PALYNOLOGY OF THE PALEOZOIC – MESOZOIC SUCCESSIONS OF THE TANGA AND RUVU BASINS, COASTAL TANZANIA

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MSc (Geology) Thesis
University of Dar es Salaam
April, 2021

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By

Stephen Peter Magohe

A Thesis Submitted in Fulfillment of the Requirements for the Degree of Master of Science (Geology) of the University of Dar es Salaam

University of Dar es Salaam
April, 2021

CERTIFICATION

The undersigned certify that they have read and hereby recommend for acceptance by the University of Dar es Salaam a thesis titled: "Palynology of the Paleozoic – Mesozoic successions of the Tanga and Ruvu basins, coastal Tanzania" in fulfillment of the requirements for the degree of Master of Science (Geology) of the University of Dar es Salaam.

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Date: 01/4/2021

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Date: 30/3/2021

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I, **Stephen Peter Magohe**, declare that this thesis is my own original work, except where acknowledged and that it has not been presented and will not be presented to any other University for a similar or any other degree award.

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ACKNOWLEDGMENTS

I thank the almighty God for granting me good health the entire time I conducted this research work. I am grateful to my academic advisors Dr Cassy Mtelela (UDSM) and Dr. Alexander J.P. Houben (TNO) for their tireless guidance and support all the time of this study. Their perseverance, technical assistance, readiness to read and improve this manuscript through their edits and comments kept me a happy student.

I am thankful to the geological survey of the Netherlands for initiating the Tanzania Stratigraphic Nomenclature Project that facilitated my palynology training and labolatory processing in the Netherland as part of this study. The University of Dar es Salaam is thanked for funding this study and providing good training and conducive thesis writing environments. The Tanzania Petroleum Development Corporation and the Petroleum Upstram Regulatory Authority are thanked for providing permission to access samples that were used in this study and for granting permission to publish some of the findings.

I thank Roel Verreussel (TNO) and Dr. Emma Msaky (TPDC/UDSM) for discussions and training on palynological data interpretation. Many thanks to palynologists and laboratory technicians at TPDC; Innocent Mvamba, Victoria Godfrey, Johannes Kakoki, Kassim, Malembela and Naomi. Nico M.M. Janssen (TNO), Natasja Welters (GML, Utrecht University), Giovanni Dammers (GML, Utrecht University) are thanked for providing training in laboratory safety and palynology sample preparation. I also thank my colleagues Mugwe Thomas (for helping to improve some of my figures), Ibrahim Lufyagila, Jamal Makishe, Paul Damian, Edimund Josephat, Gerald Chuwa, Clara Kimani, Kareem Mtili and Mary Moshi for their social and career support.

In the end, I thank my family, if it was not for their excellent upbringing, prayers, patience, trust, unconditional love, courage and good wishes, I wouldn’t have made it this far. My girlfriend is thanked for often reminding me that, there is so much life than being a palynologist.

DEDICATION

To Stephen Peter Magohe Jr.

Romans 4:18

LIST OF ABBREVIATIONS

Et.al	et alia (and others)
BH	Borehole
c.f.	Compare with
e.g.	Example
Fm.	Formation
E	East
g	Grams
GML	Group
Gp.	Group
GPS	Global Positioning System
FAD	First Appearance Datum
HCL	Hydrochloric Acid
HDPE	High-density polyethylene
HF	Hydrofluoric Acid
i.e.	That is
JPEG	Joint Photographic Experts Grroup
IEDC	International Economic Development Council
K1 – K8	Karoo Lithostratigraphic Units 1-8
Km	Kilometre
Kg	Kilogram
KK	Kakindu Borehole/ Samples
L	Litre
LAD	Last Apperance Datum
Ma.	Million Years
Mb.	Member
MK	Makarawe
NE	North East
NNW	North North West
NW	North West
PURA	Petroleum Upstream Regulatory Authority
SE	South East

Sp.	Species
SSW	South South West
P–Tr	Permian – Triassic
Ph	Potential/Power of Hydrogen
PVA	Polyvinyl alcohol
TDP	Tanzania Drilling Project
TNO	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek.
TPDC	Tanzania Petroleum Development Corporation
TSNP	Tanzania Stratigraphic Nomenclature Project
UDSM	Univeristy of Dar es Salaam
UK	United Kingdom
VND	Vunde

ABSTRACT

This study presents palynostratigraphy of Paleozoic-Mesozoic strata in the Ruvu and Tanga Basins of Tanzania that were deposited as a result of Gondwana breakup. The aim is to document important bio-events recorded through the Paleozoic-Mesozoic times in these basins as well as to establish biostratigraphy and correlation across these otherwise poorly stratigraphic constrained two basins and Tanzania coastal region at large. Indeed, this study provide an insight into Permian-Triassic phytogeography in Tanzania, while presenting for the first time palynologic ages of the Karoo-equivalent Tanga Beds and following-up contributions of a few existing palynologic studies in the Jurassic strata of the Ruvu Basin. Specifically, this study was set to research on the age of the Karoo-equivalent strata right below the break-up unconformity in the Tanga Basin, age of the sediments above the break-up unconformity in the Ruvu Basin, stratigraphic divisions that can be recognized in the Karoo and post-Karoo sequences in the Ruvu and Tanga basins and how these strata palynologically correspond to similar strata elsewhere. For this purpose, three boreholes from the Tanga Basin (Vunde - 1, Kakindu - 1 and Jihirini - 1) and one exploration well from the Ruvu Basin (Makarawe - 1) were utilized in this study.

Results from palynologic analyses in the Tanga Basin recognizes two palynological intervals that include *Vitreisporites – Klausipollenites* Interval indicating a ?late Carboniferous to early Permian age and *Jugasporites vellicoites* indicating Permian (Lopingian) age in the Kakindu-1 borehole. In addition, newly discovered fossil plants of Gondwanic affinity (*Glossopteris* genera, *Hirsutum dutoitides* and *Sphenobaiera eccaensis*) that were doubtful present in the Tanga beds are reported herein from Kakindu area. In Vunde-1 borehole of the Tanga Basin, two main palynologic intervals (i.e. *Klausipollenites schaubergeri* - *Scheuringipollenites circularis* and *Alisporites minutosaccus* - *Faunipollenites gopadensis*) are used to infer a ?late Carboniferous, Permian and end-Permian-earliest Triassic age respectively. On the other hand, in the Ruvu Basin, three palynological intervals are recognized in the lower Makarawe - 1 well cutting samples. These include *Falcisporites zapfei* Interval indicating late Permian age, *Reduviasporonites* Interval

indicating Permian-Triassic transition (Changhsingian-Induan) and *Alisporites-Falcisporites* Interval indicating Triassic age. Preserved basal Jurassic strata (deposited on top of the Karoo strata) that record the earliest possible marine inception in the Ruvu Basin are also documented just below depth 1427 m of the Makarawe - 1 well and correspond to Middle-Late Jurassic (Bajocian-Kimmeridgian age). This is based on lithofacies changes and documented sporomorph intervals (*Classopollis-Nannoceratopsis* Interval and *Wanaea clathrata* Interval).

In relation to the existing informal Karoo subdivisions in the Tanga Basin's stratigraphy, results by this study agree that, the studied boreholes in the Tanga Basin show a strong affinity to the upper part of the lower Karoo and the lower part of the upper Karoo units. Furthermore, the results warrant a correlation to the second-fourth depositional sequence in the inland Karoo type-section in Ruhuhu Basin and a Beaufort-Stormberg equivalence in main Karoo Basin of South Africa. Also the dinocyst *Nannoceratopsis pellucida* documented in the Makarawe-1 well of the Ruvu Basin signifies an immediate post-break-up association suggesting that, the Ngerengere beds of the Ruvu Basin are not Karoo equivalent but rather syn-/or post break up sequences. The two recorded palynological intervals related to post-break-up phase in the Ruvu Basin are correlated to other palynological intervals in Africa, Australia and Europe.

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CHAPTER ONE
INTRODUCTION

1.1 Background

This study seeks to constrain depositional ages and correlate the strata across the Tanga and Ruvu Basins of Tanzania using palynology and macropaleontology (paleobotany) of the sedimentary strata that were deposited in association with and just after the Gondwana breakup. The study was established in association with the Tanzania Stratigraphic Nomenclature (TSN) project - an initiative to develop the nomenclature for the offshore and onshore Tanzanian stratigraphy – with a central objective being to standardize the geology of subsurface and surface sedimentary successions. The TSNP is crucial for the proper management of the subsurface resources; and hence, maximization of the national income through improving national geological database. With more than 55 trillion cubic feet of natural gas reserve discovered so far, and active producing fields, there is a prospect for Tanzania to evolve to a major gas exporting country in the near future. With this possibility, the TSNP and other hydrocarbon exploration efforts are encouraged since they will help to improve the quality of onshore and offshore data. The link between the onshore and offshore stratigraphy, for instance, will increase an understanding of the geology and prompt more discoveries in the offshore.

Contribution of this study to the project (as well to the science in general) is the provision of biostratigraphic data that allows the studied lithostratigraphic sections to be chronostratigraphically placed. Furthermore, the study will provide palynology-derived facies interpretations for the studied interval, aiding to refine the lithostratigraphy and aspects of paleoenvironment of deposition.

1.2 Literature Review

1.2.1 Carboniferous – Jurassic Paleogeography of the Gondwana

The Gondwana supercontinent (Figure 1.1) was an amalgamation of continents that assembled in the end of Proterozoic eon (660Ma-530 Ma: McLoughlin 2001, Jokat et al. 2003, Blakey 2008). In the course of its existence during the Carboniferous to Permian times (358.9Ma-254.1 Ma), the land-masses positioned near the south pole were affected by glaciation, a phase known as the Late Paleozoic ice age (Rowley 1985, Blakey 2008, Figure 1.2 a-b). However, many compiled regional paleogeographic maps suggest that, there was no single icesheet as perceived by many (Scotese and Langford 1995), but rather a geographically selective ice coverage shifting eastward from South America (ca. 330Ma, late Carboniferous) to Australia (~ 254Ma, Late Permian, see e.g. Scotese 1998, Scotese 2015). Until the end of Permian time, East Africa was still attached to Madagascar and India although continental rifts are known to have already commenced in East Africa (Scotese 1998, Wopfner 1999, Scotese 2015). Glacial sediments of the early Permian age have also been documented in East Africa (e.g. the Idusi formation of Tanzania and the Sakoa Gp. of Madagascar, Wopfner 1999). By the late Permian times, Gondwana had shifted its position slightly northward and all the ice had melted leaving giant fresh water lakes in the many regions including South Africa (Visser 1996), East Africa (Wopfner 1999, Kreuser and Woldu 2010) and Australia (Wopfner 1999).

By Triassic times, rifting between Laurasia and North Africa began forming several continental basins (McLoughlin 2001, Scotese 2015). Initial breakup of the Gondwana supercontinent commenced in the Early Jurassic to Early Cretaceous after opening of neo-Tethys Ocean (Visser 1996). By the Middle Jurassic times, the Indian Ocean had opened, and East Africa had separated from Madagascar (Rabinowitz et al. 1983, Hankel 1994, Figure 1.2 d).

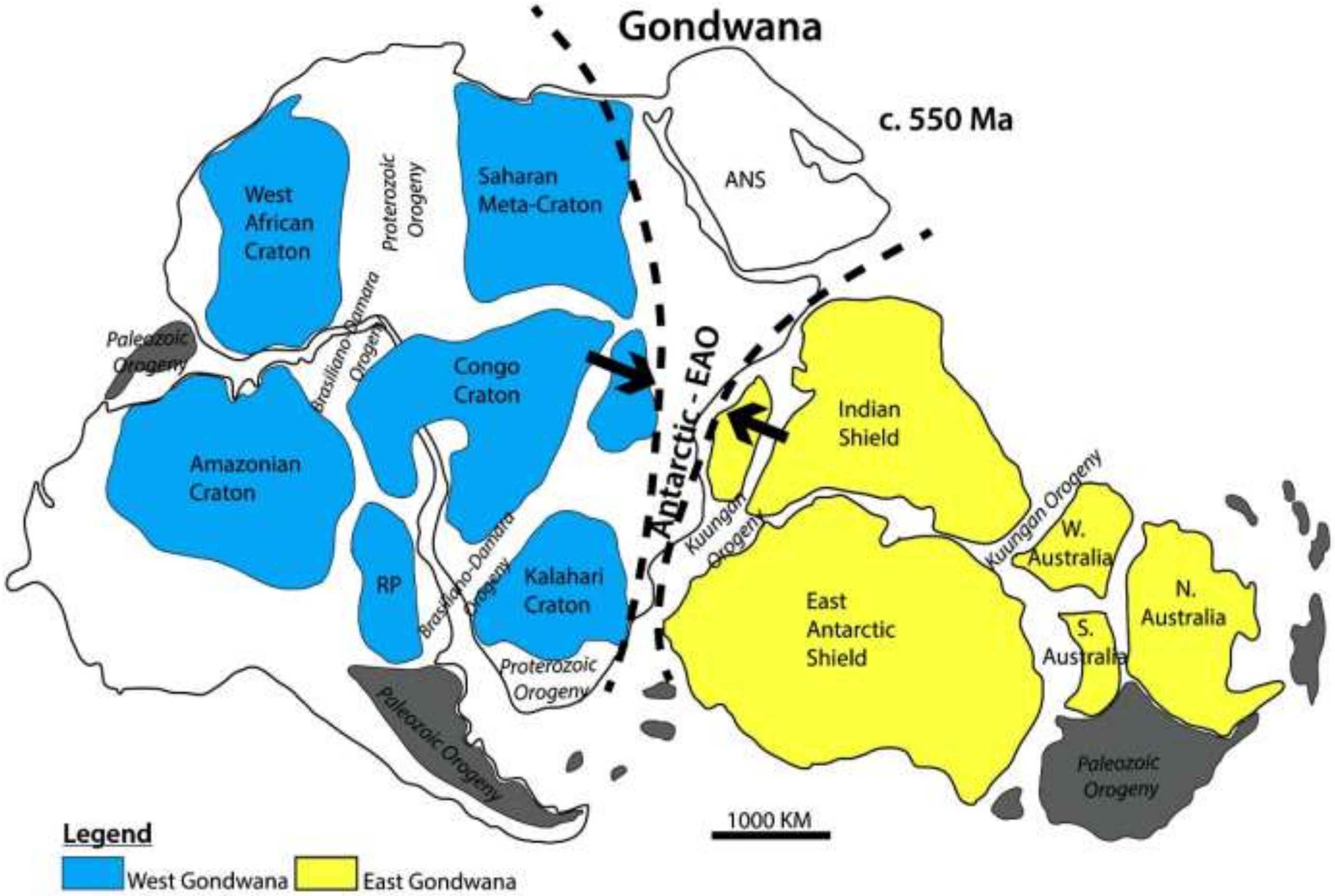

Figure 1. 1: A Neoproterozoic map of the Gondwana supercontinent (Modified after Meert et al. 2008 and Abudayeh 2018).

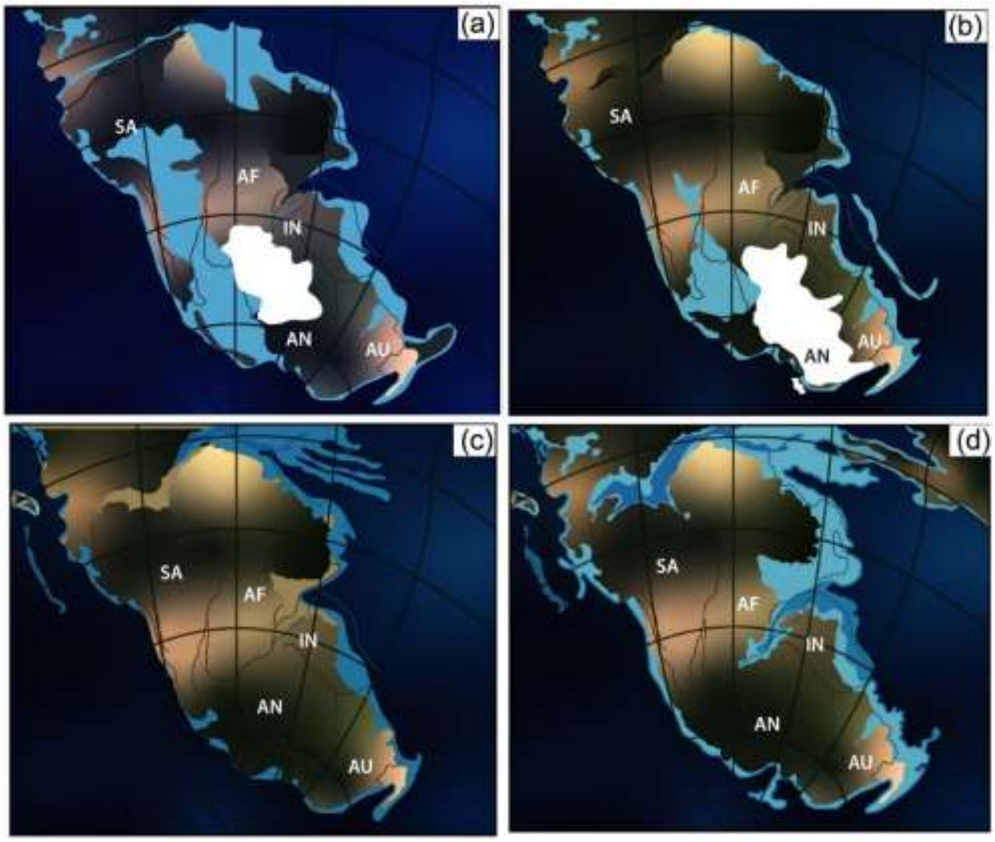

Figure 1. 2: Paleogeography of the Gondwana (a) Late Carboniferous times, 323.2Ma. - 298.9Ma. (b) Permian times, 298.9Ma. - 254.2Ma. (c) Triassic times, 252.2Ma. - 201.3Ma. (d) Middle Jurassic times, 174Ma. - 163.5Ma. (Modified from Blakey 2008). SA = South America, AF = Africa, AF = Africa, AU = Australia, IN = India, AN = Antactica.

1.2.2 Overview of the Carboniferous - Jurassic Palynostratigraphy of the African Gondwana

The geographic coverage over which palynological data are available has increased in substantially over the past six decades. Reasons for this increase are closely related to the influence of coal-bearing formations that existed in Western Europe and North America which needed to be explored (Balme 1980, Stephenson 2008). Other factors for the increase include hydrocarbon exploration in the Middle East (Truswell 1980, Stephenson 2008, Jan 2014) and intensification of stratigraphic projects in different parts of the globe, seeking to establish biostratigraphic zonation schemes based on spores and pollen (Truswell 1980).

In the African Gondwana, initial palynological studies focused on “Karoo rocks” of South Africa (Smith 1990, Smith et al.1993, Truswell 1980, Kalkreuth 1999). By then, “Karoo” as the lithostratigraphic terminology was already introduced to define rocks similar to those observed in the Karoo Basin of South Africa, but found elsewhere in the Gondwana (Catuneanu 2005). Age-estimates for these Karoo rocks range between Late Carboniferous and Middle Jurassic (Hancox and Gotz 2014). Time-equivalent strata are also known elsewhere outside Africa, and includes those found in South America (Parana Basin, Milani et al. 2008), India (Godavari and Saptura basins, Jha 2006), Antarctica (Beacon Basin, Jha and Aggarwal 2012) and Australia (Bowen Basin, McLoughlin 1994).

Like elsewhere across the world, the palynological studies related to coal exploration in Africa resulted in production/publication of various biostratigraphic schemes (Hart 1965, Falcon et al. 1984, Cesari 2007, Barbolini 2014). Coupled with other advances in dating methodologies (such as radiometric dating and vertebrate paleontology), stratigraphic palynology for the African Carboniferous – Jurassic interval has made quite a satisfactory correlation between Africa and other continents (Hankel 1987, Cesari 2007). Despite such attempts in dating and correlation, the existing Carboniferous–Jurassic biostratigraphic schemes in the region do not provide sufficient basis for establishing local and regional Karoo stratal age relationships leading to poor stratigraphic control and phytogeographic provincialism (Playford and Dino 2005, Jha 2006). This is because not enough dating has been done, existing stratigraphic reviews are restricted to certain areas (Stephenson 2008) and taxonomic methods exercised in different parts of the world are also different (Playford and Dino 2005, Jan 2014).

In Tanzania, Carboniferous – Early Jurassic non-marine strata constitute the Karoo sedimentary rocks (Hankel 1987, Kreuser et al. 1990, Kaaya 1992, Delvaux 2001, Wopfner 2002). These are well defined in the Songea Group of the inland Ruhuhu

Basin, where five Karoo units that include: (i) glacigene sequences (Gzhelian, 304Ma - 299Ma to Asselian, 298.9Ma - 295.5Ma) (ii) coal measures (Sakmarian, 295Ma - 290.1Ma to Artinskian, 290.1Ma - 282Ma) (iii) fluvial to lacustrine deposits (Kungurian, 282Ma - 272.3Ma to Capitanian, 265.1Ma - 259.8Ma) (iv) alluvial fan – playa deposits (Wordian, 272.3Ma-265.1Ma to Changhsingian, 254Ma-251.9Ma) and (v) fluvial deltaic deposits (Induan, 251.9Ma - 249.8Ma to Anisian, 246.8Ma - 241.5Ma) are known (Wopfner 2002, Catuneanu et al. 2005). The Karoo units in the inland basins have (at different times) been dated using palynology (Manum and Tien 1973, Wescott et al. 1991, Balduzzi et al. 1992, Semkiwa 1998, Kalkreuth 1999, Semkiwa 2003). In relation to the inland basins, the Karoo units are also exposed (poorly) in the coastal basin of Tanzania including the Tanga and Ruvu basins (Figure 1.4). These are overlain by the Middle Jurassic marine strata and they generally suffer lack of biostratratigraphic age-controls like many other African sedimentary basins.

1.2.3 The Tanzania On- and Offshore Basin Setting

The Tanzania coastal and offshore sedimentary basins cover an area that extends from Kenya (in the north) to Mozambique (in the south). The onshore basins comprise several sedimentary sub-basins (Figure 1.4) located along the passive continental margin of the western Indian Ocean that is characterized by an extensional tectonic style (Mpanda 1997, Kapilima 2003). The main sub – basins distinguished in coastal Tanzania include the Tanga Basin, Rufiji Basin, the Dar es Salaam Platform, the Ruvu Basin and the Mandawa Basin (Mbede and Dualeh 1997, Kent et al. 1971).

1.2.4 Regional Stratigraphic Framework

Tectonic movements largely controlled the evolution of the coastal basin of Tanzania. These include several phases of rifting associated with the Gondwana breakup (Kapilima 2003). The initial rifting phase (Carboniferous to Permian, 300Ma to 205 Ma) resulted in the deposition of siliciclastic and carbonate sedimentary rocks belonging to the Karoo Super Group (Kent et al. 1971, Mpanda 1997 and Kapilima 2003). These sediments were deposited in the down faulted basin that occasionally experienced deposition of lagoonal facies due to their connection to the open sea (Kajato and Kejo 1982). The latter phenomenon is very well observed in the Nondwa Formation of the Mandawa Basin in the southern end of the coastal Basin of Tanzania (Hudson and Nicholas 2014). The second phase of rifting (in the Late Triassic to Jurassic, 205 to 157 Ma) marks the Gondwana break-up as the result of pericratonic rifts (Kreuser 1995). This was associated with major marine transgression onto the passive continental margins of both West and East Gondwana blocks (Kapilima 2003). The latter resulted into deposition of Upper Jurassic and Lower Cretaceous strata in the coastal basins of Tanzania, Kenya, Somalia, Madagascar and Mozambique (Kapilima2003, Hudson et al 2014).

The Tanzania Coastal Basin has been a focus to many geological research since 1950s. Most of such researches were driven by a quest to find hydrocarbons (Kagya 1996, Mweneinda, 2014). Since then, a number of informal stratigraphic schemes have been proposed in the region (e.g. Seward 1922, Seward 1934, Stockley 1936, Aitken 1959, Kajato and Kejo 1982, and Leger et al. 2018). A few studies proposing formal stratigraphy are also known in central and southern parts of the coastal basin of Tanzania (e.g. Nicholas et al. 2006, Bussert et al. 2009, Hudson and Nicholas 2014 and Berrocoso et al. 2014). Synthesis of these previous studies reveals that the entire coastal basin host sedimentary strata spanning the Late Paleozoic to Recent, which are also marked by a number of north-south structural highs and east-west fault trends (Mbede et al.1997).

1.2.5 Tectono - Sedimentary Evolution of the Tanga and Ruvu Basins

The first rifting phase in the Tanga and Ruvu basins occurred during the Permo-Carboniferous to Triassic times (Kreuser 1995, Catuneanu 2005), and resulted in development of complex horsts and graben, and later deposition of continental Karoo-equivalent rocks (Kent et al. 1971, Delvaux 1991, Kreuser 1995). Many researchers term this rifting event as a failed rift, meaning it failed to result in a full continental breakup (Mpanda 1997).

The second rifting phase, commonly regarded as a reactivation of the earlier rift, is reported to have occured by Middle Jurassic to Early Cretaceous times (Mpanda 1997, Kreuser 1995, Kapilima 2003). This rifting episode is regarded as successful, as it led to continental breakup of the Gondwana supercontinent into present-day continents of southern hemisphere, including the separation of Madagascar from Africa (Kent et al. 1971, Mpanda 1997, Kapilima 2003). The main rifting phase was dominated by massive subsidence and sedimentation (Bally 1981, Salman and Abdula 1995), leading to deposition of alternating marine and transitional marine deposits in the Tanga and Ruvu basins (Kent 1971, Kapilima 2003).

Lithostratigraphic correlation between the Tanga and Ruvu basins sugget the presence of the lower Karoo rocks in the subsurface of both basins. These are part of the older karoo rocks (Upper Carboniferous-middle Permian), which are equivalent to the Dwyka and Ecca Groups of the Karoo Supergroup in South Africa (TPDC 1992, Figure 1.4). The lower Karoo rocks are succeeded by the middle Karoo (middle Permian) and upper Karoo sequences (middle Permian to early Triassic). Upper Triassic unconformity marks the boundary between Karoo - equivalent strata in Tanga (the Tanga Beds) and the overlying Ngerengere beds in the Ruvu Basin (Figure 1.4). These rocks are faulted along the Jurrasic marine strata, suggesting the probable hiatus in the Triassic and Early Jurassic (Seward 1922, Kreuser 1995, Figure 1.4). Based on fossil ammonites and reef elements, the Middle Jurassic of the Ruvu and Tanga basins (i.e. Makarawe formation, Amboni formation respectively) is known to demonstrate continental shelf conditions, with deposition of shallow water oolitic to oncolitic limestone (Kent et al. 1971, Schulter 1997, Kapilima 2003, Figure 1.4).

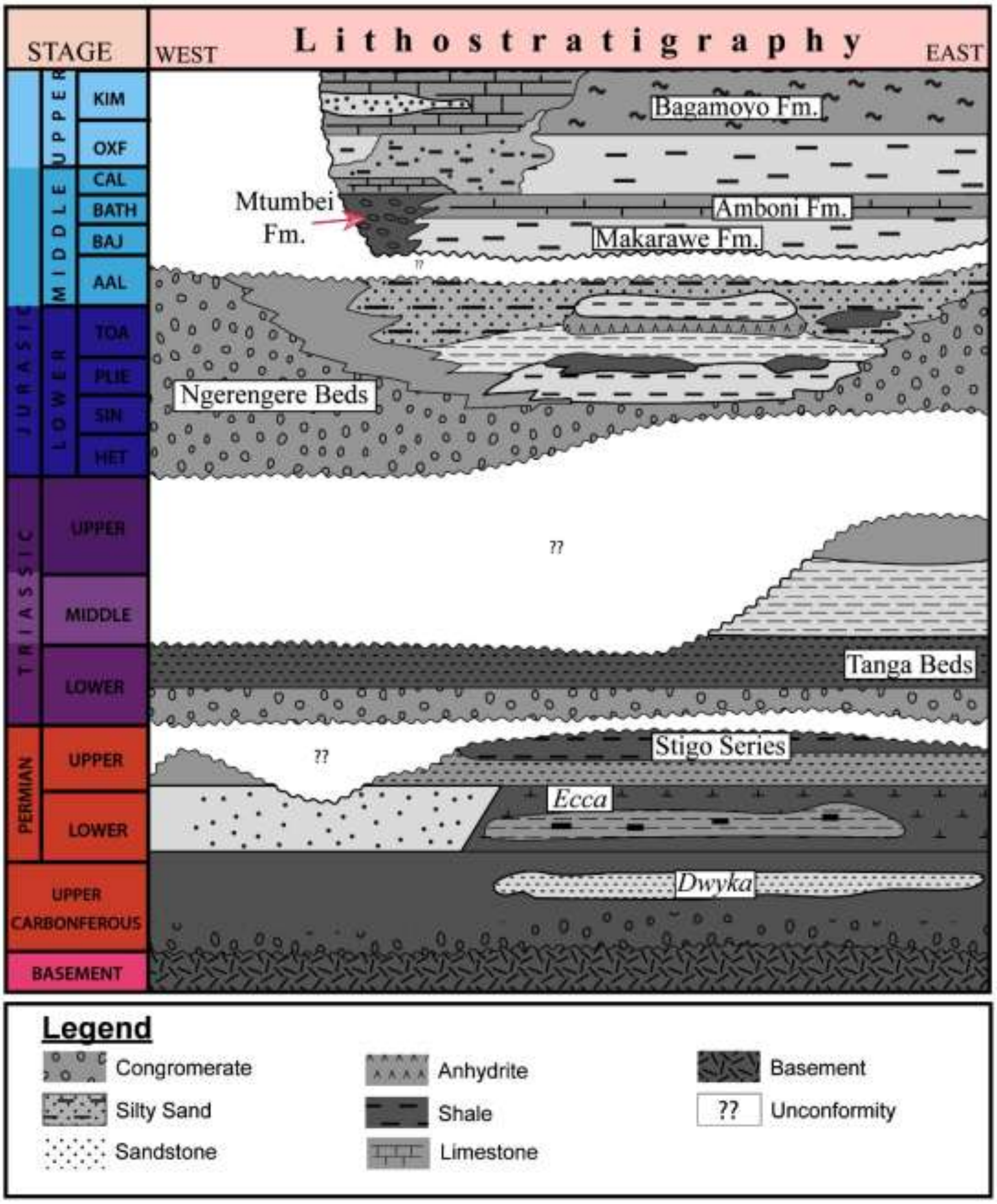

Figure 1. 3: **Stratigraphic column showing the lithostratigraphic position of the Tanga and Ngerengere Beds (Modified after TPDC 1992). AAL = Aalenian, TOA = Toarcian, PLIE = Pliensbachian, SIN = Sinemurian, HET = Hettangian.**

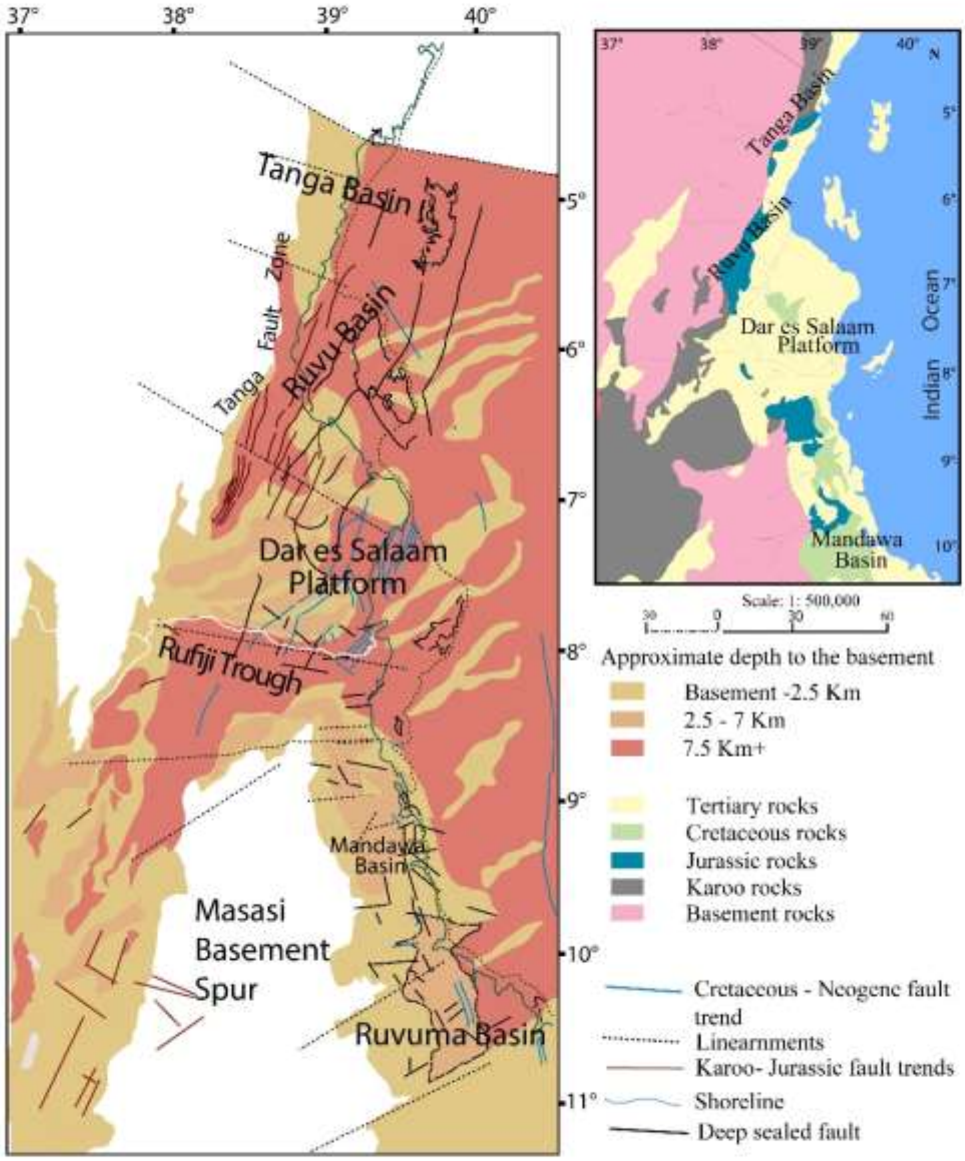

Figure 1. 4: The map of coastal Tanzania showing sub - basins location, geological feautures, structural features, depth to the basement and lithological distribution (modified after Kent et al. 1971 and TPDC 1992).

1.3 Statement of the Research Problem

The Tanga and Ruvu basins, which forms part of the onshore coastal basin of Tanzania, poses some challenges in developing local stratigraphic frameworks. These challenges include dependency on cuttings-derivered biostratigraphic datasets, low biostratigraphic resolution and poor biostratigraphic dating (Nicholas 2006, Msaky 2007, Sansom 2016). As a result, the stratigraphic control and the correlation between strata across the Tanga and Ruvu basins have been problematic. However, a few existing Mesozoic Karoo and post-Karoo palynologic studies have presented insights on the stratigraphic context of the Ruvu Basin (Balduzzi et al. 1992, Msaky 2007, Msaky 2011). In addition, some ancient paleobotanic studies (Seward 1922, Seward 1934) and vertebrate paleontological studies (Kamen-Kaye 1978) have been carried out in the Tanga Basin. It is from these studies, the three-fold informal stratigraphic subdivision of the Karoo-equivalent strata (Tanga beds) into a lower, middle and an upper unit is known in the Tanga Basin. Also, based on a synthesis of both published and unpublished reports on dating of the Jurassic strata in the Ruvu Basin, it is agreed that the earliest marine invertebrate fauna preserved in the Ruvu Basin are of Bajocian age (i.e. earliest Middle Jurassic) (Kamen – Kaye 1978, Kapilima 2003); however, insights from ammonite dated lithostratigraphic units in the basin suggest a possible Aalenian base for the Ruvu basin marine succession (Kapilima 2003).

Using limited sample size, palynology on the other hand has placed the top of the Jurassic strata to Kimmeridgian, while setting an Aalenian to Bajocian age for the base of Jurassic unit above the ‘breakup unconformity’ (Msaky 2007, Msaky 2011). In essence, the age of sedimentary units in both basins has remained inconclusive and stratigraphic framework in both basins has remained subject of further research. Major outstanding questions for understanding the stratigraphic development of the central and northern part of the Tanzania Coastal Basin are;

1. How do the Tanga Beds correspond to Karoo rocks elsewhere?
2. What is the age of the upper Tanga Beds right below the break-up unconformity?
3. What age are the sediments above the break-up unconformity in the Ruvu Basin?
4. What stratigraphic divisions can be recognized in the Jurassic sequence from the Ruvu Basin?

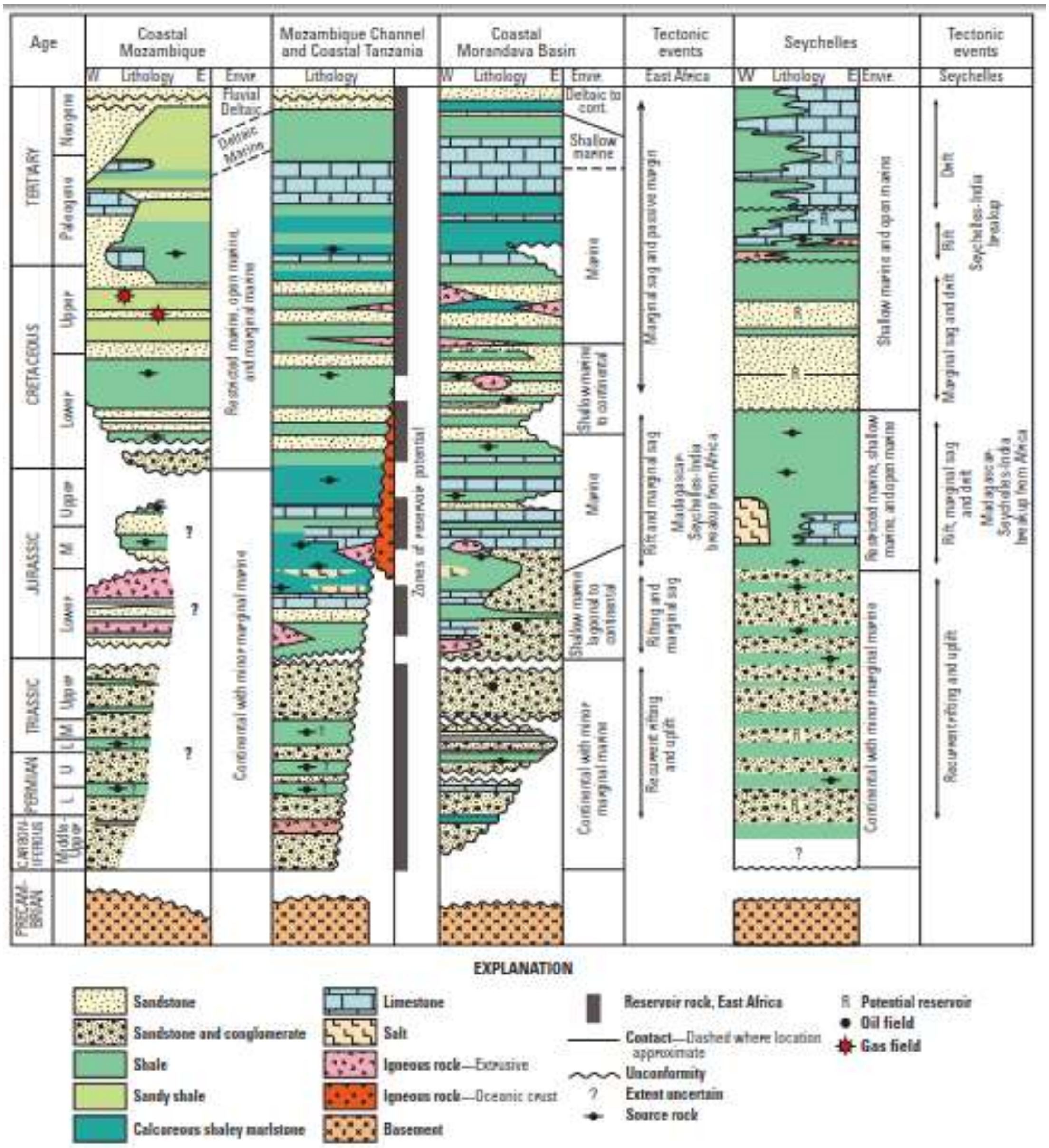

Figure 1. 5: Generalized Stratigraphic Column for the Coastal Basin of Tanzania and adjacent Basins (Brownfield 2016).

1.4 Research Objectives

The central objective of this research is to resolve the stratigraphy of the Karoo and post - Karoo (Jurassic) strata in the Tanga and Ruvu basins using palynology. The specific objectives of this research are:

1. To identify and document palynomorph distributions from drill-cores in the Tanga Basin and drill cuttings in the Ruvu Basin.

2. To biostratigraphically constrain depositional ages of the strata across the Tanga and Ruvu basins, placing them into a chronostratigraphic context.

Two objectives are more specific to these two case-studies:

a. To correlate the Karoo strata in the Ruvu and Tanga basins to the Karoo megasequences documented for the inland Karoo basin of Tanzania and establishing the age relationship between the Karoo and post break-up Jurassic strata in the Ruvu Basin.
b. To provide an insight into the composition of Jurassic organic-walled dinoflagellate cyst associations in comparison to well-studied regions elsewhere (Australia and Europe).

1.5 Research Questions

The objectives of the study are going to address the following questions:

i. What is the composition of the palynological associations of the studied core and cutting samples in the Ruvu and Tanga basins?
ii. What are the depositional ages of the Karoo interval in Tanga Basin, and Karoo and post-Karoo (Jurassic) strata in Ruvu Basin?
iii. How are strata in Tanga and Ruvu basins correlate in space and time?

The biostratigraphic data from this study is expected to provide a good age-control on stratigraphy and correlation of strata across the Tanga and Ruvu basins. New biostratigraphic ages provided by this study will surely end up to be a significant contribution both academically and economically, thereby shading light to understanding Tanzania coastal basin evolution (academically), and used as an important tool in the hydrocarbon exploration, respectively.

1.6 Materials and Methods

1.6.1 Materials

The materials used in this research included geological maps, lithological logs, structural and stratigraphic data gathered from selected outcrops and drill cores/cuttings, field gears, transmitted light microscope, software (C2, Arc Map, Adobe Illustrator, Sedlog, Win tensor) laptop and stationery. Other material included sieves of different sizes (e.g. 7μ, 10μ, 15μ, 18μ), 120 (or 250 μ), ultrasonic baths, plastic jar/beakers (0.5-1L), water splash bottles, vortex mixer shaker, portable mini centrifuge (table top centrifuge), plastic (or glass) containers (i.e. vial sample eppis), heater (32-33^{o}), disposable glass-pipettes, disposable plastic pipettes, cover-slips (several sizes can be used, 18x18, 24x32), mounting slides, burner and lighter, PVA (0.5%), glue for glass (brand G4G) and a vortex mixer shaker.

1.6.2 Methods

Study Area Location

The Ruvu and Tanga basins (Figure 1.6) are located in the central and northern Tanzania, respectively. The Ruvu basin lies in the eastern Tanzania, 115 km from Dar es Salaam, whereas the Tanga is further northward, ~ 289.5 km from Dar es Salaam. Ruvu Basin extends in the south-southwesterly direction covering an area of about 15, 000 km^2. To the eastern limit, it coincides with the present-day coastline (Mweneinda 2014).

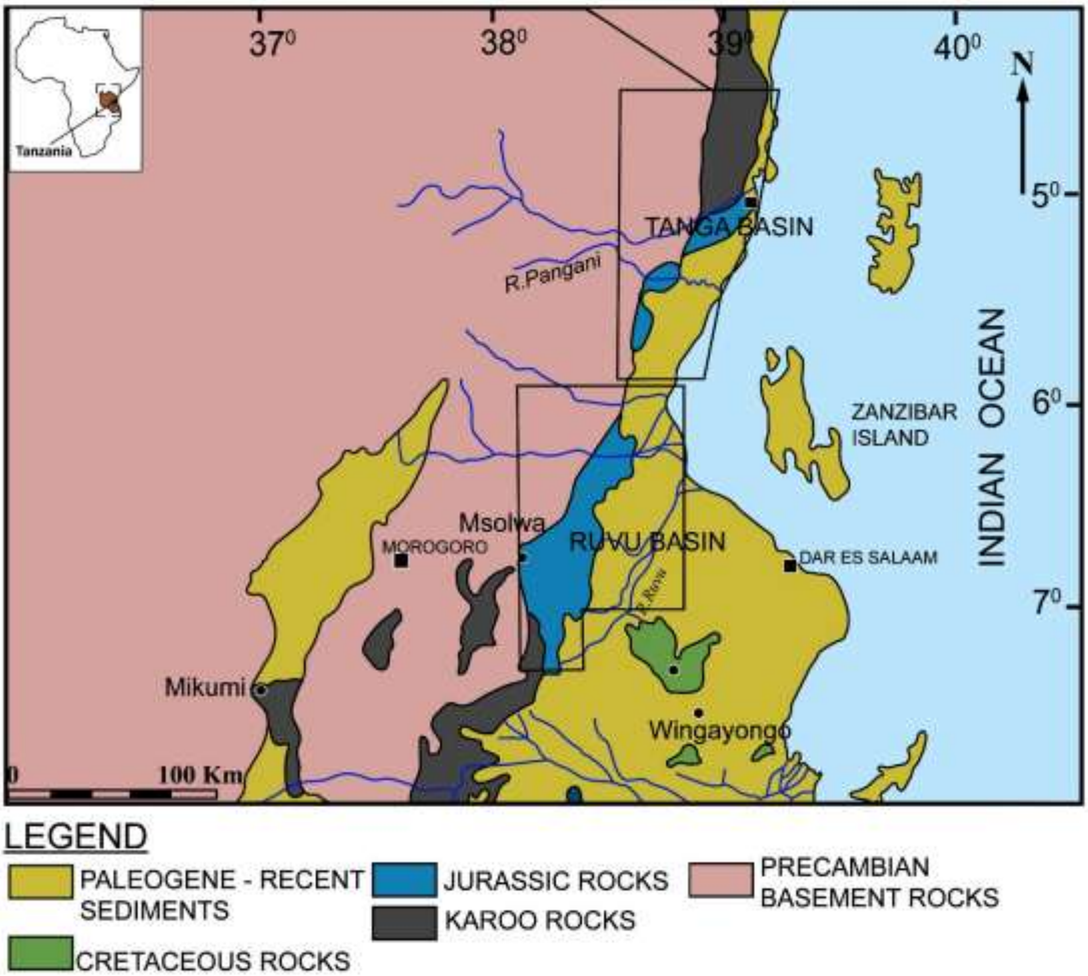

Figure 1. 6: A map showing location of the study area (i.e. the Ruvu and Tanga coastal basins) (modified from Kent et al. 1971).

Fieldwork

Geologic field visits were conducted in the Tanga and Ruvu basins aiming at documenting the existing and new exposures of targeted strata. During the fieldwork, preliminary geological information was gathered to confirm what was learnt from the literature as well as guiding the latter phases of project by deciding where exactly time should be spent. Samples were also collected from exposed sections and information pertaining to outcrop sedimentology (lithofacies, fossils, geologic structure and stratigraphy) were documented from selected outcrops.

Sample Preparation Techniques

Sample Washing and Cleaning

Washing and cleaning was carried out for all the core samples in order to remove any possible contaminants that might have been acquired in the drilling process, after the drilling process in the core storage facility or during the sampling process. Generally, cleaning and washing required running water and a clean brush. After cleaning then the samples were left on the dishes to dry ready for crushing. For the cutting samples in this study, this procedure was skipped.

Sample Crushing and Weighing

Crushing involved breaking the samples into small pieces ranging from 12 mm using a mortar and pestle. The intention was to increase the surface area and so speeding up the rate of chemical reaction. After crushing was done, weighing was performed and 5 – 15 grams was transferred plastic bottle that was well labelled.

Removal of Carbonates

The crushed samples in plastic containers were transferred into the fume hood and approximately 10 cm^3 of hydrochloric acid (37% HCl) was added. The mixture was left overnight to allow total digestion of the sample and the removal of all carbonates. Over the following days the mixture was careful decanted several times to remove all acids until the neutral pH point was attained.

Removal of Silicates

After attaining neutral pH, 38-40% Hydrofluoric acid (HF) was added to the samples. When reaction was accomplished, water was added to fill-up the sample container and the samples were left to settle over-night. When the sample had completely broken down, several rounds of decantation were carried out to ensure that the samples were neutral.

Fine Fraction Separation (Sieving)

Sieving was required to further free the palynomorphs along with other organic matter from the sediments. All the material from the sample container were poured in

0.5 - 1 L plastic container through the 120 - micron sieve. The sieved material was then poured from the plastic container onto a 10 - micron sieve. The material in a 10 - micron sieve was sifted to remove all the water before it was transferred in the crucible. The sample (in a crucible) was moved to a second ultrasonic bath (Ultrasonic bath-2) and was left to settle. Once everything had settled, the sample was moved from crucibles in ultrasonic bath-2, to a 10 - micron sieve and was sifted. Water splashing was then carefully performed using a splash bottle. The wanted sample was then slowly poured into the vials sample eppis leaving the residues behind. After this procedure, the samples were ready for the mounting procedure.

Oxidation

Preliminary investigation of the kerogen slides under the transmitted light microscope showed good color and visibility of all palynomorhs and therefore, there was no need to subject the sample to any oxidation processes.

Mounting and Slide Preparation

Mounting slides and cover - slips were prepared by holding them to the burners to remove any fatty material. After this preparation, the samples in the eppis were taken to the vortex for shacking and mixing. About two to three droplets of the sample was taken using a disposable glass-pipette and transferred into a new sample vials eppis. Two droplets of PVA were added to the sample. The sample - PVA mixture was taken to the vortex for mixing. Water was added to the sample - PVA mixture. The mixture was then sampled using another pipette and slowly poured on top of the cover-slip that was already on top of the heating media. The sample was then left to dry. Once everything was dry, one droplet of glue for glass was poured in the centre of the slide. The slide was then carefully lifted and mounted on top of a cover-slip. The slide was then cured for about 30 seconds using a (day-light) lamp.

Light Microscope analysis

Transmitted light microscope was used in the examination and analysis of the organic residues. All specimens were identified under X20 and X100 objectives (microil was used in X100 magnification) and an image was captured for selected palynomorphs.

Curation

Crushed rock samples, residues and palynological slides are curated in the collections at the Department of Geology of the University of Dar es salaam. The rest of the samples are stored at the geological survey of the Netherlands (TNO).

1.7 Thesis Structure

This thesis is organized in four chapters. The findings of the research are presented in chapter 2 and chapter 3, where as the current chapter (chapter 1) introduces the reader to the thesis.The last chapter (chapter 4) provides a summary and conclussions of the research. At the submission of this thesis, one article is already published in the Tanzania Journal of Science, resulting from preliminary findings of the research, and is attached to the end of this thesis. Chapter two and three are structured in a manuscript format, ready for submission following final reviews and a thesis viva. Below is a highlight of the content of each of the chapters in this thesis.

Chapter 1 provides an introduction to the thesis' focus, including the general overview of the TSNP. It provides the statement of the research problem, objectives of the study, research questions and significance of the study. It presents the literature review, previous studies related to stratigraphy of the studied basins and the theory behind methods used in this study.

Chapter 2 presents palynological data and interpreted ages of Karoo-equivalent strata in the Ruvu and Tanga basins, coastal Tanzania. Using palynology (and paleobotany) several distinct palynologic intervals are recognized in core samples from three stratigraphic boreholes (Vunde-1, Kakindu-1 and Jihirini-1), outcrop samples from the Tanga Basin and one deep exploration well (i.e. Makarawe-1) in the Ruvu Basin. Age interpretation derived from the documented palynologic intervals in this chapter permits comparison of the studied Karoo-equivalent strata in the Ruvu and Tanga basins to the Karoo stratigraphy in the inland Karoo basins of

Tanzania. Furthermore, the palynologically dated lithostratigraphic units are correlated to the classical Karoo sequences of South Africa.

Chapter 3 presents a palynological turnover across the Gondwana break–up unconformity in the Ruvu Basin. Using cutting samples from the Makarawe-1 well, Lugoba-1 borehole and outcrop-based field observations across the Ruvu Basin, this chapter reports new palynologic ages of the post – break up strata in the Ruvu Basin.

Chapter 4 summarises the results and provide thesis' conclusions.

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CHAPTER TWO

PALYNOSTRATIGRAPHY OF KAROO-EQUIVALENT STRATA IN THE RUVU AND TANGA BASINS, COASTAL TANZANIA

Abstract

This chapter presents a palynologic study of inferred Karoo-equivalent strata in the Ruvu and Tanga basins, coastal Tanzania. Cores of three shallow boreholes (Jihirini–1, Kakindu-1 and Vunde-1), of the Tanga Basin as well as cuttings samples from one exploration well from the Ruvu Basin, the Makarawe-1 well, were studied in order to biostratigraphically determine depositional ages. The documented palynological assemblages are dominated by pollen derived from gymnosperms, although fern pteridosperm spores are also encountered. No marine palynomorphs (e.g., dinoflagellate cysts or acritarchs) were observed in the samples from either of the basins. This suggests a terrestrial environment and consistent with a common geologic reconstruction of Karoo Supergroup across Africa. From these assemblages, four palynological intervals are recognized in the Tanga Basin. These include *Vitreisporites – Klausipollenites* Interval, *Jugasporites vellicoites* Interval, *Klausipollenites schaubergeri - Scheuringipollenites circularis* Interval and *Alisporites minutosaccus - Faunipollenites gopadensis* Interval. Based on these intervals, a Permian-Triassic age is assigned to the studied samples in the Tanga Basin. These findings are also supplemented by paleobotanical dating of the fossil plants recovered from the Kakindu River outcrop in the Tanga Basin. In the Ruvu Basin, three palynological intervals are recognized. These include *Falcisporites zapfei* Interval (late Permian), *Reduviasporonites sp.* (Permian - Triassic boundary, Changhsingian - Induan) and *Alisporites – Falcisporites* Interval (Triassic).

Based on the vegetation elements that dominated the studied intervals in both basins, the age assignments presented herein imply a single phytogeographic province in the across the two basins during the Permian to Triassic. Furthermore, the results warrant a correlation to the second-fourth depositional sequence in the inland Karoo type-section in Ruhuhu Basin and a Beaufort-Stormberg equivalence in main Karoo basin of South Africa.

2.1 Introduction

Karoo-equivalent strata in Tanzania constitute the terrestrial sedimentary rocks deposited in fault-controlled basins during the late Carboniferous to Early Jurassic (Balduzzi et al 1992, Catuneanu 2005, Hudson 2012). Similar to the Karoo basins of central western Gondwana e.g. Congo Basin (Linol et al. 2015), Luangwa Basin (Banks et al. 1995), mid-Zambezi Basin (Nyambe and Utting 1997) etc), the Tanzanian Karoo basins' development was linked to intra-cratonic phase of sedimentation that occurred during the maximum extension of Pangea Supercontinent in the late Paleozoic to early Mesozoic (Wopfner 1990, Kreuser et al.1995, Wopfner 2001). The Karoo basins in Tanzania are typically rift grabens or half grabens that are either fault-bound or in contact with the Precambrian-Paleoproterozoic basement rocks (Wopfner 1990, Semkiwa 1998). These strata are well exposed in the inland basins such as Ruhuhu, Mikumi and Rukwa basins, but rarely crop out (and are consequently poorly understood in the Coastal Basin of Tanzania. The estimated thickness for these strata is approximately 6 to 10 km in the inland basins (Balduzzi et al, 1992, Delvaux 1991), unconformably overlying the metamorphic basement (Kapilima 2003, Kent 1971).

Contrary to inland Karoo basins, where stratigraphy is relatively well constrained (Kaaya 1992, Wopfner 2002), the stratigraphic position of Karoo-equivalent strata in the Tanzanian coastal belt is poorly constrained. The lack of volcanic material in the Karoo strata of Tanzania coastal belt has made it difficult to geochronostratigraphically constrain depositional ages. Alternatively, biostratigraphic techniques have been used (Seward 1922, Seward 1934, Hankel 1987, Wopfner and Kaaya 1991, Balduzzi et al. 1992). However, the lack of sufficient biostratigraphic data has led to conflicting age assignment for most of the Karoo strata in this coastal belt. For example, there has been an ongoing debate on age and position of the Ngerengere beds in the stratigraphy of the Ruvu Basin, leading to an enigmatic boundary/transition between the Karoo and post-Karoo strata in the Ruvu Basin (Balduzzi et al.1992, Kapilima 2003). Likewise, two paleobotanical studies have dated and assigned a Triassic age for the Kakindu and

Kivundo outcrops in the Tanga Basin based on very few fragmented plant materials (Seward 1922, Seward 1934).

Using palynology, this study places the Karoo-equivalent strata in the Tanga and Ruvu basins into a chronostratigraphic context. The study combines cuttings material from a hydrocarbon exploration well, Makarawe–1 in the Ruvu Basin, with material from three short stratigraphic cores in the Tanga Basin (i.e. Jihirini-1, Kakindu–1 and Vunde–1 wells). In addition, macrofloral remains from outcrop localities in the Tanga Basin are also utilized to supplement polynology. These datasets form the basis for biostratigraphic age interpretation and correlations of the Karoo-equivalent strata of the Tanga and Ruvu basins to type-section in the inland Ruhuhu Basin as well as to other Karoo successions in the region.

2.1.1 Stratigraphic Framework of Karoo Basins in Tanzania

The type area for the Tanzanian Karoo stratigraphy is well defined by the Songea Group of the inland Ruhuhu Basin, where five Karoo units are described (Wopfner 2001). In stratigraphic order, these include: (i) glacigene sequences (ii) coal measures (iii) fluvial to lacustrine deposits (iv) alluvial fan – playa deposits and (v) fluvial deltaic deposits (Wopfner 2001, Catuneanu 2005). Sedimentation history related to these units are highlighted below and summarized in Figure 2.1.

The onset of deposition of Karoo is characterized by the glaciogenic unit (termed as K1), as revealed by varved sedimentary deposits in the Ruhuhu Basin and in few other inland Karoo basins of Tanzania (Wopfner 1994, Wopfner 2002, and Catuneanu 2005). These glacial deposits resulted from significant erosion that resulted to glacial pavements and incised paleo-valleys (Linol et al. 2016). The latter are preserved in the Tanzanian highlands, where the material was sourced (Catuneanu 2015, Linol et al. 2016, Kasanzu 2016). The second sedimentary unit in the basin is characterized by coal bearing sandstone and siltstone facies (termed as K2), whose deposition was controlled by swamps and fluvial activities (meandering rivers and braided streams) (Quennell et al. 1956, Wopfner 2002, Catuneanu 2005).

The third depositional cycle (recognized as units K3, K4 and K5) followed the coal measures, and wherever it is preserved in the Ruhuhu Basin, it records mainly red sandstone and siltstone facies (Wopfner 2001). The fourth sedimentation cycle (K6) is characterized by rudaceous alluvial fan deposits, flood plain splays and playa lake and overbank deposits of green – red silt- and mudstones (Kreuser et al. 1990, Wopfner 2002). The fifth depositional unit (K7 and K8) hosts the Manda sandstone beds that are further subdivided into Kingori and Lifua members (Figure 2.1). Depostion of the Karoo strata was controlled by tectonism and climate that varied from cold, semiarid and warm to hot in the Late Carbonifeous-Triassic period (Kreuser et al. 1990, Wopfner 2002, Figure 2.1). These depositional sequences recognized in the Ruhuhu Basin have been used to correlate with other Karoo strata elsewhere in Tanzania, and will be continually discussed in this chapter.

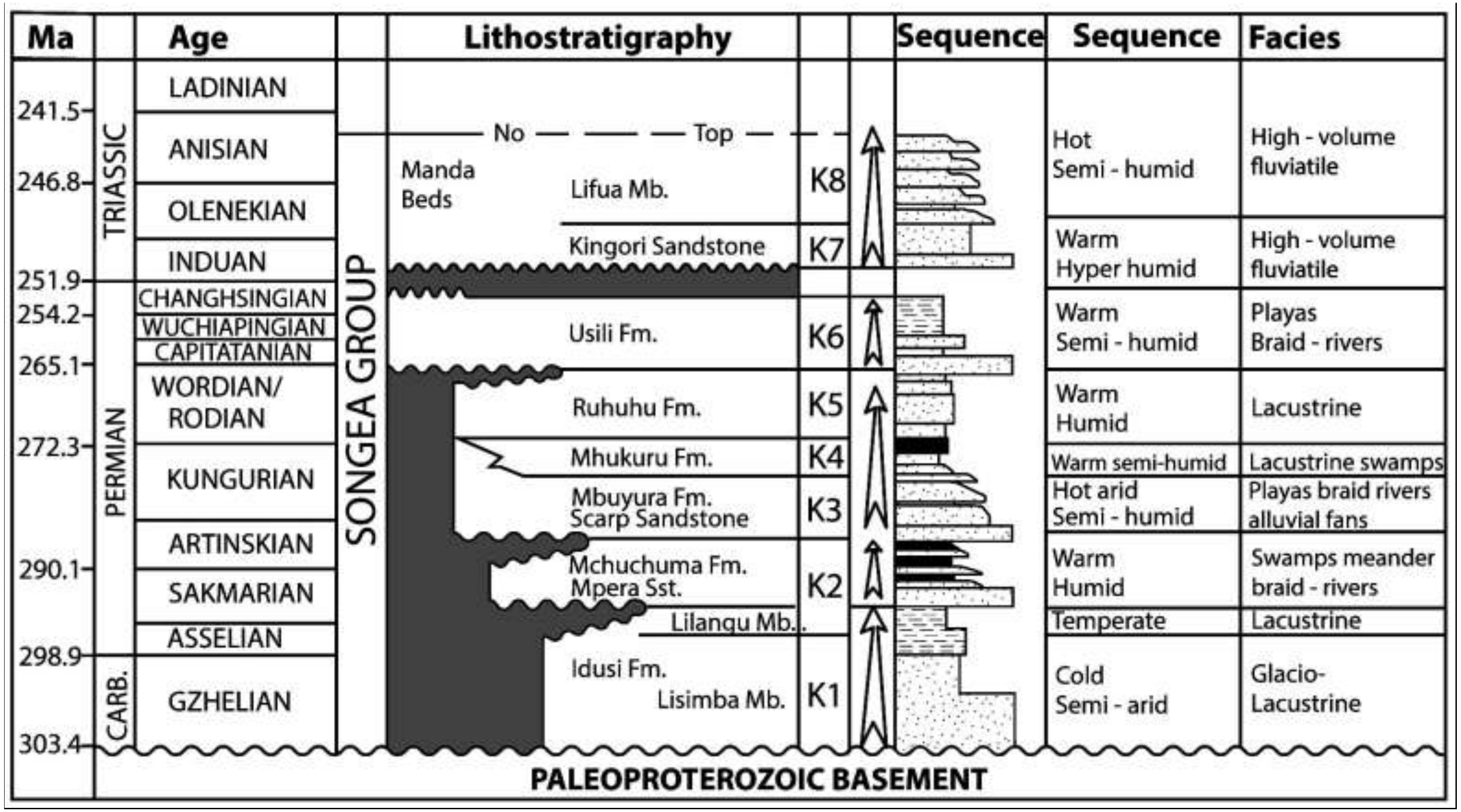

Figure 2. 1: **Stratigraphic chart of the inland Ruhuhu Basin (Songea Gp.) of Tanzania showing lithostratigraphic units, lithology and depositional environments (Modified from Wopfner 2002). Absolute time scale is adopted from Ogg et al. (2016), CARB. = Carboniferous Period.**

2.1.2 The Karoo-equivalent Strata in the Coastal Belt of Tanzania

The Karoo-equivalent rocks are known to crop out in the coastal belt of Tanzania. Indeed, there have been reported rare exposures of Karoo in the Ruvu Basin (e.g. Kent 1971, Kapilima 2003), in the Rufiji Basin (e.g. Kent et al. 1971, Hankel 1987, Wopfner and Kaaya 1991), and in the Tanga Basin (e.g. Seward 1922, Seward 1934, Kent et al.1971, and Mvile et al. 2020). The Karoo-equivalent strata of the Tanga and Ruvu basins, which are the main subject of this study (Figure 2.2), are briefly discussed below.

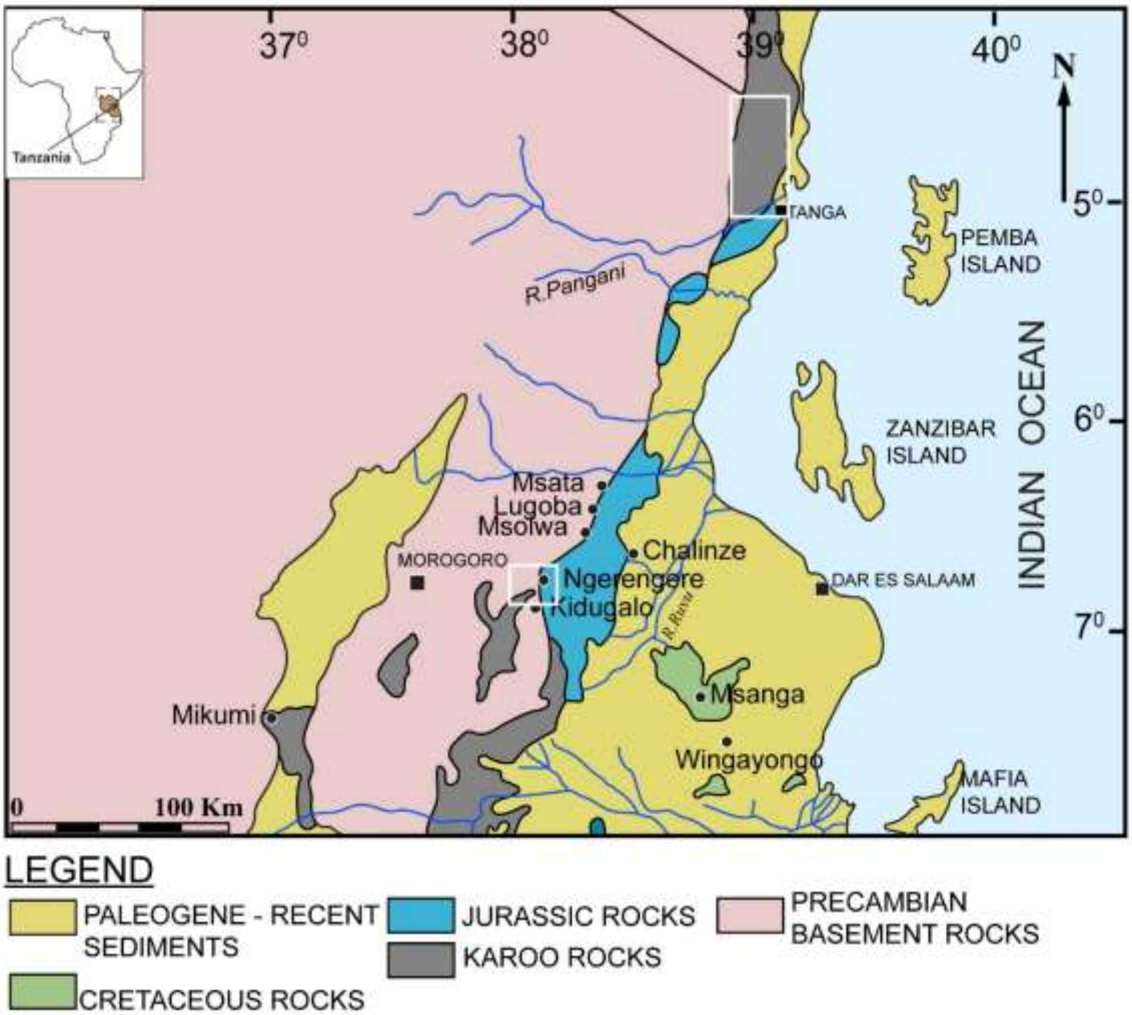

Figure 2. 2: A geologic map of the part of coastal Tanzania showing exposures of Karoo outcrops (white boxes) in the Ruvu and Tanga coastal basins (modified from Kent et al. 1971).

Karoo Exposures in the Tanga Basin

In the Tanga Basin, Karoo strata (i.e. the Tanga Beds) include: Kakindu shales exposed in the vicinity of the Kakindu River (UTM 0490076, 9450016); sandstone exposure at Kilulu hill (Mvile et al. 2020), along a road-cut exposure near Ngole bridge (UTM 509554, 9450553), Mringi Bridge (UTM 509958, 9455185) and Ndoyo Bridge (UTM 511477, 9459663) as well as a river-cut outcrop at Umba (UTM 496989, 9495589). A contact between the Permo-Triassic Karoo and Jurassic strata is exposed between Pongwe and Ngomeni areas (Stockley 1936). Stratigraphically, the Karoo strata in the Tanga Basin are informally sub-divided into lower, middle and upper units (Seward 1922, Seward 1934, Figure 2.3). The lower unit consists of the non-fossiliferous rocks that overlie the basement rocks (Seward 1922), comprising conglomerate, and arkose that are interbedded with dark, carbonate-rich shales (Figure 2.3), containing significant plant remains (Seward 1922). The lower unit is conformably overlain by the middle unit, which is characterized by thick carbonate-rich shales. These carbonate-rich shales host abundant plant remains which are poorly preserved (Seward 1922). The middle unit is conformably overlain by the upper unit, which is dominated by alternating sandstones and sandy shales.

In its field campaigns in 2014, the Tanzania Petroleum Development Company (TPDC) suspected the presence of the oldest sedimentary strata (K1) in the Tanga Basin based on lithofacies change that demonstrated presence of glacial tillites succeeded by coarse sandstones and laminites with drop stones (TPDC 2014). This observation motivated a drilling campaign in the basin aiming at understanding the Karoo succession in the basin, aiming at better understanding of the Karoo succession. Indeed, ten stratigraphic boreholes were drilled, three of which are utilized in this study.

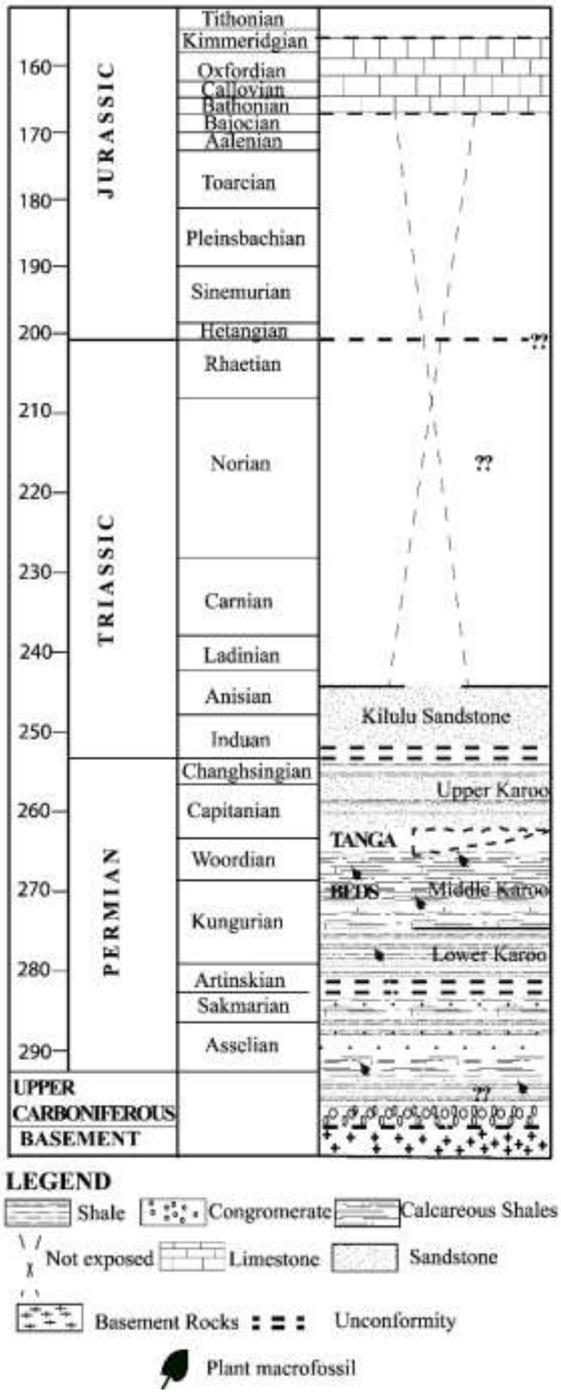

Figure 2. 3: **Paleozoic-Mesozoic lithostratigraphy of the Tanga Basin (Based on personal observations and observations made by Seward (1934), Kent et al. (1971), Catuneanu et al. (2005) and TPDC (2014).**

Karoo Exposures in the Ruvu Basin

In the Ruvu Basin, an outcrop at Ngerengere area is speculated to partly contain Karoo strata (Stockley 1936, Kent et al. 1971, Kapilima 2003). This outcrop is characterized by sandy limestone of probably Middle Jurassic in age sitting above feldspathic calcareous sandstone and conglomerates that are considered to be older than Jurassic (?potential Karoo strata) (Kent et al. 1971, Kapilima 2003). However, there are exploration wells, short stratigraphic boreholes drilled through the Ruvu Basin, along with other subsurface data that reveals extensive record of the Karoo strata in the subsurface interval of the basin.

2.1.3 Biostratigraphy of the Tanga and Ruvu Basins

Most of what is known about the ages of the Karoo rocks in the region is achieved through paleobotanical, vertebrate paleontological and a few palynological studies (Seward 1922, Seward 1934, Stockley 1936, Kamen–Kaye 1978, Hankel 1992, Smith 1995). In addition, a few published palynological data on the coastal Karoo rocks exist in the Rufiji Basin (Hankel 1987, Wopfner and Kaaya 1991). Unlike the inland Karoo basins where dating attempts using different biostratigraphic methods such as palynology (Semkiwa et al. 1997, Semkiwa 2003) have been applied, biostratigraphy/stratigraphy of coastal Karoo rocks has remained to be very poorly understood.

In the Tanga Basin, age assignment to the informally subdivided Karoo rocks into three lithostratigraphic units (Figure 2.3) was made possible by a few recovered plant macrofossils and a fossil reptile (i.e. *Tangasaurus*) (Kamen–Kaye 1978, Also see Figure 2.4). However, this biostratigraphic means of Karoo rocks dating in the Tanga basin still faces many limitations. Some of these include the fact that, the plant remains recovered were way too fragmented, some beyond recognition making the identification process very difficult (Seward 1922). Due to this it became very difficult to precisely assign the recovered specimen to their respective systematic positions in the vegetable kingdom (Seward 1922, Seward 1934). Also, for those few successfully identified specimen, according to Seward (1922), favoured European affinity rather than the expected Gondwanan Paleobotanic Province, a relationship that Seward (1922) could not account for. As a result, age assignment conclusions relied upon, besides the identified plant fossils, negative evidences such as the significant absence of the genus *Glossopteris* flora in the studied Tanga Beds sections.

However, genus *Glossopteris* was later confirmed to be present in the strata just above the beds that hosted the reptile remains (Seward 1934). The fossil reptile *Tangasaurus manelli* recovered near Kakindu area, in the vicinity of Msimabasi river (Figure 2.4) was used to support “middle Karoo” interpretation by placing the host beds into Beaurfort equivalent (probably Lower - Middle Beaurfort) (Seward 1922, Seward 1934, Kamen-Kaye 1978). At different times, the reptile remains of this kind has also been recovered in East African coastal Karoo basins and in the main Karoo basin of South Africa (Figure 2.4). The reptile bears different names in different localities such as *Kenyasaurus* in the Maji ya chumvi Formation (Kenyan Karoo), *Youngina* in the Beaurfort Gp. (South African Karoo) and *Hovasaurus* in the Sakamena Gp. (Madagascan Karoo) (Currie 1981, Smith 1995). The presence of this reptile in the Tanga beds suggests the Permo-Triassic (or a late Permian, or Beaurfort) stratigraphic position for the dated Tanga Beds (Kamen- Kaye 1978, Smith et al. 1995, Reisz 2011).

Generally, it remains very challenging to decide on the stratigraphic position of the Tanga Beds based on a few, poorly preserved plant fossils that were recovered in the “middle Karoo” beds. It has also been observed that, age inferences made for the “middle Karoo” have also been used to predict ages for the upper and lower most Karoo subdivisions in the Tanga beds. The latter suggests more speculation than actual dating. Furthermore, some plant species that were recovered such as the *Baiera tanganyinkensis* and the fauna genus *Tangasaurus* suggests an extension of the middle Karoo to ages younger than currently known.

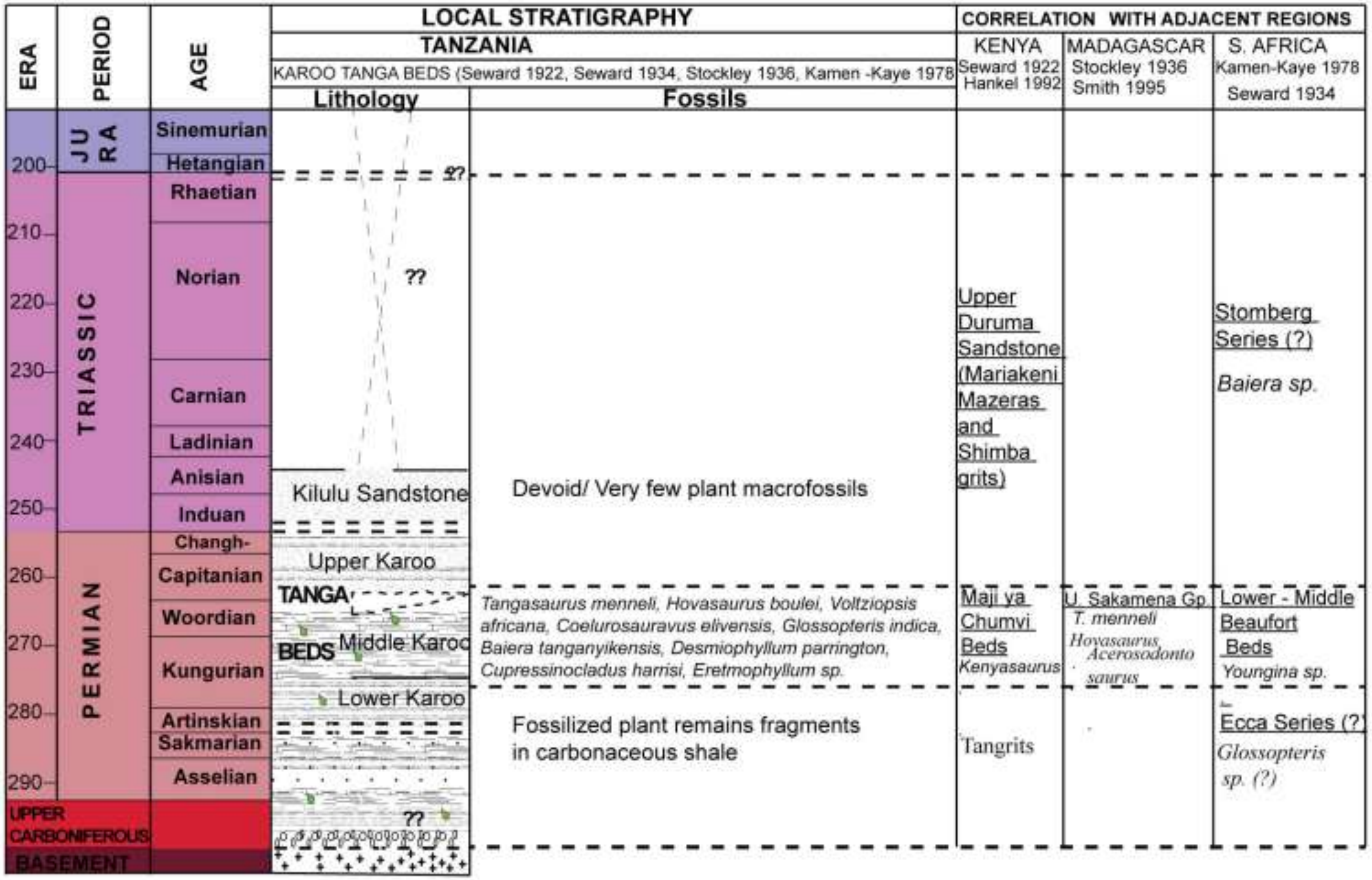

Figure 2. 4: Correlation chart of the Tanga beds stratigraphy (Compiled from Seward 1922, Seward 1934, Stockley 1936, Kamen–Kaye 1978, Hankel 1992, Smith et al. 1995).

In the Ruvu basin, Karoo outcrops are rare, but a thick interval up to approximately 2 km (McMurty 1985) is penetrated by an exploration well drilled in the basin (the Makarawe–1 well). There is only one surface exposure that has been linked to the Karoo in the basin (i.e. the Ngerengere beds). The current understanding on the depositional ages for the Ngerengere beds has evolved since the earlier works by Stokley (1936) through Kent et al (1971), Balduzzi et al (1992), Kreuser (1995) to Kapilima (2003). Stockley (1936) suggested an “upper Karoo” age for the Ngerengere beds, but he failed to find fossil evidences to support this proposal. Contrary to previous authors, Balduzzi et al. (1992) conducted a palynologic study to address the existing controversy on age of the Ngerengere beds using samples from Kizimbani-1 well. The reported assemblages included gymnosperm pollen genera *Callialasporites turbatus*, *Callialasporites damperia*, *Araucariacdiites australi*s, *Classopollis* and the organic-walled dinoflagellate cyst (dinocyst) *Nannoceratopsis gracilis* along numerous non–taeniate bisaccate pollen grains. However, most palynologic observations made by Balduzzi et al. (1992) favoured Toarcian-early Bathonian age conclusions for the Ngerengere beds and are discussed in the next chapter (i.e. chapter 3) of this thesis.

2.2 Materials and Methods

2.2.1 Materials

Materials used in this study included 39 core samples from three shallow stratigraphic boreholes in the Tanga Basin (Figure 2.6) and 7 drill cutting samples from lower/deep Makarawe–1 well (Figure 2.7). These were studied palynologically. The rest include 10 outcrop specimens from the Kakindu River that were studied for paleobotany (Figure 2.5). The sampled boreholes in the Tanga Basin included Jihirini–1 borehole (0489472E, 9454395N), Kakindu–1 borehole (0490038E, 9449985N) and Vunde–1 borehole (0497057E, 9454918N). These were drilled by TPDC in the main Karoo equivalent outcrops of the Tanga Basin i.e. at Vunde – Manyinyi village (Vunde–1)

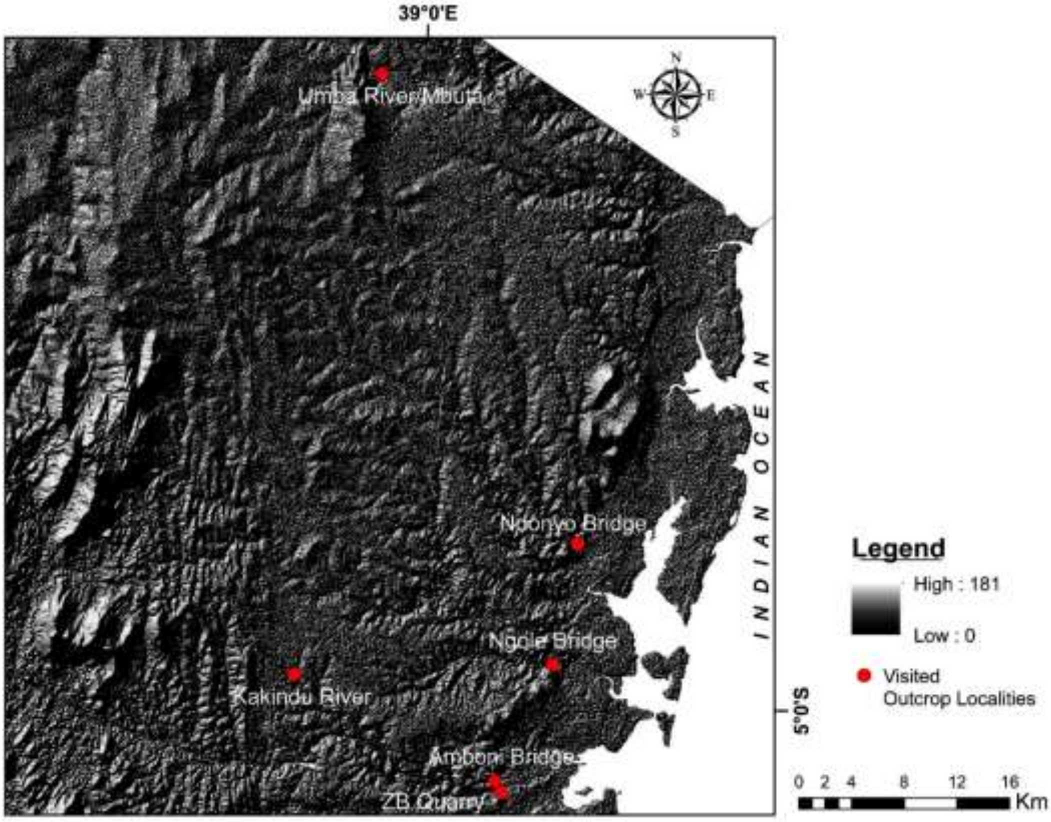

Figure 2. 5: A hill shaded relief map of (30m resolution SRTM1 - DEM) showing location of the visited Karoo equivalent outcrops during the geological fieldwork in the Tanga Basin.

borehole) and Jihirini village (Jihirini-1 and Kakindu-1 boreholes) between 2012 and 2014. The lithological details of the sampled boreholes/wells are provided in Figure 2.6. Other materials include published maps used in locating the Karoo equivalent outcrops in the Tanga Basin (Hartley and Macce 1962, Kent et al. 1971 and TPDC 2015), drilling reports for Makarawe–1 well (McCarty 1985) and Tanga Boreholes (TPDC 2015). Geographic locations during the fieldwork were recorded using a Geographic Positioning System (GPS) set to the Arc 1960 datum. Software used included C2 data analysis software (Version 1.7.2) and Adobe Illustrator CS6 (Version 16.0)

2.2.2 Methods

Field work

One-week fieldwork was conducted in the Tanga Basin aiming at locating, making geological observations and descriptions as well as sampling for further analysis. Several Karoo equivalent outcrops localities were visited (including a few post Karoo outcrops) and they include Kakindu River (0489901E, 9450104N), Umba River (496989.7E, 9495589.5N), Ndonyo Bridge (0511327E, 9459949N), Ngole Bridge (0509452E, 9450801N), Mringi bridge (509958.93E, 9455185.18N), Amboni bridge (0505048E, 9442057N), Amboni ZB Quarry (0505548E, 9441179N) (Figure 2.5).

Sampling

A total of 39 drill core samples from three shallow stratigraphic boreholes in the Tanga Basin and 62 grab samples (Figure 2.6 and) were investigated in this research. In the Ruvu Basin 7 drill cutting samples from lower/deep Makarawe-1 well were also included in this investigation (Figure 2.7). All lithologies, stratigraphic positions and locations of the studied samples from the Tanga Basin are summarized in Appendices 2.1 and 2.2 and in the section below as follows:

Vunde-1 Borehole

Sampled/ Studied Interval: 20m-175 m Lithology: Horizontal/ planar laminated silty shale: Grayish Black in color (N2); Well sorted (except for a few parts having scattered carbonate clasts), with occasional concretional structures and carbonate veins. Sedimentary structures such as cross beds and convolute laminae dominate parts of the borehole. Visible minerals include pyrite. Vast fossilized plant fragments are observed (Figure 2.6).

Lithostratigraphy: “Middle Karoo”

Jihirini-1 Borehole

Sampled/ Studied Interval: 40m-201 m

Lithology: thinly laminated shales and siltstone in places; well sorted; grayish black (N2) to medium dark grey (N4); with micro faults and abundant carbonate veins (Figure 2.6).

Lithostratigraphy: "Lower Karoo"

Kakindu -1 Borehole

Sampled/ Studied Interval: 10m-155 m

Lithology: uniformly fine-grained silty shale; medium light grey (N6) and very light grey (N) colored; occasional soft-sediment deformation; planar laminated; micro faults and abundant carbonate veins (Figure 2.6).

Lithostratigraphy: Lower to Upper Karoo

Makarawe -1 Well

Sampled/ Studied Interval: 2765m-3810 m

Lithology: Uniformly medium to coarse grained sandstone with occasional red, green and grey claystones (Figure 2.7).

Lithostratigraphy: Karoo equivalent (Tanga Beds)

Table 2. 1: Number of samples

Sample Source	Sample Type	Sample Number
Kakindu-1 BH	Drill core	12
Vunde-1 BH	Drill core	14
Jihirini-1 BH	Drill core	13
Makarawe Well	Drill Cutting	12
Tanga Basin Fieldwork	Grab samples	62

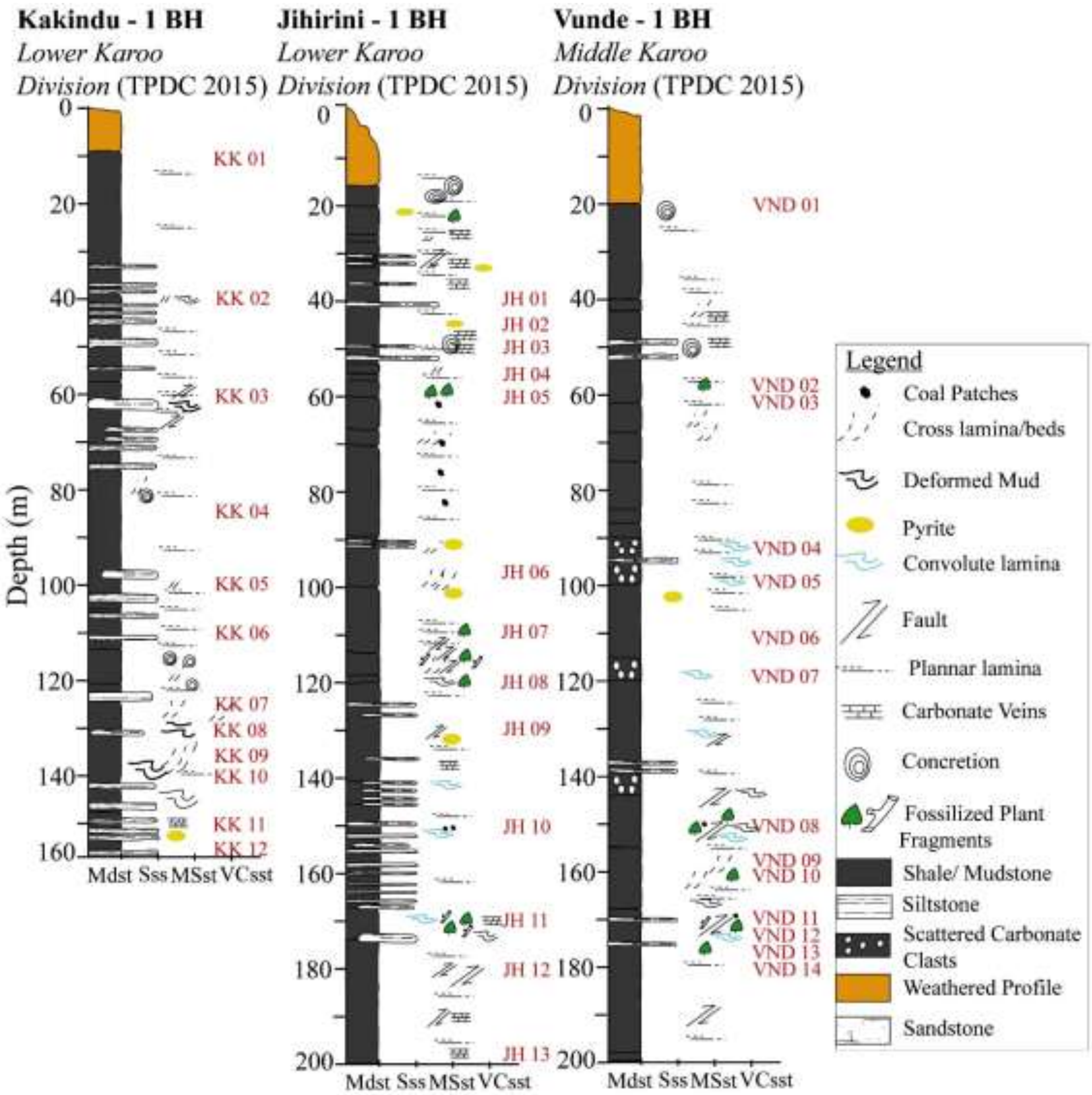

Figure 2. 6: Lithostratigraphy of the boreholes drilled through the Tanga Basin, showing sampled depths. No age boundaries are described for the boreholes following the absence of dating data. (KK 01-12 = sample number 1-12 in the Kakindu-1 borehole; JH 01-13 = sample number 1-13 in the Jihirini-1 borehole; and VND 01-14 = sample number 1-14 in the Vunde-1 borehole).

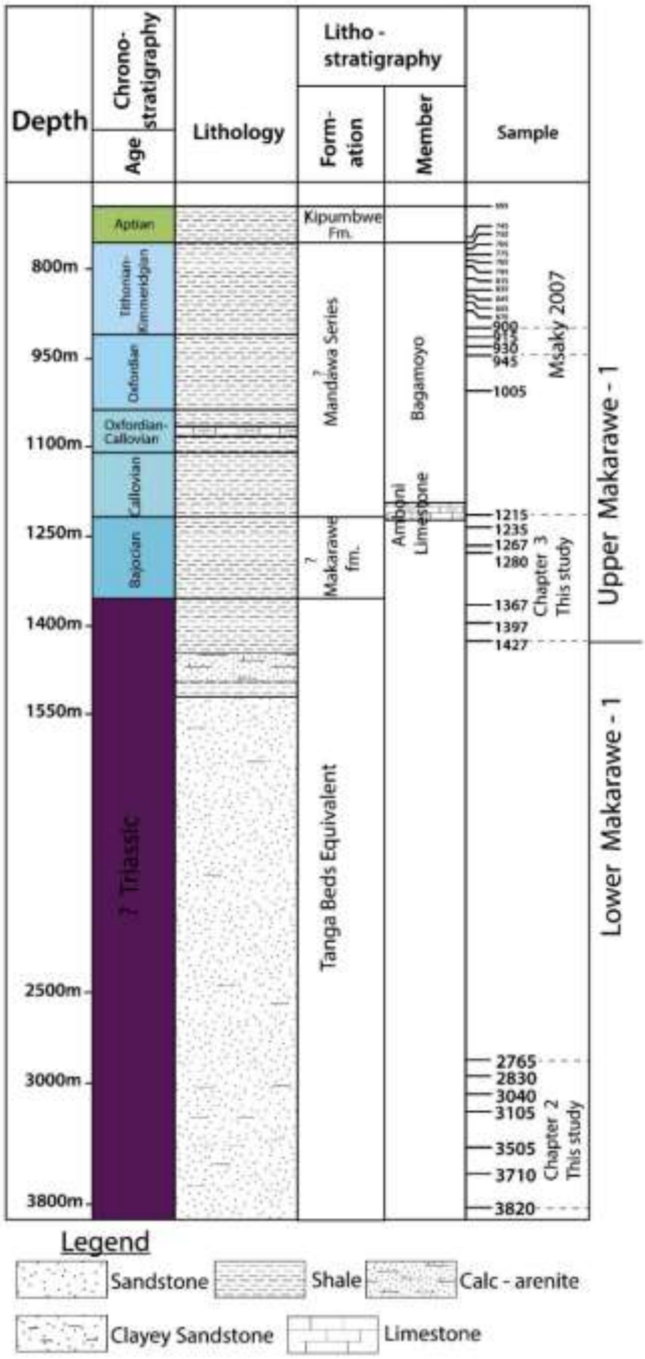

Figure 2. 7: Makarawe-1 well (Lithology, stratigraphy and sampled intervals) (Not to scale, based on interpretations by made by McCarty 1985 and Msaky 2007).

Additionally, 62 outcrop samples were collected during the field trip in the Tanga Basin (Appendix 2.2). These samples varied in quality as a result of oxidation and weathering, and therefore, for dating purpose, the focus was on only ten (10) fresh, greyish–black shale/mudstone beds exposed at the Kakindu River which hosted vast preserved plant remains (Figure 2.8-5).

Figure 2. 8: Sampling of the Tanga beds cores and outcrops: (1, 2, 4) Core descriptions and logging at the TPDC core yard, (3) A few core boxes of the Tanga beds laid down for logging and sampling and (5) Thinly laminated shales rich in plant remains at Kakindu river.

Palynological Sample Processing

Chemical Procedure

Palynological processing for the all the core and drill cutting samples was conducted at the Earth-Sciences Laboratory (GML) of the University of Utrecht. On forehand, depending on the amount of material that was available, samples were split into two halves, and the other half was sent to a different laboratory in the UK (PLS, Wales, UK). This was done to increase the chance of good results and to check for quality control. Processing of lithified rocks included the following: Cleaning of the samples (i.e. physically removing visible impurities and eventually washing) and grinding into approximately 2 mm^2 (or smaller) parts to simplify the chemical processing by increasing the surface area for a chemical reaction to take place.

The weight of the samples required for processing depended on the type of lithology. With siliciclastic clay- and siltstones, less material (approx. 5 - 8 g) was required, whereas in the calcareous intervals more material (approx. 10 – 15 g) was required. In organic-rich lithologies such as coal or black shales 1 - 3 g samples was sufficient.

The samples were placed in an acid-resistant plastic container (HDPE; preferable volume 180 ml or more) and were labelled appropriately. They were then moved to the laboratory for chemical processing in a fume hood (protected environment). Chemical processing involved adding 38 - 40% Hydrofluoric acid (HF) to the samples (a very strong reaction that can be diminished by adding more hydrofluoric acid). When reaction stopped, water was added to fill-up the sample container and the samples were left to settle over-night.

After approximately twelve hours, decantation was performed without disturbing the settled sediments. Water was filled - up again and centrifugation was conducted. After the latter procedure, the beakers with HF were placed onto an orbital shaker for about 2 hours. After two hours of shacking, the samples were again returned to a fume chamber. Eventually, the samples were washed to remove the organic matter rim formed at the side of the beaker and water was added to the samples. The samples were put away to rest for the night with closed lids. They were then decanted on the next day. Water was added, centrifugation and decantation were repeated again. After this procedure, the samples were ready to sieve.

Sieving and Mounting

Sieving was conducted to further separate/free the palynomorphs along with other organic matter from the sediments. The procedures for sieving involved opening the sample lids (i.e. samples from the chemical laboratory) and placing them into 120-micron sieve but on top of the plastic container. All the material from the sample container were poured in 0.5-1 L plastic container through the 120 - micron mesh. The empty sample container was cleaned to ensure that no sample is left behind. The sieved material was then poured from the plastic container onto a 10 - micron mesh. The material in a 10-micron mesh was sifted, by making a clock-wise rotation to remove all the air that will be visible between the cloth of the sieve and the water contact. When all the water was drained, only very fine sediment particles were visible in the sieving container and a little amount of water (i.e. amongst the material that went through the 10-micron sieve). Water was added to the sample in a sieve using a splash-bottle, while holding the sieve under a low-angle towards a crucible. Only the floating part was important at this stage, the residues are thrown away. The sample (in a crucible) was moved to a second ultrasonic bath (Ultrasonic bath-2) and was left to settle. Once everything had settled, the sample was moved from crucibles in ultrasonic bath - 2, to a 10 - micron sieve and sifted.

When the sample was dry, water splashing was carefully performed using a splash bottle. The wanted sample was then slowly poured into the vials sample eppis leaving the residues behind. After this procedure, the samples were ready for the mounting procedure.

Slide Mounting

Before approaching any procedure in this phase, a heater was switched on to attain the maximum curing temperature of 35°C. Mounting slides and cover - slips were prepared by holding them to the burners to remove any fatty material. After this preparation, the samples in the eppis were taken to the vortex for shacking and mixing. About two to three droplets of the sample was taken using a disposable glass - pipette and transferred into a new sample vials eppis. Two droplets of PVA were added to the sample. The sample -PVA mixture was taken to the vortex for mixing.

Water was added to the sample-PVA mixture. The mixture was then sampled using another pipette and slowly poured the mixture on top of the cover - slip that was on top of the heating media. The sample is then left to dry. Once everything was dry, one droplet of glue for glass was poured in the middle of the slide. The slide was then carefully lifted and mounted on top of a cover - slip. Non - pointed object was used to ensure the glue has spread throughout the cover - slip. The slide was then cured for about 30 seconds using a (day - light) lamp. The slide was then washed with pH neutral detergent, using lukewarm water, and a (tooth-) brush to get it ready for a microscopic analysis.

Microscopic palynological analyses

A transmitted-light microscope (Model: Microscope Primotech D/A cod, stage ESD, integrated with IP Camera) was used for examination of the palynomorphs and photographing. Objective magnifications of x16, x40, x60 and rarely x100 were used. The magnification of x100 was done with oil immersion to enhance observation of the fine morphological features of the palynomorphs.

Palynological analysis was both quantitative and qualitative. Qualitative analysis involved the study of palynomorphs at generic and species level under the microscope. This relied on the use of morphological properties (i.e. outline/shape, size, ornamentation and presence/absence of apertures) to recognize specific taxa. Following completion of qualitative analysis, a quantitative analysis was performed. Quantitative analysis involved counts of major palynomorph and phytoclast groups present in the assemblage. The counting (as it was intended), achieved a total of 100-200 specimens per slide to represent the entire assemblage (Appendix 2.3). For stratigraphic purpose, C2 data analysis software (version 1.7.2) was used for reconstruction of range and distribution charts. These included presence - absence range charts displaying all identified palynomorphs in the assemblage as well as semi – quantitative range charts showing percentage comparison of main taxa.

Photomicrography was conducted with a digital camera, which stored images in JPEG file format. These were later transferred to computer softwares (i.e. Adobe

Illustrator) for further analysis. The study of palynomorphs at generic and specific levels in each sample was conducted to establish the stratigraphic range of each taxa recovered. Preliminary slide observation in the laboratory indicated differences in palynomorphs yields (Table 2.2). Makarawe-1 slides yielded better preserved specimens (except for slide MK–3040 m that was barren). All the boreholes in the Tanga basin yielded palynomorphs but with a challenging preservation status.

Table 2. 2: Number of samples Vs. Palynomorph yield in subsurface samples of the Tanga and Ruvu basins.

Sample Source	Sample Type	Sample No.	Palynomorph Rich Samples	Barren Samples
Kakindu -1 BH	Drill core	12	12	0
Vunde -1 BH	Drill core	14	14	0
Jihirini -1 BH	Drill core	13	13	0
Makarawe Well	Drill Cutting	12	11	1

2.3 Results and Discussion

2.3.1 Palynostratigraphy of the "lower section" (2765 m-3820 m) of the Makarawe - 1 Well

Recovered palynomorphs from the lower Makarawe-1 well (both stratigraphic significant and associated taxa) are presented in Plates 2.4-2.8. Ranges of identified taxa are shown in Figure 2.10. Likewise, quantitative distribution patterns of the selected taxa are shown in Figure 2.11 a, whereas presence/absence patterns are shown in Figure 2.11 b. An overview of the taxonomic references of the encountered taxa is provided in photo plates section.

Generally, samples from Makarawe-1 well of the Ruvu Basin have a quantitatively large yield of palynomorphs, except for one sample (i.e. MK 3040 m), which is almost barren. The recovered palynomorphs are moderately well preserved to poorly preserved. Based on first and last occurrence of diagnostic palynomorph taxa and correlation with well-established palynological units in Antarctica (Kyle 1977), India (Kar and Ghosh 2018), Kenya (Hankel 1992) and Mozambique (Pereira et al. 2015), three main palynological intervals are identified.

These units are commonly characterized by gymnosperm pollen grains that include a range of monosaccates and bisaccates. Other sporomorph types include a significant number of spores recorded in the assemblages. In addition, a remarkable spike of the genus *Reduviasporites*, which is considered of a fungal origin are also observed. These fungal remains demonstrate a decreasing trend as moving from the bottom to the top of the lower Makarawe–1 well samples (i.e. from sample MK 3820 to sample MK 2765). No dinoflagellate cysts nor acritarchs were documented in this interval (i.e. Depth 2765 m-3820 m). The main palynological intervals recorded in the lower Makarawe–1 well samples are presented in stratigraphic order (from the oldest to the youngest) in the section below as follows;

Palynological Interval – 1: *Falcisporites zapfei* Interval

Samples: MK 3820 (3820 m) and MK 3710 (3710 m)

Definition: From the first to the last appearance of *Falcisporites zapfei*

Palynological composition: This palynological interval is dominated by trilete spores and a few non – striate bisaccate pollen (Figure 2.11 a and b). Dominant spore taxa include genus *Punctatisporites* which makes 17% of the total assemblage and genus *Anapiculatisporites* that makes 7%. Non-striate bisaccate pollen grains include *Alisporites australis* (3.8%), *Pinuspollenites* sp. (3%), *Platysaccus* sp. (2%), *Pinuspollenites stinctus* (1.5%), *Minutosaccus protonei* (3%), *Minutosaccus crenulatus* (1.5%), *Simeonespora khlomorze* (3%), and *Falcisporites zapfei* (4%). The latter is a stratigraphic significant taxon for this interval whereas *Protohaploxypinus rugatus* (1%) is the only striate bisaccate taxon recorded in the assemblage.

Other taxa completing the assemblage include spores and monusulcate pollen. Spores include *Spinitriletes echinoides* (6%), *Verrucosisporites* sp. (3%), *Proprisporites pocockii* (2%), *Raistrickia saetosa* (3%), *Gordonispora* sp. (4%) and *Aratisporites* sp. (1.5%) and *Laevigatosporites* sp. (0.4%) while observed monusulcate pollen include *Cyacadopites* sp. making 2% of the total assemblage.

Age Assignment

The microfloral assemblage of this interval is characterized by abundant trilete spores and subordinate gymnosperm pollen. Despite its presence in other samples above this zone, *Punctatisporites* sp. makes its abundance optimum (i.e. up to 17% of the total assemblage) in this interval. *Punctatisporites* sp. has been reported in the Permian of Tanzania (Hart 1967, Christopher 2010). Other trilete spores unique to this assemblage include *Calamospora* sp. which is also reported in the lower Permian of Tanzania (Christopher, 2010), *Callumispora barankensis* (lower to upper Permian) of India (Dutta et al. 1988) and the genus *Aratisporites* which is reported in the Permian of India (Pillai et al. 2016).

Recorded Permian taxa in this assemblage include *Protohaploxypinus rugatus* documented in the Lower Permian (Sakmarian-Artinskian) of the former Zaire, the Democratic Republic of Congo (Pierart 1979), *Falcisporites zapfei* and *Klausipollenites schaubegeri* documented in the late Permian palynologically dated samples of South Africa (Stapleton 1977) and Ethiopia (Davidson 1976) respectively.

A few Triassic taxa have also been recognized in this assemblage, and includes *Minutosaccus protonei* and *Minutosaccus crenulatus* documented in the Late Triassic (Ladinian-Norian) of Tanzania (Hankel 1987) as well as *Gordonispora sp.* documented in Carnian to Norian of Zimbabwe (d'Engelbronner 1996). The presence of these Triassic taxa amongst the Permian interval may be explained by contamination/caving from the (overlying) Triassic interval. An early Permian age (Sakmarian-Artinskian) is assigned to this palynological interval.

Palynological Interval - 2: *Reduviasporonites* sp. Interval

Samples: MK 3505 (3505 m) and 3105 (3105 m)

Definition: Total range of genus *Reduviasporonites*

Palynological composition: This interval is characterized by fungal remains *Reduviasporonites chalastus* and *Reduviasporonites catenulatus* documented in both samples (Figure 2.15). Associated in this interval include non - striate bisaccate pollen grains belonging to the "*Alisporites – Falcisporites* complex" (De Jersey et al. 2013) with common taxa being *Alisporites parvus* (13%), *Falcisporites australis* (26%), *Alisporites indicus* (3%), *Falcisporites minutisaccus* (3%) and *Alisporites australis* (5%). Other bisaccates have also been recorded and they include *Protohaploxypinus rugatus* (1%), *Pinuspollenites* sp. (4%), Somaroppolenites *specious* (5%), *Kamthisaccites* sp. (0.5%) and *Minutosaccus maedleri* (1%). *Callialasporites turbatus* (1%) and *Cycadopites* sp. (3%), *Ephedripites* sp. (%) makes a few pollen grains in the assemblage. Observed spores in the assemblage include: *Retusotriletes* sp. (1%), *Anapiculatisporites* sp. (10%), *Punctatisporites* sp. (3%), *Raistrickia* sp. (1%) and *Gordonispora* sp. (0.8%).

Age Assignment

The genus *Reduviasporonites* in this interval suggests a correlation to the the Permian-Triassic boundary interval. The marker species (i.e. *R. chalastus* and *R. catenulatus*) are observed to make their first appearance in the late Permian and demise in abundance in the Early Triassic (Elsik 1999, Foster et al. 2002). This may suggests an uppermost Permian (Changhsingian) lower age limit and a lowermost Triassic (Induan) upper age limit for this interval. This fungal event is well documented in the Permian–Triassic transition of Mozambique (Pereira et al. 2016, Galasso et al. 2019), Madagascar (Rampino 2017), Kenya (Hankel 1992), South Africa (Steiner et al 2003) and worldwide (Visscher et al. 2011). Other non-fungal sporomorphs in this interval that supports the P-T transition interpretation include a bisaccate pollen *Falcisporites australis* which is also recorded in the Upper Permian to Lower Triassic of Kenya (Hankel 1991).

Associated presence of Late Triassic taxa in this assemblage such as *Minutosaccus maedleri* and *Falcisporites minutosaccus* recorded in the Upper Triassic of India (Vijaya and Murthy 2012, Tripathi and Vijaya 2006) as well as *Alisporites parvus* documented in Late Triassic of Morocco (Cousminer and Manspeizer 1976) may possibly suggest caving in this interval. Hence, based on the presence of the fungal genera *Reduviasporonites* in this interval and supporting sporomorph distribution patterns, a Permian - Triassic transition is inferred for this palynological interval.

Palynological Interval - 3: *Alisporites – Falcisporites* Interval

Samples: MK 2765 (2765 m), MK 2830 (2830 m) and MK 3040 (3040 m)

Definition: From the last appearance of the genus *Reduviasporonites* to first appearance of genus *Classopollis*. Inception of *Classopolis* spp. at the end of this interval is discussed in detail in the next chapter (i.e. chapter 3).

Palynological composition: This palynologic interval is characterized by the dominance of non - striate bisaccate pollen grains belonging to the *Alisporites - Falcisporites complex*. These include *Alisporites australis* (16.5%) and *Falcisporites australis* (14%) as dominant taxa. Sub - dominat taxa in the interval include *Alisporites parvus* (9%), *Hamiapollenites minimus* (1.3%), *Lueckisporites virkkiae* (0.6%), *Alisporites trissacate* (0.5%), *Protohaploxypinus rugatus* (3%), *Platysaccus* sp. (2%), *Paraciccites bilateralis* (0.6%), *Pinuspollenites* sp. (0.6%), *Corrisaccites alutas* (2%), *Striatoabicites* sp. (0.6%), *Callialasporites turbatus* (2%), *Platysaccus rugatus* (4%), *Satsangisaccites nidpurensis* (1%), *Anapiculatisporites* sp. (6%), *Cycadopites* sp. (2%), *Retusotrilete* sp. (1%), *Punctutisporites* sp. (1.3%), *Raistrickia* sp. (3%), *Gordonispora* sp. (1.6%), non-striate bissacate pollen and bissacate fragments making up to 40% composition. Trilete spores are also observed in very few amount (i.e. not more than 1%).

Age Assignment

This interval shows similarity with the underlying interval due to persistence of the *Alisporites/Falcisporites* complex and a few spores recorded. The only difference with the underlying interval is the fact that, no fungal spike is observed in this interval instead, the *Alisporites - Falcisporites* complex appears to be more significant/ dominant. Dominance of *Alisporites australis, Falcisporites australis* and *Alisporites parvus* in this assemblage suggest a wide range of Triassic age (Figure 2.10). However, other occurrences recorded from the Permian (late Permian mostly) have shown their first appearance in this zone suggesting the presence of reworked Permian palynomorphs in this interval. These include *Hamiapollenites minimus* (Jha and Aggarwal 2017) *Lueckisporites virkkiae* (Jha et al. 2014), *Paraccisites bilateralis* (Maheshwari and Srivastava 1984), *Corrisaccites alutas* (Tripathi 1996) and *Satsangisaccites nidpurensis* (Tiwari et al 1996).

Rare abnormal gymnosperms having three air sacs have also been recorded. These includes *?Alisporites trisaccate* that are obseved only in this interval. Trisaccates are reported globally in the P - T assemblages (Foster and Afonin 2005, Benca et al. 2018). Such teratological phenoma are considered a consequence of environmental stress. These pollen however were not observed in the preceding assemblage (i.e. Palynologic interval-2), which was linked to the P - T transition interval. Based on the observed taxa of stratigraphic significance, a Triassic age is suggested for the studied samples making this interval.

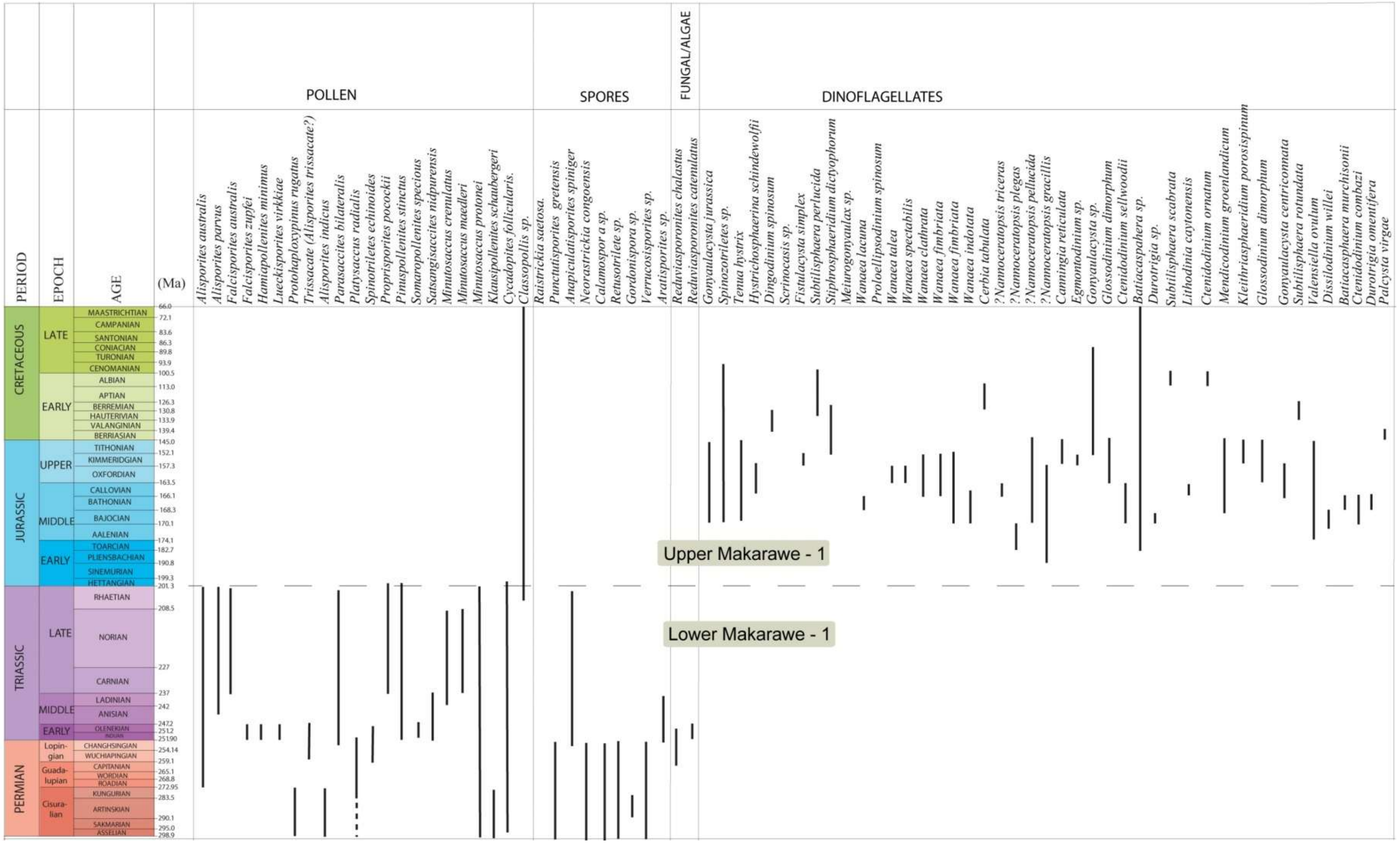

Figure 2. 9: Stratigraphic range chart of significant taxa of the deep Makarawe–1 samples.

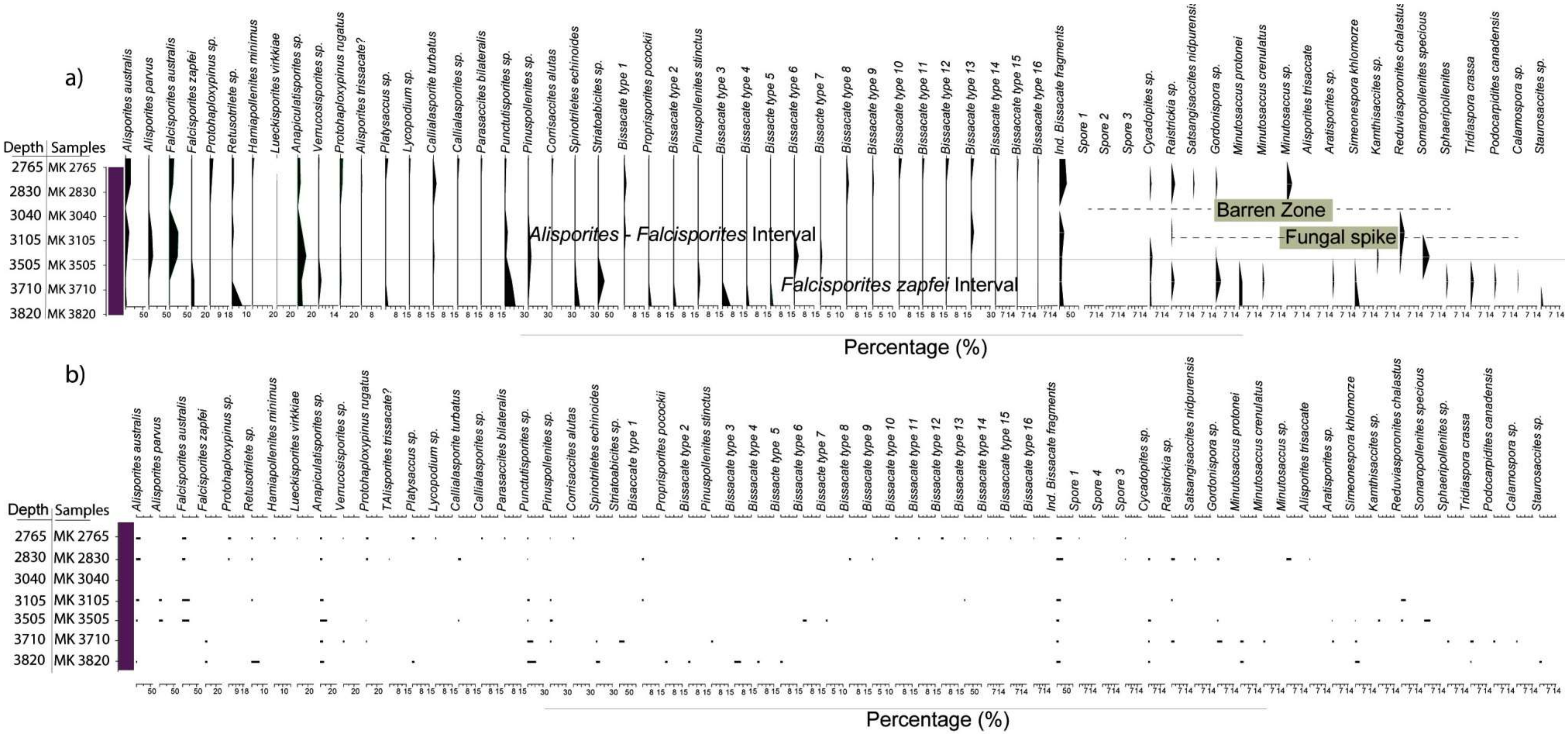

Figure 2. 10: a) **Relative abundance of selected palynomorph groups from the deep Makarawe-1 borehole samples (i.e. depth 2765m–3820m) showing their stratigraphic distribution (plotted as percent of total palynomorph counts, including the bissacate fragments)** b) **Presence–Absence chart for selected palynomorphs recovered in the deep Makarawe–1 samples**

2.3.2 Palynostratigraphy of Tanga Beds Cores (Kakindu-1, Jihirini-1 and Vunde-1 Boreholes)

All the investigated samples from the Tanga Beds (i.e. Kakindu-1, Jihirini-1 and Vunde-1 core samples) yielded abundant palynomorphs (Table 2.2). The preservation quality for the recovered miospores was generally very poor for Kakindu-1 and Vunde-1 boreholes. This means that, about half of the material in each slide were degraded beyond recognition. The remaining half in the assemblages was suitable for palynological identification based on amb shapes, sizes, visible ornamentations and presence or absence of apertures. Samples from Jihirini-1 borehole had very poor preservation making the identification and recognition process impossible. Hence, for the Tanga cores, Jihirini-1 borehole is excluded in age discussions for the Tanga Beds.

Sixty (60) miospore taxa (including 51 pollen taxa, 9 spore taxa) were recognized from Kakindu-1 and Vunde-1 boreholes. Rare fungal spores/ algae were also observed to make part of the recognized palynologic interval. Images for selected palynomorphs are shown in Plates 2.9 - 2.13, quantitative distribution patterns of the selected taxa in Figures 2.16 and 2.18a where by presence/absence patterns are shown in Figures 2.13 and 2.14 b.

Based on first and last occurrences of palynomorph taxa, relative abundances and ranges of selected taxa through the successions, two palynologic intervals are recognized in Kakindu-1 borehole, and three other palynologic intervals in Vunde-1 borehole (Figure 2.12). Similarly to the lower Makarawe-1 samples, no dinoflagellates or acritarchs were observed amongst documented taxa in Kakindu-1 and Vunde-1 boreholes (Figure 2.12 and 2.14 a). Definition of palynologic intervals documented in Kakindu-1 and Vunde-1 boreholes is presented below in ascending stratigraphic order (i.e. from the bottom to the top of the boreholes).

2.3.2.1 Palynostratigraphy of the Kakindu–1 Borehole

For the Kakindu-1 borehole, two (2) main palynologic intervals were identified which suggest a late Carboniferous - early Permian (Asselian - Kungurian) and late

Permian (Lopingian) age. These palynologic intervals are characterized mainly by gymnosperm pollen that include both striate and non–striate bisaccate forms. Spores and other monosaccates pollen were also observed.

Palynologic Interval – 1: *Vitreisporites* sp. - *Klausipollenites scheubergeri* Interval
Samples: KK 12 (155 m), KK 07(125 m) and KK 05 (100.4 m)
Definition: From first to last appearance of *Vitreisporites* sp. and *Klausipollenites scheubergeri*

Palynological Composition

The palynologic intervals identified between depths 100m-155 m is marked by the dominance of bisaccate pollen grains (Figure 2.12). The main taxa documented include *Vitreisporites* sp. *(c.f. pallidus?)* (57.1%), *Scheuringipollenites circularis* (29.3%), *Satsangiccisites nidpurensis* (6.7%), *Paleopodocarpites alatus (c.f. annulatus)* (12.2%), *Crucissacites variosulcatus* (2.4%), *Pinuspollenites* sp. (7.3%), *Paleopinacites perfectus* (14.6%), *Pteruchipollenites thomasii* (7.3%), *Striatites tentulus* (4.9%), *Lunatisporites sp.* (2.4%), *Faunipollenites singrauliensis* (7.3%) and *Corrisaccites alatus* (2.4%). Other miospore taxa found associated with the bisaccates include various spores belonging to *Cordaites* sp. (3.6%) and other spores (2.4%) that were indetermined due to preservation problems (Figure 2.12).

Age Assignment

The microfloral assemblage recovered in this interval has only few diagnostic constitutents for the Late Carboniferous and many for the early Permian. The miospores are represented mainly by gymnosperms *Vitreisporites* sp. and *Sheuringipollenites circularis* which are widely accepted to mark the Late Carboniferous to Early Permian of Australia and Antarctica (Norris 1965, Kemp 1977). *Klausipollenites schaubergeri* and *Protohaploxypinus limpidus* although are a bit more long–ranging, they also corroborate this interpretation. Documented spores belonging to genus *Cordaitina* as well as most of the remaining bissacate pollen genera imply an early Permian age (i.e. Asselian - Kungurian). Therefore, based on the presence of a few Late Carboniferous markers and numerous early Permian markers, a Late Carboniferous - early Permian age is postulated for this interval.

Palynologic Interval – 2: *Jugasporites vellicoites* Interval

Samples: KK 02 (40.4 m), KK 03 (60.4 m) and KK 04 (84.3 m)

Definition: From first to last apperance of *Jugasporites vellicoites*.

Palynological Composition

This interval shows some similarities with the underlying samples (i.e. Late Carboniferous to early Permian) in the way that it is also dominated by saccate pollen belonging to genus *Jugasporites vellicoites* up to 17% abundance of the total assemblage. Associated taxa include *Jugasporites gams* (2%), *Corrisaccites alutas* (3%), *Pteruchipollenites thomasii* (8%), *Cordaitina* sp. (12%), *Alisporites* sp. (30%), *Scheuringipollenites circularis* (8%), *Pinuspollenites minimus* (10%), *Protohaploxypinus limpidus* (1%), *Klausipollenites devolvens* (1%), *Paleopodocarpites alatus* (2%), *Alisporites ovatus* (6%), *Falcisporites stabilis* (10%) and *Alisporites australis* (4%).

Age Assignment

The oldest record of *Jugasporites vellicoites* is widely accepted to mark late Permian (Lopingian) age in the African Gondwana (Hart 1963), India (Maheshwari 1969) and Antarctica (Rakotoarivero 1970). The increase in abundance of a typical Permian spore belonging to genus *Cordaitina* also support a late Permian interpretation. Other late Permian miospores in this interval include *Jugasporites gams, Crucissacites variosulcatus, Faunipollenites gopadensis, Faunipollenites singrauliensis* and *Pinuspollenites sp.* (Figure 2.12 and 2.13). Hence, a late Permian age is assigned to this interval.

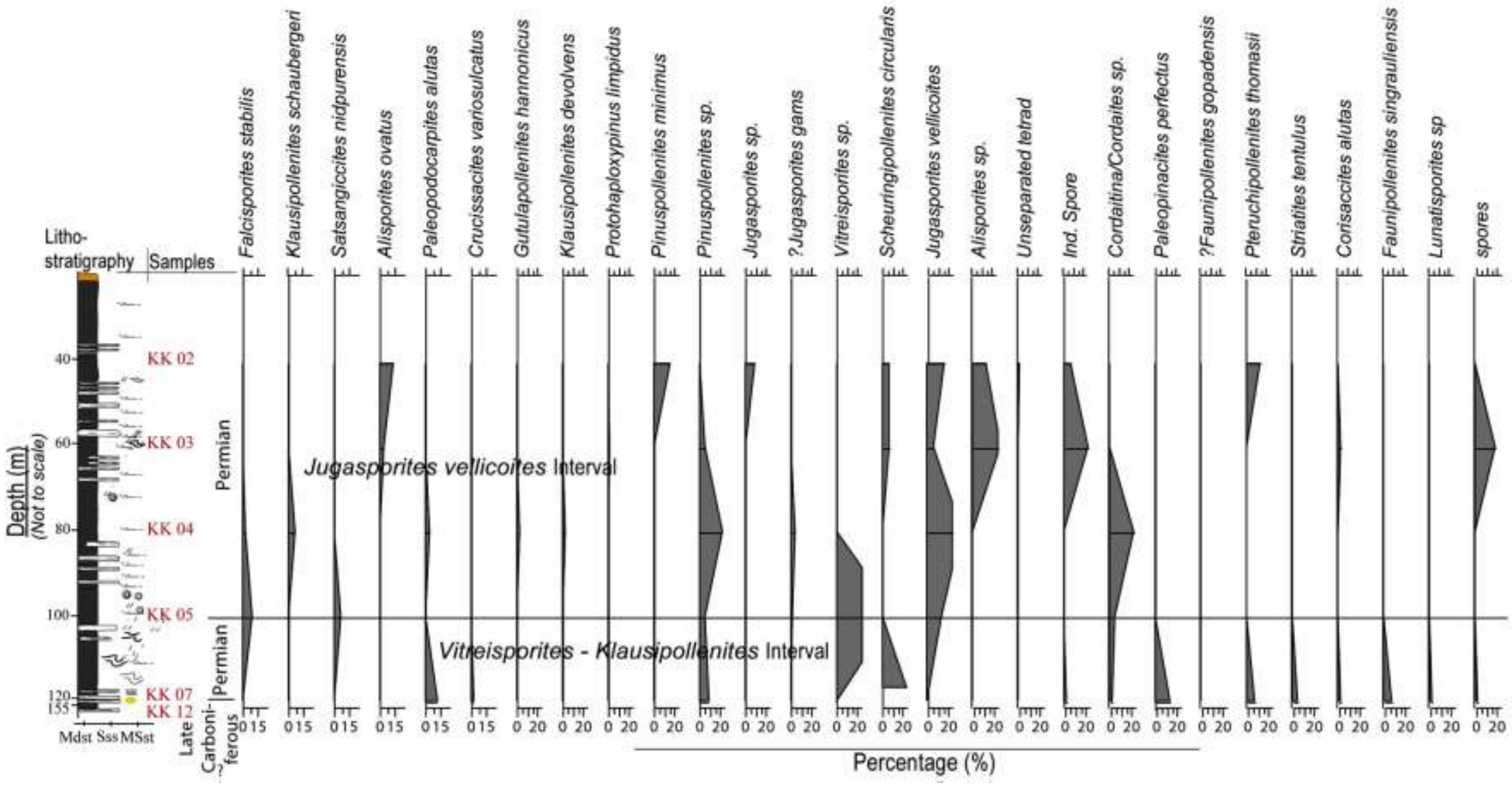

Figure 2. 11: Relative abundances (%) of pollen and spores through Late Carboniferous - Permian transition in Kakindu-1 borehole.

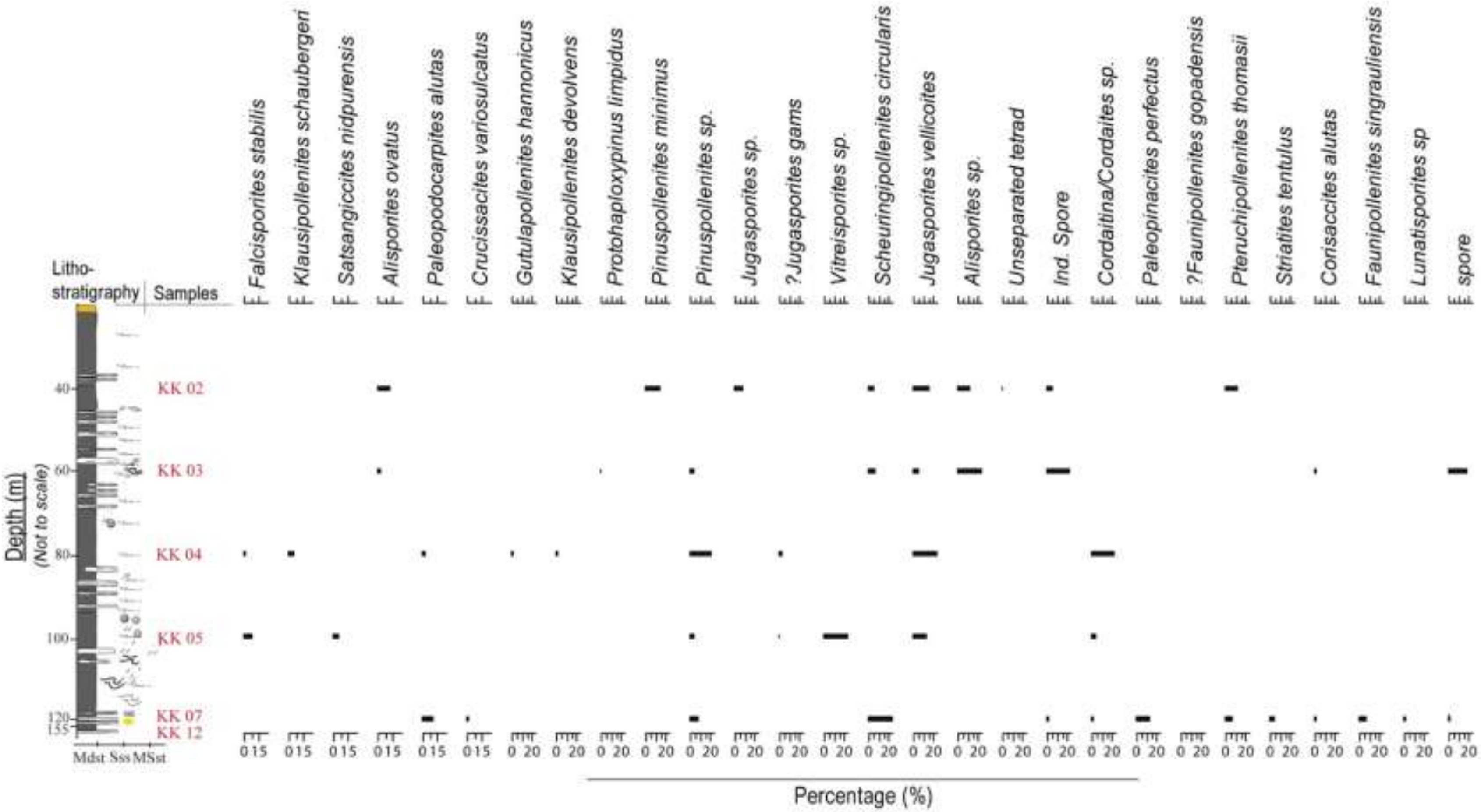

Figure 2. 12: Relative abundances (%) of pollen and spores and presence/absence of terrestrial palynomorphs in Kakindu-1 borehole.

2.3.2.2 Kakindu Outcrop Floral Assemblage

Fossil plants extracted from the Kakindu outcrop at the vicinity of Kakindu River, are also considered in age discussions. These include five main taxa, perfectly to imperfectly preserved plant fragments. A few of the recovered plant remains resembles to those ones described in the Tanga beds (e.g. Seward 1922, Seward 1934), South Africa (e.g. Anderson 1983), Madagascar (e.g. Rayner 1992), Witteberg Series of the Cape colony (e.g. Seward 1901), Duruma sandstones (e.g. Gregory 1926) and in other parts of the Gondwana (e.g. McLoughlin 1994, McLoughlin 2005, McLoughlin 2011). Description and age of the recovered specimens is provided in the section below.

Glossopteridales

Hirsutum dutoitides (PLATE 2.1 a, b and c)

Elongate petrified leaf (up 12 - 14 cm), narrowly to very narrowly oblong (i.e. maximum width 1.5 cm) progressively narrower towards one end (i.e. towards the base). Poorly visible venations, but whenever preserved, they tend to display repeating branching out patterns that are and inclined at intermediate angle. The midrib is well preserved (Plate 1 a.).

Sphenobaiera eccaensis (PLATE 2.2a)

Elongate/linear petrified leaf (a fragment of 12 cm long) with poorly visible venations that terminates/tapers gradually at the narrow base. No midrib is visible but rather poorly preserved parallel veins that are closely spaced and they show a branching out trend.

Peltaspermales

Lepidopteris madagascariensis (PLATE 2.2 b - c, PLATE 2.3 a - c)

Moderately well preserved bipinnate petrified leaf, approximately 5 - 6 cm long and 1.5 cm maximum width, pinnae sub–opposite showing sub opposite branching patterns that have an alignment of approximately 65^0. These are 1mm apart connected to a very distinct midrib running from the base to the apex (Figure 2.3 a).

Ginkgoales

Ginkgoites dutoitii (PLATE 2.2 d)

Moderately well-preserved petrified leaf specimen having a fan or wedge shape. Neither a distinct petiole nor a visible mid vein are observed in this specimen. The leaf shows bifurcating venation patterns.

Voltziales/ Coniferales

Genus *Voltziopsis* (PLATE 2.2 e)

Well preserved leaf specimen with branched shoots, approximately triangular shaped, 6 - 8 mm size showing branched shoots.

The fossil plants documented from the Kakindu outcrop by this study suggest Late Permian to Mid-Triassic age. The Glossopteridales genera *Hirsutum dutoitides* and *Sphenobaiera eccaensis* that were doubtful present in the Kakindu Beds (Seward 1934) and thus restricting the proposed age to Triassic (Seward 1922, Seward 1934) have been documented in the current study. These resembles to Glossopteridales reported in the Late Permian of South Africa (Anderson 1983) and thus suggesting the possibility of an age older than Triassic for the Tanga Beds. It should be noted that during the Permian time, the Gondwana continents were characterized by the presence of *Glossopteris* flora as shown by many palynological records in India and Africa (Jha 2006). *Lepidopteris madagascariensis* is known from the Late Permian to Late Triassic of Madagascar and South Africa (Anderson 1983, Rayner 1992) while *Ginkgoites dutoitii* is reported in the Lower to Mid - Triassic of South Africa (Anderson 1983).

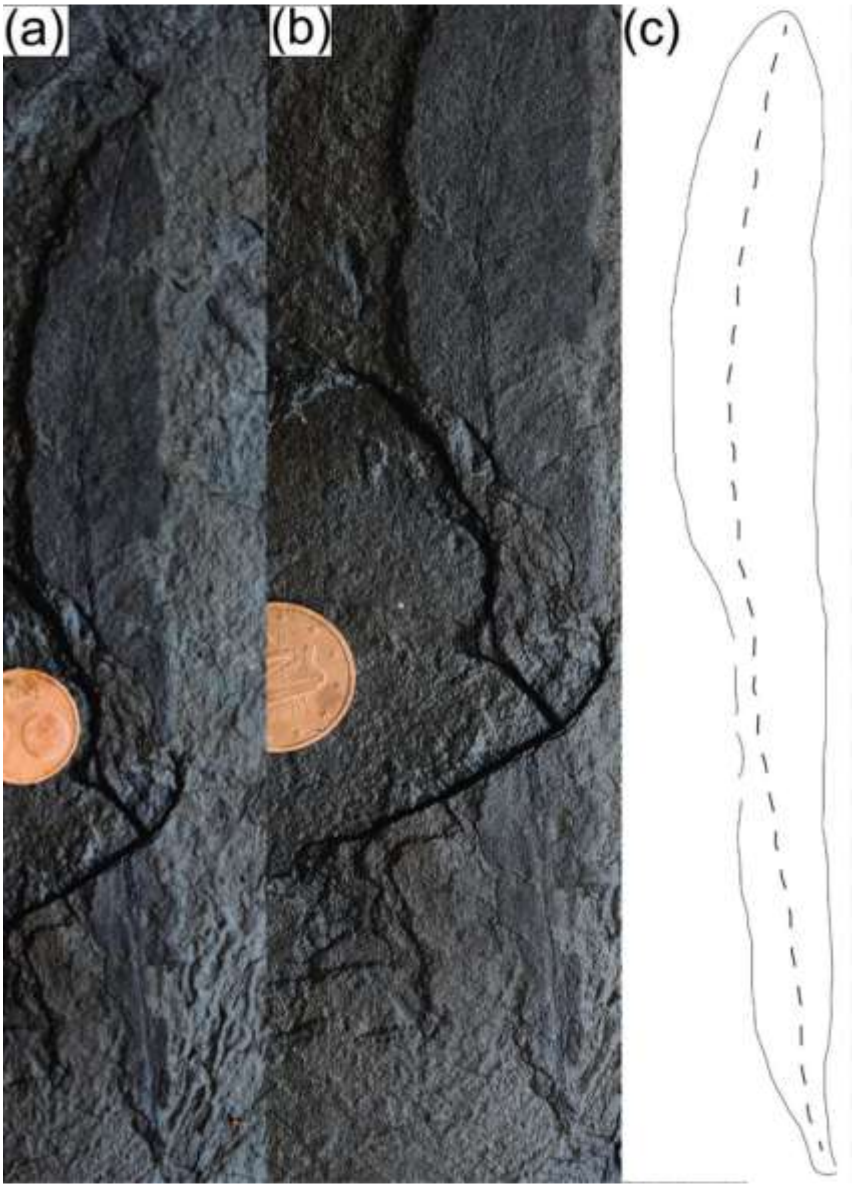

Plate 2. 1: **(a) - (b). Photographs of Glossopterid *Hirsutum dutoitides* recovered from the Kakindu outcrop c). *Hirsutum dutoitides* illustration.**

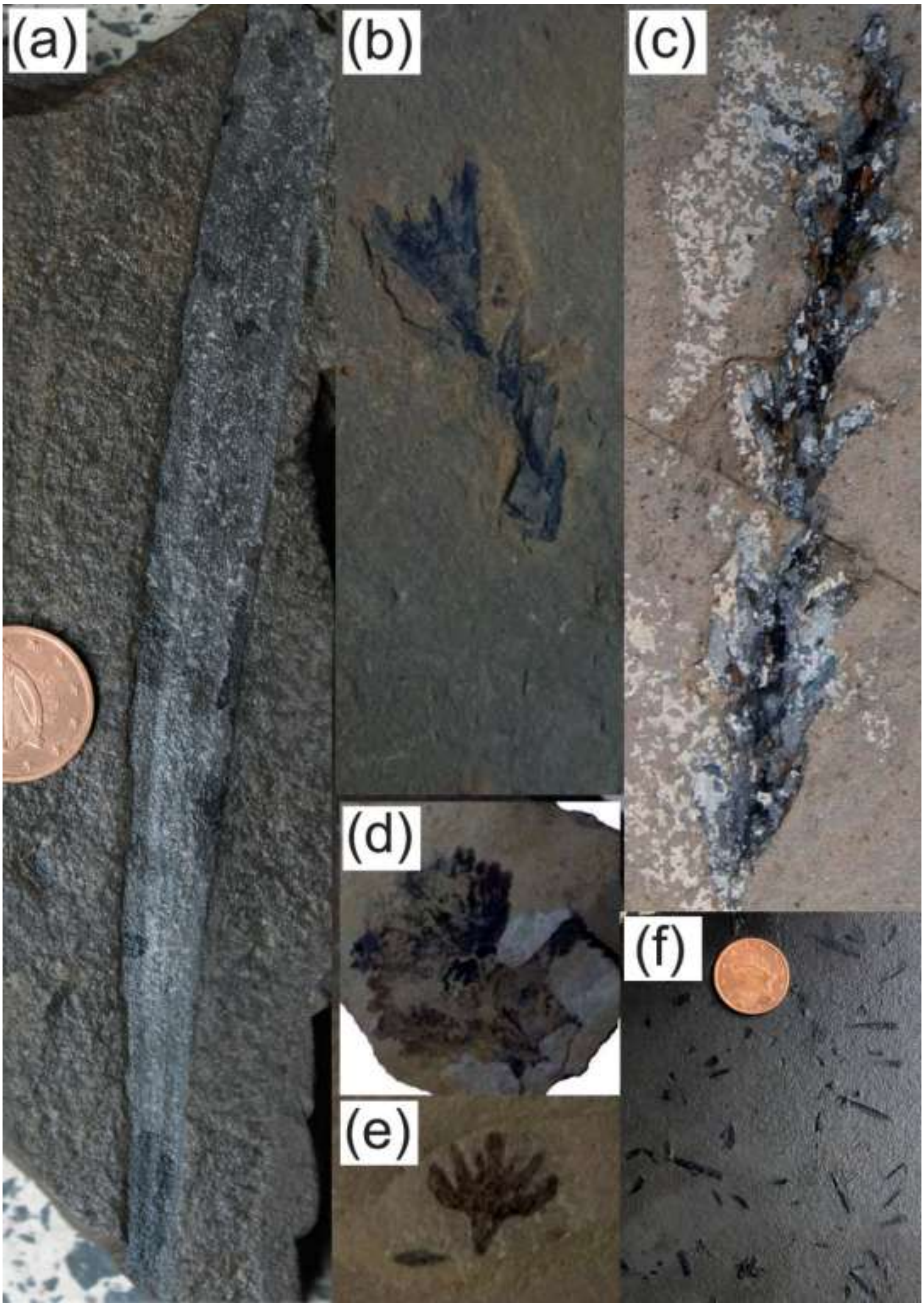

Plate 2. 2: **(a).** ***Sphenobaiera eccaensis*** **(b)-(c).** ***Lepidopteris madagascariensis*** **(d).** ***Ginkgoites dutoitii*** **(e). Genus** ***Voltziopsis*** **(f). Indeterminate.**

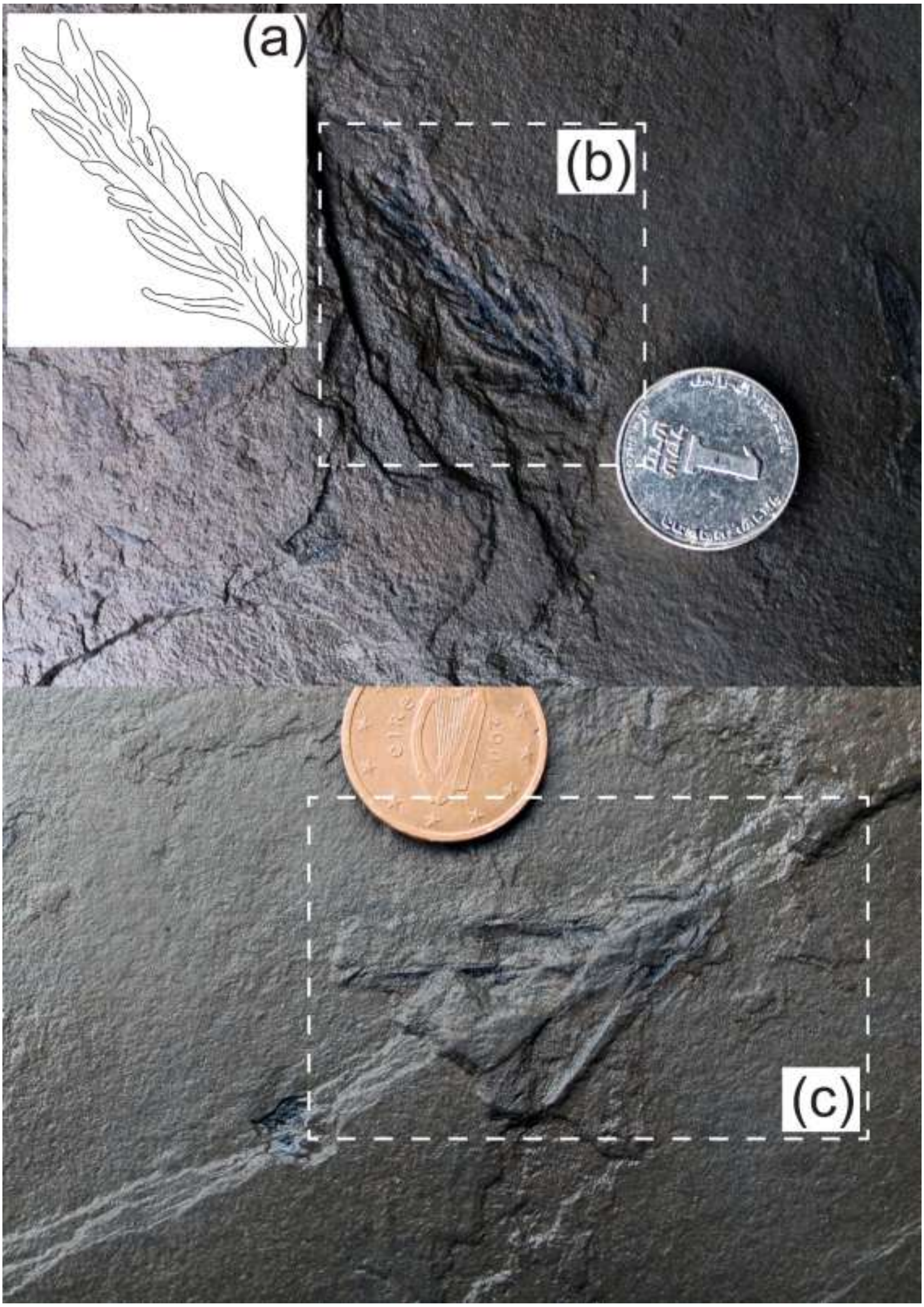

Plate 2. 3: (a) - (c) Photographs and illustration of *Lepidopteris madagascariensis* recovered in the Kakindu outcrop.

2.3.3 Palynostratigraphy of the Vunde-1 Borehole

The palynological residues from the Vunde-1 core generally turned out to be degraded. Only a few fairly well-preserved specimens could be identified. For those ones identified, amb shapes and remnant ornamentation played a vital role in recognition. It is from this basis therefore, three (3) main palynological intervals were identified in Vunde-1 borehole. Like the assemblages in Kakindu-1 boreholes the main miospore components in Vunde-1 include vast gymnosperm pollen grains.

Palynologic Interval - 1: *Klausipollenites schaubergeri - Scheuringipollenites circularis* Interval

Samples: VND 14 (194.3 m), VND 13 (175 m) and VND 10 (160 m)

Definition: From first to last appearance of *Klausipollenites schaubergeri-Scheuringipollenites circularis.*

Palynological composition

The miospore in this interval include *Pinuspollenites* sp. *(5.6%), Alisporites australis (7.4%), Jugasporites nubilus (12.96%), Scheuringipollenites circularis (4%), Klausipollenites scheubergeri (16.7%), ?Retusotrilete* sp. *(31.48%), Ginkgocycadophytus* sp. *(5.56%), Cyacadopites sp. (3.7%), ?Reduviasporonites sp. (5.6%) and Cordaitina* sp. *(5.6%), Paleopodocarpites alutas* (c.f. *annulatus*) (10%), *Klausipollenites* sp. (1%), *Pinuspollenites* sp. (7%), *Jugasporites vellicoites* (40%), *Jugasporites* sp. (4.3%), and a significant percent of spherical spores (up to 50% in VND-13 and 28% in VND-10) that could not be placed to their correct generic or specific position.

Age Assignment

Despite the presence of a few pollen taxa that could potentially indicate a Late Carboniferous age, this interval lacks purely diagnostic Carboniferous taxa. *Klausipollenites schaubergeri* that dominates the total assemblage in this interval is a long ranging taxon spanning Upper Carboniferous to Permian as reported in Madagascar (Truswell 1980), Gabon (Adloff 1986) and Ethiopia (Jardin 1974. Therefore, only *Scheuringipollenites circularis* which is reported from Late

Carboniferous - early Permian of Argentina (Cesari 1995) can be used to support a late Carboniferous age implication in Vunde–1 borehole.

On the other hand, this interval is characterized by the presence of pollen and spore taxa characteristic of Permian age. These include four (4) early Permian (Sakmarian-Kungurian) diagnostic taxa i.e. *Paleopodocarpites alatus* reported from Kungurian of the African Gondwana (Hart 1970), *?Retusotriletes* sp. reported from the late Artinskian of Madagascar (Hankel 1993), *Ginkgocycadophytus sp.* reported from the late Artinskian of Tanzania and Madagascar (Rakotoarivelo 1971) and *Lueckisporites virkkiae* reported from early Sakmarian of Madagascar (Rakotoarivelo 1971) and South African Karoo (Doubinger 1960). Furthermore, two late Permian (Lopingian) diagnostic forms that include *Jugasporites vellicoites* which dominates in the assemblage, and *Paleopinacites perfectus* are recognized. These taxa are recorded from palynologically dated rocks in Argentina (Zavattieri 2018) and African Gondwana (Hart 1970).

The remainder of the taxa in the assemblage is of less biostratigraphic significance. These include long ranging taxa such as *Cyacadopites sp.*, *Alisporites australis, Falcisporites zapfei, podocarpites alatus, Striatopodocarpites* sp., and *Cordaitina/Cordaites sp*. Therefore, the first recognized palynological interval in Vunde-1 borehole permits dating of the studied samples to lower Permian (Sakmarian - Kungurian).

Palynologic Interval - 2: *Alisporites minutosaccus - Faunipollenites gopadensis* Interval

Samples: VND 07 (119 m), VND 05 (99 m), VND 02 (58 m), VND 01 (20 m)
Definition: From first to last appearance of *Alisporites minutosaccus* and *Faunipollenites gopadensis.*

Palynological composition

This zone is also characterized by a number of gymnosperm pollen as dominant miospores in the assemblage. These include bisaccate pollen;- *Faunipollenites gopadensis* (14%), *Satsangisaccites ovatus* (7%), *Paleopodocarpites alutas* (c.f. annulatus) (15%), *Podocarpites alatus* (1.6%), *Striatopodocarpites sp.* (2.5%), *Klausipollenites devolvens* (3.5%), *Alisporites minutosaccus* (3.3%), *Pinuspollenites sp.* (6.7%), *Jugasporites* sp. (11.7%), Scheuringipollenites sp. (27.3%), *Paleopinaciles perfectus* (10.2%), Falcisporites zapfei (1.56%), *Pteruchipollenites thomasii* (4%), *Pityosporites nigraeformis* (1.95%), *Lueckisporites virkkiae* (4%), Ind. trilete spore (up to 30%).

Age Assessment

Most of the palynomorphs characterizing this zone are cited as probable indicators of the Permian - Triassic transition of the ancient Gondwana. Identified index taxa for the late Permian-early Triassic include *Alisporites minutosaccus* and *Faunipollenites gopadensis* reported from P-Tr of India (Srivastava 1974). *Faunipollenites gopadensis* shows a general increase from sample VND-07 reaching its maximum diversity in sample VND-02 where it also terminates. A conifer pollen of genus *Pinuspollenites* recorded in this palynozone also shows an increasing trend as moving from deeper to shallower samples of Vunde-1 well, its acme being the shallow most sample (i.e. VND - 01). The latter reported from the P - Tr transition of Kenya (Hankel 1992).

Long ranging Permian-Triassic species were also recorded. These include *Striatopodocarpites labrus* recorded in the Permian – Triassic of India (Tiwari 1965), *Lueckisporites virkkiae* recorded in the Permian to middle Early Jurassic of Madagascar (Rakotoarivelo 1971), *Jugasporites sp.* recognized in the early Permian to Late Triassic of Congo (Maheshwari 1969) and Madagascar (Rakotoarivelo 1971), *Klausipollenites sp.* reported from the Permian – Triassic rocks of Zaire (Kedves 1986) and genus *Cycadopites* which is known from the Carboniferous to Jurassic of South Africa , Mali, Zaire and Madagascar (Rakotoarivelo 1970, Hart 1970, Bose 1974, Cahen 1983, Falcon 1984). Rare Late Triassic taxon *Pteruchipollenites* *thomasii* recorded in the Carnian - Norian of Antarctica (Taylor 1989, Farabee 1989) has also been observed making a significant part in this palynologic interval. These might be attributed to reworking. Hence, this palynological interval permits dating of the studied samples to late Permian-earliest Triassic (or P - T transition).

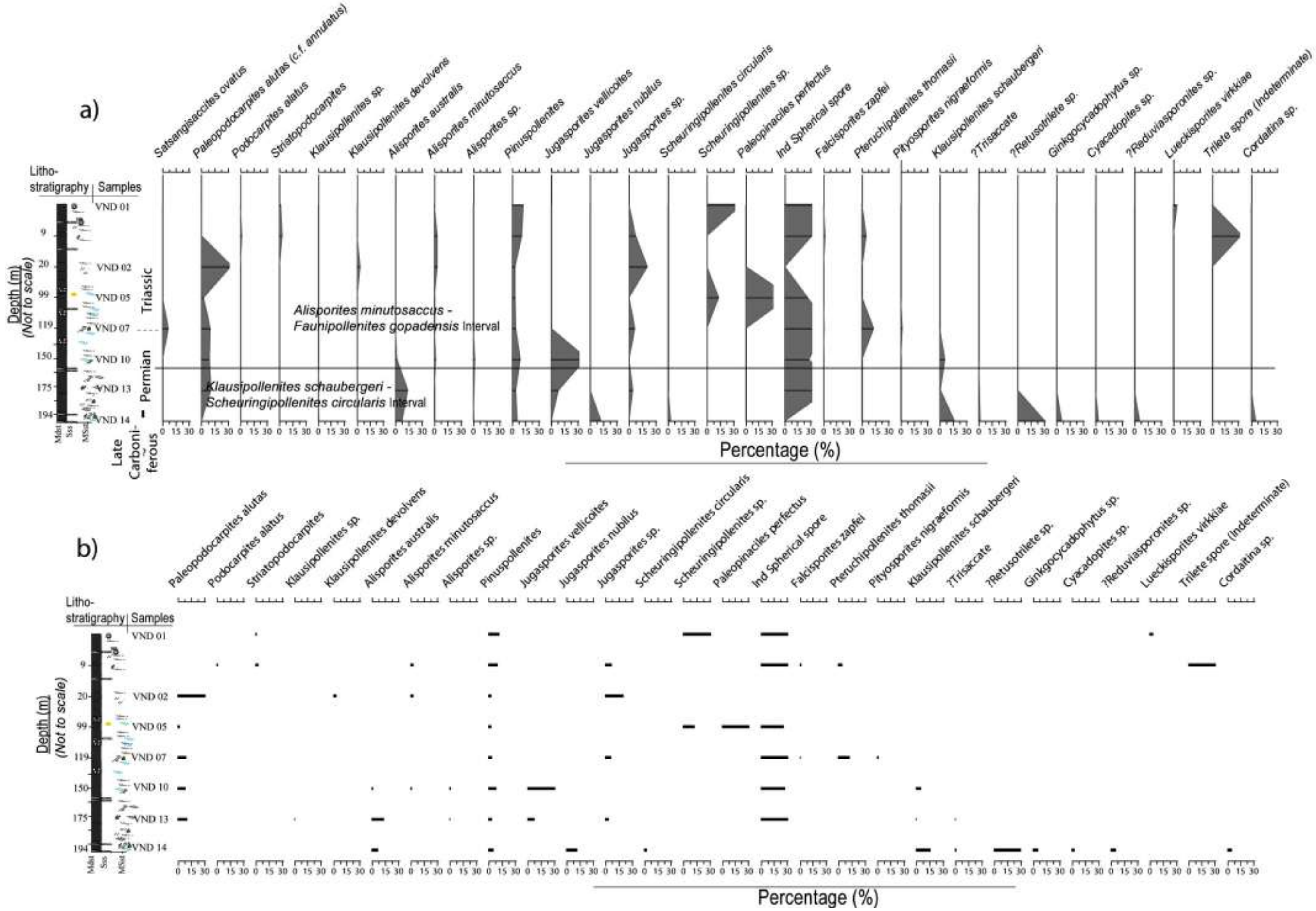

Figure 2. 13: (a) Relative abundance of selected palynomorph groups from Vunde-1 borehole samples showing their stratigraphic distribution (plotted as percent of total palynomorph counts, including the bissacate fragments) (b) Presence-Absence chart for selected palynomorphs recovered in Vunde-1 well samples

2.3.4 Karoo Stratigraphy of the Ruvu – Tanga Basins in a Local and Regional Geological Context.

Both micro– and macrofloras documented in the Ruvu and Tanga basins made possible the placement of the Karoo equivalent lithostratigraphic units into a chronologic context in this study. In doing so, a common denominator for all samples in the investigated basins (i.e. Ruvu and Tanga basins) is that, they all show a Permian-Triassic age range (Figure 2.14 and 2.15), with a weak Late Carboniferous signature in a few samples. Based on the vegetation elements that dominated the documented intervals (including the presence of the *Glossopteris* flora that is also recorded in the Tanga Basin), the age inferences in the current study may imply a single phytogeographic province during the Permian-Triassic time in a local scale.

In relation to the informal Karoo subdivisions made in the Tanga Basin's stratigraphy using paleobotany (Seward 1922), new findings by this study agree that, the two studied boreholes in the Tanga Basin (i.e. Kakindu-1 and Vunde-1) show a strong affinity to the upper part of the lower Karoo unit and the lower part of the upper Karoo (Figure 2.14). This is in contrary to what was reported prior to this study that, the entire Vunde-1 borehole represented the middle Karoo division (TPDC 2014). Furthermore, the findings by the current study (Figure 2.14) recognizes an upper part of the Lower Karoo (Asselian-Kungurian) and a lower part of an Upper Karoo (Lopingian). This is also contrary to the previously infered stratigraphic subdivisions that suggested a Lower Karoo for the entire Kakindu-1 borehole (TPDC 2014). It should be noted that, due to sampling gaps and preservation drawbacks, the middle Karoo subdivision could not be properly defined by this study but it is suspected between depth 120 m-160 m of the Vunde-1 borehole and depth 80 m-100 m of the Kakindu-1 borehole (Figure 2.14).

In the Ruvu Basin, the dating of lower Makarawe-1 well to Permian-Triassic also suggest a correlation to the lower – upper Karoo equivalent Tanga Beds (Figure 3.15). However, detailed sampling is required to properly define the stratigraphy of the lower Makarawe-1 well and to establish a solid inter-basin scale stratigraphic relationship.

A degree of closer similarity (to the Tanga and Ruvu Basins) can also be established in correlation to the coal bearing Permian strata in the inland Karoo basins of Tanzania (i.e. Namwele-Mkomolo, Muze, Galula and Songwe - Kiwira) (Semkiwa et al. 1998, Semkiwa 2003). In these basins, the recorded early Permian assemblages e.g. *Scheuringipollenites-Protohaploxypinus* Zone of the Mchuchuma Formation (Semkiwa 1998, Semkiwa 2003) shows some resemblance to the early Permian miospores intervals i.e. *Klausipollenites* - *Scheuringipollenites* Interval and *Klausipollenites* - *Vitreisporites* Interval documented in this study. Thus inferred age of the studied samples in the Tanga and Ruvu basins permits a correlation to the second, third and fourth depositional sequence in the classical Karoo section of the Ruhuhu Basin. However, slight differences in miospore composition have been noted as well.

At a regional scale, the ?Late Carboniferous-early Permian intervals observed in this study can be correlated to *Cruccisaccites monoletus* Zone of Brazilian Late Carboniferous (Cesari 2006), Assemblage 2 , early Permian of Chuperbhita coalfield, Rajmahal Basin, India (Tripathi 2000) and *Klausipollenites scheubergeri* Zone of Late Carboniferous - early Permian of Israel (Horowitz 1974) while the late Permian-early Triassic intervals in this study shows similarities to *Falcisporites – Klausipollenites* (Zone III and IV) of Indian Early Triassic, (Kar and Ghosh 2018), *Protohaploxypinus microcorpus zone*, Kenyan Late Permian (Hankel 1992), *Protohaploxypinus – Striatopodocarpites zone* (Assemblage zone 3) of Mozambican Permo - Triassic (Pereira et al. 2015), *Gutullapollenites hannonicus – cladaitina veteadensis* assemblage zone, Lopingian of of Argentina (Gutierrez 2018), *Jugasporites zone* , Lopingian of Argentina (Zavattieri 2018), and Palynozone 3 of the Indian Permo-Triassic transition (Jha 2012).

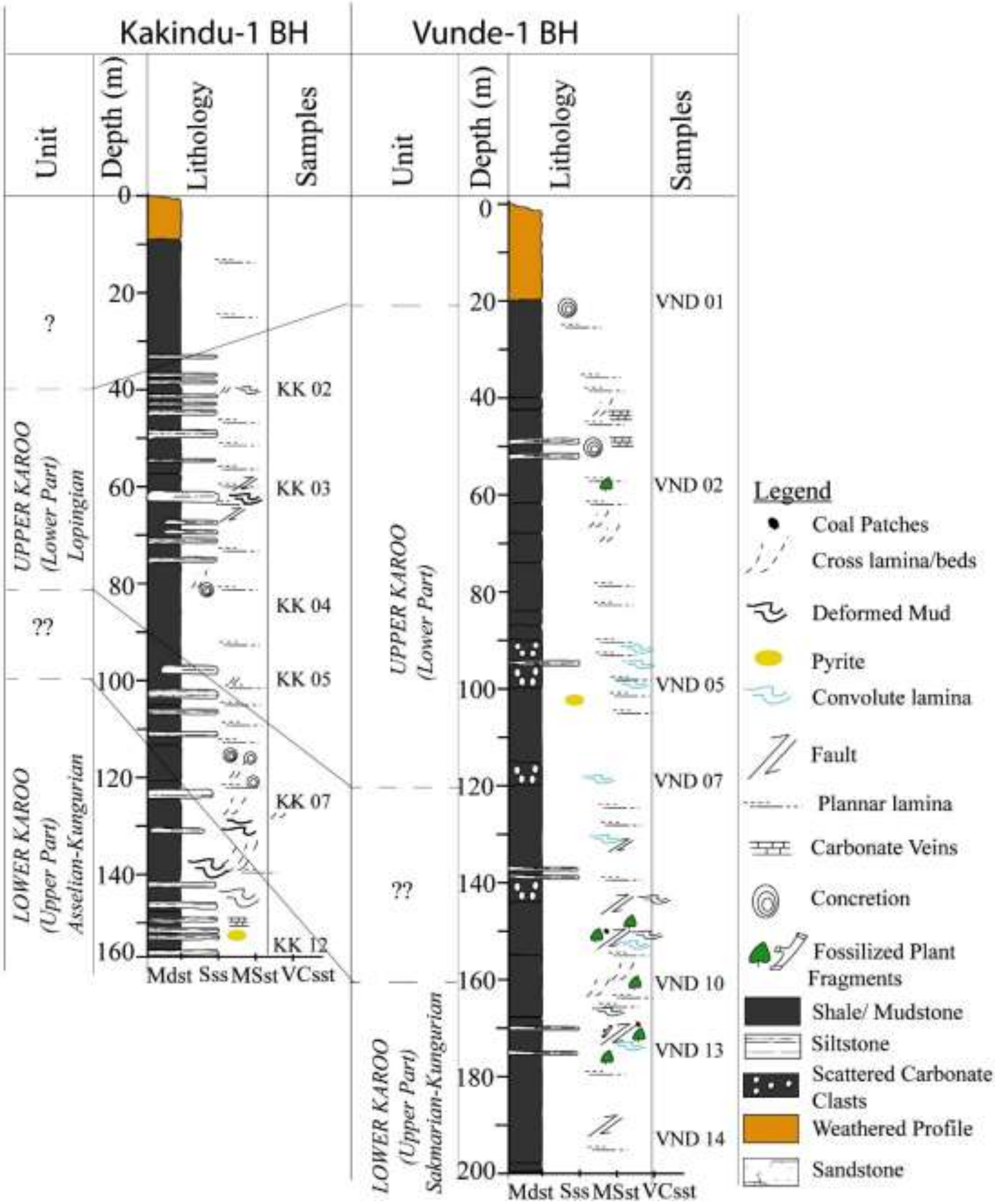

Figure 2. 14: Stratigraphy of the Kakindu-1 and Vunde-1 boreholes of the Tanga Basin a proposed by this study.

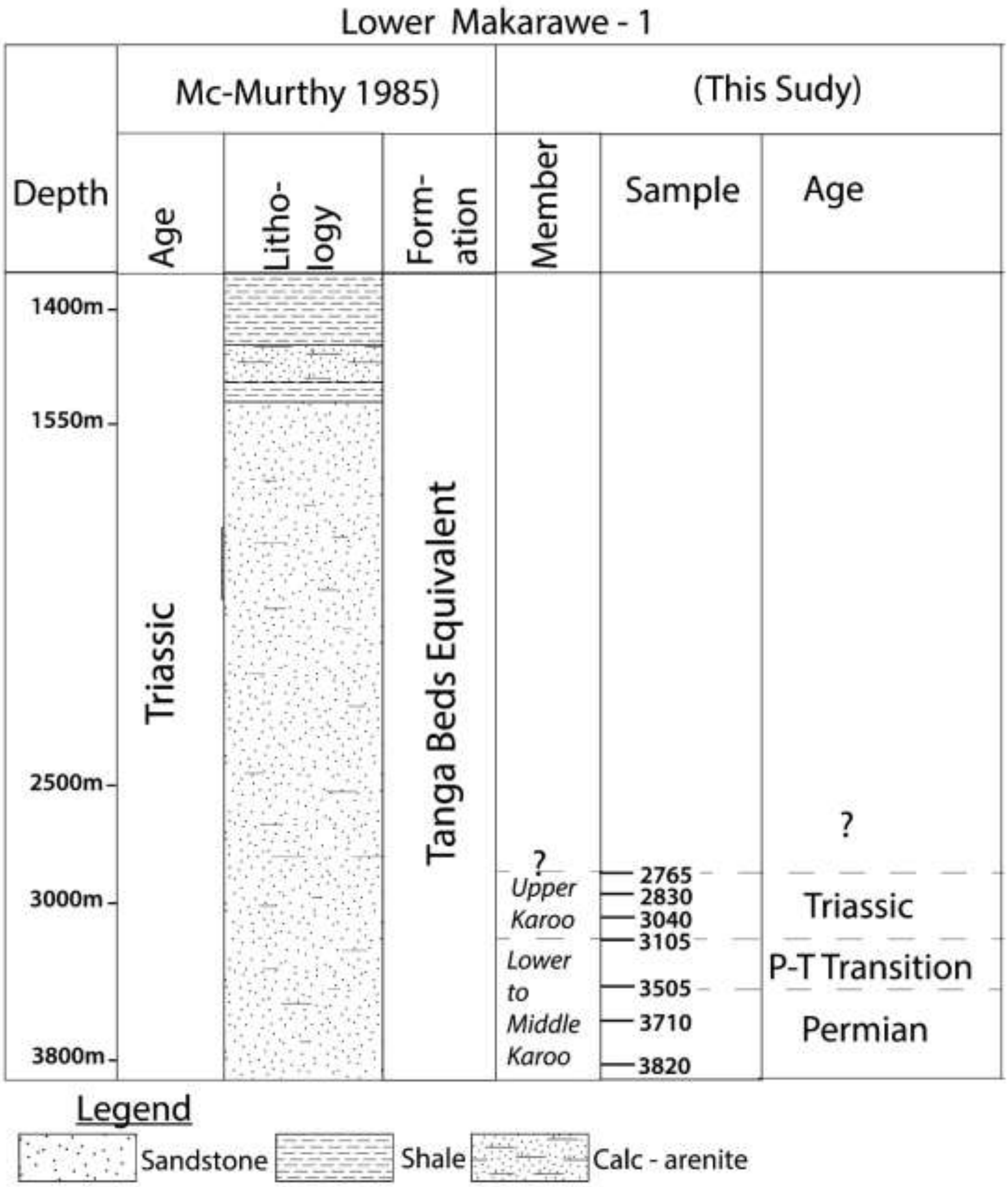

Figure 2. 15: Stratigraphy of the lower Makarawe-1 well of the Ruvu Basin as proposed by this study.

2.4 Conclusion (s)

Palynological investigation was carried out in drill-core samples from three stratigraphic boreholes in the Tanga Basin (i.e. Vunde-1, Kakindu-1 and Jihirini-1 boreholes) and from well-cutting samples from the lower portion of the Makarawe–1 well (i.e. depth 2765 m-3820 m). The Tanga boreholes and the lower Makarawe-1 well samples have previously not been studied in detail. Despite preservation drawbacks of the Tanga cores, a few well-preserved recovered specimens were of sufficient quality for a palynological investigation; and thus, permitted dating of these strata. Furthermore, an extremely good palynomorphs diversity in samples from both Tanga and Ruvu basins made this study a success.

The nature of documented assemblages are dominated by pollen derived from gymnosperms, although fern pteridosperm spores are also documented. No marine palynomorphs (e.g. dinoflagellate cysts or acritarchs) were observed in the samples from both basins suggesting a purely terrestrial succession. Based on first and last apperance of index taxa in the Tanga boreholes, and first or last apperance in the lower Makarawe-1 well, the vertical distribution of recovered palynomorphs exhibited taxa of biostratigrahic significance enabled recognition of several palynologic intervals as follows:

a) In the Tanga Basin, two palynological intervals are recognized from Kakindu-1 borehole. These include *Vitreisporites – Klausipollenites* Interval (? Late Carboniferous to early Permian age) and *Jugasporites vellicoites* (Permian i.e. Lopingian) age. Age dating for the Kakindu samples is supplemented by paleobotanical dating that in addition inferred a late Permian to late Triassic age using the outcrop samples from Kakindu River. In Vunde - 1 borehole, two main palynologic intervals (i.e. *Klausipollenites schaubergeri-Scheuringipollenites circularis* and *Alisporites minutosaccus - Faunipollenites gopadensis*) were used to infer a ?late Carboniferous, Permian and end-Permian – earliest Triassic age respectively.

b) In the Ruvu Basin, three palynological intervals are recognized in the lower Makarawe-1 samples. These include *Falcisporites zapfei* Interval (late

Permian), *Reduviasporonites* Interval (Permian-Triassic transition, i.e Changhsingian - Induan) and *Alisporites–Falcisporites* Interval (Triassic).

c) The position of the studied samples in the informal Karoo stratigraphy in the Tanga Basin suggest a lower Karoo (upper part) to Upper Karoo (lower part) for the studied boreholes in the basin. Position of all the samples relative to the classical Karoo stratigraphic sequences suggests second, third and fourth depositional sequence and a Beaufort - Stormberg equivalence in a regional scale. However, the confidence level remains questionable for the Tanga Beds samples due to its current state of palynomorphs preservation.

d) The palynofloras documented inboth Ruvu and Tanga Basins suggest Permian-earliest Triassic age. Based on the vegetation elements that dominated the documented intervals (including the presence of *Glossopteris* flora in the Tanga Basin), the dating results by the current study may imply a single phytogeographic province in the studied basins during the Permian – earliest Triassic time.

2.5 Acknowledgements

I thank the University of Dar es Salaam for funding the fieldwork in the Tanga and Ruvu basins. I am grateful to the Tanzania Petroleum Development Corporation (TPDC) and Petroleum Upstream Regulatory Authority (PURA) for providing the materials used in this study and permission to publish the results. The Geological Survey of the Netherlands (TNO) is thanked for funding all the analyses related to this research work.

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CHAPTER THREE
PALYNOSTRATIGRAPHY OF JURASSIC STRATA IN THE ONSHORE RUVU BASIN, TANZANIA

Abstract

Palynologic investigation of the sedimentary strata deposited in association with Gondwana breakup in the Ruvu Basin of the coastal region Tanzania provides insight in the depositional ages of this, otherwise poorly stratigraphic constrained basin. Palynomorphs preserved within the subsurface intervals (1215 - 1235m) of the Makarawe-1 well were recovered and microscopically analyzed. Based on the ranges of dinoflagellate cysts supplemented by pollen–spore ranges, two main palynological intervals (*Classopollis* - *Nannoceratopsis* Interval and *Wanaea clathrata* Interval) are established. The established intervals correspond to the late Middle Jurassic to Late Jurassic (Bajocian - Kimmeridgian) and suggest a possible correlation with Lugoba formation - Malivundo formation - Magindu formation of the Ruvu Basin of Tanzania while confirming the evidence of the Jurassic strata, overlying the Late Carboniferous - Permian/early Triassic Karoo Supergroup in the basin. The findings presented herein suggest an extension of the *Wanaea clathrata* Interval (Oxfordian-Kimmeridgian age) from 900-945 meters of the Makarawe-1 well, based on previous works, to 1215 - 1235 meters of the Makarawe-1 well in this study. Furthermore, the *Nannoceratopsis* sp. dominated association documented in this study is an indicative of an immediate post-break-up association. With similarity to the Ngerengere dinocyst assemblage documented in previous works, further suggest that the Ngerengere beds are not Karoo equivalent but rather syn- or post the break up sequences.

The two recorded intervals are highly similar to other palynologically dated lithostratigraphic units in Africa, Australia, Europe and America. Ultimately, the data resulting from this study add important insights on stratigraphic framework and correlation of the poorly stratigraphically constrained coastal basin.

3.1 Introduction

The continental margin of Tanzania experienced significant marine incursions during the Jurassic (201.4-145.0 Ma, Kamen–Kaye 1978), and was associated with the breakup of the Gondwana Supercontinent, which led to the opening of the Indian Ocean and drifting of Madagascar to its current geographical position (Schlüter 1997, Blakey 2008). At present, marine sedimentary strata exposed in the coastal Tanzania are examples of the sedimentary rocks that were deposited after or in association with the continental break up of Gondwana (Kapilima 2003). In the Ruvu Basin, these include ammonite-rich marls exposed at the vicinity of Kidugalo railway station (Kent 1971, Kapilima 2002) and coral limestones cropping out as ridges at Msolwa, Msata and Lugoba constituting the Lugoba formation (Schlüter 1997, Kapilima 2003).

Several studies aiming to delineate the age of the breakup unconformity and the subsequent post breakup succession in the Ruvu basin have been conducted. A few amongst these were published and they include research on ammonite biostratigraphy (Kapilima 2003), micropaleontology (Mweneinda 2014), palynology (Balduzzi 1991, Msaky 2007, Msaky 2011) and reef paleontology (Kamen - Kaye 1978). Other works of similar nature include reports from local/ international oil companies and academic research dissertations (Kapilima 1984, McMurtry 1985, Corelab and TPDC 2009, Kihanga 2017, Matulanya 2017, Versteijlen 2018). These have remained unpublished but their contribution in the geology and stratigraphy of the Ruvu basin cannot be ignored. From a collective synthesis of both published and unpublished reports on dating of the Jurassic strata in the Ruvu Basin, it is agreed that the oldest Jurassic marine invertebrate fauna recorded in the Ruvu Basin is of Bajocian age (i.e. Middle Jurassic) (Kamen–Kaye 1978, Kapilima 2003). However, due to the taxonomic concerns in the ammonite studies in the Ruvu basin, precise biostratigraphic placement of the Jurassic succession into its proper stratigraphic position remains questionable. Furthermore, insights from ammonite dated lithostratigraphic units in the basin suggest a possible Aalenian base for the Ruvu basin marine succession (Kapilima 2003). To date, the precise age of the base of the Jurassic strata in the Ruvu Basin has remained questionable.

Better age constraints will help to determine the timing and nature of the Gondwana breakup regionally. This chapter is, therefore, presents a palynologic investigation of the post breakup strata in Ruvu Basin, with the ultimate goal of establishing a better stratigraphic constraint on the Jurassic succession in the Ruvu Basin. In addition, significant gas reserves have been discovered in the onshore Ruvu Basin (Mambakofi-1 well, Figure 3.1) and in the nearby onshore and offshore sub-basins to the South (Kiyuga 2016, Geo EXpro 2016). Thus, findings from this study provide important insights into future hydrocarbon exploration in the Ruvu Basin, as optimal recovery from the existing field requires a reliable stratigraphic control.

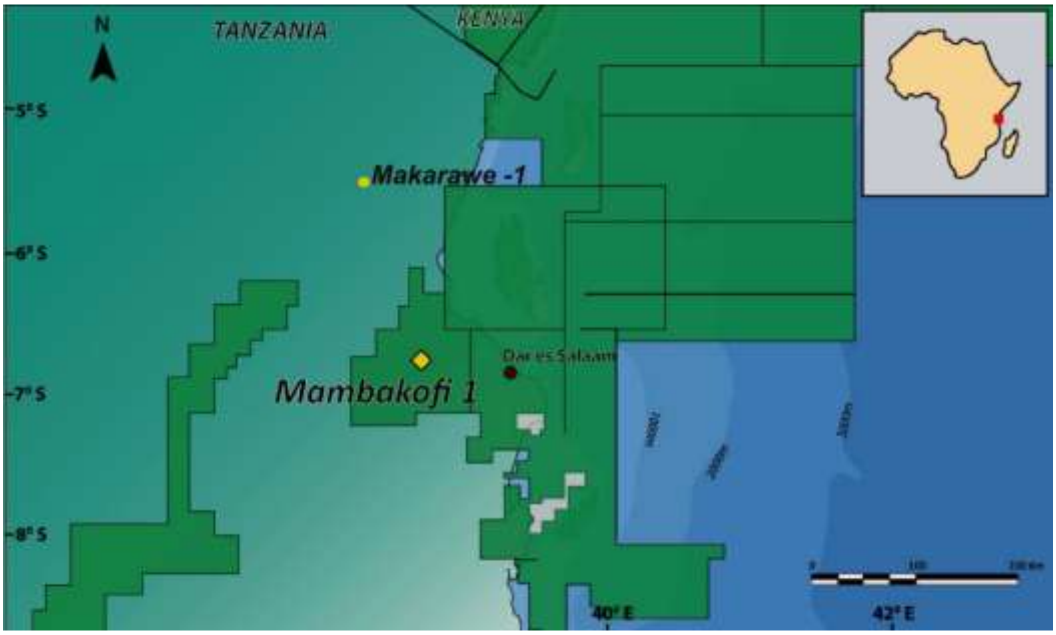


Figure 3.1: Map showing the location of Mambakofi – 1 gas discovery well and the Makarawe-1 well in the onshore Ruvu Basin, Tanzania (Modified from Geo Expro 2016).

3.1.1 Geological Setting and Context

3.1.1.1 The Breakup of Gondwana

The breakup of Gondwana led to a series of rift systems that occurred parallel to the ancient orogenic belts (Delvaux 2001, Gaiger 2004). The earlier rifting phase (i.e. Permo-Carboniferous to Triassic) resulted in development of complex horsts, graben and deposition of continental Karoo - equivalent rocks (Kent et al. 1971, Thompson et al. 2019, also see chapter 2 of this study). This rifting event is considered by many a “failed rift” (e.g., Mpanda 1997, Hudson 2014). Another rifting event, commonly regarded as “reactivation of the earlier rift”, occurred in Middle Jurassic to Early Cretaceous (Kapilima 2003, Hudson 2014). This rifting episode is regarded as the successful one, as it led to the continental breakup of the Gondwana supercontinent into present-day continents of Southern Hemisphere, including the separation of Madagascar away from Africa (Kent et al. 1971, Mpanda 1997, Kapilima 2003).

The main rifting phase was dominated by massive subsidence and sedimentation (Bally 1981, Salman and Abdula 1995, Nicholas et al. 2007), leading to deposition of alternating marine and transitional marine deposits. This phase was followed by a period of tectonic quiescence and development of passive continental margin across the eastern African coast, until the Paleogene when tectonic reactivation occurred.

The depositional history of the Ruvu Basin’s sediments during the Middle Jurassic is therefore related to the break–up of the Gondwana supercontinent (Kent 1971, Kapilima 2003, Versteijlen 2018). Nevertheless, poor understanding of lithostratigraphic context within the basin resulting from uncertain timing of deposition has led to faulty in many proposed post - rift depositional history models which requires to be updated.

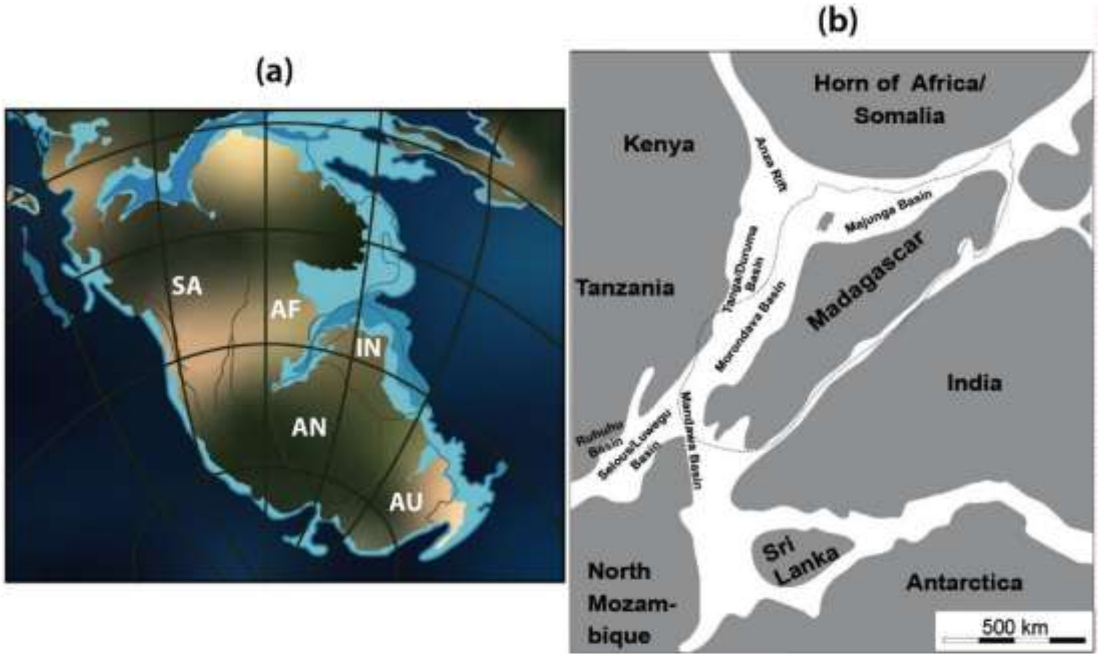


Figure 3. 2: a) Global paleogeography and paleo–tectonics in the Middle Jurassic, ca. 170 Ma showing the flooding between Africa and India, eminent signs for the Gondwana Breakup (Modified from Blakey 2008) b) Close-up reconstruction of the Gondwana fragments (Modified from Geiger 2006). SA = South America, AF = Africa, AF = Africa, AU = Australia, IN = India, AN = Antactica.

3.1.2 Litho and Biostratigraphy of the Ruvu Basin

Like in the most sedimentary basins of coastal Tanzania, and as explained earlier in this chapter, the Jurassic chronostratigraphic position of the Ruvu Basin is inconclusive. The current accepted stratigraphy of the Jurassic succession in the basin (Figure 3.3) was achieved by a few palynologic studies (Balduzzi et al. 1992, Msaky 2007, Msaky 2011), interpretations based on regional geological correlation (Henning 1924, King 1954, Catuneanu et al. 2005, Kihanga 2017, Matulanya 2017, Versteijlen 2018) and most remarkably by ammonite biostratigraphy (Kapilima 1984 and Kapilima 2003). These strata includes (from older to younger) the Ngerengere fm., Ruvu fm., Lugoba fm., Malivundo formation, Magindu formation and Chalinze formation (Kapilima 1984). The following section provides a short overview of these lithostratigraphic units, and the available bio - and chronostratigraphic context. Figure 3.3 provides a summary of these considerations.

Ngerengere formation

The type locality of the Ngerengere formation is a railway cut section on the central railway between Kidugalo and Ngerengere areas (King 1954). The formation is characterized by sandy limestone, of suspected Middle Jurassic age and bedded feldspathic calcareous sandstone and congromerates of an age older than middle Jurassic (? potential Karoo, Figure 3.3). The latter unit is not exposed except in quarried properties elsewhere (e.g. in Lugoba, Msata, Tarawanda and Msolwa). Fragments of the basement rocks up to 0.5 m in diameter have been observed in the Ngerengere Formation (Kent et al. 1971). Occasional limestone beds (some oolitic) and shales also make part in this formation (Kent et al. 1971).

According to Kent et al (1971), the lithology of the Ngerengere formation suggests rapid deposition that represents a very short time. Initial age indications for the Ngerengere beds were inferred from the presence of fossil coral (*Cladophyllia*). This was recovered in the limestone band and was used to infer an Upper Jurassic age. Other fossil evidence includes the “Recks Fossil Band” (Figure 3.3), which was observed in the sandstone unit within the Ngerengere formation Based on its fossil content, this band was assigned a mid – Jurassic age (i.e. Aalenian to Bathonian, Kent et al. 1971).

Ammonites were used to date the shales within the Ngerengere formation as Bajocian, partly suggesting equivalence to the Kidugalo oolite (Kent et al. 1971, Figure 3.3). Since stratal relationship in the basin suggest that the Kidugalo oolite overlies the Ngerengere sandstone, an early Middle – Jurassic age is suggested for the sandstone unit within the Ngerengere formation (Kent et al. 1971). Kapilima (1984) suggested an Early Jurassic to the Earliest Middle Jurassic (i.e. Aalenian age) for the entire Ngerengere formation Considering the absence of floral studies by then, and even after a palynology research conducted in the Ngerengere formation (Balduzzi et al. 1991, see also Figure 3.4), it has not been possible to assign proper ages or confidently state the stratigraphic position of the Ngerengere strata in the Ruvu Basin’s stratigraphy.

Ruvu formation

The type locality for the Ruvu formation include the area between Kidugalo (i.e. at the Kidugalo train station) and Magindu (Henning 1924, Kapilima 1984). The formation is characterized by coral–bearing calcareous sandstones, sandy and oolitic limestone as well as clays and marl (Figure 3.3). In the Kidugalo area, the exposed Ruvu formation comprises the Kidugalo member and Station member (Kapilima 1984). The Kidugalo member lies concordant on the Ngerengere formation and consists of an alternating succession of oolitic limestone and sandstone (Kent et al. 1971, Kapilima 1984). The Station member superimposes the Kidugalo member and consists of alternating succession of silty clays and marl (Kent et al. 1971). The type locality for the Station member is also at the train station Kidugalo. The lower part of the Kidugalo member was assigned to Aalenian age through ammonites and the upper part of the station beds is classified in the upper Aalenian (Kent et al. 1971).

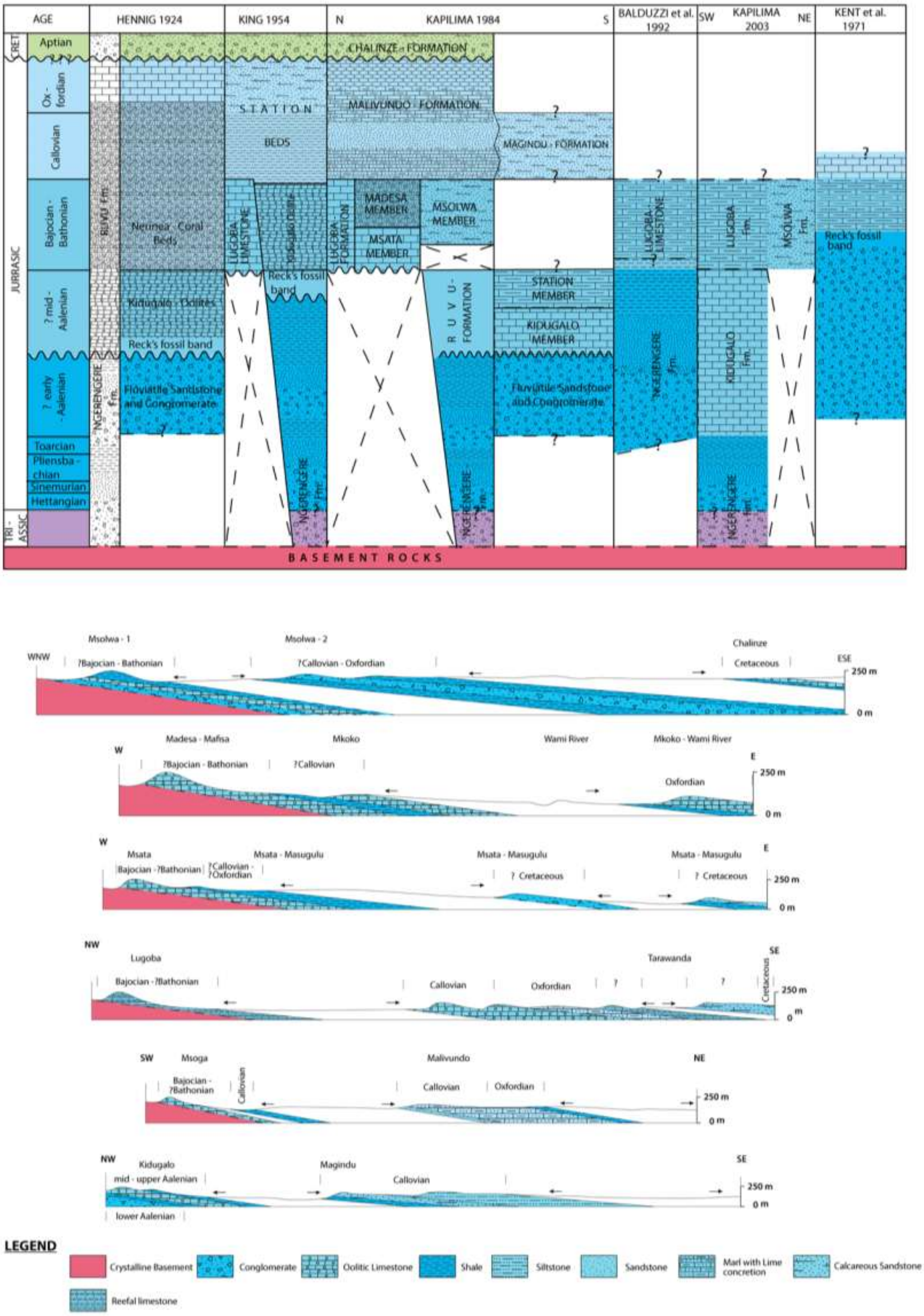


Figure 3. 3: Stratigraphic column and cross sections of the Ruvu Basin (Modified from Henning 1924, King 1954, Kent et al. 1971, Kapilima 1984, Balduzzi et al. 1992 and Kapilima 2003).

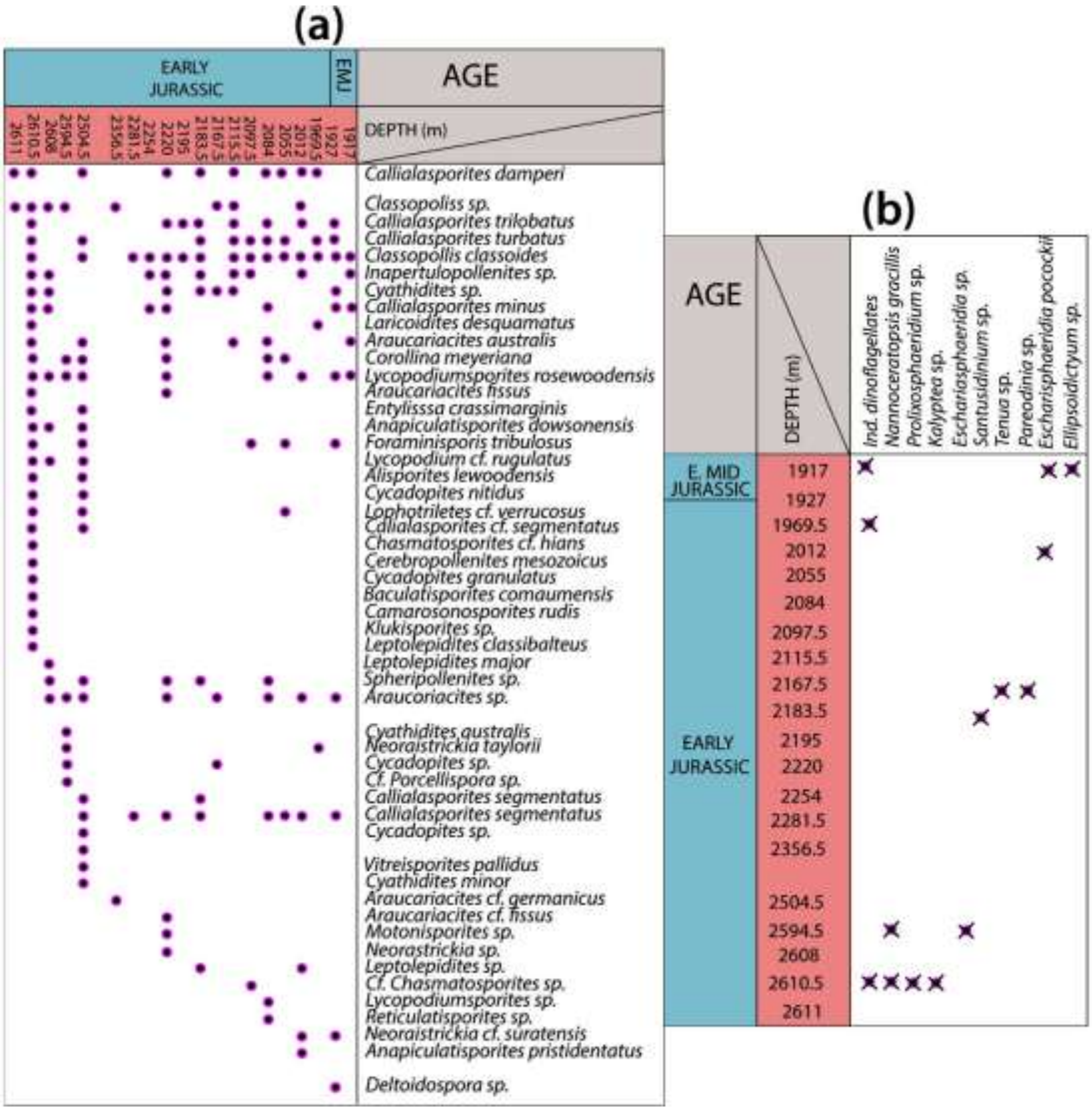


Figure 3. 4: (a) A chart showing ranges of spore and pollen from the Ngerengere formation of the Kizimbani Well (Modified after Balduzzi et al. 1992). EMJ= Early Middle Jurassic (Bajocian-Bathonian) (b) A chart showing ranges of dinoflagellate cysts Ngerengere beds of the Kizimbani Well (Modified after Balduzzi et al. 1992). E. Mid Jurassic = Early Mid Jurassic (Bajocian-Bathonian).

Lugoba formation

The Lugoba formation (Kapilima 2003, Figure 3.3) is best defined between Lugoba area and Wami River and at an abandoned quarry along the Lugoba - Talawanda gravel road (Kapilima 1984, Matulanya 2017). Based on ammonite dating, the age of the Lugoba formation is estimated to be Bajocian or Bajocian to Bathonian

(Kapilima 1984, Kapilima 2003). Generally, in this area, several separate limestone hills are observed to follow the Tanga fault trend orientation (Kapilima 1984). Fossil data and lithological facies changes Kapilima (1984) further subdivides the Lugoba Formation into Msata, Msolwa and Madesa members (see Figure 3.3).

Msata member

The Msata member type locality is the hilly exposure (abandoned quarry) which is located beyond the Mkombezi river bridge, on the left side along the Lugoba – Msata tarmac road. It is characterized by marine sediments in direct contact with the crystalline basement rocks (Kapilima 1984). The sedimentary succession comprises of detrital limestones or silty limestone (Kapilima 2003), with visible clasts of quartz, feldspar and rock fragments from the basement rocks (Kapilima 1984, Joyna 2017). The proportion of terrigenous clastic tends to be so high in some parts making the grab samples in these parts to appear like calcareous cemented sandstones (Kapilima 1984). The age of the Msata Member is estimated to ?Lower Bajocian by dating of three ammonite fragments and correlation to Kambe limestone in Kenya (Kapilima 1984, Kapilima 2003). Although commonly accepted in Tanzania, dating of the Lugoba formation is highly questionable because of a few specimens used and their fragmentary nature.

Msolwa member

The type locality for the Msolwa member is a quarry near Msolwa village, approximately 3 km east of the Chalinze town (Kapilima 1984). The quarry is currently abandoned, but partly operational and it exposes approximately 20 to 35 m thick coarse-fine grained calciarenites, partly calcirudites (Kapilima 1984, Kihanga 2017, Versteijlen 2018). Kapilima (1984) reports marine shells, calcareous algae and coral detritus as the visible fossils in the Msolwa member. The sedimentary rocks of the Msolwa Member display significant graded stratification (Kapilima 1984, Kihanga 2017, Matulanya 2017 and Versteijlen 2018). Middle Jurassic (i.e. ?Bajocian-Callovian) age is proposed for the Msolwa Member (Kapilima 1984, Kapilima 2003).

Madesa member

The type locality for Madesa member are the sections along Madesa (10 km NE of Msata) and Mafisa areas (4 km NE from Madesa) (Kapilima 1984, Figure 3.5). Other sections include a road cut from Madesa to Mkoko, approximately 3-4km NE from Mafisa and another section, 4-5 km E from Mkoko on the south bank of the Wami River. It is characterised by litho and bio – facies that are similar to the Msata Member, except for the fact that, the top of Madesa Member is overlain by small insitu coral sticks/reefs (Figure 3.3). The age of this formation is not certain.

Malivundo formation

The Malivundo formation is well defined between the Wami River and Malivundo village (Kapilima 1984). Classical sections include sections at Malivundo village (8 - 11 km SE from Msoga), river cut sections along Mbiki River (8 km SE of Msoga), sections found about 1 km east of the Mbiki Bridge and Msoga village. General lithological descriptions for Malivundo formation comprise dominant limy silt to sandstone with marl and occasional limestone concretions (Kapilima 1984, Figure 3.3). The latter are reported only in the marl unit. Ammonite biostratigraphy has assigned ?upper Callovian to middle Oxfordian age to the Malivundo Formation (Kapilima 1984).

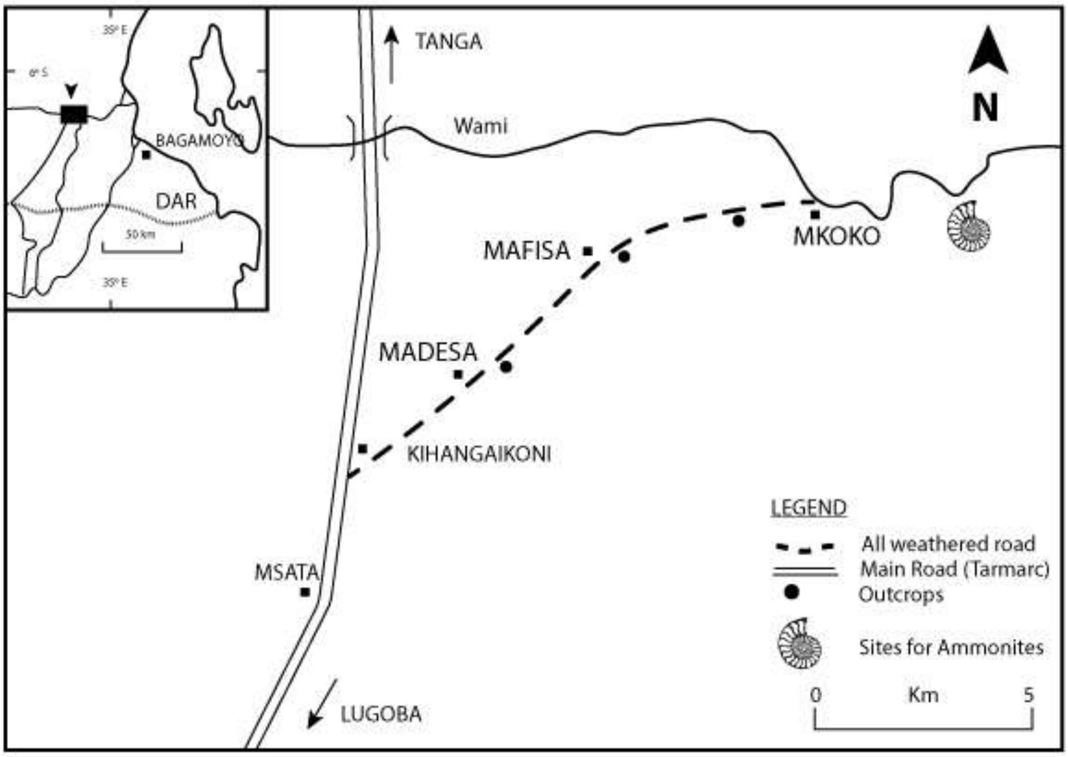


Figure 3. 5: Sketch map showing the location of sedimentary rocks outcrops (Jurassic) and ammonite localities at the Madesa-Wami profile of the Ruvu Basin (Modified from Kapilima 1984).

Magindu formation

Reference section for Magindu formation is located 1 km north of the Magindu train station on the flanks of a small valley and a rail cut, 4 km E of Magindu, along the railway line (Kapilima 1984). It comprises of an alternating storage of marl of Callovian age (Kapilima 1984) and chalky silt to sandstones, rich in thick shelled pelecypods.

Chalinze formation

Chalinze formation is characterised by mainly conglomeratic sandstones located 4 km to 18 km E of Msolwa village. The congromerate unit in this formation is overlain by marl (Kapilima 1984, Figure 3.3). The age of this formation is not very clear except for the upper part that was assigned an Aptian age (or younger) based on foraminiferal dating (Kapilima 1984).

It should be noted that, other lithostratigraphic terms are known in relation to the Ruvu Basin's stratigraphy. These include the Makarawe formation (Bajocian) and the Bathonian-Kimmeridgian Bagamoyo formation (McMurty 1985). The latter is an equivalent of the Mandawa Series penetrated by the Makarawe-1 well (McMurty 1985, Msaky 2007).

3.2 Materials and Methods

3.2.1 Materials

8 Palynological slides prepared out of 7 cutting samples from Makarawe–1 were investigated. The cuttings represented the upper intervals of the Makarawe–1 (i.e. 1215m 1427m) well. This is an exploration well drilled by International Economic Development Council (IEDC) in the Ruvu Basin in 1984. The samples from the Makarawe-1 capture the transition of the Karoo-equivalent Tanga beds (see Chapter 2) to the inferred Jurassic section (e.g., the Makarawe formation after McMurthy 1985 and/or the Lugoba-Malivundo formation after Kapilima 1984). Furthermore, this study utilized lithostratigraphic information obtained in the Lugoba -1 short borehole drilled by Twiga Cement in the Ruvu Basin. Published maps used in locating the classical Jurassic outcrops in the basin were also part of the material. These included; the map published by Kent et al. (1971) and sketch maps (and geological maps) produced by Kapilima (1984). Other material included drilling reports for Makarawe–1 well (McMurthy 1984). Geographic locations during the fieldwork were recorded using a Geographic Positioning System (GPS) set to the Arc 1960 datum.

3.2.2 Methods

Field work

Geological field work was conducted in two main phases, the first phase being reconnaissance. The intention was to visit the Jurassic outcrops in the Ruvu Basin in order to map the main lithofacies, measure and sample the exposed sections of interest (Figure 3.5). Lithology of all surveyed tracks during the reconnaissance (i.e. at Msolwa, Lugoba, Msata and Tarawanda) is shown in Figure 3.6 and Figure 3.7 A-D. After laboratory processing of the reconnaissance samples, a detailed fieldwork was conducted in the basin. This also involved visiting a rig site at Lugoba where Twiga cement was coring the Lugoba limestone (Lugoba–1 well, Figure 3.7 b) as part of their exploration routine. Following the lack of stratigraphic nomenclature in the basin, lithostratigraphic terms used by Henning (1924), Kapilima (1984) and Kapilima (2003) were adopted in this study.

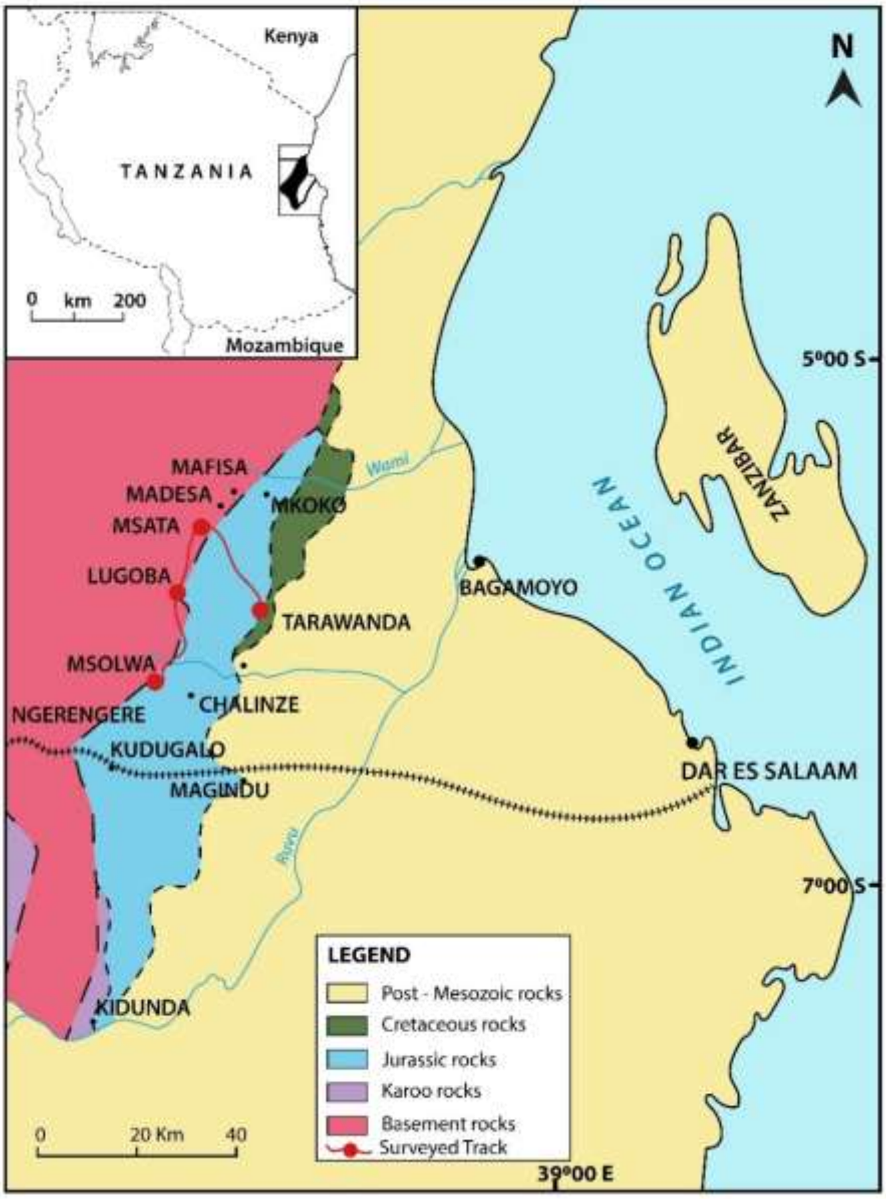


Figure 3. 6: The geological map of the Ruvu basin showing the Jurassic outcrops and surveyed tracks (Modified from Kapilima 1984 and Kent et al. 1971).

Sampling

Samples used in this study involved 8 drill cutting samples from the upper/shallower intervals of Makarawe – 1 well (i.e. 1215 m – 1427 m, also see Figure 3.8 a). All the samples were taken at the transition between what is referred to as the Tanga Beds (i.e. samples 1367 m, 1397 m and 1427 m) and the Makarawe Formation (i.e. samples 1215 m, 1235 m, 1267 m and 1280 m), a subdivision made by McMurtry (1985) in the Makarawe–1 drilling report (McMurtry 1985). Lithologically, the ?"Makarawe Formation" (? Bajocian) constitute pale to medium gray argillaceous limestone alternating with very dark – grey carbonaceous claystones while the "Tanga Beds" equivalent consisted of a sandstone unit alternating with greenish grey claystones/shales (McMurtry 1985 and personal observations).

The limestone in the Makarawe formation (i.e. Amboni limestone, Figure 3.8 a) is partly correlative with the Lugoba formation, an interval penetrated at around depth 1215 m of the Makarawe-1 well and the entire Lugoba–1 well (McMurtry 1985, Figure 3.8 a and b). Part of this limestone in the Makarawe–1 well was also sampled for palynological analysis in this study in the Makarawe–1 well.

Laboratory work for Palynology

Palynological processing for the Makarawe–1 cuttings was conducted at the Earth - Sciences Laboratory (GML) of the University of Utrecht. Generally, processing involved grinding the lithified rock samples (i.e. outcrop samples) into approximately 2 mm^2 (or smaller) parts to simplify the chemical processing by increasing the surface area for a chemical reaction to take place.

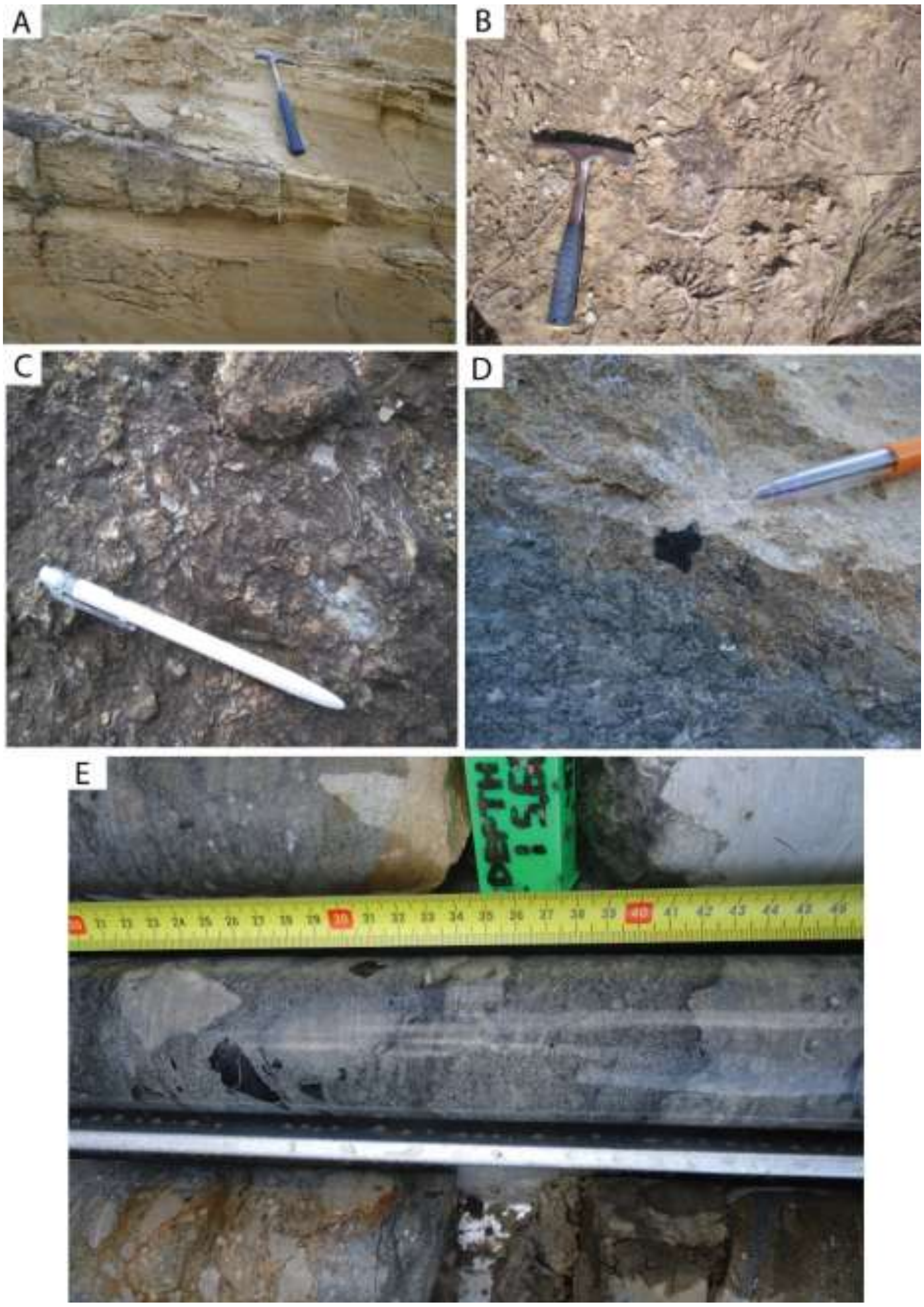


Figure 3. 7: Mesozoic outcrops of the Ruvu basin A). Alternating calc - lutite and calc - siltite sequences at Msata. B - C). Limestone with well - preserved reefal ecosystem at Lugoba D). Coal fragment in calc – arenite (Msolwa Member) (Lugoba Formation). E). Core photograph from Lugoba-1 borehole showing coal fragments and calcite pebbles in calc–arenite; and reefal ecosystem in limestone.

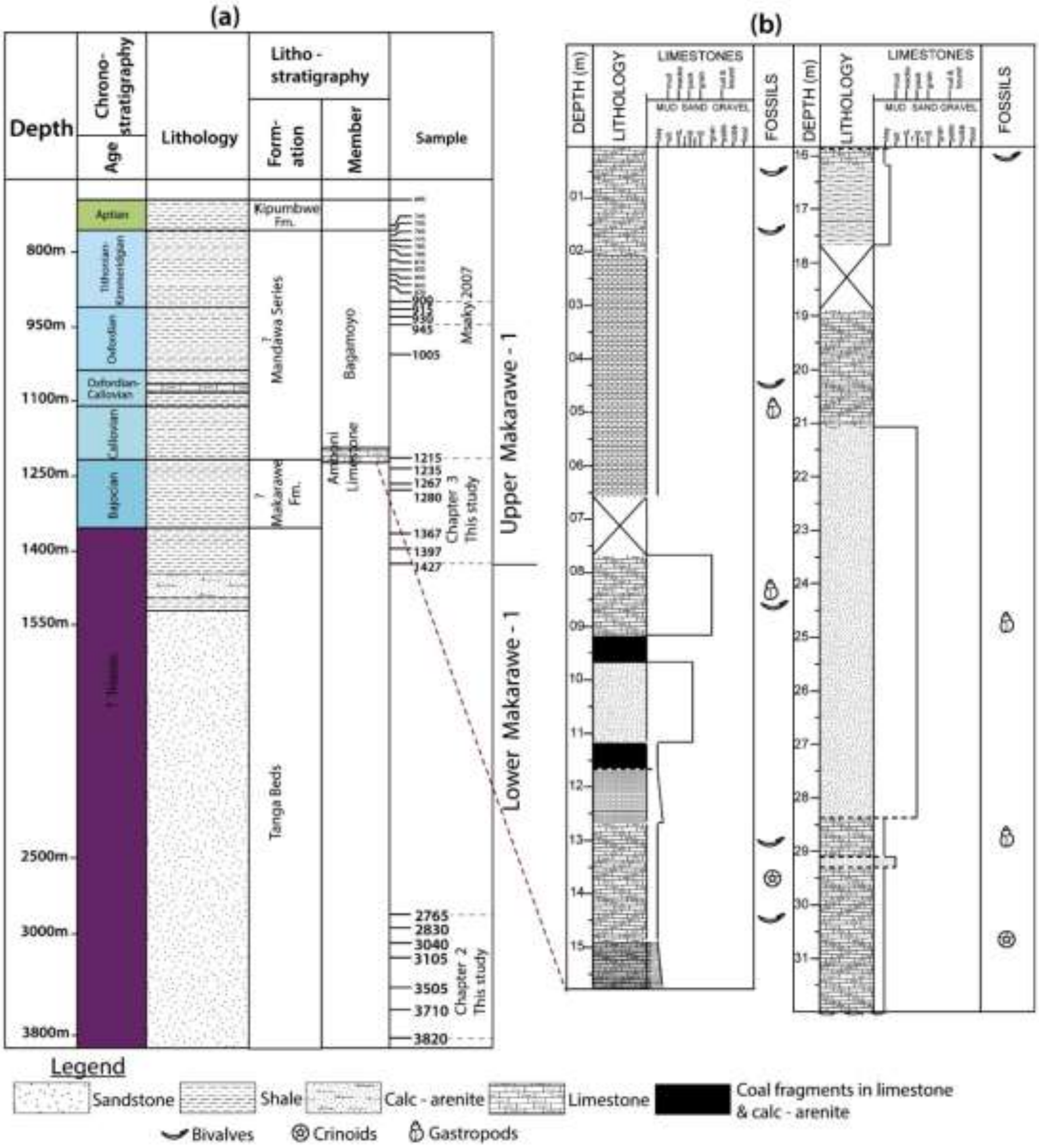


Figure 3. 8: a). Makarawe-1 well (Lithology, stratigraphy and sampled intervals) (The stratigraphic and lithological interpretations are after McCarty 1985 and Msaky 2007) b). Lugoba–1 short stratigraphic borehole.

For the drill cuttings, the required size was already achieved by the drilling process. Because the material was slightly calcareous, approximately 10 – 15 g was required for the chemical procedure. The samples were placed in an acid-resistant plastic container (HDPE; preferable volume 180 ml or more) and labelled appropriately (Figure 3.9 c). The samples were then moved to the laboratory for chemical processing where they were specifically put in a fume - hood (protected environment).

While in the fume hood, hydrofluoric acid (38 - 40%) was added to the samples (a very strong reaction that could be diminished by adding more hydrofluoric acid). Whenever the reaction stopped, water was added to fill - up the sample containers and then left to settle over - night. After twelve hours, decantation was performed with great precautions to avoid disturbing the settled sediments. After this procedure, water was filled - up again, centrifugation was performed and beakers with hydrofluoric acid were placed onto an orbital shaker for about 2 hours. After two hours of shacking, the samples were returned to a fume chamber. Eventually, the samples were washed to remove the organic matter rim that formed at the side of the beaker and water was added again to the samples. The samples were then put away for the rest of the night with closed lids. After approximately 12 hours, another round of decantation was performed. Water was added, centrifugation and decantation were also repeated again. This marked the end of chemical procedure and the samples were ready to sieve.

Seaving involved opening the sample lids and placing them into 120 - micron sieve. All the material from the sample container were poured in 0.5 - 1 L plastic container through the 120 - micron sieve. The sieved material was then poured from the plastic container onto a 10 - micron sieve. The material in a 10-micron sieve was sifted, by making a clock-wise rotation to remove all the air that was visible between the cloth of the sieve and the water contact. When all the water was drained, only very fine sediment particles were visible in the sieving container and a little amount of water (i.e. amongst the material that went through the 10-micron mesh). Water was added to the sample in a sieve using a splash-bottle, while holding the sieve under a low-angle towards a crucible. Only the floating part was important at this stage, hence, the residues were thrown away. The sample (in a crucible) was moved to a second ultrasonic bath (Ultrasonic bath-2) and was left to settle. Once everything had settled, the sample was again moved from crucibles in ultrasonic bath-2, to a 10 - micron sieve and sifting was performed. After this procedure, the samples were ready for mounting.

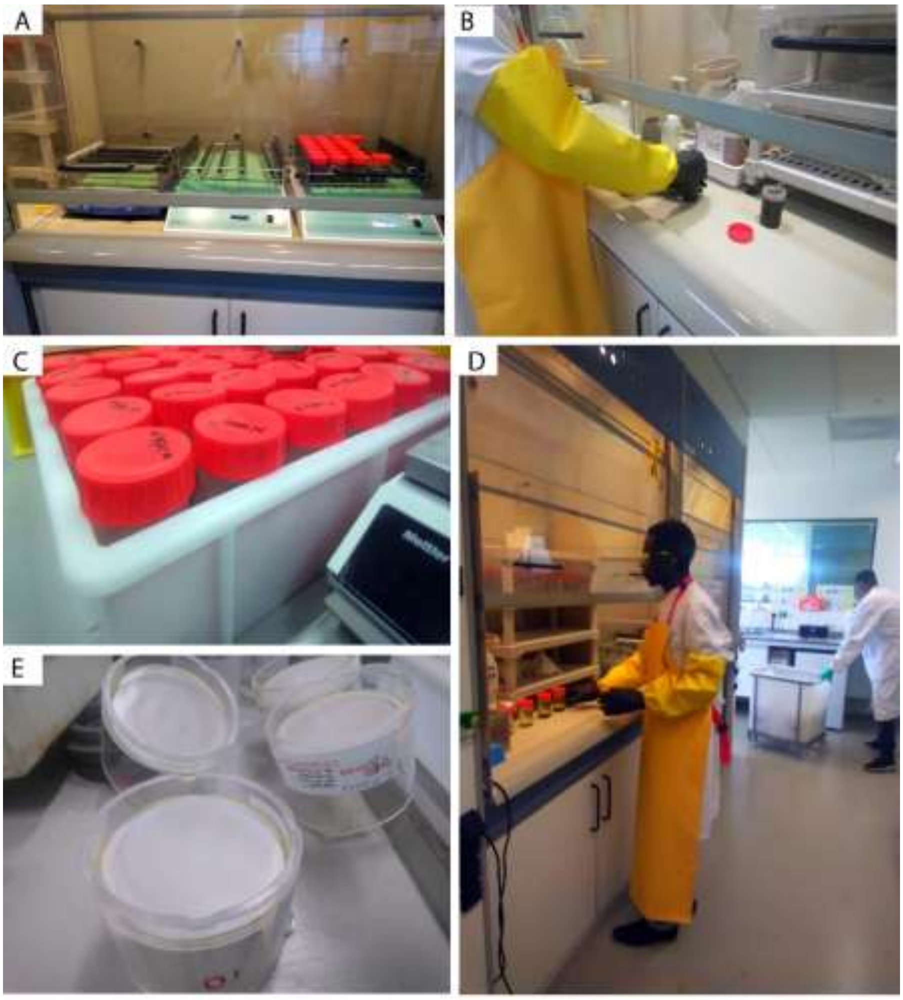


Figure 3. 9: A). Crushed samples in the orbital shackers. B). Preparing the samples for chemical procedures in the fume hood C). Sample handling after crushing and prior to chemical procedures D). Decantation in the fume hood and centrifugation E). 10 and 120 - micron Sieves.

Mounting slides and cover-slips were prepared by holding them to the burners to remove any fatty material. After this preparation, the samples in the eppis were taken to the vortex for shacking and mixing. About two to three droplets of the sample was taken using a disposable glass - pipette and transferred into a new sample vials eppis. Two droplets of PVA were added to the sample. The sample-PVA mixture was taken to the vortex for mixing with additional water to the sample-PVA mixture. The mixture was then sampled using another pipette and slowly poured on the top of the cover-slip that was already on top of the heating media. Once the droplets were dry, one droplet of “glue for glass” was poured on the surface of the slide. The slide was then carefully lifted and mounted on top of a cover-slip. A blunt object was used to ensure the glue has spread throughout the cover-slip. The slide was then cured for about 30 seconds using a (day-light) lamp.

Qualitative Analysis

Qualitative analysis involved observation and recognition of various palynomorph taxa under the microscope. This was specifically the study of palynomorphs at generic and species levels and it relied on the use of morphological properties (i.e. outline/shape, size, ornamentation and presence/absence of apertures) to recognize each individual taxon. All Makarawe-1 slides yielded better preserved specimen (except for slide MK–3040 m that was barren). Unfortunately, all the outcrop samples from the Ruvu basin did not yield any palynomorphs and therefore, nothing is reported about them in this study. Leica transmitted microscope fitted with a digital camera available at the department of geology (UDSM) was used in examining all the slides. The calibrated stage available on the mechanical stage made possible recording of the coordinate locations for selected palynomorph specimen for future referencing. Photomicrographs of the selected specimen were taken using digital camera fitted on the microscope. The individual photomicrographs were used in plate compilation. Taxonomy of organic-walled dinoflagellates follows that cited in Williams et al. (2017) unless indicated otherwise.

Quantitative Analysis

Following completion of qualitative analysis, a quantitative analysis was performed. Quantitative analysis involved counts of major palynomorphs present in each slide. Beforehand, the organic matter visible under the microscope were categorized as palynomorphs (i.e. pollen, spores, organic-walled dinoflagellate cysts (dinocysts), fungi, algae, *Botryococcus*, acritarchs and fungal spore) and phytodebris (i.e. Transluscent phytoclasts, cortex tissues, Transluscent “cuticle”, membraneous tissues, opaque phytoclasts, fungal remains, foraminiferal test linings, amorphous organic matter, and resin particles). Depending on the richness of organic matter on the slides, counting achieved a total of 100 - 200 specimens per slide to represent the entire assemblage. Analysis was performed at 500 - 1250 x magnification. Palynological intervals were established based on index spores, pollen and dinoflagellates. C2 data analysis software (version 1.7.2), Sedlog 3.1 and Adobe Illustrator Suite (CS6) were used for reconstruction of range and distribution charts. These included presence–absence range charts displaying all identified palynomorphs in the assemblage as well as semi–quantitative range charts showing percentage comparison of main taxa.

3.3 Results

3.3.1 Palynostratigraphy of the Upper Makarawe–1 (1215 - 1427 m)

Investigated samples from the "upper section' of the Makarawe–1 well (i.e. 1215 - 1427 m) yielded palynomorphs of good to excellent preservation quality especially in the upper most intervals (1215 m and 1235 m). Dinoflagellate cysts were recognized and identified based on the cyst morphology (following the recommendations of Evitt 1985). Pollen and spores were also identified based on amb shapes, sizes, visible ornamentations and presence/absence of apertures. Therefore, forty seven (47) palynomorph taxa (i.e. 38 dinoflagellate cysts and 5 pollen taxa, 3 trilete spore taxa and 1 acritarch taxon) were recorded from the Makarawe–1 slides. Images for selected palynomorphs are shown in plates 3.1-3.12, quantitative distribution patterns of the selected taxa in Figures 3.10 and 3.11. The taxonomic appendix (Appendix 1) provides a list of recorded species and their taxonomic references.

The identification of palynologically/stratigraphically distinct intervals for the upper Makarawe–1 samples is based mainly on the ranges of dinoflagellate cysts supplemented by pollen–spore ranges. The resulting palynological intervals documented in this study are compared with other palynologically dated lithostratigraphic units in Africa i.e. Tanzania (Msaky 2007) and Madagascar (Chen 1978), Australia (Helby 1987, Burger 1996, Mantle 2005, Riding et al., 2010) and Europe (Riding 1984, Riding and Thomas, 1992, Poulsen and Riding 2003). In order to counteract the possible caving effect, the basis for establishing palynological intervals included consideration of the first downhole occurrence (or in other words, the stratigraphic highest occurrence) of taxa. The ammonite intervals for the Jurassic of the Ruvu Basin established by Kapilima (1984) and Kapilima (2003) are continuously discussed in this context (Figures 3.12 and 3.14).

The Jurassic and Cretaceous time–units used in herein follows the classification made in the 2016 Geologic Time Scale (Ogg et al. 2016), the subdivisions established by the International Sub commission on Jurassic Stratigraphy (Morton 2008) and those established by the International Subcommission on Cretaceous Stratigraphy. However, explanations are offered for stratigraphic subdivisions outside the adopted standards by this study. Therefore, from the quantitative analysis of the Makarawe – 1 sample (Figure 3.10 and 3.11) based on relative frequencies of individual dinoflagellate taxa and other identified sporomorphs in the assemblages, the following were observed;

Palynological Composition of Samples MK 1267-MK 1427 (Depth 1265-1427 m)

The lowermost palynological interval is defined between 1267-1427 m. It comprises an assemblage of moderately well preserved to poorly preserved palynomorphs as compared to the overlying interval (i.e. depth 1215-1235 m). In this interval, vast amounts of *Classopollis* pollen grains seems to dominate the assemblage. This pollen group is produced by plants that are affiliated with aridity-tolerant Cheirolepidiaceaen conifers (Alvin 1982). Other pollen are also documented and they include pollen grains derived from Auracariaceae (i.e. *Callialasporites*), Polyplicates (i.e. *Ephedripites*), Bennettitalean (*Excesipollenites)*, Cyacadales (i.e. *Cyacadopites*) and small percent of trilete spores (4%) (Figure 3.10). *Excesipollenites* sp. makes 0.5% of the total assemblage while *Ephedripites* sp. and *Callialasporites grandis* makes 0.49% and 0.6% of the total assemblage respectively.

A few dinocysts belonging to genus *Nannoceratopsis* (0.9%) are also observed and they make subdominant component in the palynological assemblage next to spores. These include *Nannoceratopsis triceras* (0.52%), *Nannoceratopsis dictyambonis*

(0.63%) *and Nannoceratopsis gracilis* (0.97%), *Nannoceratopsis plegas* (0.63%), *Nannoceratopsis magnicornus* (0.5%) and *Nannoceratopsis pellucida* (0.4%).

Palynological composition of samples MK 1215 and MK 1235 (Depth 1215 m and 1235 m)

Very well preserved palynological assemblage recovered from samples representing depth 1215-1235 m revealed overwhelming dinocyst abundance in comparison to the underlying interval (1235-1427 m) (Figure 3.10). This interval is composed of *Wanaea clathrata* (0.8%), *Wanaea talea* (1.3%), *Wanaea spectabilis* (0.87%), *Wanaea lacuna* (0.43%), *Wanaea fimbriata* (0.85%), *Wanaea digitata* (0.75%), *Wanaea indotata* (0.4%), *Nannoceratopsis gracilis* (0.85%), *Gonyaulacysta jurassica* (0.4%), *Tenua hystrix* (3.04%), *Hystrichosphaerina schindewolfii* (0.9%), *Glossodinium dimorphum* (0.75%), *Dingodinium spinosum* (1.74%), *Scriniocassis* sp. (1.3%), *Fistulacysta simplex* (0.9%), *Subtilisphaera pellucida* (1.3%), *Stiphrosphaeridium dictyophorum* (0.43%), *Paleocysta* sp. (%), *Cerbia tabulata* (0.87%), ?*Canningia reticulata* (0.43%),*?Sentusidium tanzaniensis* (1.3%) and *Egmontodinium* sp. (0.43%), *Ctenidodinium sellwoodii* (0.6%), *Batiacasphaera* sp. (%), *Durotrigia* sp. (%), *Mendicodinium groenlandicum* (1.13%), *Adnatosphaeridium multispinosum* (0.75%), *Kleithriasphaeridium simplicispinum* (0.38%), *Gonyaulacysta centriconnata* (0.75%), *Subtilisphaera rotundata* (1.13%), *Valensiella ovulum* (0.38%), *Dissiliodinium willei* (1.5%), *Batiacasphaera mulchisonii* (1.13%), *Ctenidodinium combazi* (1.5%), *Durotrigia omentifera* (1.13%), *Palaecysta virgae* (0.75%), *Subtilisphaera scabrata* (1.2%), *Lithodinia caytonensis* (0.6%) and *Ctenidodinium ornatum* (0.75%).

Pollen grains that were also observed in this interval and they include, *Excesipollenites* sp. (1.3%), *Callialasporites* sp. (1.74%) and *Ephedripites* sp. (1.7%). *Classopollis* pollen grains (up to 65%) are recorded in this zone but contrary to the underlying zone, the *Classopollis* abundance shows a decreasing trend in abundance (Figure. 3.10).

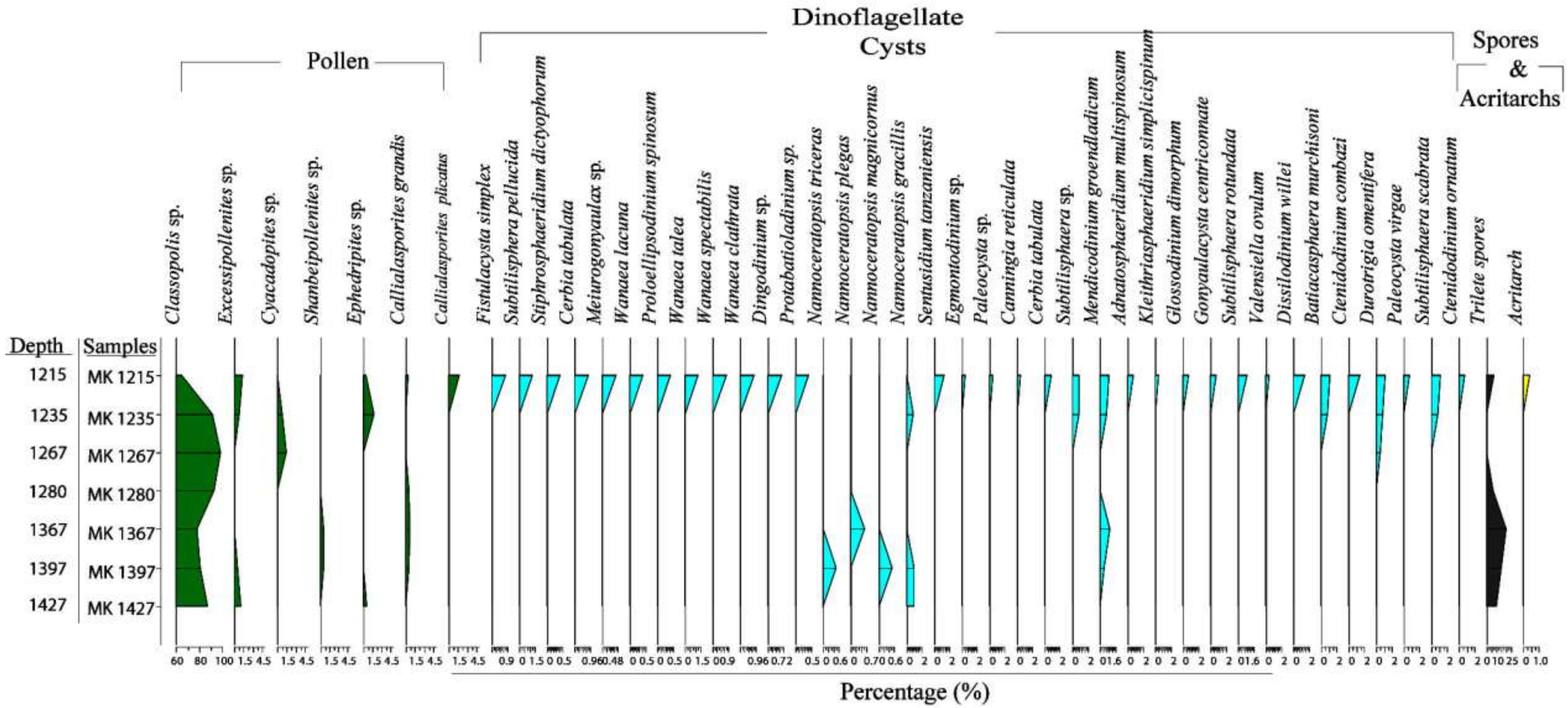


Figure 3. 10: **Relative abundance chart of selected palynomorph groups from the Makarawe–1 well samples showing their distribution (plotted as percent of total palynomorph counts).**

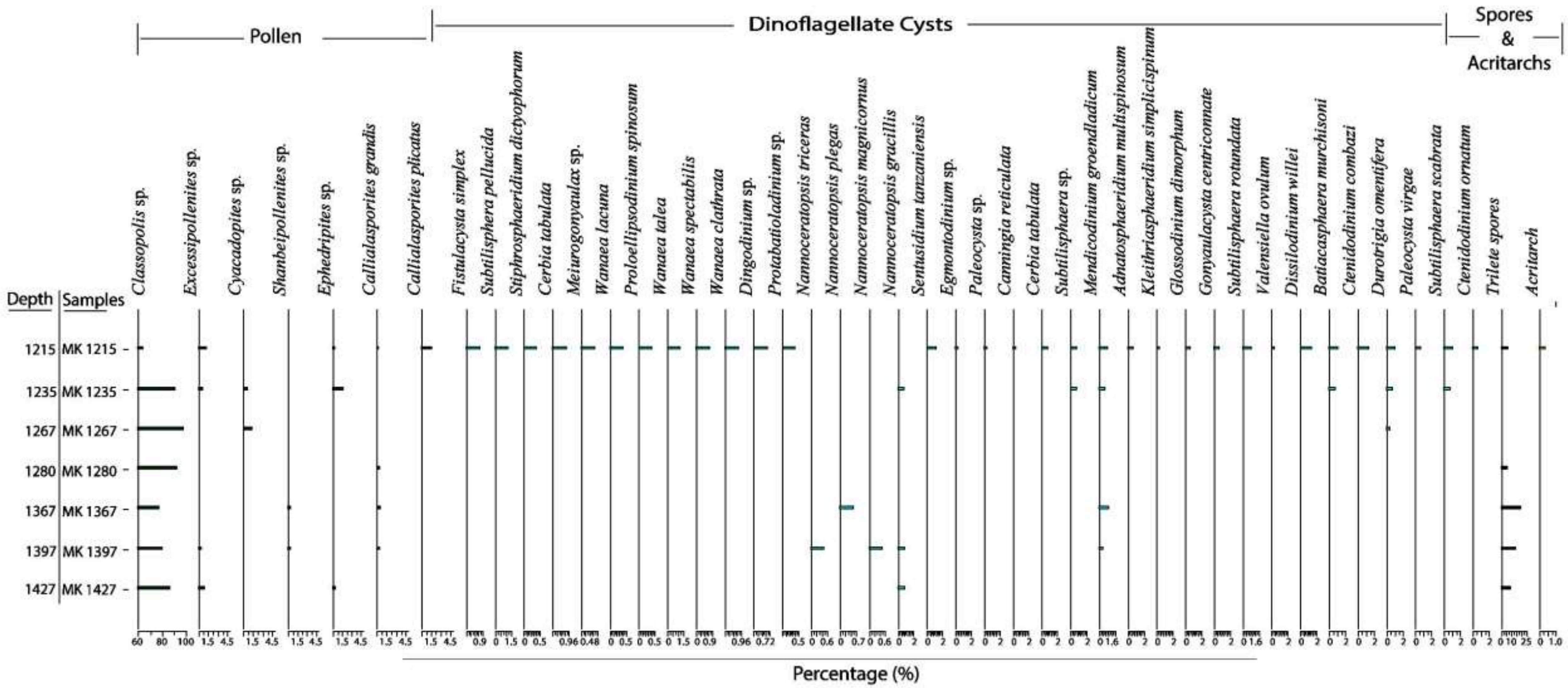


Figure 3. 11: Relative abundance (%) of pollen and spores, and presence -absence of palynomorphs of the Makarawe–1 well.

3.4 Discussion

3.4.1 Age Assessment

Samples MK 1267, MK 1280, MK 1367, MK 1397 and MK 1427 (Depth 1267 - 1427 m) (Bajocian - Oxfordian)

The mass - ocurence of *Classopollis* (Figure 3.10) recorded in the samples between 1267 m and 1427 m is widely accepted to mark the onset of the Jurassic in the Gondwana and worldwide (Vakhrameev 1981, Srivastava 1976). Furthermore, exceptionally *Classopollis* pollen abundancy (up to 98%) is well recorded and reported in the Upper Jurassic of the Gondwana (Pocock and Jansonius 1961).

Additionally, a dinocysts taxon *Nannoceratopsis pellucida* documented in this interval is stratigraphic significant taxa for the Middle to Late Jurassic and can be used in this context to infer a Bajocian-Early Oxfordian age for the studied samples. *N.pellucida* Interval is known in the late Bajocian-Oxfordian of Tanzania (Balduzzi et al.1992), Bajocian-Bathonian of Madagascar (Chen 1978), and Bajocian-Oxfordian of Europe (Riding 1991, Riding and Thomas1992, Riding 2010). Other documented species belonging to genus *Nannoceratopsis* include the *N.triceras, N.dictyambonis* and *N.gracilis.* These are also reported in the Callovian-Oxfordian of Australia (Riding et al. 1999), Egypt (Keeley et al. 1990) and Tanzania (Balduzzi et al. 1992). The presence of *Mendicodinium groendlandicum* documented in this interval (Figure 3.10) can also be used to support the Middle Jurassic (Bathonian) assertation for this interval. However, additional taxa *Nannoceratopsis plegas* (Toarcian-Aalenian; Ainsworth 1989, Poulsen and Poulsen 1996) and *Nannoceratopsis magnicornus* (Toarcian; Bucefalo 1999, Van de Schootbrugge 2005) are also documented. Their presence may be ascribed to reworking, implying that, Lower Jurassic marine strata can be encountered in the vicinity of the Makarawe-1 well in the Ruvu Basin.

Samples MK 1215 and MK 1235 (Depth 1215 - 1235 m) (Oxfordian - Kimmeridgian)

A wide range of dinocysts belonging to genus *Wanaea* is a characteristic of the Late Jurassic (Callovian – Kimmeridgian) of the African Gondwana (Clen 1978, Msaky

2007), NW Australia (Helby 1987, Burger 1996, Mantle 2005) and Europe (Riding 1984, Riley et al. 1982, Smelror and Below 1993, Poulsen and Riding 2003). In principle, the genus *Wanaea* is a significant marker genus for Middle to Late Jurassic strata in both the North and Southern hemispheres (Riding and Helby 2001, Msaky 2001). In Tanzania, species belonging to this group (i.e. *Wanaea clathrata*, *Wanaea spectabilis* and *Wanaea talea*) have been recorded and reported in the upper intervals of Makarawe - 1 well (depth 900 – 945 m, Msaky 2007, Also Figure 3.11). In the current study, most of the recognized *Wanaea* species in the assemblage (i.e. *Wanaea acollaris, Wanaea digitata, Wanaea clathrata, Wanaea fimbriata, Wanaea indotata, Wanaea spectabilis,* and *Wanaea talea*) suggest an Oxfordian – Kimmeridgian age (i.e. Late Jurassic, Msaky 2007). However, the presence of *W. digitata* and *W. acollaris* among the assemblage may suggest an age older than Oxfordian (up to Late Bathonian; Woolam 1982, Riding 2010). The presence of other dinocyst species in association such as *Gonyaulacysta jurassica, Tenua hystrix, Fistulacysta simplex, Nannoceratopsis pellucida, Glossodinium dimorphum* and *Mendicodinium gloenlandic* also support a late Jurassic interpretation (Powell 1992, Riding et al., 2010, Msaky 2011). Similarity in composition of the assemblage documented by this study to the one reported by Msaky (2007) and Msaky (2011) in intervals 900 m-945 m of the same well (i.e. Makarawe -1) may possibly suggest the extension of this zone from 1215 m-1235 m to 900 m. However, there is a chance that the samples at intervals 1215m-1235 m were affected by contamination/ caving that was introduced by a casing placed at 1215 m.

3.4.2 Correlation of the Ruvu Basin's Dinoflagellate Assemblages to other Palynological Records

Well-preserved and diverse palynological assemblages in the studied interval in the Ruvu Basin, make a useful reference assemblage for correlating the post – break – up strata with other assemblages elsewhere (Figure 3.13). Hence, this section attempts to correlate the Late Jurassic biogeographic similarities between the sedimentary strata of the Ruvu Basin (documented in this study) and coeval strata elsewhere. As stated earlier (in section 3.3.1 of this chapter), two distinct palynologically dated stratigraphic intervals are recognized in the current study. These include Callovian –

Oxfordian interval dominated by *Classopolis* pollen (*Classopolis* - *Nannoceratopsis* Interval) and the Oxfordian – Kimmeridgian interval dominated by the dinocyst genus *Wanaea* (*Wanaea clathrata* Interval, Figures 3.13).

***Classopollis – Nannoceratopsis* Interval**

The *Nannoceratopsis* dominated association (i.e. the *Classopolis* - *Nannoceratopsis* Interval), is comparable in many aspects to Zone VI of the Ankamotra - 1 well in the northwestern Madagascar (Chen 1978) and Zones DSJ11 - DSJ12 of northwest Europe (Poulsen and Riding 2003). However, in contrast to many Late Jurassic assemblages in Europe (e.g. Poulsen and Riding 2003, Abbink 2004, Verreussel et al. 2018) and the Late Jurassic Madagascan assemblages (Chen 1978) which shows high diversity dinocyst associations with no *Classopollis* pollen, the low diversity documented in the Makarawe-1 assemblages with dominant *Classopollis* pollen may represent a fairly local/regional phenomenon. Co-occurence of *Classopollis* pollen and *Nannoceratopsis* spp. in the Makarawe-1 well signify a fairly restricted marine conditions explained by the exclusive presence of euryhaline/fresh-water tolerant dinoflagellate *Nannoceratopsis* (Palliani et al. 2002, Skupien et al. 2015), with a strong monsoonal terrestrial climate that boosts *Classopollis* proliferation (Bonis et al. 2010, Kujau et al. 2013).

***Wanaea clathrata* Interval**

Africa (Tanzania and Madagascar)

The dinocysts of the second recognized palynological interval (i.e. *Wanaea clathrata* Interval) clearly correlates with the Oxfordian to basal Kimmeridgian interval defined by Msaky (2007; 2011) in the same well (i.e. Makarawe-1, depths 900 m-945 m) (Figure 3.11). A few associated dinoflagellate cysts genera (e.g. *Dingodinium, Subtilisphaera, Egmontodinium, Canningia, Gonyaulacysta, Mendicodinium* and other *Wanaea* species) documented by Msaky (2007) and Msaky (2011) also appear in association with this interval (1215-1235 m).

In Madagascar (Chen, 1978), a few species of *Wanaea* are recorded, being reported in the Late Jurassic (Callovian - Kimmeridgian) of the Morondava Basin. The species documented in Madagascar are similar to those reported by this study and they include *Wanaea clathrata* and *Wanaea digitata* making a significant assemblage in Zone VI of the Ankamotra-1 well in the northwestern Madagascar (Chen 1978). In relation to the ammonite Intervals (Kapilima 1984, Kapilima 2003), the *Wanaea clathrata* dinocyst interval well correlates to the Oxfordian-Kimmeridgian Chalinze Formation (Figure 3.12). This is in contrast to a correlation made by Msaky (2007) where the studied interval (900 m - 945 m) was correlated to middle part of the Bagamoyo Formation (Oxfordian).

Australia

The *Wanaea clathrata* Interval documented in this study can be corelated the late Oxfordian to Early Kimmeridgia *Wanaea clathrata* Acme Zone *of* the *Pyxidiella* Superzone documented in the North West Shelf, Australia (Riding et al. 2010). This Superzone (Oxfordian to Kimmeridgian) comprises main three dinocyst zones that include *Wanaea spectabilis* Interval Zone, *Wanaea clathrata* Acme Zone, and *Dingodinium swanese* Interval Zone (Riding et al. 2010, Also see Figure 3.12). The *Wanaea clathrata* Interval Zone is also reported by Helby et al. (1987), Mantle (2005) in northwestern Australia. Furthermore, a close resemblance to *Wanaea Clathrata* Interval is noted in Australian Kimmeridgian-Oxfordian Zone 6b and Zone 6c (Helby 2004, Figure 3.12). Similar to the Australian Intervals, the *Wanaea clathrata* Interval in the upper Makarawe-1 well has *Gonyaulacysta jurassica*, *Wanaea spectabilis*, *Mendicodinium groenlandicum, Nannoceratopsis pellucida*, and *Systematophora* spp. as associated taxa.

Europe

An Oxfordian-Kimmeridgian dinoflagellate cyst interval that resembles the *Wanaea clathrata* Interval in the upper Makarawe - 1 is the Oxfordian to earliest Tithonian *Gonyaulacysta ceratophora* Zone (Riding and Thomas 1992) and *Gonyaulacyta jurassica - Scriniodinium crystallinum* Zone (Polsen and Riding 2003) of NW Europe (Figure 3.14). However, it is noted that the occurence of dinoflagellate *Wanaea clathrata* in European assemblages is doubted/ or poorly documented (Woolam 1982). Instead, *Wanaea digitata* and *Wanaea fimbriata* are recorded in the

European Late Callovian - Early Oxfordian (Woolam 1982, Riding 1999, Polsen and Riding 2003). These forms represent an age older than Oxfordian (i.e. up to Bathonian) in Tanzania and Australia (Woolam 1982, Burger 1996, Msaky 2007, Riding et al. 2010, Figure 3.13).

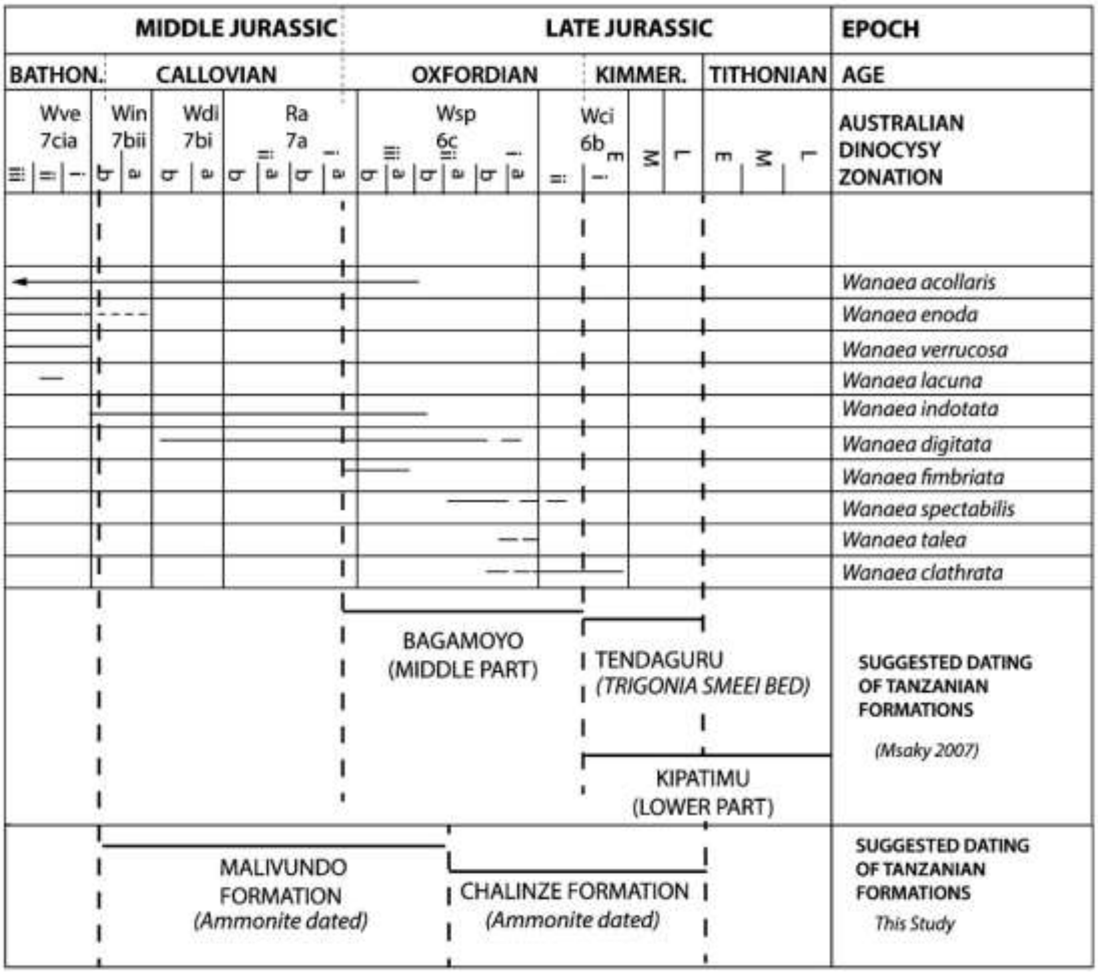


Figure 3. 12: A correlation chart showing stratigraphic ranges of Wanaea species from Makarawe–1 Well (upper intervals) against the Australian dinocyst zonation (modified from Helby 2004 and Msaky 2007). Wci = Wanaea clathrata, Wsp = Wanaea spectabilis, Ra = Rigaudella aemula, Wdi = Wanaea digitata, Win = Wanaea indotata, Wve = Wanaea verrucosa, BATHON. = Bathonian, KIMMER. = Kimmeridgian.

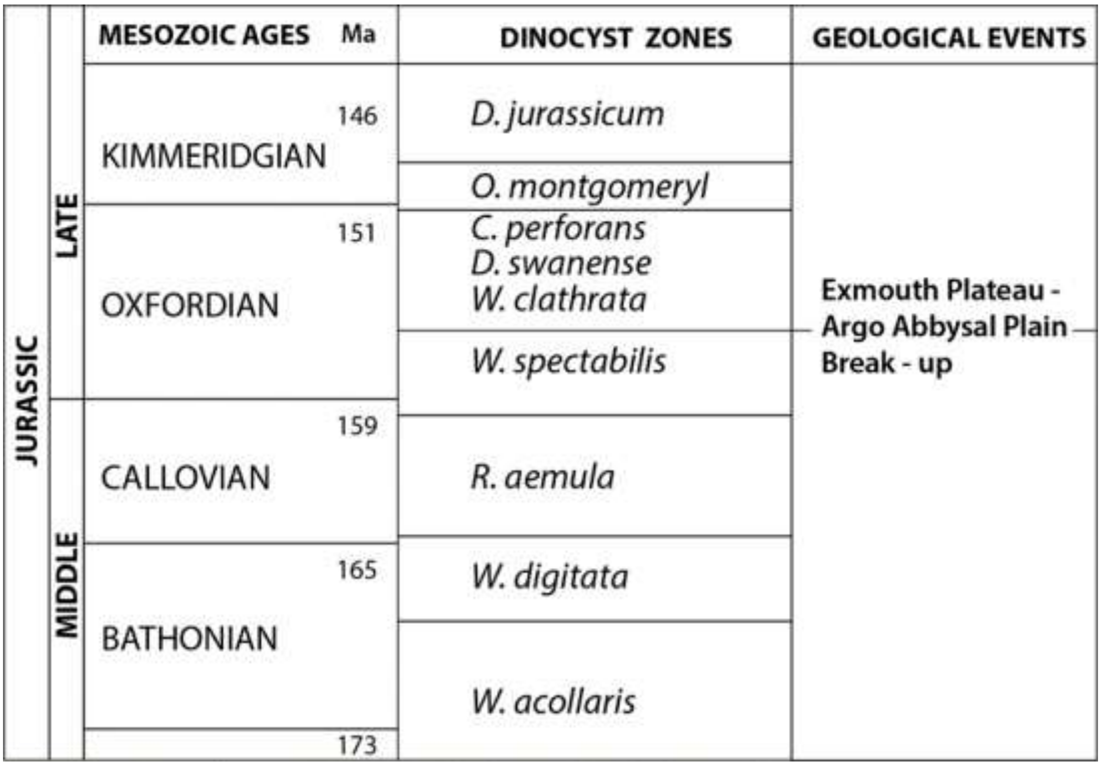
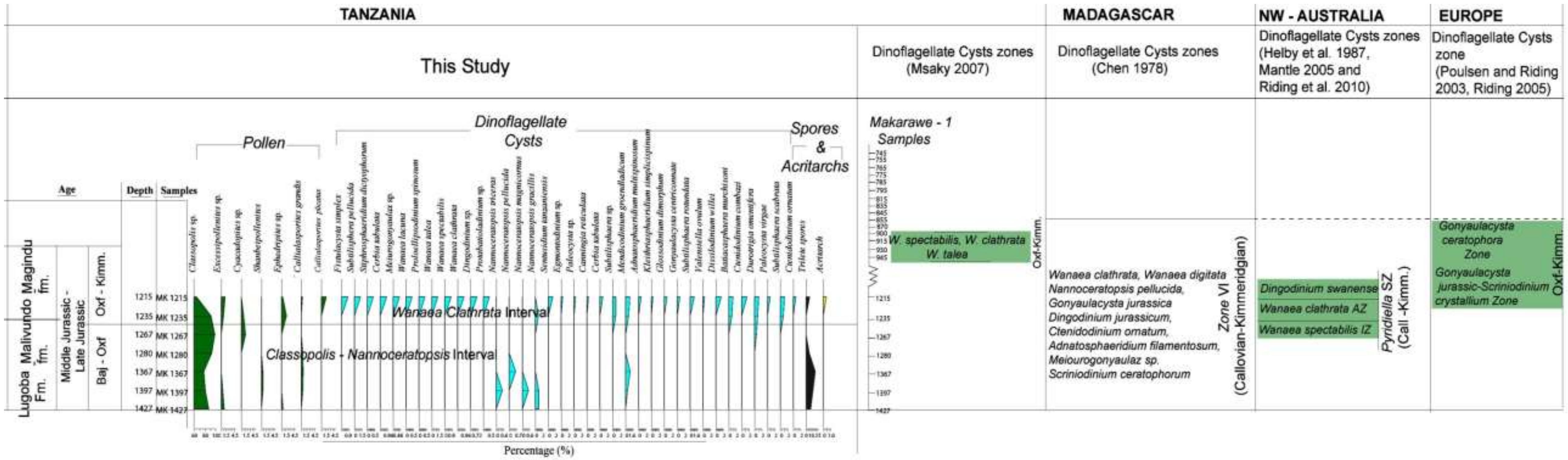


Figure 3. 13: Offshore Western Australia Middle - Late Jurassic palynologic zonation (Modified from Burger 1996).



Relative abundance chart of selected palynomorph groups from the upper Makarawe–1 well samples showing the dinocyst intervals and their relationship with similar assemblages elsewhere. Oxf = Oxfordian, Kimm = Kimmeridgian, Baj. = Bajocian, IZ = Interval Zone, AZ = Assemblage Zone, SZ = Superzone.

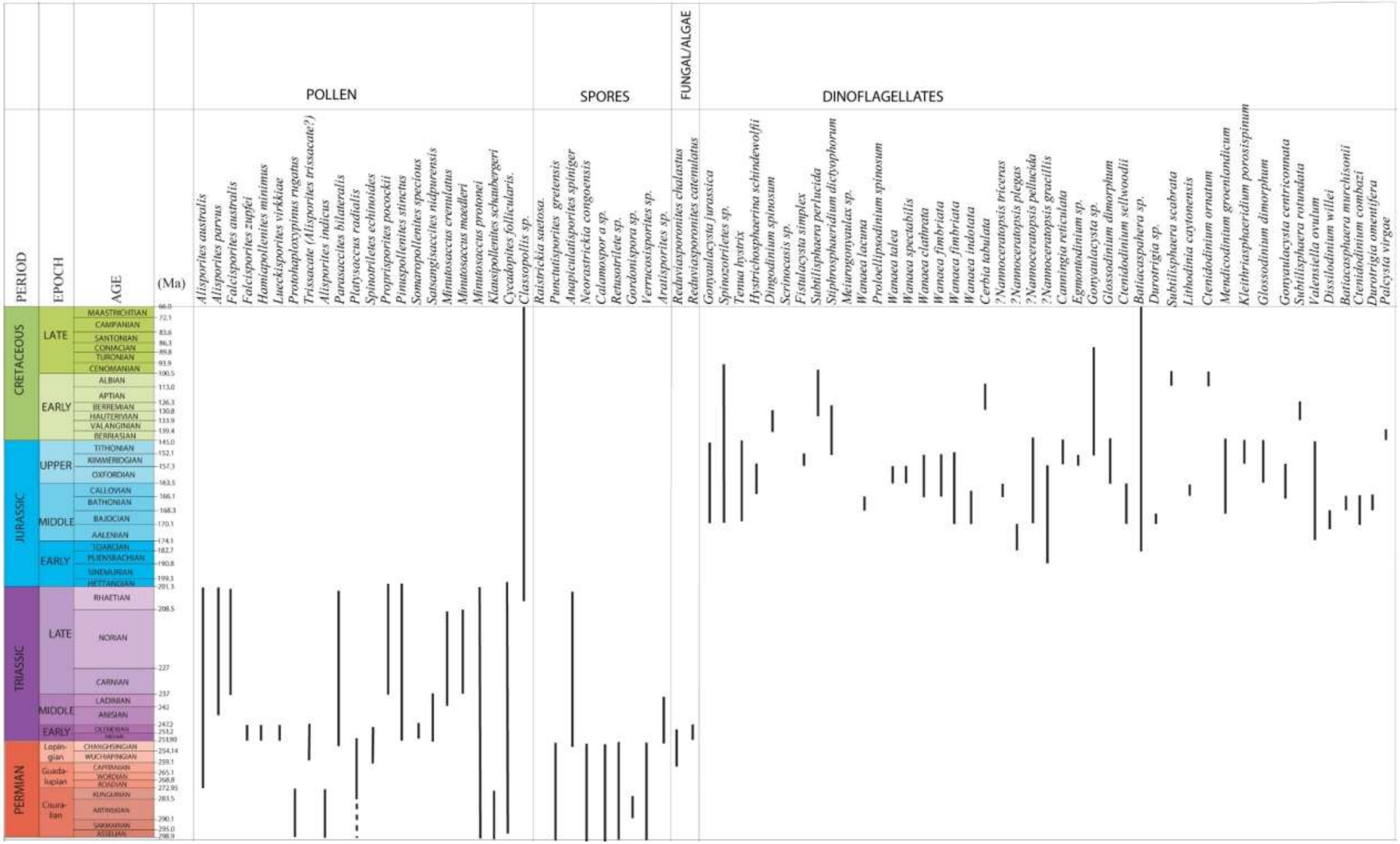


Figure 3. 15: Stratigraphic range chart of selected taxa in both lower/ deeper and the upper/shallower Makarawe–1 samples.

3.5 Conclusion

Using drill cutting samples from the upper Makarawe-1 Well (1215 - 1427 m) of the Ruvu Basin in Tanzania, this study identified vertical distribution palynomorph taxa of stratigraphic importance and recognized palynologically dateable lithostratigraphic units that fits the Gondwana breakup scheme. Furthermore, the following conlcussions can be drawn from the palynological results obtained in this study:

1. Two main dinocyst intervals (i.e. *Classopollis – Nannoceratopsis* Interval and *Wanaea clathrata* Interval) are established based on vertical succession of the identified palynomorph taxa (both miospores and dinoflaggelates). The *Wanaea clathrata* Interval is documented at depths 1215 - 1235 m, whereas the *Classopollis – Nannoceratopsis* interval is recorded at depths 1235 - 1427 m of the upper Makarawe–1 well. Palynological analysis in this study has further proven that, the *Wanaea clathrata* interval recorded in this study is coeval with a *Wanaea* rich interval documented by Msaky (2007) and Msaky (2011) at depth 900 - 945 m of the same well. This may possibly suggest an extension of this interval (i.e. 900 - 1235 m).

2. The dated lithostratigraphic units of the upper Makarawe–1 samples correspond to late Mid Jurassic - Late Jurassic (Bajocian - Kimmeridgian). This suggest a possible correlation to the ammonite dated lithostratigraphic units (i.e. Lugoba Formation - Malivundo Formation - Magindu Formation) of the Ruvu Basin. This may further imply that the studied intervals were deposited after the breakup of the Gondwana supercontinent and confirms the evidence of the Mid-Jurassic strata resting on the Karoo sequence that was observed in the deep/lower Makarawe–1 subsurface samples in chapter 2. Furthermore, the two recorded intervals are quite high in similarity and well correlates to other palynological intervals in Africa, Australia and Europe.

3. The dinocyst *Nannoceratopsis pellucida* documented in the first recorded interval of the Makarawe-1 well is indicative of an immediate post–break - up

association. Similar to the Ngerengere dinocyst assemblage documented in previous works, this finding further suggests that the Ngerengere beds are not Karoo equivalent but rather syn- or post the breakup strata.

3.6 Acknowledgements

I specifically thank Dr. Emma Msaky (TPDC) for inspiring the follow – up sampling in the Makarawe–1 well and for her valuable expertise in discussing the aspects of the Jurassic palynology in the Ruvu Basin. A very special thanks to Emmanuel Mwajombe (Geofields Tanzania Ltd.) for allowing a visit to the rig site at Lugoba (Lugoba–1 borehole) in the Ruvu Basin. John Gama is thanked for productive discussions related to Jurassic stratigraphy of the coastal tanzania.

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CHAPTER FOUR

CONCLUSIONS AND RECOMMENDATIONS

This study took advantage of the presence of palynomorphs preserved in sedimentary rocks of the Ruvu and Tanga onshore basins to provide new biostratigraphic ages and document bio-events recorded through the Permian – Triassic of coastal Tanzania. Using core samples from three stratigraphic boreholes in the Tanga onshore Basin (Vunde-1, Kakindu-1 and Jihirini-1 boreholes) and cutting samples from the Makarawe–1 well of the Ruvu onshore Basin, palynology (supplemented by paleobotany in a few parts), has proven efficient in dating the Karoo - equivalent strata in the Ruvu and Tanga basins, as well as the post break-up Jurassic succession deposited above the Karoo rocks in the Ruvu Basin.

Findings from the second chapter present the ages of Karoo equivalent rocks in both basins (i.e. Tanga and Ruvu) from inferences made based on terrestrial palynomorph assemblages that prevailed prior to the break–up of the Gondwana supercontinent. In the Tanga Basin, four palynological intervals are recognized in the studied samples from two boreholes (i.e. Kakindu-1 and Vunde-1). These include *Vitreisporites–Klausipollenites* Interval (Late Carboniferous to Permian age), *Jugasporites vellicoites* Interval (Permian i.e. Lopingian), *Klausipollenites schaubergeri-Scheuringipollenites circularis* (Late Carboniferous – Permian) Interval and *Alisporites minutosaccus-Faunipollenites gopadensis* Interval (Late Permian – earliest Triassic). In addition, this chapter reports new discovery of the fossil plants of Gondwanic affinity in the Tanga beds. These include *Glossopteris* genera, *Hirsutum dutoitides* and *Sphenobaiera eccaensis* that were doubtful present in the Tanga beds. In agreement with palynology, these palnt remains suggests a Triassic age and older (i.e. Late Permian) for the Tanga Beds at Kakindu area, therefore confirming their presence amongst the Tanzanian assemblages of Gondwanic affinity that was previous in question. Likewise, palynology recognizes three palynologic intervals in the Ruvu Basin (lower Makarawe-1 well) which include *Falcisporites zapfei* Interval (late Permian), *Reduviasporonites sp.* (Permian–Triassic boundary, Changhsingian - Induan) and *Alisporites – Falcisporites* Interval (Triassic). Generally, position of the studied samples in relation to the existing informal Karoo subdivisions in the Tanga Basin suggests a fit into lower Karoo (upper part) to upper Karoo (lower part) units. Furthermore, and in relation to the existing Karoo megasequences in the inland basin, samples from both basins can be correlated with the second to fourth depositional mega sequences while suggesting a Beaufort – Stormberg equivalence in a regional scale.

Results from chapter three indicate that, after the break-up of the Gondwana supercontinent, new phase of sedimentation began in the Ruvu Basin as evidenced by a significant palynological turnover recorded in the Makarawe-1 well (i.e. inception of restricted marine deposition). The latter is recorded in two documented palynological intervals in the upper Makarawe–1 well (i.e. *Classopollis* – *Nannoceratopsis* Interval and *Wanaea clathrata* Interval). It is from these intervals that the late Mid Jurassic - Late Jurassic (Bajocian – Kimmeridgian) age is infered for the studied samples. Co-occurence of terrestrial and marine sporomorphs in the Makarawe-1 well signify a fairly restricted marine conditions explained by the exclusive presence of euryhaline/fresh-water tolerant dinoflagellate *Nannoceratopsis*, with a strong monsoonal terrestrial climate that favours *Classopollis* proliferation. Thus, the vertical succession of palynomorphs in Makarawe–1 well records important bio – events that are related to the break–up of the Gondwana supercontinent and confirms the evidence of the Jurassic strata resting on the Karoo sequences in the basin. These findings permit a possible correlation of the studied interval to the ammonite dated lithostratigraphic units (i.e. Lugoba fm.-Malivundo fm.-Magindu fm.) in the Ruvu Basin. The documented intervals also correlate to other palynological intervals in Africa, Australia and Europe.

As part of the Tanzania Stratigraphic Nomenclature Project (TSNP), findings of this study contribute to establishing the stratigraphic framework of the strata in the coastal Tanzania by providing new biostratigraphic age data and correlation of strata across the Tanga and Ruvu basins. This contribution provide insight into understanding the Tanzania coastal basin evolution. However, more work is still required in the Tanga beds to account for (i) taphonomy of the palynomorphs hosted within the Karoo equivalent Tanga beds and (ii) litho- and palynofacies analyses that will help to decipher depositional environments for the Karoo equivalent Tanga beds. In the Ruvu Basin, given its importance, age of the basal Jurassic marine strata still needs to be clearly resolved. This study recommends a follow- up study that will focus on the intervals where the Triassic – Jurassic transition is suspected by the current study in the Makarawe-1 well. Other wells/boreholes that are available in the Ruvu Basin would also add to the data quality when brought into this context.

PHOTOMICROGRAPHS OF SELECTED TAXA IN THE RUVU BASIN (i.e. LOWER MAKARAWE–1 WELL SAMPLES)

Plate 2.4 – 2.8

All photomicrographs were taken at a magnification of X 1000, unless stated otherwise**.**

Plate 2.4 Explanation

A. *Hamiapollenites minimus*, Slide number: MK 2765, Depth: 2765m

B. *Satsangisaccites nidpurensis*, Slide number: MK 2830, Depth 2830m

C. *Falcisporites zapfei*, Slide number: MK 3710, Depth 3710m

D. *Alisporites toralis*, Slide number: MK 3820, Depth 3820m

E. *Platysaccus radialis*, Slide number: MK 3710, Depth 3710m

F. ?*Protodiploxypinus sp.* Slide number MK 3710, Depth 3710m

G. *Platysaccus radialis/ ?Falcisporites sp.* , Slide number: MK 3710, Depth 3710m

H. *Alisporites australis*, Slide number MK 3820, Depth 3820m

I. *Protohaploxypinus limpidus*, Slide number MK 3710, Depth 3710m

J. *Ginkgocycadophytus nitidus*, Slide number MK 3105, Depth 3105m

K. *?Klausipollenites*, Slide number Mk 2765, Depth 2765

L. *?Klausipollenites*, Slide number Mk 2765, Depth 2765

M. *?Klausipollenites*, Slide number Mk 2765, Depth 2765

N. *Platysaccus radialis*, Slide number MK 3820, Depth 3830m

O. *Falcisporites sp.*, Slide number MK 3710, Depth 3710m

PLATE 2.4

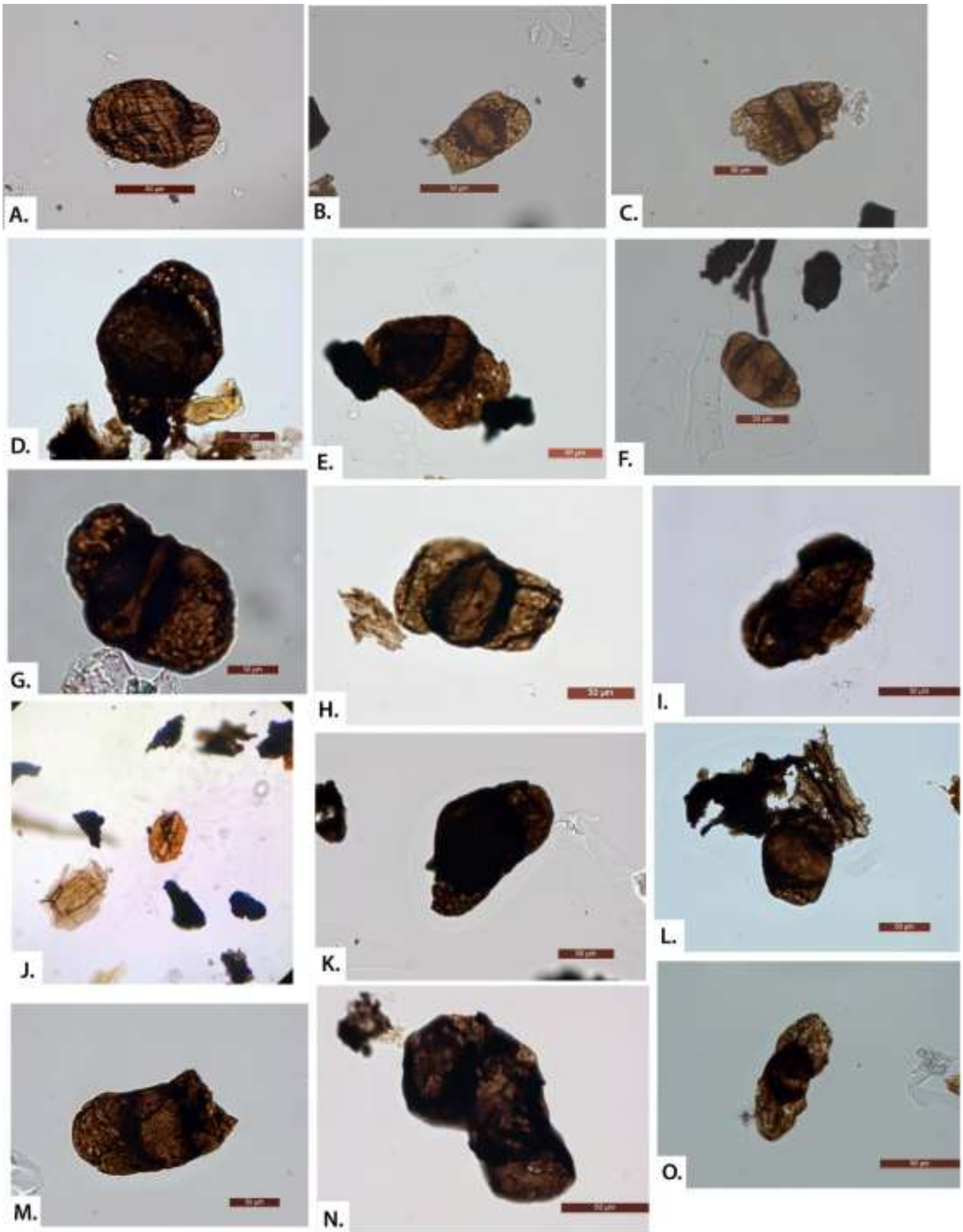


Plate 2.5 Explanation

A. *Alisporites indicus,* Slide number MK 3105, Depth 3105m

B. *Falcisporites minutosaccus,* Slide number MK

C. *Alisporites sp.* / *Jugasporites sp.* Slide number MK 3105, Depth 3105m

D. *Trilete spore,* Slide number MK 2765, Depth 2765

E. *?Lunatisporites gopadensis/ Jugasporites nubilus,* Slide number MK 3105, Depth 3105

F. *Alisporites sp.* Slide number MK 3105, Depth 3105m

G. *Pteruchipollenites gracilis,* Slide number MK 3015, Depth 3105

H. *?Falcisporites sp.,*Slide number MK 3015, Depth 3105

I. *Pinuspollenites sp./Klausipollenites sp.,* Slide number MK 3105, Depth 3105m

J. *Minutosaccus maedleri / Alisporites angustus* Slide number MK 2765, Depth 2765

K. *Pteruchipollenites gracilis,* Slide number MK, Depth

L. *Cyacadopites sp.,* Slide number 3105, Depth 3105m

PLATE 2.5

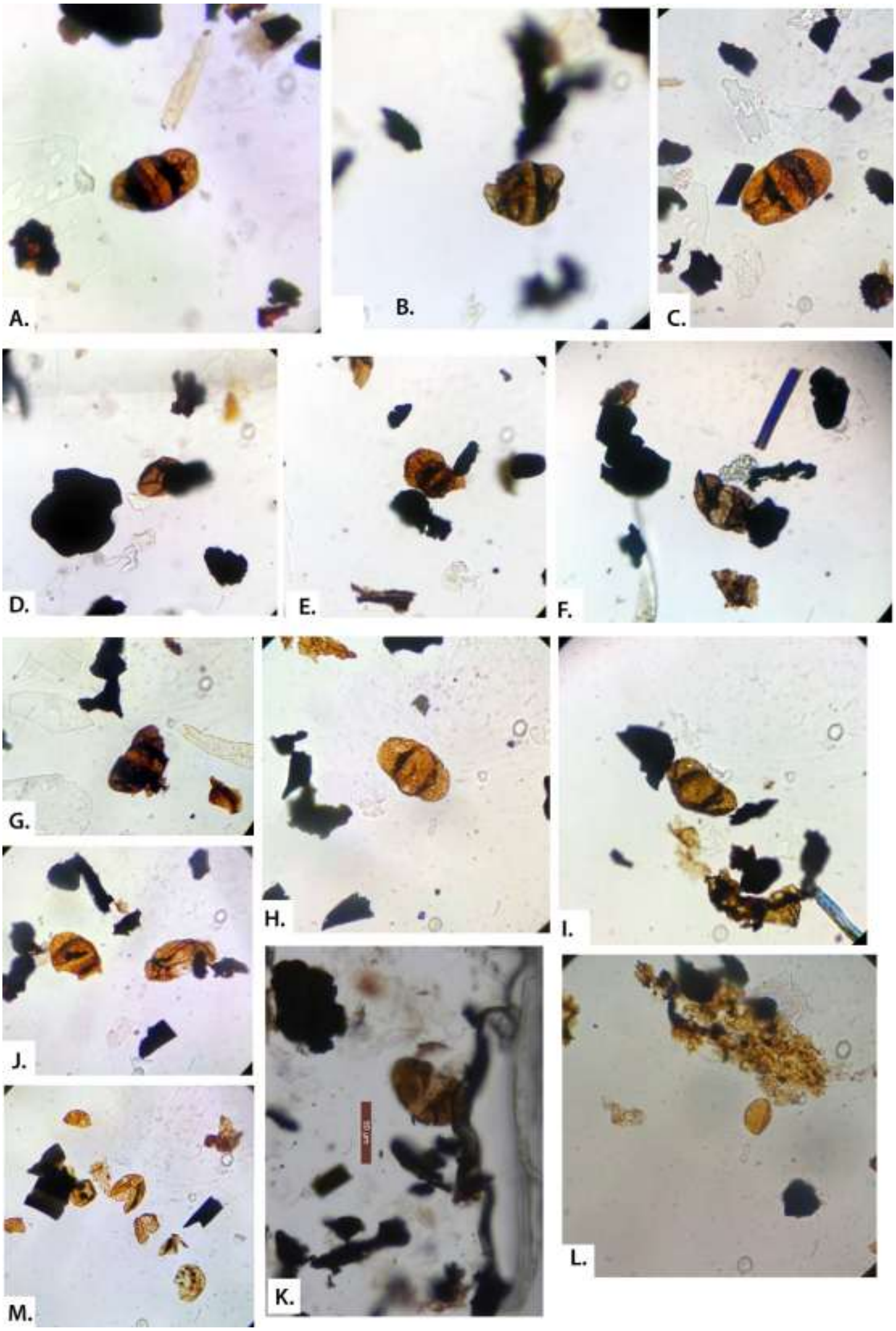


Plate 2.6 Explanation

A. ?*Falcisporites sp./ ?Jugasporites sp.* Slide number MK 3710, Depth 3710m

B. *Vitreisporites pallidus,* Slide number Slide number MK 3105, Depth 3105m

C. *?Klausipollenites,* Slide number Mk 2765, Depth 2765m

D. *Protohaploxypinus rugatus,* Slide number 3505, Depth 3505m

E. *Falcisporites zapfei,* Slide number 3710, Depth 3710m

F. *Minutosaccus protoniei,* Slide number 3820, Depth 3820m

G. *Protohaploxypinus limpidus,* Slide number MK 3710, Depth 3710m

H. ?*Simeonospora khlonovae,* Slide number 3820, Depth 3820m

I. ?

J. *Spinotriletes echinoides /? Keuperisporites baculatus,* Slide number MK 3710, Depth 3710m

K. *Punctatisporites gretensis,* Slide number MK 3710, Depth 3710m

L. *Callumispora barankesis,* Slide number MK 3820, Depth 3820m

M. *Punctatisporites sp.,* Slide number MK 3710, Depth 3710m

N. *Granamegamonocolpites campbellii,* Slide number MK 3820, Depth 3820m

PLATE 2.6

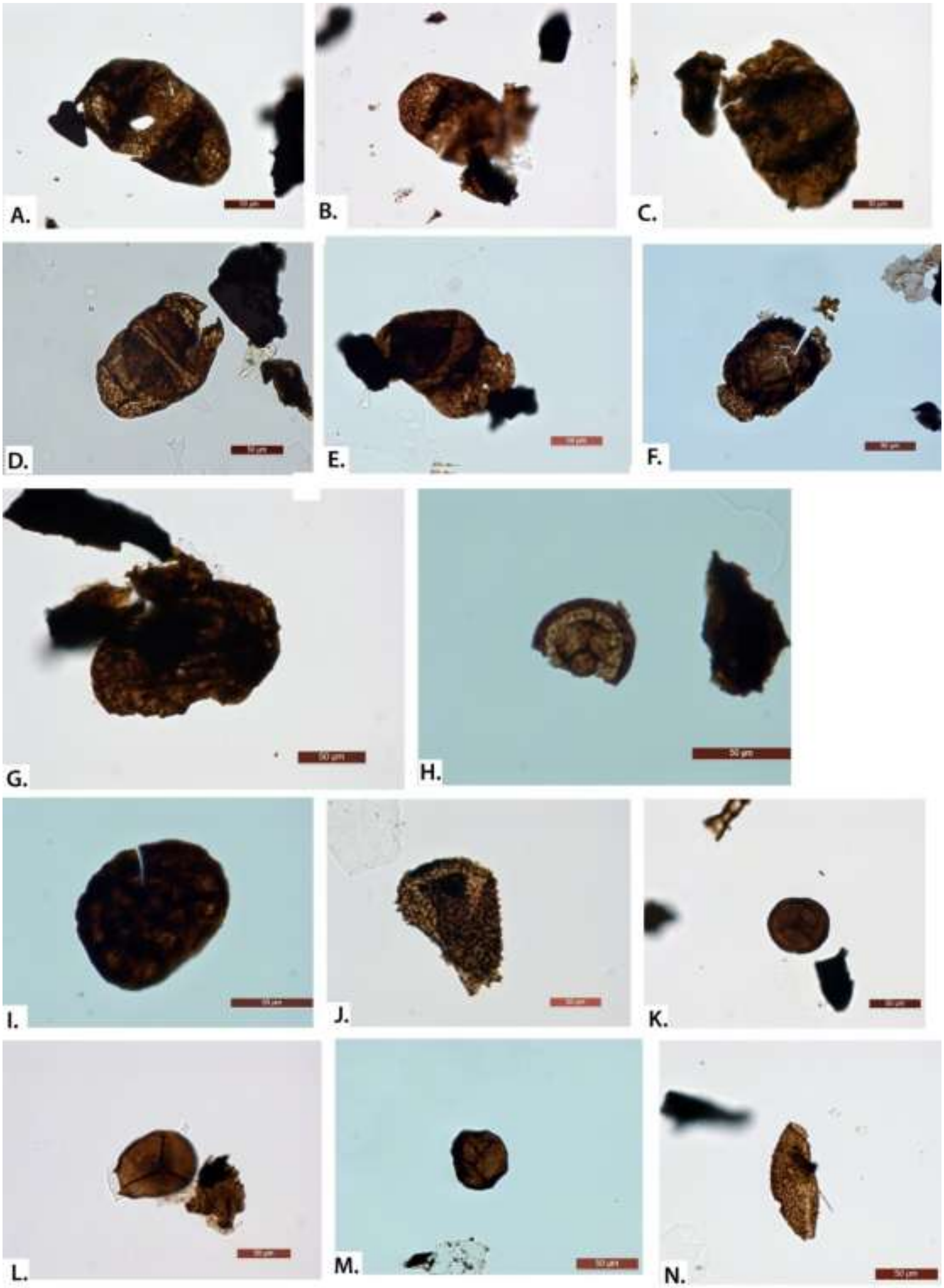


Plate 2.7 Explanation

A. *Converrucosisporites sp.,* Slide number MK 3505, Depth 3505m

B. *Raistrickia saetosa,* Slide number MK 3505, Depth 3505m

C. *Aratisporites sp.*, Slide number MK 3710, Depth 3710m

D. *Punctatisporites sp.,* Slide number MK 3505, Depth 3505m

E. *Anapiculatisporites sp.* Slide number MK 3820, Depth 3820m

F. *Trilete spore,* Slide number MK 3710, Depth 3710m

G. *Shanbeipollenites quadratus /?Folded bisaccate,* Slide number MK 3710, Depth 3710m

H. *Anapiculatisporites sp.* Slide number MK 3820, Depth 3820m

I. *Raistrickia saetosa,* Slide number MK 3710, Depth 3710m

J. *Punctatisporites sp.,* Slide number MK 3505, Depth 3505m

K. *Anapiculatisporites spiniger,* Slide number MK 3505, Depth 3505m

L. *Trilete spore,* Slide number MK 2765, Depth 2765m

M. *Cyacadopites sp. / Shanbeipollenites sp.,* Slide number MK 3710, Depth 3710m

N. *Anapiculatisporites sp.* Slide number MK 3820, Depth 3820m

O. *Trilete spore,* Slide number MK 3710, Depth 3710m

P. *Trilete spore,* Slide number MK 3710, Depth 3710m

PLATE 2.7

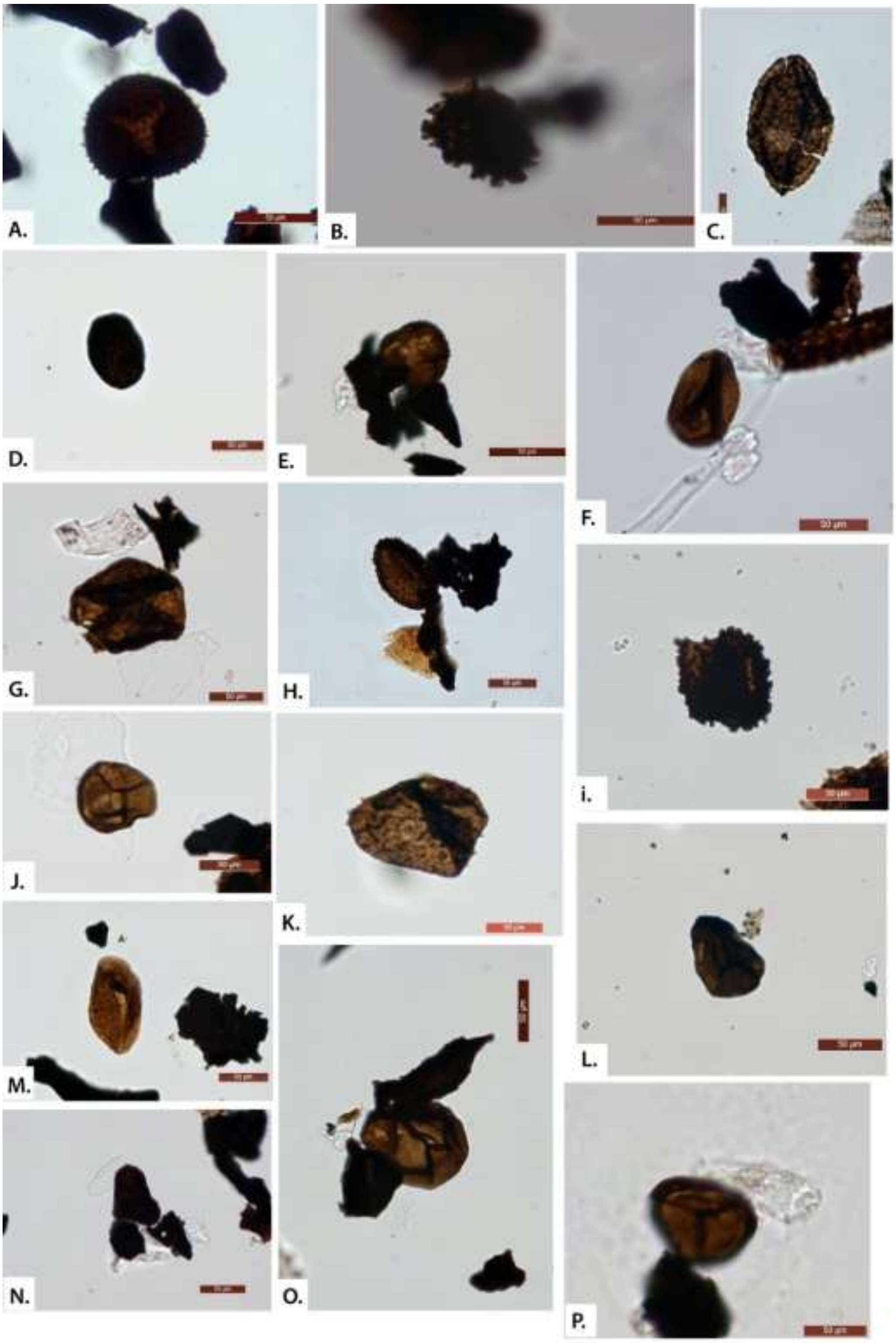


Plate 2.8 Explanation

A. *Reduviasporonites chalastus,* Slide number MK 3105/3505, Depth 3105m – 3505m

B. *Anapiculatisporites sp.*, Slide number MK 3505, Depth 3505m

C. *Spinotriletes echinoides /? Keuperisporites baculatus,* Slide number MK 3710, Depth 3710m

D.*?*

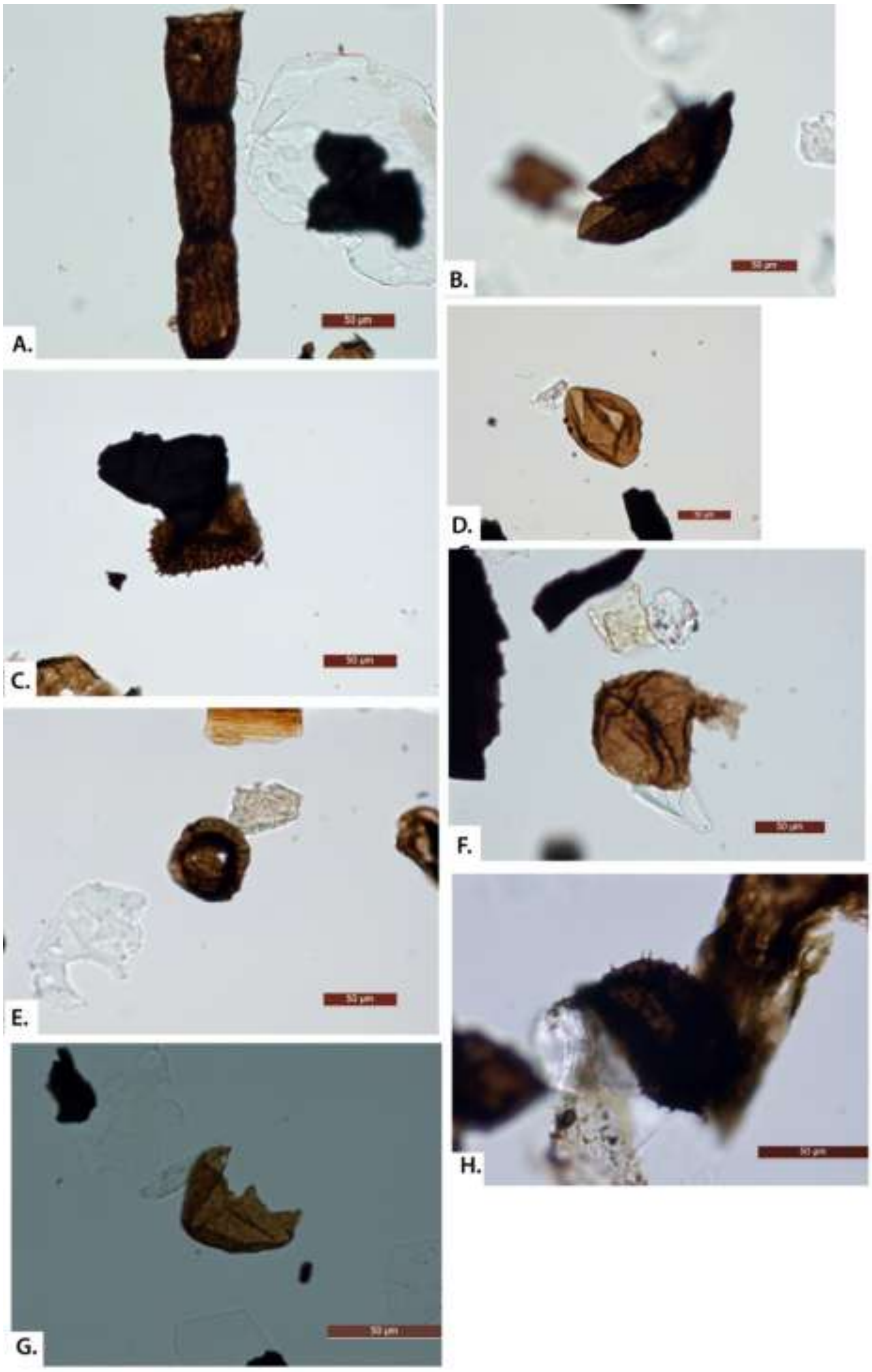
E.*?*

F. *Anapiculatisporites sp.*, Slide number MK 3505, Depth 3505m

G. *Folded trilete spore*

H. *Anapiculatisporites sp.,* Slide number MK 3505, Depth 3505m

PLATE 2.8



PHOTOMICROGRAPHS OF SELECTED TAXA IN THE TANGA BASIN (i.e. VUNDE-1 AND KAKINDU-1 BOREHOLES)

Plate 2.9 – 2.13

All photomicrographs were taken at a magnification of X 1000, unless stated otherwise**.**

Plate 2.9 Explanation

A. ?, Slide number VND 9, Depth 9m

B. *Lueckisporites virkkiae*, Slide number VND 9, Depth 9m

C. *Faunipollenites gopadensis/ ?Pinuspollenites sp.*, Slide number VND 61, Depth 61m

D. *Striatites tentulus*, Slide number VND 61, Depth 61m

E. *Podocarpites alatus*, Slide number VND 20, Depth 20m

F. *Striatites tentulus*, Slide number VND 61, Depth 61m

G. *Striatopodocarpites labrus*, Slide number VND 61, Depth 61m

PLATE 2.9

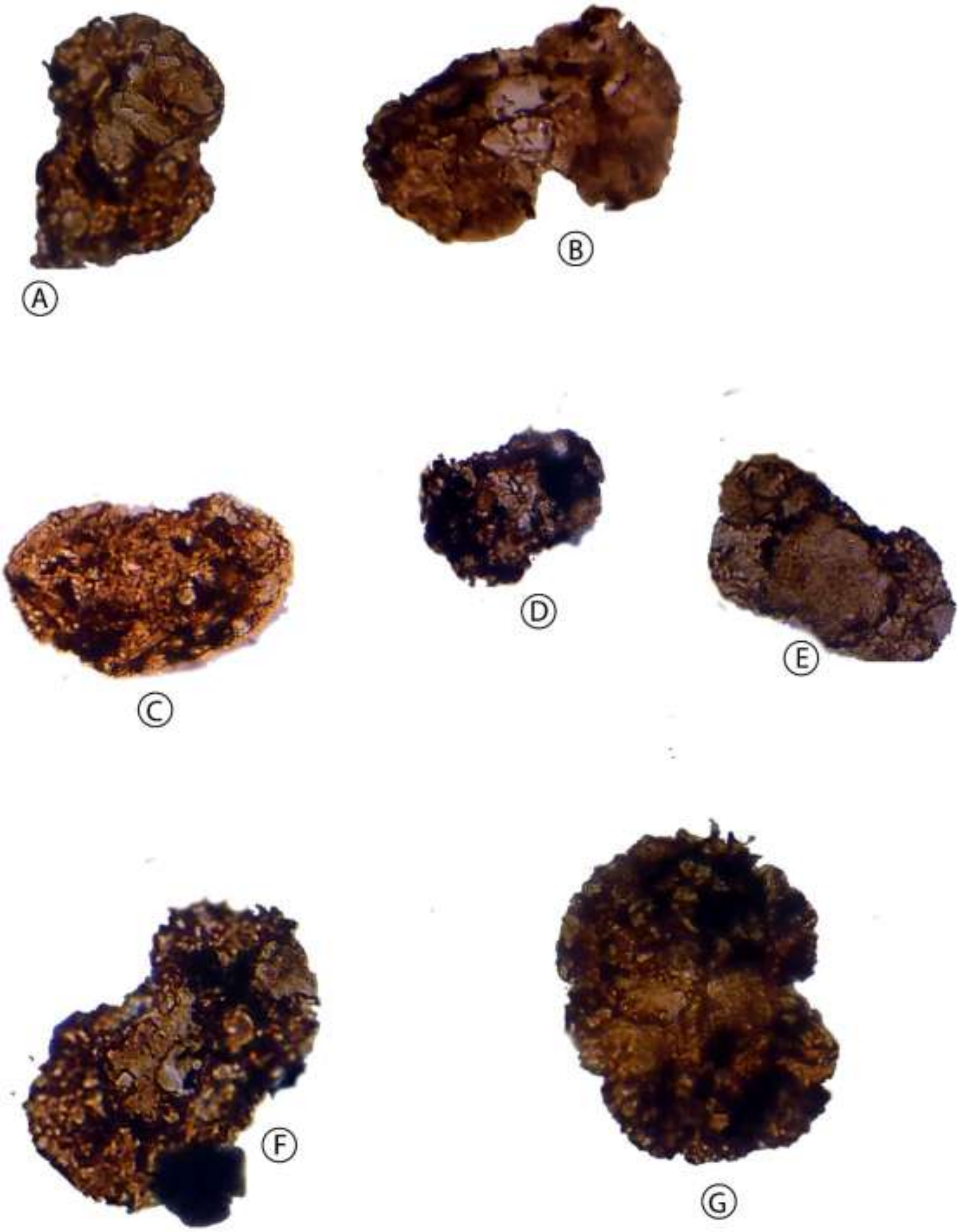


Plate 2.10 Explanation

A. *Pinuspollenites sp.*, Slide number KK 84.3, Depth 84.3m

B. *Jugasporites sp.*, Slide number KK 84.3, Depth 84.3m

C. *Staurosaccites sp. (c.f. S. quadrifidus),* Slide number KK 84.3, Depth 84.3m

D. *Pinuspollenites sp.*, Slide number VND 84.3, KK 84.3m

E. *Klausipollenites devolvens,* Slide number KK 84.3, Depth 84.3m

F. ?*Jugasporites gams,* Slide number VND KK Depth 84.3m

PLATE 2.10

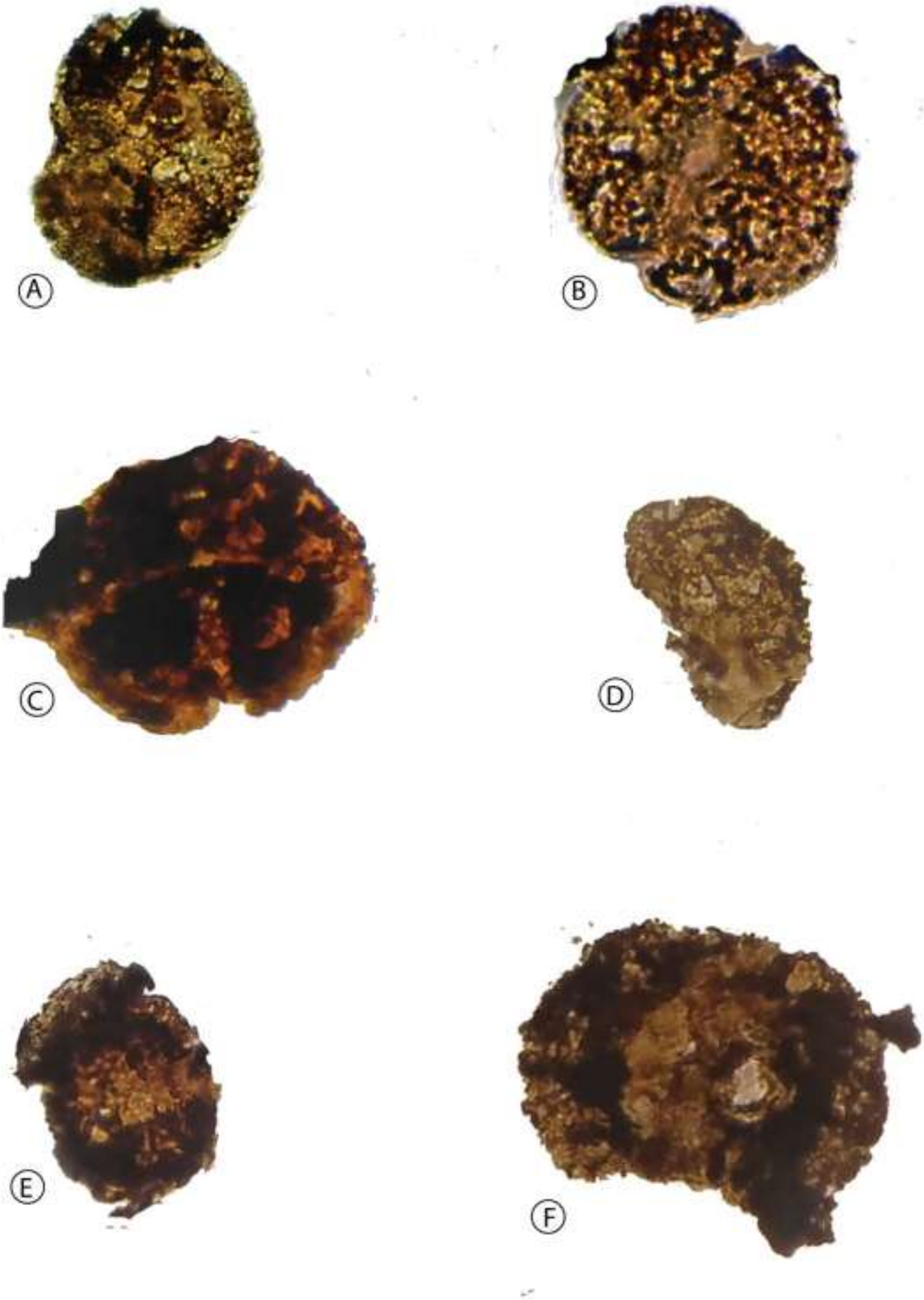


Plate 2.11 Explanation

A. *Striatites tentulus*, Slide number KK 100, Depth 100m

B. *Satsangisaccites nidpurensis*, Slide number KK 120, Depth 120m

C. *Vitreisporites sp.*, Slide number KK 120, Depth 120m

D. *Pteruchipollenites thomasii*, Slide number KK 120, Depth 120m

E. *Faunipollenites sp.*, Slide number KK 100, Depth 100m

F. *Vitreisporites sp.*, Slide number KK 100, Depth 100m

G. *Vitreisporites sp.*, Slide number KK 60, Depth 60m

PLATE 2.11

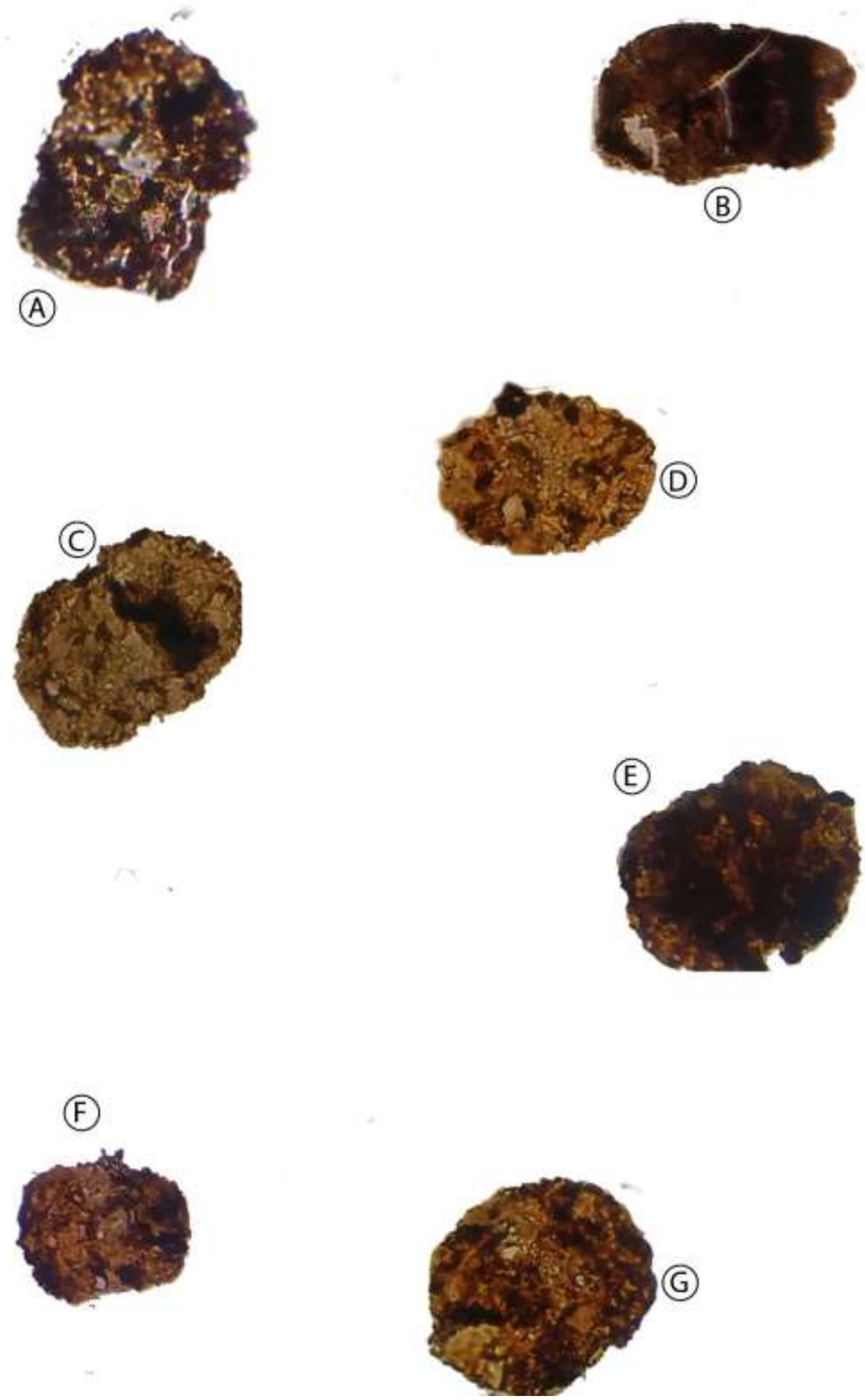


Plate 2.12 Explanation

A. *Klausipollenites schaubergeri,* Slide number VND 194.3, Depth 194.3m

B. *Jugasporites nubilus,* Slide number VND 194.3, Depth 194.3m

C. *Jugasporites vellicoites,* Slide number VND 194.3, Depth 194.3m

D. *Klausipollenites sp. (c.f. ?vestitus),* Slide number VND 194.3, Depth 194.3m

E. *Pinuspollenites sp.*, Slide number VND 175, Depth 175m

F. ?*Faunipollenites gopadensis,* Slide number VND 175, Depth 175m

G. *Jugasporites sp.,* Slide number VND 175, Depth 175m

H. *Jugasporites vellicoites,* Slide number VND 175, Depth 175m

I. *Jugasporites vellicoites,* Slide number VND 150.7, Depth 150.7m

J. *Jugasporites vellicoites,* Slide number VND 150.7, Depth 150.7m

K. *?Reduviasporonites sp.*, Slide number VND 194.3, Depth 194.3m

Plate 2.12

Plate 2.13 Explanation

A. *Cordaitina sp.***,** Slide number VND 194.3, Depth 194.3m

B. *Jugasporites sp.,* Slide number VND 194.3, Depth 194.3m

C. *Jugasporites sp.,* Slide number VND 194.3, Depth 194.3m

D. *Pinuspollenites divulgatus,* Slide number VND 194.3, Depth 194.3m

E. *Jugasporites sp.,* Slide number VND 194.3, Depth 194.3m

F. ?

G. *Scheuringipollenites circularis,* Slide number VND 194.3, Depth 194.3m

H. *Jugasporites sp.,* Slide number VND 194.3, Depth 194.3m

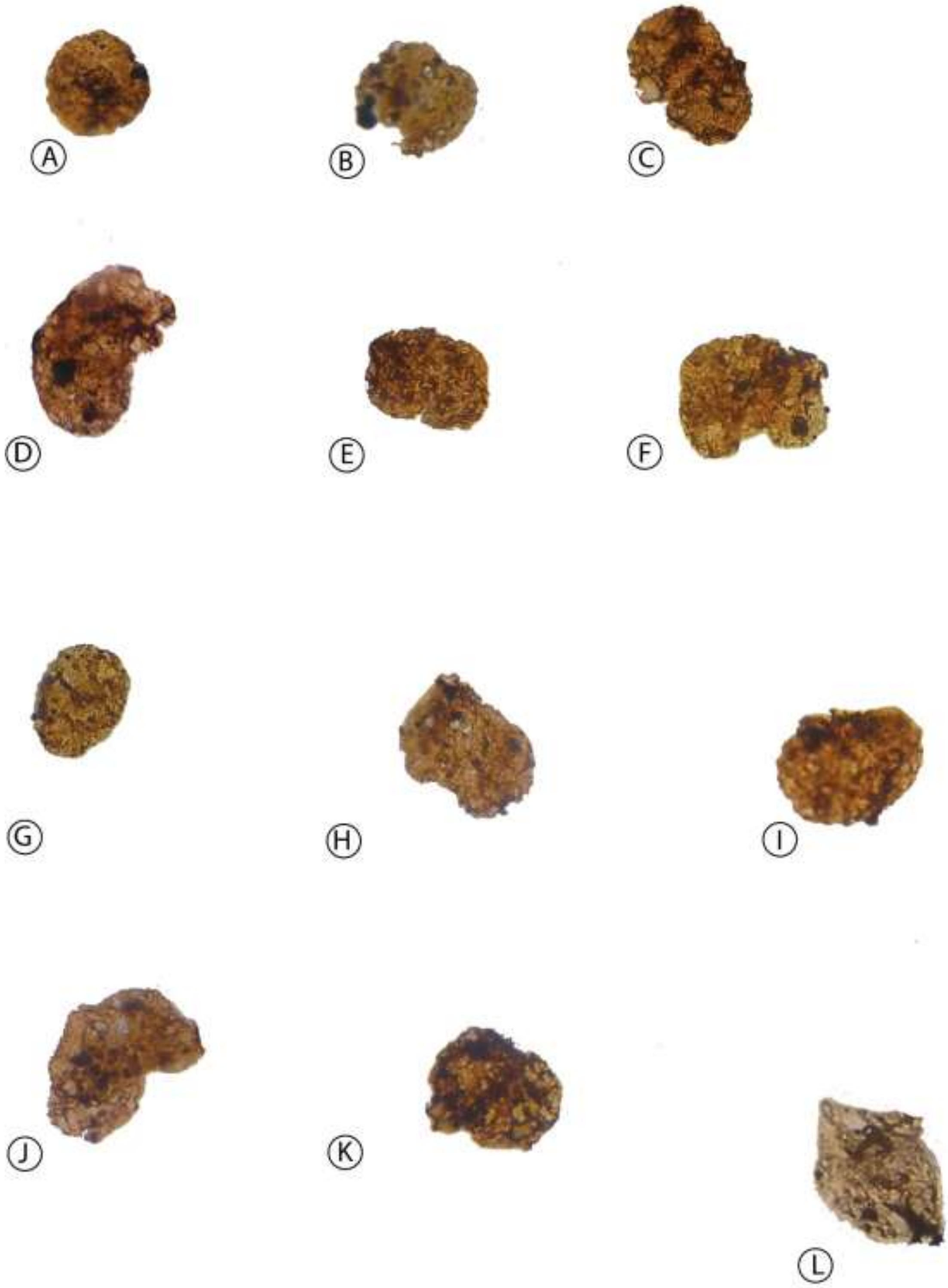
I. *Scheuringipollenites circularis,* Slide number VND 194.3, Depth 194.3m

J. *Pinuspollenites divulgatus,* Slide number VND 194.3, Depth 194.3m

K. *Jugasporites sp.,* Slide number VND 194.3, Depth 194.3m

L. *Cyacadopites sp. / Shanbeipollenites sp.,* Slide number VND 194.3, Depth 194.3m

Plate 2.13



PHOTOMICROGRAPHS OF SELECTED TAXA IN THE RUVU BASIN (UPPER/SHALLOW MAKARAWE–1 SAMPLES)

Plate 3.1 Explanation

A. *Wanaea clathrata*, MK 1215, Depth 1215m

B. *Wanaea spectabilis*, MK 1215, Depth 1215m

C. *Wanaea digitata*, MK 1215, Depth 1215m

D. *Wanaea digitata*, MK 1215, Depth 1215m

E. *Wanaea fimbriata*, MK 1215, Depth 1215m

F. *Wanaea clathrata* MK 1215, Depth 1215m

G. *Wanaea digitata*, MK 1215, Depth 1215m

H. *Wanaea digitata*m, MK 1215, Depth 1215m

Plate 3.1

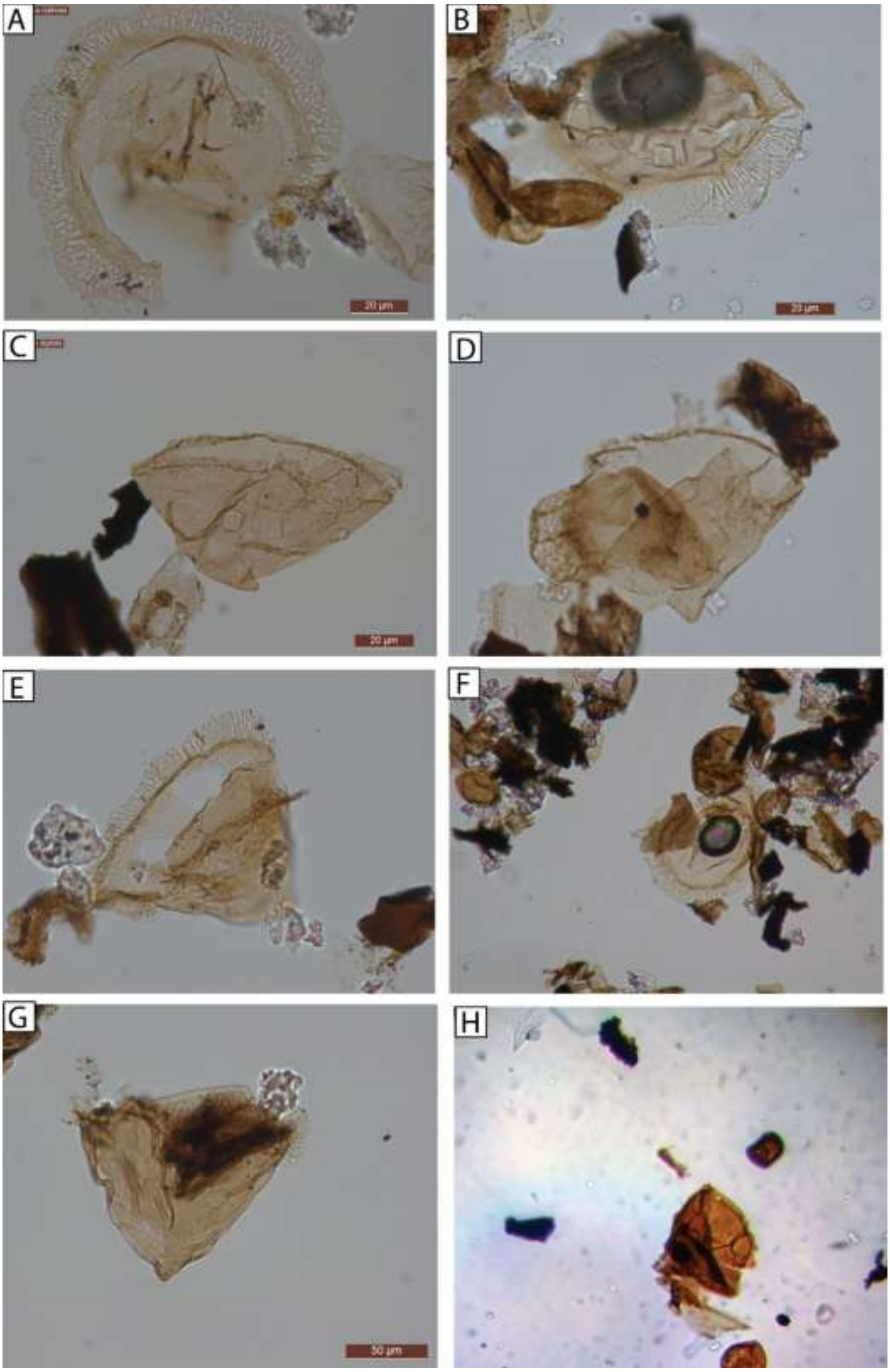


Plate 3.2 Explanation

A. *Wanaea fimbriata*, MK 1215, Depth 1215m

B. *Wanaea fimbriata*, MK 1215, Depth 1215m

C. *Wanaea acollaris*, MK 1215, Depth 1215m

D. *Wanaea clathrata*, MK 1215, Depth 1215m

E. *Dissiliodinium ventrogranum,* MK 1215, Depth 1215m

F. *Ctenidodinium combazi*, MK 1215, Depth 1215m

G. *Dissiliodinium willei,* MK 1215, Depth 1215

H. *Ctenidodinium combazi,* MK 1215, Depth 1215m

Plate 3.2

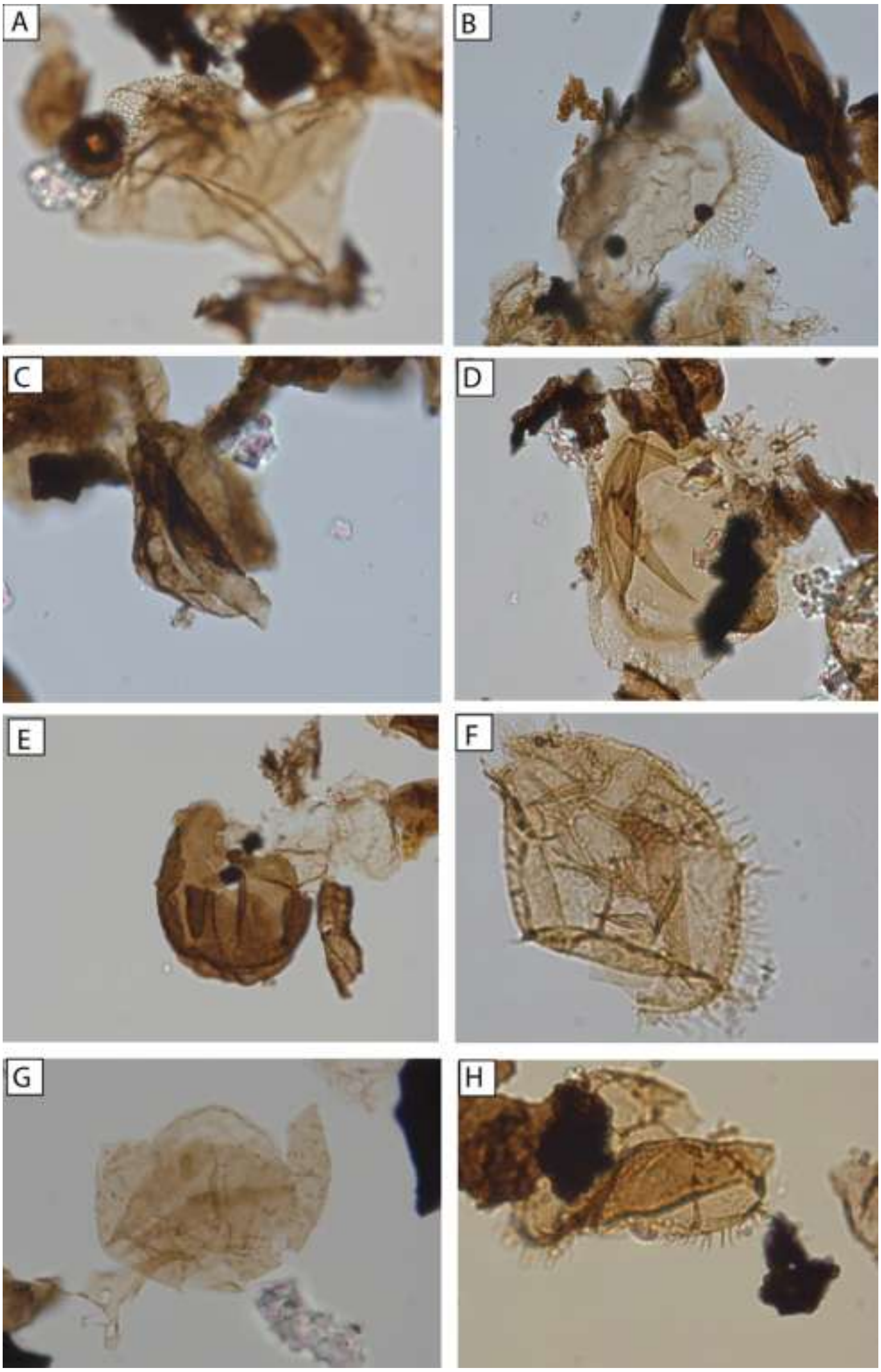


Plate 3.3 Explanation

A. *Dingodinium spinosa,* MK 1215, Depth 1215m

B. *Dingodinium spinosa,* MK 1215, Depth 1215m

C. *Batiacasphaera murchisoni*

D. *Dissiliodinium willei,* MK 1215, Depth 1215

E. *Batiacasphaera sp.,* MK 1215, Depth 1215m

F. *Batiacasphaera murchisoni,* MK 1215, Depth 1215m

G. *Tenua hystrix*

H. *? Durotrigia omentifera,* MK 1215, Depth 1215m

Plate 3.3

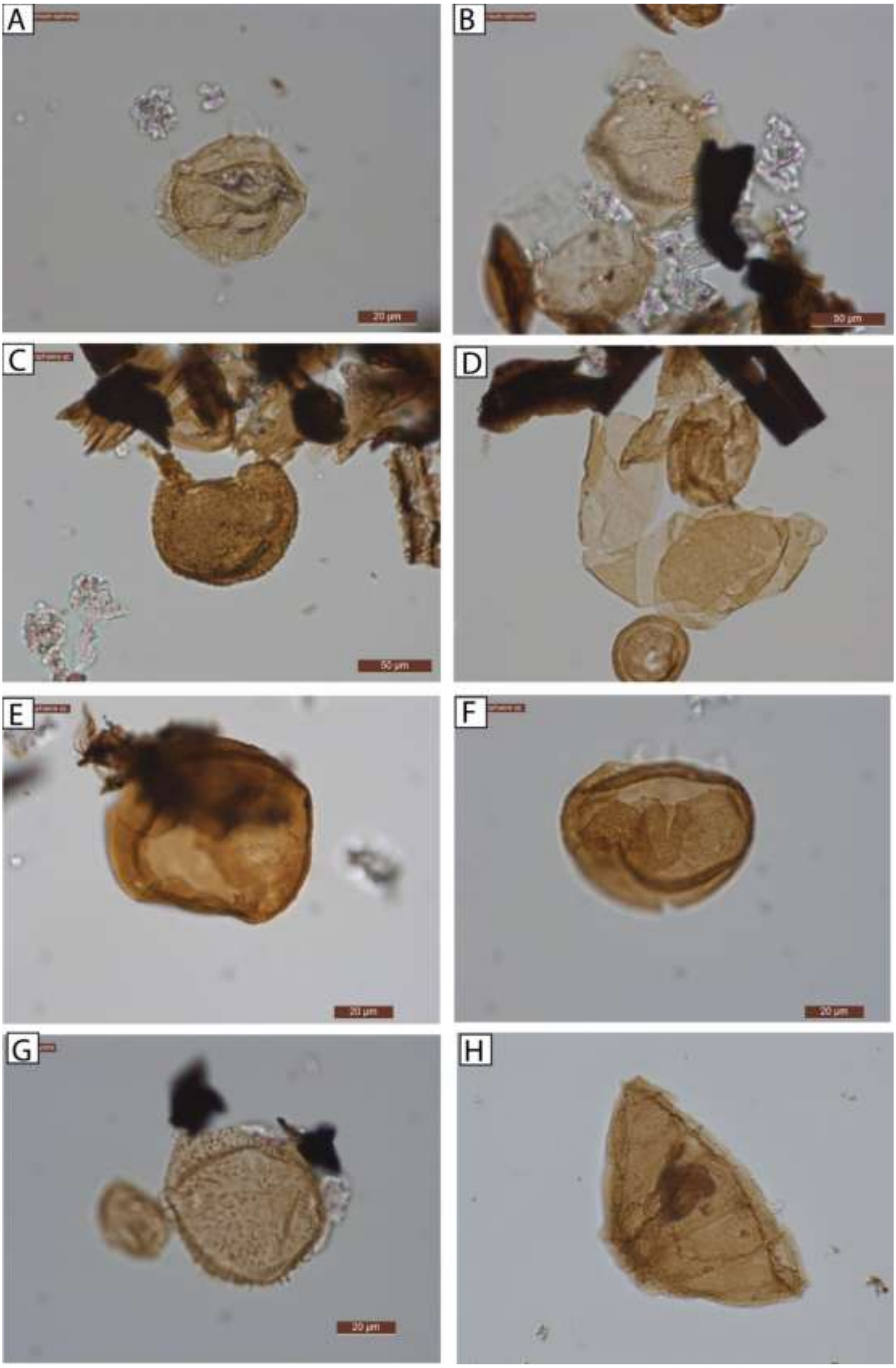


Plate 3.4 Explanation

A. *Ctenidodinium combazii,* MK 1215, Depth 1215m

B. *Gonyaulacysta jurassica,* MK 1215, Depth 1215m

C. *Bradleyella? sp. cf. B. adela,* MK 1215, Depth 1215m

D. *?*

E. *?Ellipsoidictyum cinctum*, MK 1215, Depth 1215m

F. *Dingodinium spinosa,* MK 1215, Depth 1215m

G. *Dingodinium sp.* MK 1215, Depth 1215m

H. *Dingodinium spinosa,* MK 1215, Depth 1215m

Plate 3.4

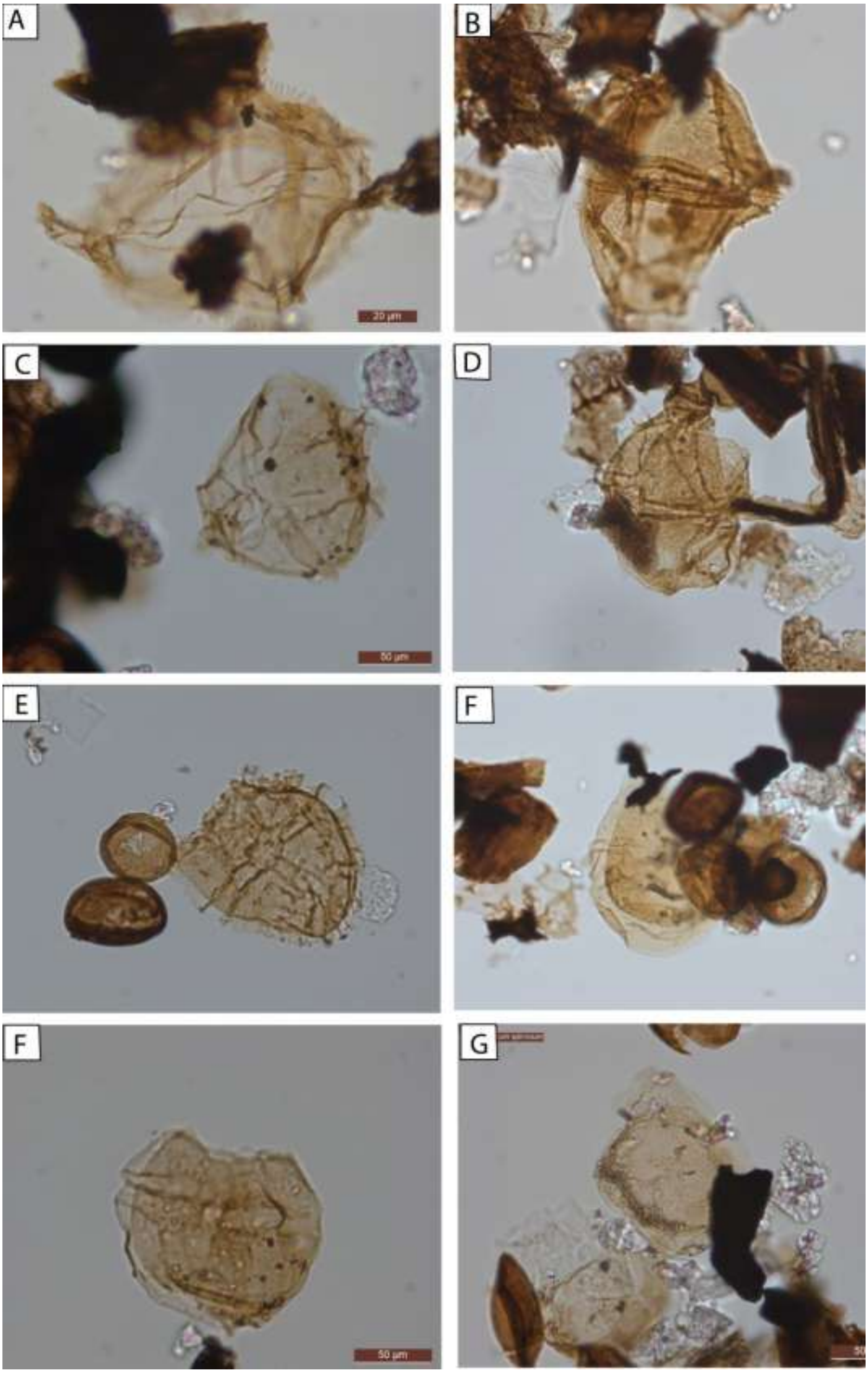


Plate 3.5 Explanation

A. *? Pareodinia sp. /Subtilisphaera rotundata,* MK 1215, Depth 1215m

B. *Gonyaulacysta jurassica,* MK 1215, Depth 1215m

C. *Subtillisphaera sp***.**

D. *Gonyaulacysta jurassica*, MK 1215, Depth 1215m

E. *?Ellipsoidictyum cinctum*, MK 1215, Depth 1215m

F. *Hystrichosphaerina schindewolfii,* MK 1215, Depth 1215m

G. *?Paleocysta virgae,* MK 1215, Depth 1215m

H. *Gonyaulacysta centriconnata*, MK 1215, Depth 1215m

Plate 3.5

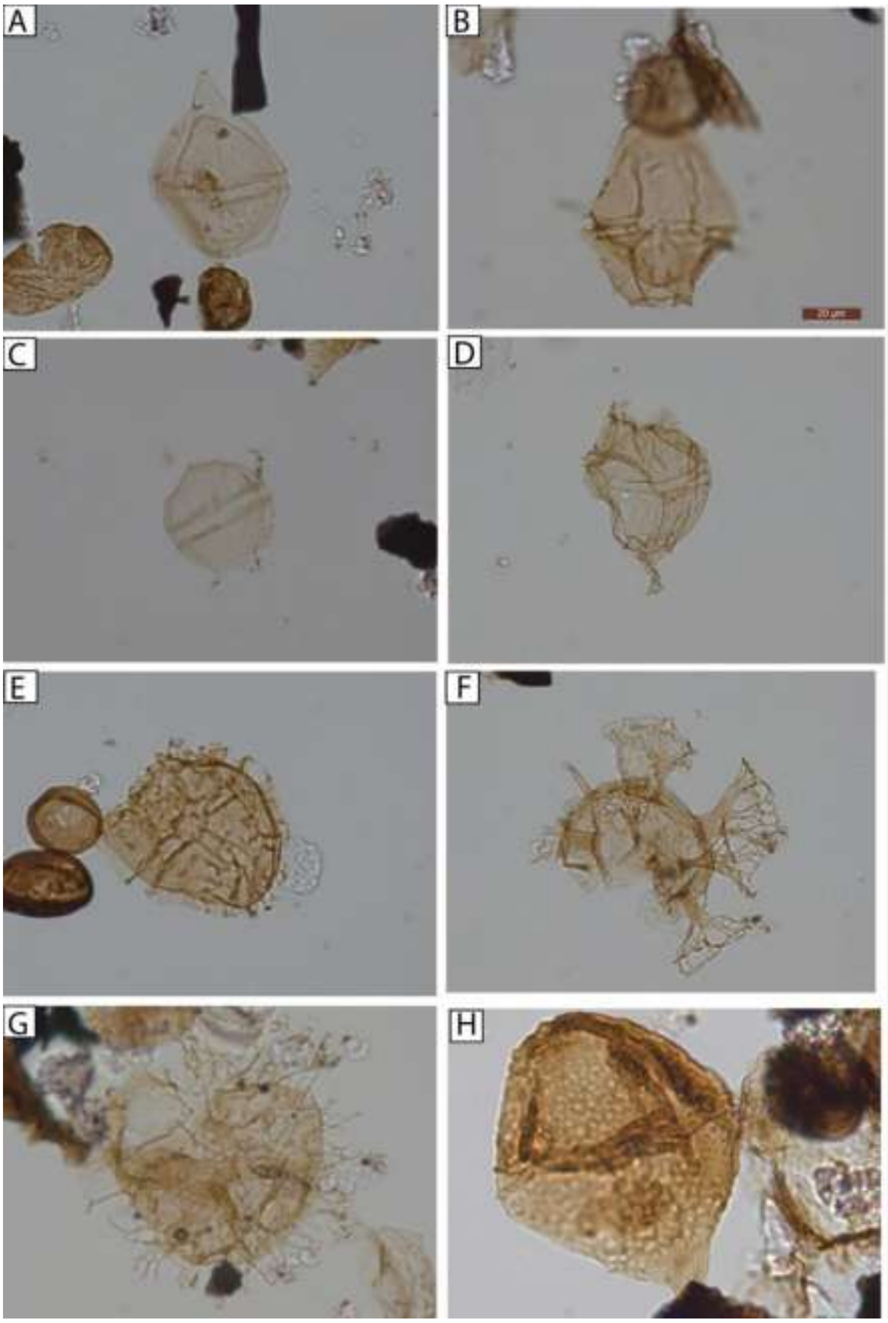


Plate 3.6 Explanation

A. *Lithodinia caytonensis,* MK 1215, Depth 1215m

B. *Subtililisphaera perlucida,* MK 1215, Depth 1215m

C. **?**

D. *Subtililisphaera scabrata,* MK 1215, Depth 1215m

E. *Nannoceratopsis sp?* MK 1215, Depth 1215m

F. *?Subtilisphaera sp.,* MK 1215, Depth 1215m

G. *Fistulacysta simplex/ Clathroctenocystis asapha,* MK 1215, Depth 1215m

H. **?**

Plate 3.6

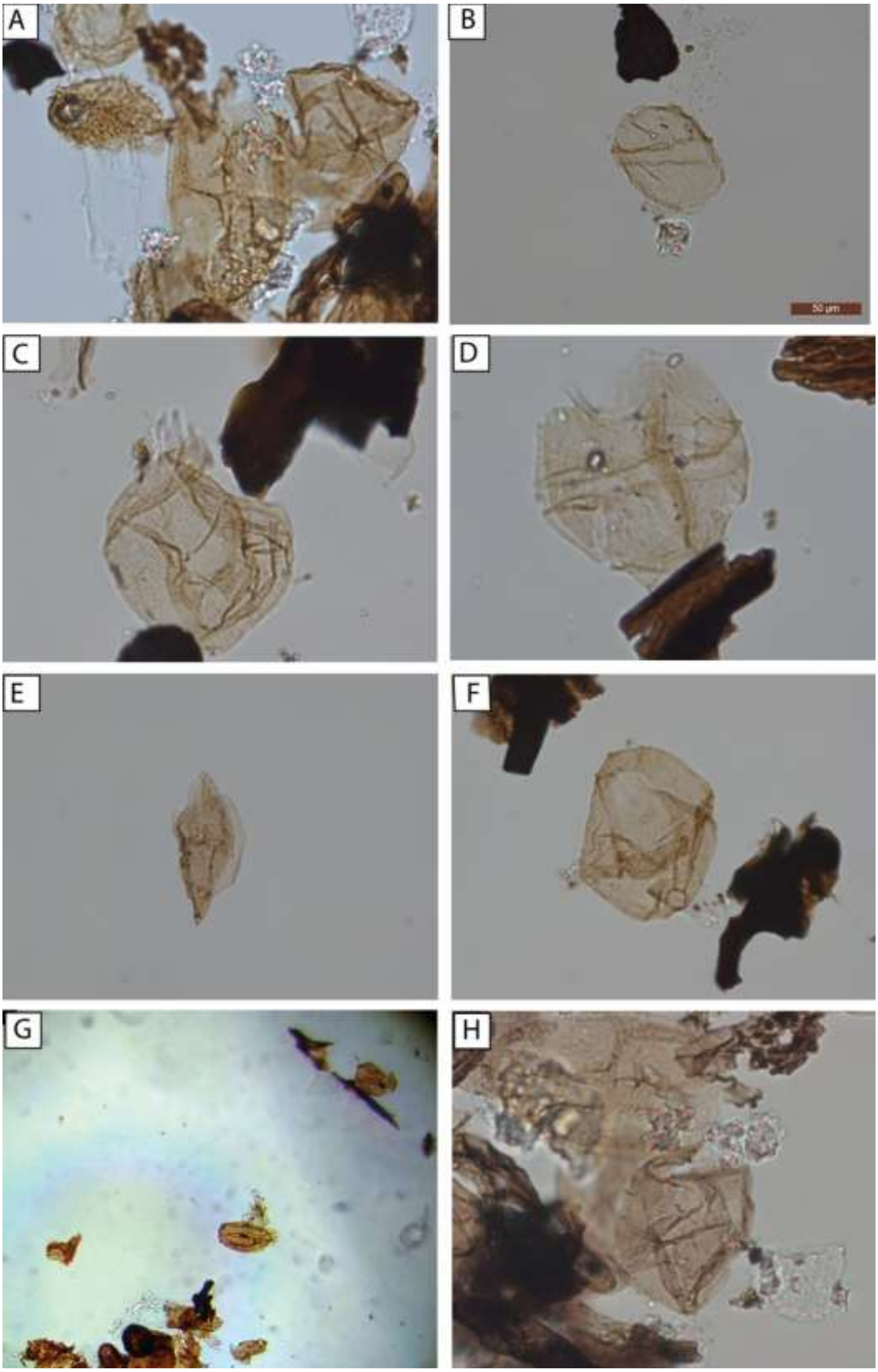


Plate 3.7 Explanation

A. *? Impletosphaeridium sp.*

B. *Hystrichosphaerina schindewolfii*, MK 1215, Depth 1215m

C. *Paleocysta virgae*, MK 1215, Depth 1215m

D. *Adnatosphaeridium multispinosum*, MK 1215, Depth 1215m

E. *?Paleocysta sp.*

F. *?Paleocysta virgae,* MK 1215, Depth 1215m

G. *Tenua hystrix*, MK 1215, Depth 1215m

H. *Oligosphaeridium porosum*, MK 1215, Depth 1215m

Plate 3.7

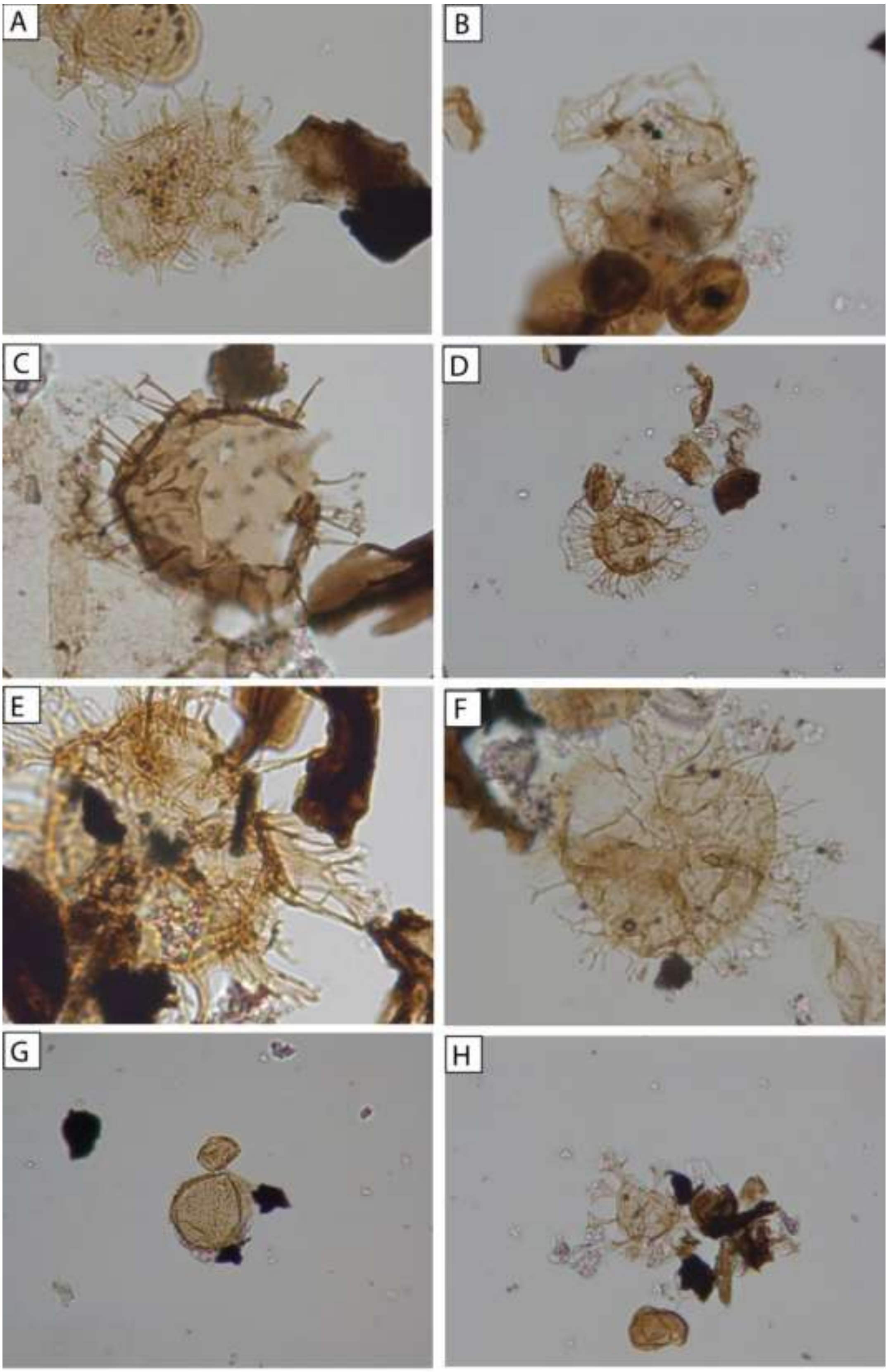


Plate 3.8 Explanation

A. *Nannoceratopsis pellucida,* MK 1235, Depth 1235m

B. *Nannoceratopsis dictyambonis,* MK 1215, Depth 1215m

C. *Dingodinium spinosa,* MK 1215, Depth 1215m

D. *Valenciella ovulum,* MK 1215, Depth 1215m

E. *? Tenua hystrix,* MK 1215, Depth 1215m

F. *Meiourogonyaulax sp.*

G. *Paleocysta virgae,* MK 1215, Depth 1215m

H. *Nannoceratopsis gracilis* MK 1235, Depth 1235

Plate 3.8

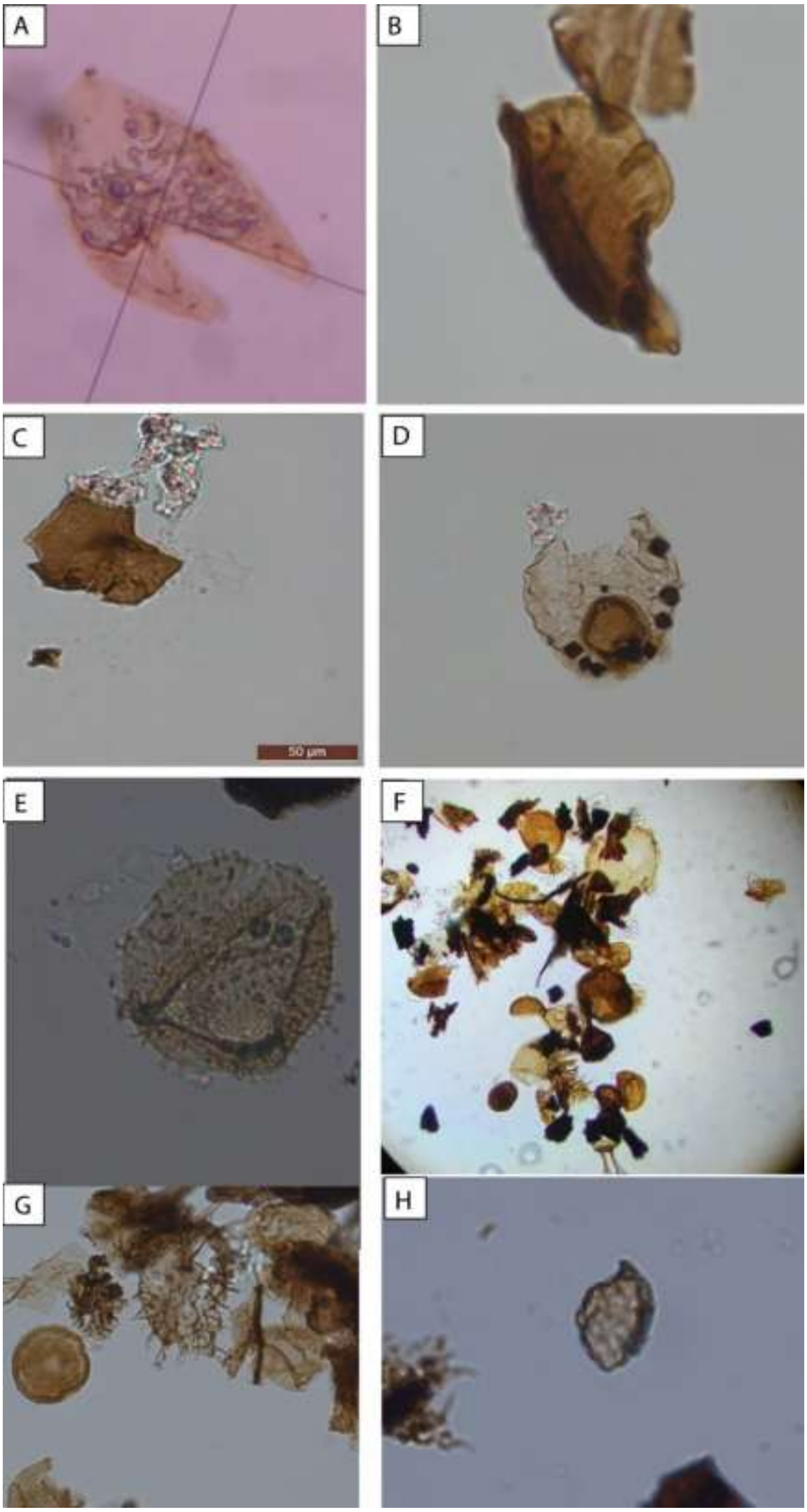


Plate 3.9 Explanation

A. *?Ctenidodinium sp.,* MK 1215, Depth 1215m

B. *Ctenidodinium ornatum,* MK 1215, Depth 1215m

C. *?Dissiliodinium sp.,* MK 1215, Depth 1215m

D. *?Scrinocasis sp.*

E. **?**

F. *?Sentusidinium sp.*

G. *?Callialasporites plicatus,* MK 1215, Depth 1215m

H. *Ephedripites sp.,* MK 1427, Depth 1215m

Plate 3.9

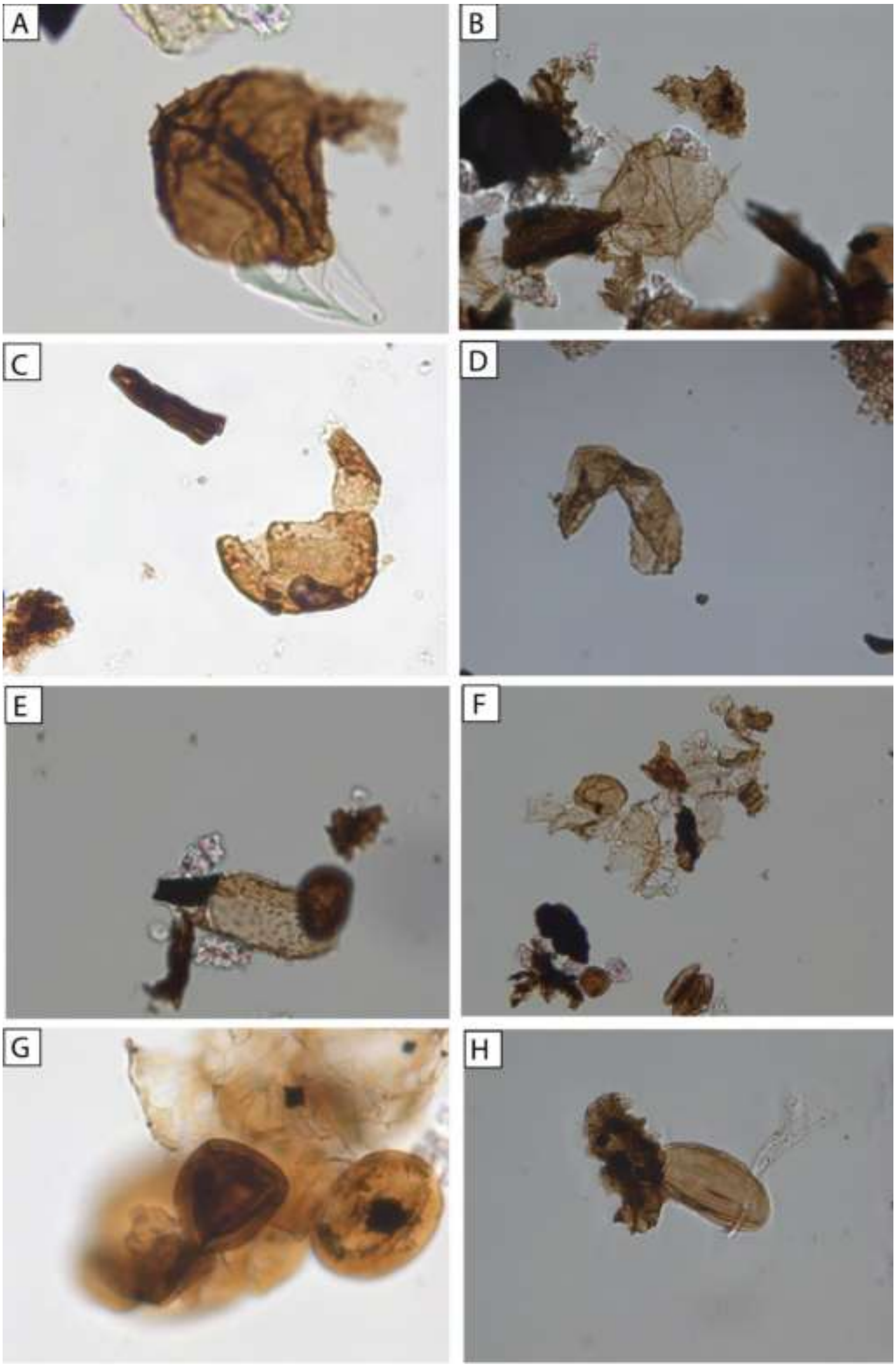


Plate 3.10 Explanation

A. *Callialasporites trilobatus*, MK 1280, Depth 1280m

B. *Callialasporites trilobatus*, MK 1215, Depth 1215m

C. *Callialasporites grandis*, MK 1215, Depth 1215m

D. *Callialasporites trilobatus*, MK 1367, Depth 1367m

E. *Excessipollenites sp.*, MK 1427, Depth 1427m

F. *Excessipollenites sp.*, MK 1397, Depth 1397m

G. *Trilete spore*

H. *Trilete spore*

Plate 3.10

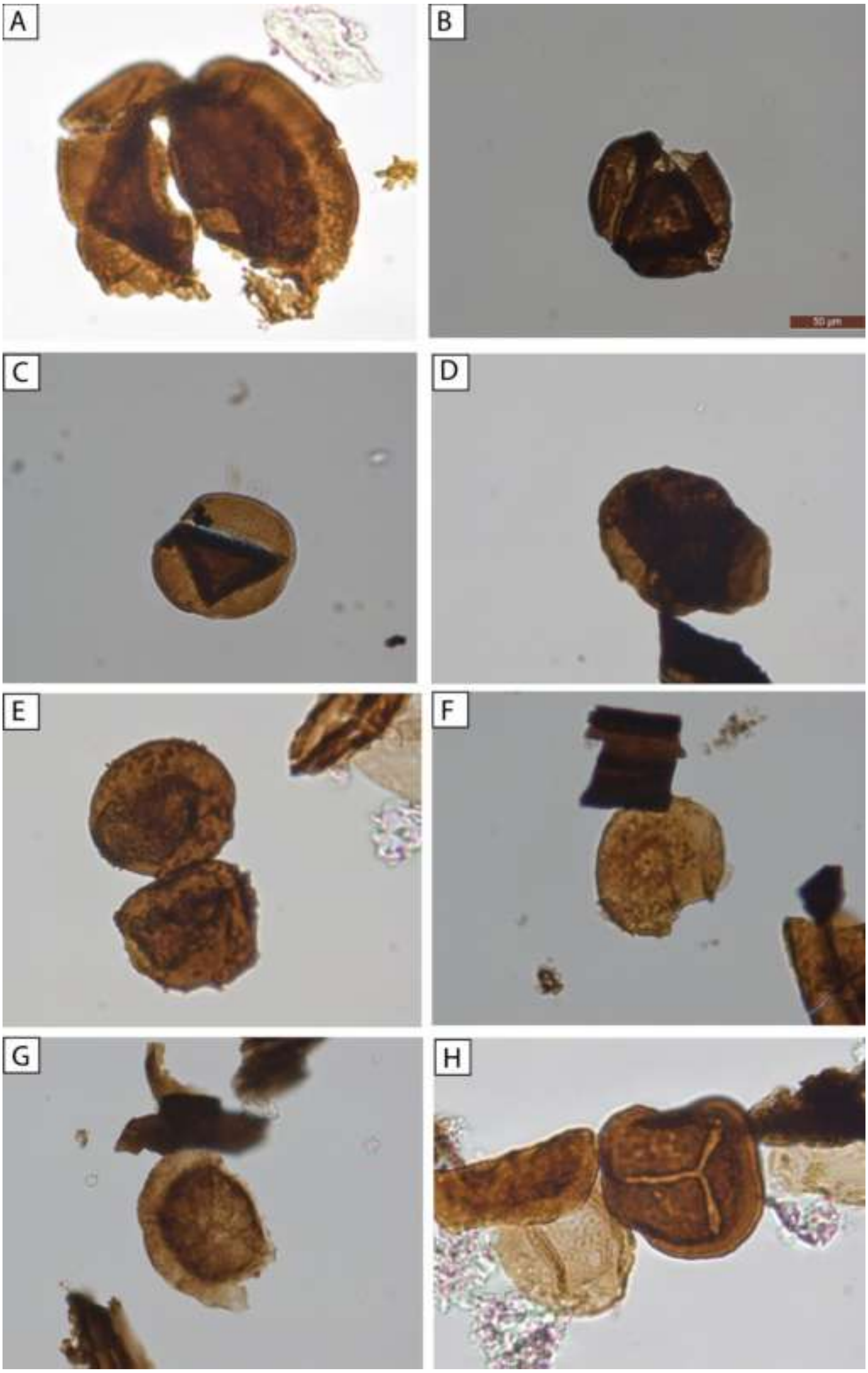


Plate 3.11 Explanation

A. *Cyacadopites sp. / Shanbeipollenites sp.,*MK 1267, Depth 1267m

B. *Cyacadopites sp. / Shanbeipollenites sp.*, MK 1267, Depth 1267m

C. *Mendicodinium groenlandicum,* MK 1367, Depth 1367m

D. *Mendicodinium groenlandicum,* MK 1215, Depth 1215m

E. **?**

F. *Trilete spore*

G. *?Gordonispora fossulata*

H. *Trilete spore*

Plate 3.11

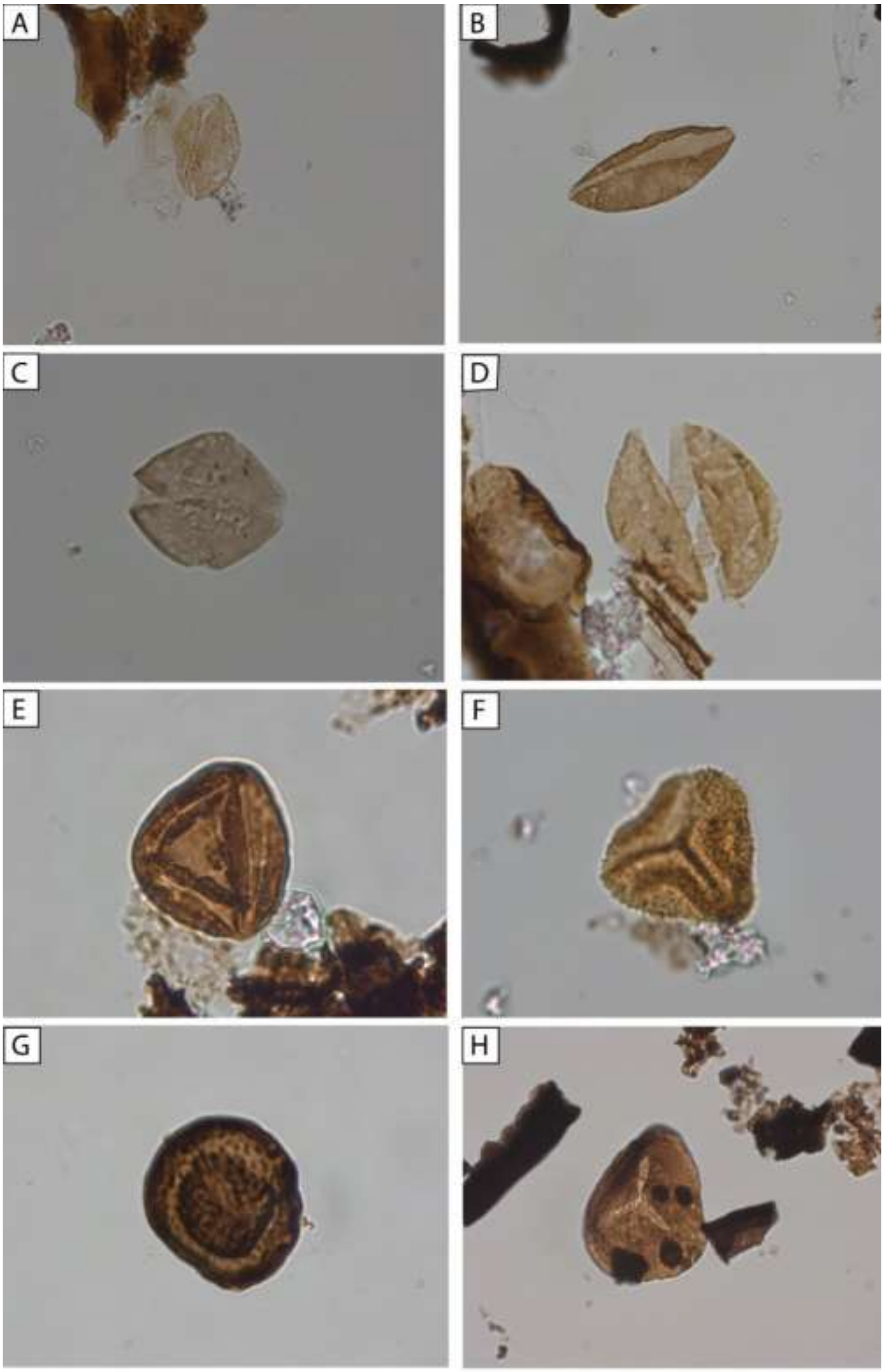


Plate 3.12 Explanation

A. *Classopollis sp.*, MK 1215, Depth 1215m

B. *Classopollis sp.*, MK 1215, Depth 1215m

C. *Classopollis sp.*, MK 1215, Depth 1215m

D. *Classopollis sp.*, MK 1215, Depth 1215m

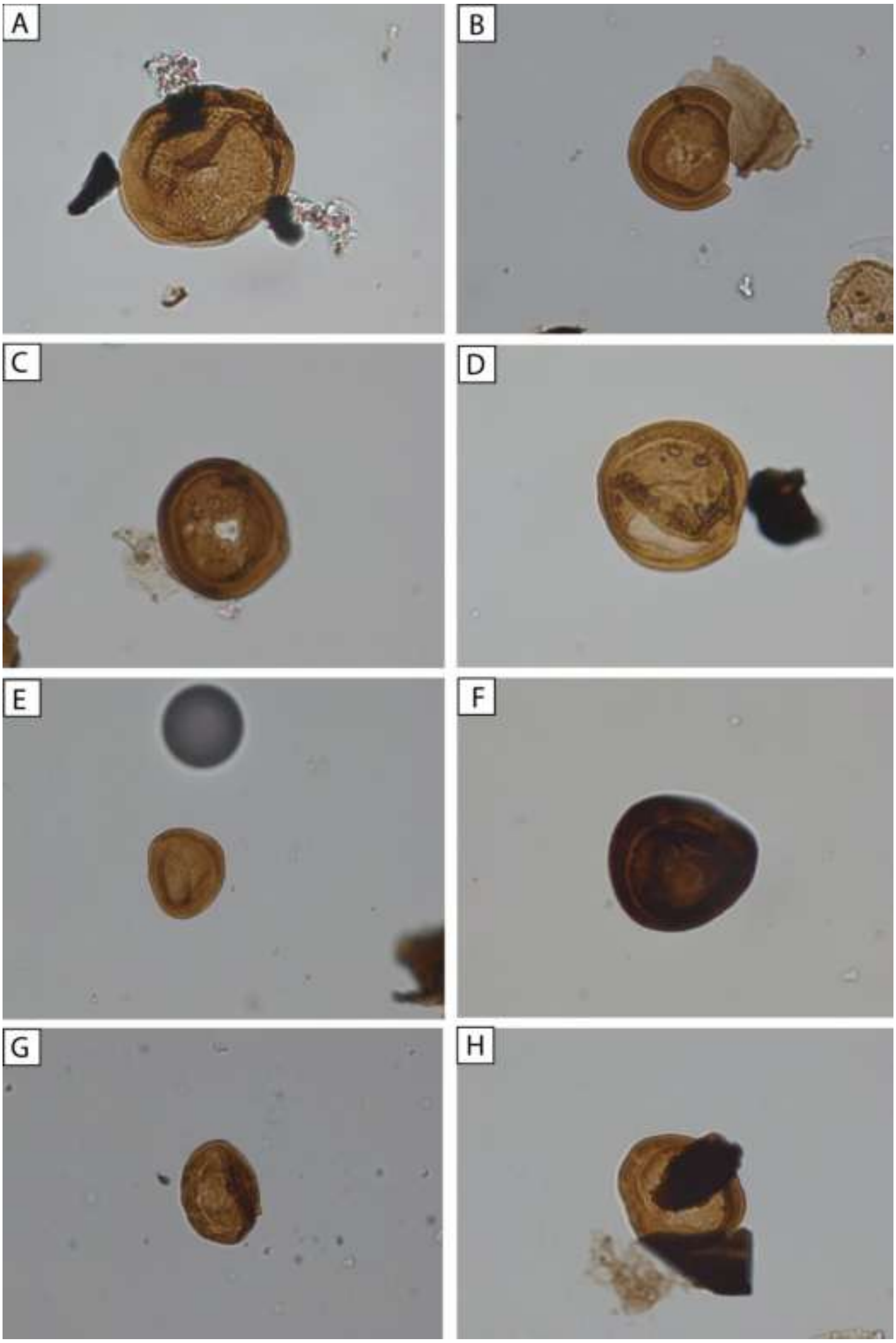
E. *Classopollis sp.*, MK 1215, Depth 1215m

F. *Classopollis sp.*, MK 1215, Depth 1215m

G. *Classopollis sp.*, MK 1215, Depth 1215m

H. *Classopollis sp.*, MK 1215, Depth 1215m

Plate 3.12



APPENDICES

Appendix 1: Taxonomic Appendix to Chapters 2 and 3

List of Sporomorph Taxa

Alisporites angustus Ouyang and Norris 1999

Alisporites australis de Jersey 1962

Alisporites indicus Srivastava 1974

Alisporites toralis Maheshwari 1969

Alisporites sp. A type of *Alisporites* which is not differentiated on species level but correspond to genus description of de Jersey 1962.

Anapiculatisporites spiniger Geleta 1998

Anapiculatisporites sp. (Plate 2.7., e)

Aratisporites sp. (Plate 2.7., c)

Callialasporites spp.

All encountered specimens corresponding to genus *Callialasporites* as described by (Maheshwari 1974) Vijaya 2009. Encountered species are: *Callialasporites trilobatus* (Maheshwari 1974) Vijaya 2009, *Callialasporites grandis* (Maheshwari 1974) Vijaya 2009, *Callialasporites damperia* Maheshwari 1974) Vijaya 2009; *Callialasporites grandis* (Maheshwari 1974) Vijaya 2009, *Callialasporites plicatus* (Maheshwari 1974) Vijaya 2009.

Cycadopites sp. Balduzzi et al. 1992

Excessipollenites sp. A type of *Excessipolenites* which is not differentiated on species level but correspond to genus description of Balme 1957.

Callumispora barankesis Srivastava 1970

Classopollis sp. de Jersey 1965, Balduzzi et al. 1992

Converrucosisporites sp. (Plate 2.7., a)

Cordaitina sp. A type of *Cordaitina* which is not differentiated on species level but correspond to genus description of Hart 1965.

Cyacadopites sp. A type of *Cyacadopites* which is not differentiated on species level but correspond to genus description of Hart 1965.

Falcisporites minutisaccus Tiwari 1996

Falcisporites zapfei Jardin 1974

Falcisporites sp. A type of *Falcisporites* which is not differentiated on species level but correspond to genus description of de Jersey 1962.

Faunipollenites gopadensis Jha 1996

Faunipollenites sp. (Plate 2.11., e)

Ginkgocycadophytus nitidus de Jersey 1962

Granamegamonocolpites campbellii Jain 1968

Hamiapollenites minimus Jha 1996

Jugasporites gamsi Foster 1983

Jugasporites nubilus Hart 1965

Jugasporites vellicoites Zavattieri et al. 2018

Jugasporites sp. A type of *Jugasporites* which is not differentiated on species level but correspond to genus description of Zavattieri et al. 2018

Keuperisporites baculatus Brugman et al. 1985

Klausipollenites devolvens Fisher 1979

Klausipollenites schaubergeri Jardin 1974

Klausipollenites c.f. vestitus Bose 1976

Klausipollenites sp. A type of *Klausipollenites* which is not differentiated on species level but correspond to genus description of de Jersey 1969.

Lueckisporites virkkiae Rakotoarivelo 1960, Hart 1970, Hankel 1987, Wescot 1991

Lunatisporites gopadensis Srivastava 1974

Minutosaccus maedleri Maheshwari et al. 1978

Minutosaccus protoniei Maheshwari 1979

Platysaccus radialis Falcon 1984

Protohaploxypinus limpidus de Jersey 1970

Pteruchipollenites gracilis Cesari 1986

Protohaploxypinus rugatus Segroves 1970

Protohaploxypinus limpidus de Jersey 1970

Punctatisporites sp. Hart 1962, Christopher 1971, Liao 1980, Hart 1970.

Podocarpites alatus Hart 1970

Pteruchipollenites thomasii Farabee 1990

Pinuspollenites sp. Hankel 1992

Pinuspollenites divulgatus Qu et al. 1986

Punctatisporites gretensis Rakotoarivelo 1960

Shanbeipollenites quadrangulatus Schrank 2004

Raistrickia saetosa Sultan 1986

Reduviasporonites chalastus Foster 2002

Reduviasporonites sp. Wilson 1962

Striatites tentulus Maheshwari 1979

Shanbeipollenites sp. A type of *Shanbeipollenites* which is not differentiated on species level but correspond to genus description of Shrank 2004

Simeonospora khlonovae Hankel 1993

Spinotriletes echinoides Kumar 1988

Scheuringipollenites circularis Cesari 1995

Satsangisaccites nidpurensis Srivastava 1974

Spinotriletes echinoides Doubinger 1997

Striatopodocarpites labrus Bose 1968

Staurosaccites sp. (c.f. S. quadrifidus) Hankel 1987, Hankel 1993, Hankel 1997

Vitreisporites pallidus de Jersey 1964

Vitreisporites sp. A type of *Vitreisporenites* which is not differentiated on species level but correspond to genus description of de Jersey 1964.

List of Dinoflagellate Cyst Taxa

For authors see Lentin and Williams 2017

Adnatosphaeridium multispinosum

Batiacasphaera sp. (Plate 3.3.,e)

Batiacasphaera murchisonii

Bradleyella cf. adela Woolam 1983

Canningia reticulata

Cerbia tabulata

Clathroctenocystis asapha

Ctenidodinium combazi

Ctenidodinium ornatum

Ctenidodinium sellwoodii

Ctenidodinium sp. A type of *Ctenidodinium* which is not differentiated on species level but correspod to genus description of Eisenack 1935.

Dissiliodinium ventrogranum

Dissiliodinium willei

Dissiliodinium sp. A type of *Dissiliodinium* which is not differentiated on species level but correspond to genus description of Riding and Thomas 1988.

Dingodinium spinosa

Dingodinium sp. (Plate 3.4.,g)

Durotrigia omentifera

Egmontodinium sp. A type of *Egmontodinium* which is not differentiated on species level but correspond to genus description of Gitmez and Sarjeant (1972).

Ellipsoidictyum cinctum

Fistulacysta simplex

Glossodinium dimorphum

Gonyaulacysta centriconnata

Gonyaulacysta jurassica

Hystrichosphaerina schindewolfii

Impletosphaeridium sp. (Plate 3.7.,a)

Kleithriasphaeridium porosispinum

Lithodinia caytonensis

Meiourogonyaulax sp. (Plate 3.8.,f)

Mendicodinium groenlandicum

Nannoceratopsis dictyambonis

Nannoceratopsis gracilis

Nannoceratopsis pellucida

Nannoceratopsis plegas

Nannoceratopsis triceras

Oligosphaeridium porosum

Pareodinia sp. (Plate 3.5.,a)

Nannoceratopsis sp. (Plate 3.6.,e)

Paleocysta virgae

Proloellipsodinium spinosum

Scrinocasis sp. (Plate 3.9.,d)

Sentusidinium sp. (Plate 3.9.,f)

Stiphrosphaeridium dictyophorum

Subtililisphaera scabrata

Subtililisphaera perlucida

Subtilisphaera rotundata

Subtilisphaera scabrata

Subtilisphaera sp. (**Plate 3.6., f**)

Tenua hystrix

Valensiella ovulum

Wanaea acollaris

Wanaea clathrata

Wanaea digitata

Wanaea fimbriata

Wanaea indotata

Wanaea lacuna

Wanaea spectabilis

Wanaea talea

Appendix 2: Outcrop Sample Catalogue for the Tanga Basin Field Work

Kakindu section: at kakindu stream, near kakindu -1 borehole

S/N	**Sample _ID**	**Co – ordinates**	**Description/ Field Name**
1	KKS/1/01	37M, 0490076, 9450016, 4m ASL	Greyish – Black Shale/ Mudstone
2	KKS/1/02	37M, 0490076, 9450016, 4m ASL	Greyish – Black shales
3	KKS/1/03	37M, 0490076, 9450016, 4m ASL	Bottom – Middle Section transition; Black Shale.
4	KKS/03/01	37M, 0490076, 9450016, 4m ASL	Greyish – Black Shales
5	Laterite	37M, 048991, 9450068, 102m ASL	Laterite
6	KKF - 07	37M, 0490076, 9450016, 4m ASL	Indeterminate fossilized material on a silty shale.
7	KKF - 06	37M, 0490076, 9450016, 4m ASL	Indeterminate fossilized material on a silty shale.
8	KKF - 01	37M, 0490076, 9450016, 4m ASL	Indeterminate fossilized material on Micaceous shale.
9	KKF - 03	37M, 0490076, 9450016, 4m ASL	Petrified ?Cordaites and other plant fragments on black shale
10	KKF - 051	37M, 0490076, 9450016, 4m ASL	Petrified ?Cordaites and other plant fragments on black shale
11	KKF - 052	37M, 0490076, 9450016, 4m ASL	Black Shale
12	KKF - 053	37M, 0490076, 9450016, 4m ASL	Petrified ?Cordaites and other plant fragments on black shale
13	KKF - 054	37M, 0490076, 9450016, 4m ASL	?Ripples on Black Shale Surface
14	KK -02	37M, 0490076, 9450016, 4m ASL	*?Voltzia*, ?*Cordaites* and other fossilized Plants fragments.

Appendix 3: Core Sample Catalogue

I. Jihirini–1 Borehole

EOH = 206 m

Core diameter = ??

S N	SAMPLE No.	DEPTH (m)	GEOLOGICAL DESCRIPTION	STRATIGRAPHY
1	JH 01	40	Medium dark gray (N4), in color, fine grained.	LOWER KAROO
2	JH 02	45	?? Not logged; sample taken.	LOWER KAROO
3	JH 03	50	Medium dark gray (N4) in color, fine grained, carbonate veins and concretion impression observed.	LOWER KAROO
4	JH 04	55	?? Not logged; sample taken.	LOWER KAROO
5	JH 05	60	?? Not logged; sample taken.	LOWER KAROO
6	JH 06	95	Mainly medium dark gray (N4) in color; fine grained; horizontal laminated (consists of alternating medium dark gray and very light gray (N8) lamina).	LOWER KAROO
7	JH 07	110	Grayish black (N4), in color, fine grained, well sorted, a micro fault is observed.	LOWER KAROO
8	JH 08	120	?? Not logged; sample taken.	LOWER KAROO
9	JH 09	130	Medium dark gray (N4) in color; fine grained, well sorted, a micro fault is observed.	LOWER KAROO
10	JH 10	150	?? Not logged; sample taken.	LOWER KAROO
11	JH 11	170	Medium dark gray (N4) in color, fine grained, shows carbonate alteration at some point.	LOWER KAROO
12	JH 12	180	?? Not logged; sample taken.	LOWER KAROO
13	JH 13	201.4	Medium dark gray (N) in color;	LOWER KAROO

II. Vunde–1 Borehole

EOH = 206 m

Core diameter = 47 mm

S N	**SAMPLE**	**DEPTH (m)**	**BRIEF GEOLOGICAL DESCRIPTION**	**STRATIGRAPHY** (TPDC 2014)
1	VND 01	20	Massive grayish black in color (N2), well sorted fine grained with observed concretion.	MIDDLE KAROO
2	VND 02	58	Massive grayish black in color (N2), well sorted fine grained; visible carbonate veins.	MIDDLE KAROO
3	VND 03	61	Massive grayish black in color (N2), well sorted fine grained. Cross laminations observed.	MIDDLE KAROO
4	VND 04	94	Not logged, sample taken.	MIDDLE KAROO
5	VND 05	99	Massive grayish black in color (N2), well sorted fine grained. Cross and convoluted laminations observed at 97.12m.	MIDDLE KAROO
6	VND 06	106	Not logged, sample taken, noted Pyritization at 102m.	MIDDLE KAROO
7	VND 07	119	Horizontal laminated grayish black in color (N2), well sorted fine grained.	MIDDLE KAROO
8	VND 08	150	?? Not logged, sample taken.	MIDDLE KAROO
9	VND 09	155	?? Not logged, sample taken.	MIDDLE KAROO
10	VND 10	160	Massive grayish black in color; Plant material observed.	MIDDLE KAROO
11	VND 11	168	??Not logged, sample taken.	MIDDLE KAROO
12	VND 12	170	Horizontal laminated grayish black in color (N2), well sorted fine grained with carbonized plant debris observed in cross sectional view of the core.	MIDDLE KAROO
13	VND 13	173??	Convolute laminated grayish black in color (N2), well sorted fine grained.	MIDDLE KAROO
14	VND 14	175	Laminated grayish black in color (N2), well sorted fine grained, Plant material observed.	MIDDLE KAROO

III. Kakindu–1 Borehole

EOH = 158 m

Core diameter = 62 mm

S N	**SAMPLE**	**DEPTH (m)**	**BRIEF GEOLOGICAL DESCRIPTION**	**STRATIGRAPHY** (TPDC 2014)
1	KK 01	**10**	Fine grained; Medium light gray (N6) and very light gray in color; alternating planar lamina.	LOWER KAROO
2	KK 02	**40**		
3	KK 03	**60**	Fine grained; Medium light gray (N6) and very light gray planar laminated silty-mudstone; a few micro faults observed. This interval is close to the interval with deformed mud.	LOWER KAROO
4	KK 04	**85**	Fine grained; Medium light gray (N6) and very light gray planar laminated silty-mud, with a few exceptions at the near intervals (e.g. cross lamina and concretions at 82). This interval is close to the interval with deformed mud.	LOWER KAROO
5	KK 05	**100**	Fine grained; Medium light gray (N6) and very light gray planar laminated silty-mudstone.	LOWER KAROO
6	KK 06	**110**		LOWER KAROO
7	KK 07	**125**	Fine grained; Medium light gray (N6) and very light gray in color; observed cross lamina.	LOWER KAROO
8	KK 08	**130**	Thinly laminated; Fine grained; Medium light gray (N6) and very light gray alternating lamina; Also thickly laminated beds that alternates with the fine muds and coarse calcareous (?) silt.	LOWER KAROO
9	KK 09	**135**		
10	KK 10	**140**	Medium light gray (N6); fine grained;- Medium light gray (N6) and very light gray alternating planar lamina.	LOWER KAROO
11	KK 11	**150**	Uniformly fine grained particles, with pyritic alteration at 155m; Occasional carbonate veins are observed in convolute manner.	LOWER KAROO
12	KK 12	**155**		LOWER KAROO