefficient : 1	
☒ Less than 100,000 inhabitants in 50 km radius	1.0
☐ Between 100,001 and 200,000 inhabitants in 50 km radius	
☐ Between 200,001 and 1.000,000 inhabitants in 50 km radius	
☐ More than 1.000,000 inhabitants in 50 km radius	
Proximity to recreational areas (choose just one option). Coefficient : 1	
☒ Geosite located more than 5 km from a recreational area (camping, beach, etc.)	1.0
☐ Geosite located between 2 and than 5 km from a recreational area	
☐ Geosite located between 500 m and 2 km from a recreational area	
☐ Geosite located less than 500 m from a recreational area	
Vulnerability due to anthropic threats (add all Vu_A) :	
Dimension factor D_F (choose just one option)	
☐ Metric-size elements (vulnerable to a simple visit) (value : 1)	
☐ Decametric-size elements (not vulnerable to visits but sensitive to more aggressive human activities) (value : 1)	
☐ Hectometric-size elements (may be subject to some degradation by human activity) (value : 0.5)	
☒ Kilometric-size elements (not easily vulnerable by human activity) (value : 0.1)	4.0
Susceptibility to degradation ($S_D = Vu_N \times D_F$) :	
$S_D > 10$: High susceptibility to degradation; $5 \leq S_D \leq 10$: intermediate ; $0 \leq S_D < 5$: low	
Risk of degradation ($R_D = V \times S_D$) :	
$R_{DA}>200$: high ; $50 \leq R_{DA} < 200$: intermediate ; $R_{DA} < 50$: low	

6. SUPPLEMENTARY DATA FOR GEOSITE MANAGEMENT			
Difficulty of the visit :	☒ Easy	☐ Intermediate	☐ Difficult
Is there a hazard threat for visitors? Yes ☐ No ☒			
If yes, explain :			
☐ Viewpoint, lookout	☐ Interpretive pannels, tables, etc.	☐ Itineraries	
Is there access for disabled persons : Yes ☐ No ☒ Comment :			
Distance to a paved road (in km) : 8km to the paved road Chitima-Magoé			
Duration of a normal visit (in min) :			
Date this form was first filled in : 25.07.2020	Date of the last update :		
Person filling in the form : Nelson Nhamutole	Person(s) updating the form :Nelson Nhamutole		

APPENDIX C

Mapembera Fossil Forest

GENERAL INFORMATION		
1. IDENTIFICATION		
Identification number or code : 1PG		
Name of the site : **Mapembera**		
Physical description : The physical description is approached in the geoheritage section 4.3.4		
Confidentiality :	☒ Public	☐ Confidential

Source of collections :	☐ Yes		☐ No
If yes, **location of collections :**			
2. LOCATION			
X : **S 15° 44' 40.9"**	Y : **031° 41' 14.9" E**	UTM Zone : **36S**	Type of coordinates : **geográficas**
Altitude Max.	Min.	**Area** (estimate):	
Related 1:50.000 maps:			
Place locally known as : **Mapembera,**			
Province, municipality or county : **Tete, Magoé**			
Department or state :			
Region : **Centre of Mozambique**			
Description of the itinerary to access the site : **The Mapembera fossil forest is situated 16Km from the Magoé district**			
Is permission required for visit ? (need for prior authorization) :	☐ Yes		☐ No
3. GEOLOGICAL CONTEXT			
Geological domain : **Sedimentar domain**			
Description of geological processes and elements : (Include supplementary information in the Annex)			
Age of the processes : Late Permian	Lower age limit		Upper age limit
Age of the elements :	Lower age limit		Upper age limit

4. INTEREST				
Main type of geological interest (choose just ONE option)				
☐ Stratigraphical	☐ Sedimentological	☐ Geomorphological	☐ Paleontological	
☐ Tectonic	☐ Petrological-geochemical		☐ Metallogenetic	
☐ Mineralogical	☐ Hydrogeological	☐ History of geology	☐ Pedology, edaphology	
Justification :				
Secondary type(s) of geological interest (choose one or more options)				
☐ Stratigraphical	☐ Sedimentological	☐ Geomorphological	☐ Paleontological	
☐ Tectonic	☐ Petrological-geochemical		☐ Metallogenetic	
☐ Mineralogical	☐ Hydrogeological	☐ History of geology	☐ Pedology, edaphology	
Justification :				
NON-geological interest of the site (choose one or more options)				
☐ Mining-industrial	☐ Use of thermal-mineral water	☐ Biological (flora, fauna)	☐ Landscape	
☐ Architectural	☐ Archeological	☐ Ethnological (traditions)	☐ Historical and cultural	
Justification of the non-geological interest :				
Representativity (choose just one option). Coefficient : 2 for SV and 0.5 for EV				**Points**
☐ Somewhat useful as a model to represent, even if partially, a geological phenomenon				
☐ Useful as a model to partially represent a geological phenomenon				
☐ Useful as a model to fully represent a geological phenomenon				
☐ The best example, within the geological area under consideration, to fully represent a geological phenomenon				4.0
Type locality (choose just one option). Coefficient : 1 for SV and 0.5 for EV				
☐ The site does not comply by itself with any of the following criteria				
☐ Regional reference locality				2.0
☐ Reference locality (for stratigraphy, paleontology, petrology, mineralogy, geomorphology, etc.) used at international scale, or type locality of local fossils or biozones with a long history of scientific use				
☐ Stratotype accepted by the IUGS or mineral type locality of the IMA				
Level of scientific knowledge (choose just one option). Coefficient : 2 for SV				

□ There are no scientific publications or theses on the site	
■ There are scientific publications or theses on the site	2.0
□ Studied by several scientific teams, with theses and scientific publications in national journals	
□ Studied by several scientific teams, with theses and scientific publications in international journals	
State of conservation (choose just one option). Coefficient : 1 for SV and 1 for EV	
□ Unfavourable bad: the site has major degradations or is virtually destroyed	
□ Unfavourable inadequate: with degradations that prevent the appreciation of certain characteristics of interest	
■ Favourable with modifications: there are certain degradations which do not affect decissively the value of the site	3.0
□ Favourable: the site is well preserved, almost intact	
Observation conditions (choose just one option). Coefficient : 1 for SV, 1 for EV and 0.5 for TV	
□ With elements that strongly hide the features of interest	
□ With elements that obscure the site and prevent the appreciation of certain features of interest	
□ With elements that do not prevent to observe the site in its integrity, although it is done with difficulty	
■ Perfectly observable in its entirety and with ease	4.0
Rareness (choose just one option). Coefficient : 2 for SV and 1 for EV	
■ There are several similar sites in the area	1.0
□ The site is one of the few examples known at the regional level	
□ The site is the only known example at the regional level	
□ The site is the only known example at the national or international level	
Geodiversity (choose just one option). Coefficient : 1 for SV and 1 for EV	
□ The site only has one main type of interest	
□ The site presents another type of interest, in addition to the main one, but it is not remarkable	
■ Two types of interest, in addition to the main one, or only one additional type, but remarkable	3.0
□ Three or more types of interest, in addition to the main one, or just two, but the two outstanding	
Scientific value (add all SV) :	
> 20 : very high value **10 ≤ V ≤ 20 : high value** **4 ≤ V < 10 : intermediate value**	
Educational potential (choose just one option). Coefficient : 2 for EV	
□ The site does not respond, by itself, to any of the following criteria	
□ Useful to illustrate the contents of university programs	
■ Useful to illustrate the contents of programs at any level of the educational system, or it is used in the educational activities of universities	3.0
□ The site is used routinely in educational activities at any level of the education system	
Logistic infrastructures (choose just one option). Coefficient : 1 for EV and 1 for TV	
■ The site does not meet, by itself, any of the following criteria:	1.0
□ Accommodation and restaurant for groups up to 20 people within 25 km	
□ Accommodation and restaurant for groups up to 40 people within 25 km	
□ Accommodation and restaurant for groups up to 40 people within 5 km	
Accessibility (choose just one option). Coefficient : 1 for EV and 1 for TV	
□ The site does not meet, by itself, any of the following criteria (such as, for example, paved road without the possibility of parking, footpath, off-road track, boat, etc.):	
■ Direct access by unpaved road accessible by cars	2.0
□ Direct access by asphalt road with possibility of parking for cars	
□ Direct access by asphalt road with possibility of parking for buses	
Dimensions of the site (choose just one option). Coefficient : 0.5 for EV and 0.5 for TV	
□ Metric-size elements (vulnerable to a simple visit)	
■ Decametric-size elements (not vulnerable to visits, but sensitive to more aggressive human activities)	2.0
□ Hectometric-size elements (may be subject to some degradation by human activity)	
□ Kilometric-size elements (not easily vulnerable by human activity)	
Beauty or spectacularity (choose just one option). Coefficient : 0.5 for EV and 2.5 TV	
□ The site does not meet, by itself, any of the following criteria:	
□ (1) Large amplitude relief, or 2) large courses or bodies of water (or ice), or 3) remarkable chromatic variety. Also, attractive fossils and/or minerals.	
■ Coincidence of two of the three preceding characteristics. Also, attractive fossils and/or minerals.	3.0

☐ Coincidence of the three preceding characteristics.	
Educational value (add all EV) :	
Possibilities for outreach (choose just one option). Coefficient : 2 for TV	
☐ The site does not meet, by itself, any of the following criteria:	
☐ The site is clearly understandable by people with a certain cultural level	
☒ The site is clearly illustrative of the importance or usefulness of geology for people with any cultural level	3.0
☐ The site is frequently used for outreach activities	
Supplementary touristic attractions (choose just one option). Coefficient : 0.5 for TV	
☐ The site does not meet, by itself, any of the following criteria:	
☒ 1) Possibility of outdoor activities, or 2) The site is less than 5 km from a recreational area, or 3) The site is within 5 km of another cultural or natural feature	2.0
☐ Meets two of the previous criteria	
☐ Meets three of the previous criteria	

Non-fragility (resistance) of the site (choose just one option). Coefficient : 1 for TV	**Points**
☐ Site with unconsolidated or consolidated lithologies, but soft and highly fractured and / or weathered	
☐ Site with soft but consolidated lithologies, with little fracturing and / or weathering	
☒ Site with resistant or very resistant lithologies, but with strong fracturing and / or weathering	3.0
☐ Site with highly resistant lithologies (quartzites or similar), with little fracturing and no weathering	
Socioeconomic level of the region (choose just one option). Coefficient : 1 for TV	
☐ The site is in an area with higher income, education level and employment level than the regional average	
☐ The site is in an area with similar income, education level and employment level than the regional average	
☒ The site is in an area with lower income, education level and employment level than the regional average	3.0
☐ The site is in an area under socio-economic decline	
Touristic value (add all TV) :	

5. PROTECTION AND SUSCEPTIBILITY OF DEGRADATION			
Is the site already included in a prior inventory? Yes ☒ No ☐			
If yes, reference and date : Ferrara and Marques (2004), Cumbe (2007), Araújo and Nhamutole (2017)			
Legal instruments for protection : Yes ☐ No ☒			
If yes, reference and date :			
URL address :			
Is there physical protection ? : Yes ☐ No ☒			
Soil property :	Public (%)	Private (%)	
Current use of the site : **The Locals use the surrounding area (Zambezi river) to extract water for their needs.In addition, fishing is also an activity to have in account.**			
Fragility F (choose just one option)			**Points**
☐ Highly resistant lithologies (quartzites or similar), with little fracturing and no weathering			
☒ Resistant or very resistant lithologies but with strong fracturing and / or weathering			2.0
☐ Soft but consolidated lithologies, with little fracturing and / or weathering			
☐ Unconsolidated or consolidated lithologies, but soft and highly fractured and / or weathered			
Natural threats T_N (choose just one option)			
☐ Site not significantly affected by natural processes (geological or biological)			
☐ Site affected by slightly active natural processes (geological or biological)			
☒ Site affected by moderately active natural processes (geological or biological)			3.0
☐ Site affected by intensively active natural processes (geological or biological)			
Natural vulnerability ($Vu_N = F \times T_N \times 30/9$) :			
Intrinsic vulnerability: Yes ☐ No ☐ Partially ☐			
Interest for mineral or water extraction (choose just one option). Coefficient : 2			
☐ Geosite without interest for mineral or water extraction			
☐ Geosite with intermediate interest for mineral or water extraction, but with alternative extraction areas			
☒ Geosite with intermediate interest for mineral or water extraction, and without alternative extraction areas			3.0

☐ Geosite with great interest for mineral or water extraction	
Possibility of looting (choose just one option). Coefficient : 2	
☐ There is no paleontological or mineralogical deposit, or it is difficult for looting	
☐ Paleontological or mineralogical site of low value and easy looting	
☒ Paleontological or mineralogical site of great value, with many specimens and easy looting	3.0
☐ Paleontological or mineralogical site of great value, with few specimens and easy looting	
Proximity to infrastructures or urban areas (choose just one option). Coefficient : 2	
☒ Geosite without threats	1.0
☐ Geosite located less than 100 m from a main road, less than 1 km from an industrial activity, or within 2 km of urban areas	
☐ Geosite nearby an industrial or urban area, or located less than 25 m from a main road	
☐ Geosite in an industrial or urban area, or located by a main road	
Accessibility (choose just one option). Coefficient : 2	
☐ The site does not meet, by itself, any of the following criteria (such as, for example, paved road without the possibility of parking, footpath, off-road track, boat, etc.):	
☒ Direct access to the site by unpaved road accessible by cars	2.0
☐ Direct access by asphalt road with possibility of parking for cars	
☐ Direct access by asphalt road with possibility of parking for buses	

Population density (choose just one option). Coefficient : 1	
☒ Less than 100,000 inhabitants in 50 km radius	1.0
☐ Between 100,001 and 200,000 inhabitants in 50 km radius	
☐ Between 200,001 and 1.000,000 inhabitants in 50 km radius	
☐ More than 1.000,000 inhabitants in 50 km radius	
Proximity to recreational areas (choose just one option). Coefficient : 1	
☒ Geosite located more than 5 km from a recreational area (camping, beach, etc.)	1.0
☐ Geosite located between 2 and than 5 km from a recreational area	
☐ Geosite located between 500 m and 2 km from a recreational area	
☐ Geosite located less than 500 m from a recreational area	
Vulnerability due to anthropic threats (add all Vu_A) :	
Dimension factor D_F (choose just one option)	
☐ Metric-size elements (vulnerable to a simple visit) (value : 1)	
☐ Decametric-size elements (not vulnerable to visits but sensitive to more aggressive human activities) (value : 1)	
☐ Hectometric-size elements (may be subject to some degradation by human activity) (value : 0.5)	
☒ Kilometric-size elements (not easily vulnerable by human activity) (value : 0.1)	4.0
Susceptibility to degradation ($S_D = Vu_N \times D_F$) :	
$S_D > 10$: High susceptibility to degradation; $5 \leq S_D \leq 10$: intermediate ; $0 \leq S_D < 5$: low	
Risk of degradation ($R_D = V \times S_D$) :	
$R_{DA}>200$: high ; $50 \leq R_{DA} < 200$: intermediate ; $R_{DA} < 50$: low	

6. SUPPLEMENTARY DATA FOR GEOSITE MANAGEMENT			
Difficulty of the visit :	☒ Easy	☐ Intermediate	☐ Difficult
Is there a hazard threat for visitors? Yes ☐ No ☒			
If yes, explain :			
☐ Viewpoint, lookout	☐ Interpretive pannels, tables, etc.	☐ Itineraries	
Is there access for disabled persons : Yes ☐ No ☒ Comment :			
Distance to a paved road (in km) : 8km to the paved road Chitima-Magoé			
Duration of a normal visit (in min) :			
Date this form was first filled in : 25.07.2020		Date of the last update :	
Person filling in the form : Nelson Nhamutole		Person(s) updating the form :Nelson Nhamutole	

APPENDIX D

Nhambando Fossil Forest

GENERAL INFORMATION			
1. IDENTIFICATION			
Identification number or code : 6PG			
Name of the site : **Carangache**			
Physical description : See the description in the Geoheritage section 4.3.5			
Confidentiality :	☒ Public	☐ Confidential	
Source of collections :	☐ Yes	☐ No	
If yes, **location of collections :**			
2. LOCATION			
X : **S 15° 43' 32.5"**	Y : **032° 18' 14.9" E**	UTM Zone : **36S**	Type of coordinates : **geográficas**
Altitude Max.	Min.	**Area** (estimate):	
Related 1:50.000 maps:			
Place locally known as : **Carangache**			
Province, municipality or county : **Tete, Cahora Bassa**			
Department or state :			
Region :**Centre of Mozambique**			
Description of the itinerary to access the site : **This locality is situated 51Km to Chitima and 3Km along the road Chitima-Magoe. The 51km are made by paved road and the rest 3km by unpaved road**.			
Is permission required for visit ? (need for prior authorization) :	☒ Yes	☐ No	
3. GEOLOGICAL CONTEXT			
Geological domain : **Sedimentar domain**			
Description of geological processes and elements : (Include supplementary information in the Annex)			
Age of the processes : Late Permian	Lower age limit	Upper age limit	
Age of the elements :	Lower age limit	Upper age limit	

4. INTEREST			
Main type of geological interest (choose just ONE option)			
☐ Stratigraphical	☐ Sedimentological	☐ Geomorphological	☒ Paleontological
☐ Tectonic	☐ Petrological-geochemical		☐ Metallogenetic
☐ Mineralogical	☐ Hydrogeological	☐ History of geology	☐ Pedology, edaphology
Justification :			
Secondary type(s) of geological interest (choose one or more options)			
☐ Stratigraphical	☐ Sedimentological	☐ Geomorphological	☐ Paleontological
☐ Tectonic	☐ Petrological-geochemical		☐ Metallogenetic
☒ Mineralogical	☐ Hydrogeological	☐ History of geology	☐ Pedology, edaphology
Justification :			
NON-geological interest of the site (choose one or more options)			
☐ Mining-industrial	☐ Use of thermal-mineral water	☒ Biological (flora, fauna)	☒ Landscape
☐ Architectural	☐ Archeological	☐ Ethnological (traditions)	☐ Historical and cultural
Justification of the non-geological interest :			

Representativity (choose just one option). Coefficient : 2 for SV and 0.5 for EV	**Points**
□ Somewhat useful as a model to represent, even if partially, a geological phenomenon	
□ Useful as a model to partially represent a geological phenomenon	
□ Useful as a model to fully represent a geological phenomenon	
■ The best example, within the geological area under consideration, to fully represent a geological phenomenon	4.0
Type locality (choose just one option). Coefficient : 1 for SV and 0.5 for EV	
□ The site does not comply by itself with any of the following criteria	
■ Regional reference locality	2.0
□ Reference locality (for stratigraphy, paleontology, petrology, mineralogy, geomorphology, etc.) used at international scale, or type locality of local fossils or biozones with a long history of scientific use	
□ Stratotype accepted by the IUGS or mineral type locality of the IMA	
Level of scientific knowledge (choose just one option). Coefficient : 2 for SV	
□ There are no scientific publications or theses on the site	
■ There are scientific publications or theses on the site	2.0
□ Studied by several scientific teams, with theses and scientific publications in national journals	
□ Studied by several scientific teams, with theses and scientific publications in international journals	
State of conservation (choose just one option). Coefficient : 1 for SV and 1 for EV	
□ Unfavourable bad: the site has major degradations or is virtually destroyed	
□ Unfavourable inadequate: with degradations that prevent the appreciation of certain characteristics of interest	
■ Favourable with modifications: there are certain degradations which do not affect decissively the value of the site	3.0
□ Favourable: the site is well preserved, almost intact	
Observation conditions (choose just one option). Coefficient : 1 for SV, 1 for EV and 0.5 for TV	
□ With elements that strongly hide the features of interest	
□ With elements that obscure the site and prevent the appreciation of certain features of interest	
□ With elements that do not prevent to observe the site in its integrity, although it is done with difficulty	
■ Perfectly observable in its entirety and with ease	4.0
Rareness (choose just one option). Coefficient : 2 for SV and 1 for EV	
■ There are several similar sites in the area	1.0
□ The site is one of the few examples known at the regional level	
□ The site is the only known example at the regional level	
□ The site is the only known example at the national or international level	
Geodiversity (choose just one option). Coefficient : 1 for SV and 1 for EV	
□ The site only has one main type of interest	
□ The site presents another type of interest, in addition to the main one, but it is not remarkable	
■ Two types of interest, in addition to the main one, or only one additional type, but remarkable	3.0
□ Three or more types of interest, in addition to the main one, or just two, but the two outstanding	
Scientific value (add all SV) :	
> 20 : very high value 10 ≤ V ≤ 20 : high value 4 ≤ V < 10 : intermediate value	
Educational potential (choose just one option). Coefficient : 2 for EV	
□ The site does not respond, by itself, to any of the following criteria	
□ Useful to illustrate the contents of university programs	
■ Useful to illustrate the contents of programs at any level of the educational system, or it is used in the educational activities of universities	3.0
□ The site is used routinely in educational activities at any level of the education system	
Logistic infrastructures (choose just one option). Coefficient : 1 for EV and 1 for TV	
□ The site does not meet, by itself, any of the following criteria:	
□ Accommodation and restaurant for groups up to 20 people within 25 km	
■ Accommodation and restaurant for groups up to 40 people within 25 km	3.0
□ Accommodation and restaurant for groups up to 40 people within 5 km	
Accessibility (choose just one option). Coefficient : 1 for EV and 1 for TV	

☐ The site does not meet, by itself, any of the following criteria (such as, for example, paved road without the possibility of parking, footpath, off-road track, boat, etc.):	
☒ Direct access by unpaved road accessible by cars	2.0
☐ Direct access by asphalt road with possibility of parking for cars	
☐ Direct access by asphalt road with possibility of parking for buses	
Dimensions of the site (choose just one option). Coefficient : 0.5 for EV and 0.5 for TV	
☐ Metric-size elements (vulnerable to a simple visit)	
☒ Decametric-size elements (not vulnerable to visits, but sensitive to more aggressive human activities)	2.0
☐ Hectometric-size elements (may be subject to some degradation by human activity)	
☐ Kilometric-size elements (not easily vulnerable by human activity)	
Beauty or spectacularity (choose just one option). Coefficient : 0.5 for EV and 2.5 TV	
☐ The site does not meet, by itself, any of the following criteria:	
☐ (1) Large amplitude relief, or 2) large courses or bodies of water (or ice), or 3) remarkable chromatic variety. Also, attractive fossils and/or minerals.	
☒ Coincidence of two of the three preceding characteristics. Also, attractive fossils and/or minerals.	3.0
☐ Coincidence of the three preceding characteristics.	
Educational value (add all EV) :	
Possibilities for outreach (choose just one option). Coefficient : 2 for TV	
☐ The site does not meet, by itself, any of the following criteria:	
☐ The site is clearly understandable by people with a certain cultural level	
☒ The site is clearly illustrative of the importance or usefulness of geology for people with any cultural level	3.0
☐ The site is frequently used for outreach activities	
Supplementary touristic attractions (choose just one option). Coefficient : 0.5 for TV	
☐ The site does not meet, by itself, any of the following criteria:	
☒ 1) Possibility of outdoor activities, or 2) The site is less than 5 km from a recreational area, or 3) The site is within 5 km of another cultural or natural feature	2.0
☐ Meets two of the previous criteria	
☐ Meets three of the previous criteria	

Non-fragility (resistance) of the site (choose just one option). Coefficient : 1 for TV	**Points**
☐ Site with unconsolidated or consolidated lithologies, but soft and highly fractured and / or weathered	
☐ Site with soft but consolidated lithologies, with little fracturing and / or weathering	
☒ Site with resistant or very resistant lithologies, but with strong fracturing and / or weathering	3.0
☐ Site with highly resistant lithologies (quartzites or similar), with little fracturing and no weathering	
Socioeconomic level of the region (choose just one option). Coefficient : 1 for TV	
☐ The site is in an area with higher income, education level and employment level than the regional average	
☐ The site is in an area with similar income, education level and employment level than the regional average	
☒ The site is in an area with lower income, education level and employment level than the regional average	3.0
☐ The site is in an area under socio-economic decline	
Touristic value (add all TV) :	

5. PROTECTION AND SUSCEPTIBILITY OF DEGRADATION			
Is the site already included in a prior inventory? Yes ☒ No ☐			
If yes, reference and date : Ferrara and Marques (2004), Cumbe (2007), Araújo and Nhamutole (2017)			
Legal instruments for protection : Yes ☐ No ☒			
If yes, reference and date :			
URL address :			
Is there physical protection ? : Yes ☐ No ☒			
Soil property :	Public (%)	Private (%)	
Current use of the site : **The Locals use the surrounding area (Zambezi river) to extract water for their needs.In addition, fishing is also an activity to have in account.**			
Fragility F (choose just one option)			**Points**
☐ Highly resistant lithologies (quartzites or similar), with little fracturing and no weathering			

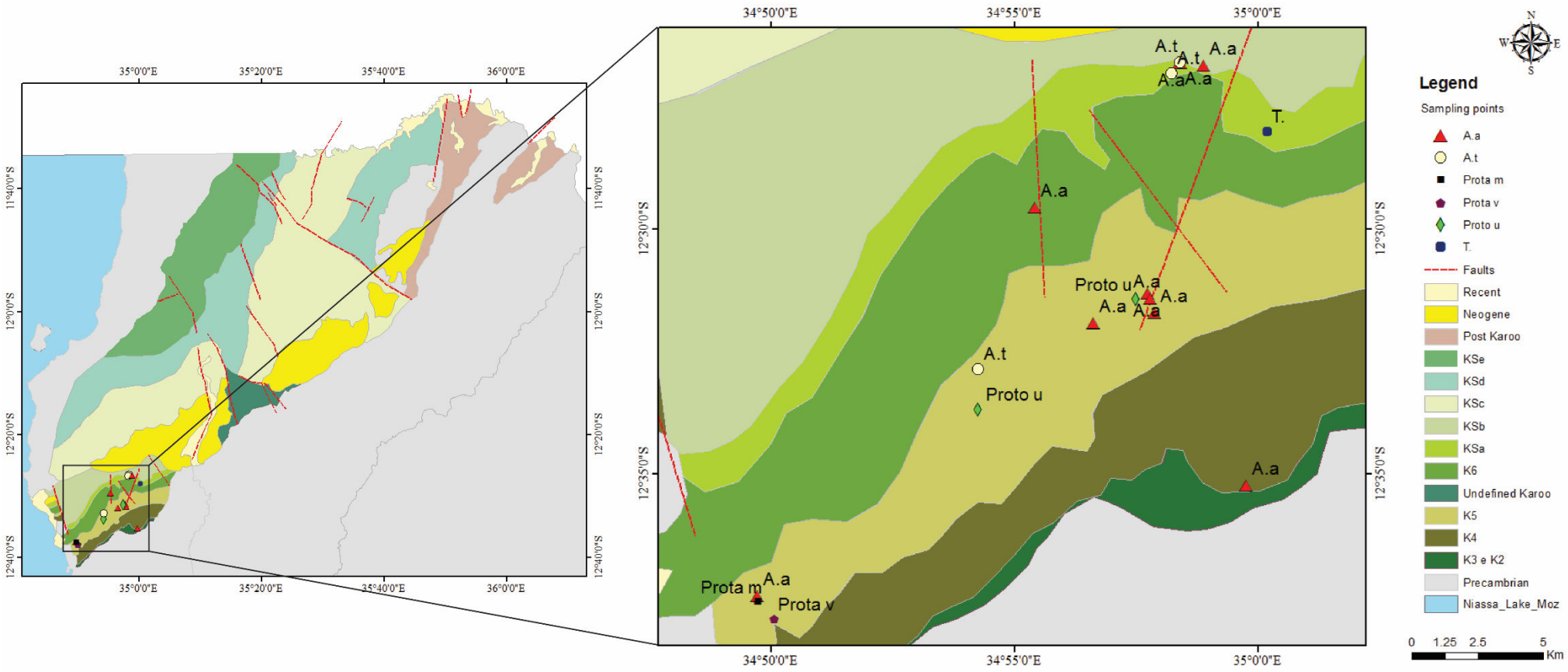
☒ Resistant or very resistant lithologies but with strong fracturing and / or weathering	2.0
☐ Soft but consolidated lithologies, with little fracturing and / or weathering	
☐ Unconsolidated or consolidated lithologies, but soft and highly fractured and / or weathered	
Natural threats T_N (choose just one option)	
☐ Site not significantly affected by natural processes (geological or biological)	
☐ Site affected by slightly active natural processes (geological or biological)	
☒ Site affected by moderately active natural processes (geological or biological)	3.0
☐ Site affected by intensively active natural processes (geological or biological)	
Natural vulnerability ($Vu_N = F \times T_N \times 30/9$) :	
Intrinsic vulnerability: Yes ☐ No ☐ Partially ☐	
Interest for mineral or water extraction (choose just one option). Coefficient : 2	
☐ Geosite without interest for mineral or water extraction	
☐ Geosite with intermediate interest for mineral or water extraction, but with alternative extraction areas	
☒ Geosite with intermediate interest for mineral or water extraction, and without alternative extraction areas	3.0
☐ Geosite with great interest for mineral or water extraction	
Possibility of looting (choose just one option). Coefficient : 2	
☐ There is no paleontological or mineralogical deposit, or it is difficult for looting	
☐ Paleontological or mineralogical site of low value and easy looting	
☒ Paleontological or mineralogical site of great value, with many specimens and easy looting	3.0
☐ Paleontological or mineralogical site of great value, with few specimens and easy looting	
Proximity to infrastructures or urban areas (choose just one option). Coefficient : 2	
☒ Geosite without threats	1.0
☐ Geosite located less than 100 m from a main road, less than 1 km from an industrial activity, or within 2 km of urban areas	
☐ Geosite nearby an industrial or urban area, or located less than 25 m from a main road	
☐ Geosite in an industrial or urban area, or located by a main road	
Accessibility (choose just one option). Coefficient : 2	
☐ The site does not meet, by itself, any of the following criteria (such as, for example, paved road without the possibility of parking, footpath, off-road track, boat, etc.):	
☒ Direct access to the site by unpaved road accessible by cars	2.0
☐ Direct access by asphalt road with possibility of parking for cars	
☐ Direct access by asphalt road with possibility of parking for buses	

Population density (choose just one option). Coefficient : 1	
■ Less than 100,000 inhabitants in 50 km radius	1.0
□ Between 100,001 and 200,000 inhabitants in 50 km radius	
□ Between 200,001 and 1.000,000 inhabitants in 50 km radius	
□ More than 1.000,000 inhabitants in 50 km radius	
Proximity to recreational areas (choose just one option). Coefficient : 1	
■ Geosite located more than 5 km from a recreational area (camping, beach, etc.)	1.0
□ Geosite located between 2 and than 5 km from a recreational area	
□ Geosite located between 500 m and 2 km from a recreational area	
□ Geosite located less than 500 m from a recreational area	
Vulnerability due to anthropic threats (add all Vu_A) :	
Dimension factor D_F (choose just one option)	
□ Metric-size elements (vulnerable to a simple visit) (value : 1)	
□ Decametric-size elements (not vulnerable to visits but sensitive to more aggressive human activities) (value : 1)	
□ Hectometric-size elements (may be subject to some degradation by human activity) (value : 0.5)	
■ Kilometric-size elements (not easily vulnerable by human activity) (value : 0.1)	4.0
Susceptibility to degradation ($S_D = Vu_N \times D_F$) :	
$S_D > 10$: High susceptibility to degradation; $5 \leq S_D \leq 10$: intermediate ; $0 \leq S_D < 5$: low	
Risk of degradation ($R_D = V \times S_D$) :	
$R_{DA}>200$: high ; $50 \leq R_{DA} < 200$: intermediate ; $R_{DA} < 50$: low	

6. SUPPLEMENTARY DATA FOR GEOSITE MANAGEMENT			
Difficulty of the visit :	■ Easy	□ Intermediate	□ Difficult
Is there a hazard threat for visitors? Yes ■ No □			
If yes, explain : **The Nhambando site is integrated within the protected area. The animals living in the park are the main treats for the potential visitors. Such animals consists on crocodiles, hippopotamus, snakes, etc.**			
□ Viewpoint, lookout	□ Interpretive pannels, tables, etc.	□ Itineraries	
Is there access for disabled persons : Yes □ No ■ Comment :			
Distance to a paved road (in km) : 8km to the paved road Chitima-Magoé			
Duration of a normal visit (in min) :			
Date this form was first filled in : 25.07.2020		Date of the last update :	
Person filling in the form : Nelson Nhamutole		Person(s) updating the form :Nelson Nhamutole	

APPENDIX E

Metangula Graben Map with the distribution of taxon across the formations



A.a= *A. africanum*, A.t=*A. teixeirae*, Prota v=*P.* sp. nov. 1, Prota m=*P.* sp. nov. 2, Proto u=*P. uniseriale*, T=*Taxodioxylon*

APPENDIX F

List of prepared samples divided into categories, well and badly preserved ones in a relatively stratigraphic order from the Permian and Triassic formations of Mozambique.

		Fossil Woods		
Province	**Formations**	**Prepared and analysed samples**	**Well-preserved**	**Badly preserved**
Tete	Cádzi F.	09	04	05
	Matinde Formation	109	20	89
	Moatize F.	10	0	10
	Vúzi F.	-	-	-
Niassa	KSb F.	06	01	05
	KSa F.	05	04	01
	K6 F.	05	01	04
	K5 F.	26	10	16
	K4 F.	05	01	04
	K3 F.	-	-	-
	K2 F.	-	-	-

APPENDIX G

List of some recognised fossil forest based on UNESCO Hertitage list, Won and Singtuen, 2018, Brito *et al*., 2014, Maksoud and Metwaly, 2020, Rößler, 2013.

Country	Name of the Forests	Dimension ($Km^{2)}$	Age	Geoturism activities
United States of America	Petrified Forest National Park	378.52	Late Triassic	Site used for geotourism (UNESCO Heritage site)
Greece	Petrified Forest of Lesvos	150	Lower Miocene	Site used for geotourism (UNESCO World Heritage site)
Zâmbia	Chirundu Fossil Forest	43	Late Jurassic	Site used for geotourism
Namibia	Petrified Forest of Khorixas	44.5	Carboniferous	Site used for geotourism
Argentina	Talampaya National Park	275.3	Triassic	Site used for geotourism (UNESCO World Heritage site)
Brazil	Tocantis Petrified	320	Permian	The site has been only used for scientific purposes
Egypt	Maadi Petrified Forest	10	Oligocene	The site has been only used for scientific purposes
Germany	Petrified Forest of Chemnitz	Not given	Permian	Site used for geotourism
Thailand	Petrified Forest of Pak	30	Quaternary	The site has been only used for scientific purposes
China	Xinhang Fossil Forest	250	Devonian	The site has been only used for scientific purposes

Mozambique (this dissertation)	Tete Fossil Forest	Approximately 3000	Late Permian	The site has been only used for scientific purposes

APPENDIX H

Growth rings Type S

