Palaeoenvironments during a terminal Oligocene or early Miocene transgression in a fluvial system at the southwestern tip of Africa

D.L. Roberts¹, F.H. Neumann^{2,3,4*}, H.C. Cawthra^{4,5}, A.S. Carr⁶, L. Scott⁷, E.U. Durugbo⁸, M.
S. Humphries⁹, R.M. Cowling⁴, M.K. Bamford³, C. Musekiwa⁵, M. MacHutchon⁵

¹*Deceased September 2015, Department of Geography, University of the Free State,
Bloemfontein, South Africa*

²*Forschungsstelle für Paläobotanik, University of Münster, Heisenbergstrasse 2, 48149
Münster, Germany. E-mail: fneumann1971@gmail.com (corresponding author)*

³*Evolutionary Studies Institute, University of the Witwatersrand, Private Bag 3, WITS,
Johannesburg, 2050 South Africa. E-mail: marion.bamford@wits.ac.za*

⁴*Centre for Coastal Palaeoscience, Nelson Mandela Metropolitan University, PO Box 77000,
Port Elizabeth, 6031, South Africa, E-mail: rmc@kingsley.co.za*

⁵*Geophysics Competency, Council for Geoscience, PO Box 572, Bellville 7535, South Africa.
E-mail: hcawthra@geoscience.org.za, cmusekiwa@geoscience.org.za,
michael@geoscience.org.za*

⁶*Department of Geography, University of Leicester, University Road, Leicester LE1 7RH,
UK, Email: asc18@leicester.ac.uk*

⁷*Department of Plant Sciences, University of the Free State, Bloemfontein, South Africa, E-
mail: scottl@ufs.ac.za*

⁸*Department of Biological Sciences, Redeemer's University, P.M.B. 230. Ede, Osun state,
Nigeria. E-mail: durugboe@run.edu.ng*

⁹*Molecular Sciences Institute, School of Chemistry, University of the Witwatersrand, Private
Bag 3, WITS, Johannesburg, 2050, South Africa. E-mail: marchump@gmail.com*

* corresponding author

ABSTRACT

A multi-proxy study of an offshore core in Saldanha Bay (South Africa) provides new insights into fluvial deposition, ecosystems, phytogeography and sea-level history during the late Paleogene-early Neogene. Offshore seismic data reveal bedrock topography, and provide evidence of relative sea levels as low as -100 m during the Oligocene. 3D landscape reconstruction reveals hills, plains and an anastomosing river system. A Chattian or early Miocene age for the sediments is inferred from dinoflagellate taxa *Distatodinium craterum*, *Chiropteridium lobospinosum*, *Homotryblum plectilum* and *Impagidinium paradoxum*. The subtropical forest revealed by palynology includes lianas and vines, evergreen trees, palms and ferns, implying higher water availability than today, probably reduced seasonal drought and stronger summer rainfall. From topography, sedimentology and palynology we reconstruct Podocarpaceae-dominated forests, Proto-Fynbos, and swamp/riparian forests with palms and other angiosperms. Rhizophoraceae present the first South African evidence of Palaeogene/Neogene mangroves. Subtropical woodland-thicket with Combretaceae and *Brachystegia* (*Peregrinipollis nigericus*) probably developed on coastal plains. Some of the last remaining Gondwana elements on the sub-continent, e.g., Araucariaceae, are recorded. Charred particles signal fires prior to the onset of summer dry climate at the Cape. Marine and terrestrial palynomorphs, together with organic and inorganic geochemical proxy data, suggest a gradual glacio-eustatic transgression. The data shed light on Southern Hemisphere biogeography and regional climatic conditions at the Palaeogene-Neogene transition. The proliferation of the vegetation is partly ascribed to changes in South Atlantic oceanographic circulation, linked to the closure of the Central American Seaway and the onset of the Benguela Current ~14 Ma.

KEY WORDS

Palaeoecology, terminal Oligocene/early Miocene, marine transgression, southern Africa, coastal environment, 3D landscape reconstruction, biostratigraphy

1. INTRODUCTION

The Fynbos and Succulent Karoo Biomes, located at the southern tip of Africa, are biodiversity hotspots with a high level of endemism. The most species- and endemic-rich parts of Fynbos are associated with winter-rainfall, rough topography, oligotrophic soils and recurrent fire (Cowling and Lombard, 2002; Goldblatt and Manning, 2002; Verboom et al., 2015). Fynbos climates are underpinned by cyclonic winter rainfall, which in concert with cold currents of the Benguela Upwelling System, are controlled by the South Atlantic Anticyclone as it migrates northward in winter (Tyson, 1999). To the north the anticyclone prevents monsoonal rainfall, resulting in drier conditions with karroid vegetation. The establishment of this climatic framework is pertinent to the spread and diversification of the Fynbos Biome (Linder, 2003), which is hypothesised to have emerged during the Miocene, leading to the demise of drought- and fire-intolerant forests (Linder et al., 1992; Linder and Verboom, 2015). Given the widespread diversification of Fynbos lineages as early as the Oligocene (Linder, 2005), it has been suggested that a Proto-Fynbos biome may have been associated with skeletal soils of the Cape Fold Belt and sandplains of the lowlands during a cooler and drier period with enhanced seasonality, probably the late Eocene-early Oligocene (Linder and Verboom, 2015). Previously there were no palaeoarchives available to test this hypothesis, but the current study sheds light on the outcome of this process.

Neogene polleniferous deposits (e.g., Elandsfontyn Formation), are preserved on the lowlands of the south-western Cape at Noordhoek, Rondeberg, Langebaanweg and Knysna (Figure 1). These sites indicate that Fynbos vegetation was preceded by tropical/subtropical forests (Coetzee, 1978; Coetzee and Rogers, 1982; Coetzee, 1983; Scott,

1995; Thiergart et al., 1963; Thiergart, 1964; Carr et al., 2010a; Sciscio et al., 2013, 2016; Roberts et al., 2011, 2013). Many taxa are extinct in the region today and some are no longer found in Africa. The floras exhibit a distinct Gondwanan rather than tropical-African character (Neumann and Bamford, 2015).

The cause(s) and timing of the transition from the tropical/sub-tropical late Palaeogene/early Neogene floras to the present Fynbos is yet to be understood. The chronologies of these archives is pertinent because the West Coast sites probably represent brief time intervals, rendering the broader trends unclear (Roberts et al., 2013). Despite similarities in palynofloras and depositional milieu, the archives potentially represent a long age range, extending from Oligo-Miocene to late Miocene (Coetzee, 1983). The offshore data presented here are an important step towards placing West Coast Neogene fluvio-paludal deposits in chronological context thanks to our study site's proximal setting with stratigraphically relevant dinoflagellate cysts.

Figure 1. Geological map showing Elandsfontyn Formation and localities mentioned in text.

(2-column fitting, colour)

Offshore boreholes in Saldanha Bay facilitate studies of fluvio-paludal depositional style, chronology, sea level history, ecosystems and phytogeography within the terminal Oligocene or early Miocene (Figure 1, 2, 3, Figure 4B). Neoproterozoic basement topography and Cenozoic stratigraphic relationships of the Neogene Sandveld Group are revealed by a seismic survey and 3D modelling. Here, core SBQW4/23 provides a 10-m-thick succession of polleniferous organic rich silts and clays. These strata, deposited by the Palaeo-Berg River (Figure 1) (Rogers, 1980), represent an older section of the late Oligocene-Miocene Elandsfontyn Formation than those studied by Coetzee and Rogers (1982) and Sciscio et al. (2013) ~14km inland at Langebaanweg (see discussion below).

Figure 2. Oligo-Miocene Elandsfontyn Formation in relation to global Cenozoic sea levels (after Miller et al., 2005a). Global sea-level curve for the interval 7 to 65 Ma derived by backstripping data (blue) (van Sickel et al., 2004); long-term fit to a backstripped curve (black). Global sea-level for the interval 0 to 7 Ma derived from $\delta^{18}\text{O}$ (purple). Benthic foraminiferal $\delta^{18}\text{O}$ synthesis from 0 to 65 Ma (red). The portion of the $\delta^{18}\text{O}$ curve from 0 to 65 Ma from Miller et al. (1987). Abbreviations: Pleis. – Pleistocene; NHIS – Northern Hemisphere Ice Sheets. GSSP (golden nail) only shown for Paleogene-Neogene (Chattian-Aquitania) boundary

2. REGIONAL SETTING

2.1 Geology

This study centres on Saldanha Bay (Figure 1). The geological basement comprises deformed Neoproterozoic metasediments of the Malmesbury Group and plutons of the late Precambrian - early Cambrian Cape Granite Suite (Roberts and Siegfried, 2014; Figure 4B). A passive intraplate, trailing edge tectono–seismic model has been inferred for this coastline; the coastal belt constitutes a platform on which sea level fluctuations reflect glacio-eustasy rather than vertical crustal motion (Roberts et al., 2011; Figure 2). This platform originated during the late Mesozoic fragmentation of Gondwana and was influenced by Cenozoic marine transgressions (Pether, 1994; Vaughan and Pankhurst, 2008; Roberts et al., 2011). It is bounded on the landward margin by the Cape Fold Belt and is sporadically blanketed by Miocene-Holocene marginal marine, fluvial and aeolian deposits of the Sandveld Group (Figure 1) (Roberts and Brink, 2002; Roberts et al., 2006), with thicker deposits occupying depressions in the basement. The depressions were inferred to have been incised by rivers during Oligocene sea level lowstands (Rogers, 1982; Roberts et al., 2011, Figure 2, Figure 3). Although it has not yet been documented within the depositional record of the Cape, global evidence suggests an elevated sea level during the Middle Miocene Climatic Optimum (Zachos et al., 2001, Figure 2). Neogene uplift has been suggested for southern South Africa (Partridge and Maude, 1987; 2000), but the nature, timing and even the existence of such events is debated (Flowers and Schoene, 2010; Erlanger et al., 2012; Ng et al. 2014. Although Pliocene units are known (e.g. LBW; Roberts et al., 2011), Miocene deposits are yet to be dated and constrained within a tectonic framework.

2.2 Phyto-geographic history from the Cretaceous until the Neogene

The phytochorion of southern Africa reflects influences from Australia and Madagascar rather than tropical Africa (Coetzee et al., 1983). The fragmentary Late Cretaceous

and Cenozoic botanical record comprises sites along the Atlantic seaboard and kimberlite infillings in the western interior (Scholtz, 1985; Coetzee et al., 1983; Scott et al., 1997; Neumann and Bamford, 2015). Gymnosperms and cryptogams dominated Early Cretaceous microfloras with a gradual appearance of angiosperms like *Clavatipollenites* (probable Chloranthaceae affinity). Araucariaceae and Podocarpaceae wood are known from Early Cretaceous sites (Bamford, 2004). Pollen of flowering plants became more diverse in the Late Cretaceous (Scott, 1976; McLachlan and Pieterse, 1978; Sandersen et al., 2011). Maastrichtian-Paleocene sediments from a kimberlite pipe in Namaqualand revealed a palynoflora pointing to warm-temperate/subtropical, dry climate, with conifers (Podocarpaceae including probable *Dacrydium*; Araucariaceae, Tsugaceae), Fynbos elements (Proteaceae, Restionaceae, Ericaceae), Chloranthaceae, Casuarinaceae/Myricaceae, Euphorbiaceae, Anacardiaceae, Caesalpiniaceae, and Arecaceae. As contemporary Fynbos lineages are shade-intolerant (Richardson and Cowling, 1992; Manders, 1990), the Proto-Fynbos probably occurred in a mosaic with subtropical forest and thicket and not, as proposed by Scholtz (1985), as a forest understorey (Cowling et al., 2005). Probable Palaeocene deposits at Koingnaas (Namaqualand) contain Araucariaceae and Podocarpaceae pollen (De Villiers and Cadman, 2001).

Eocene offshore deposits adjacent to the Orange River mouth comprise Asteraceae (Mutisieae) pollen, which together with their presence in South American deposits suggest that the family originated in the southern Atlantic region (Barreda, 1993; Zavada and De Villiers, 2001; Scott et al., 2006; Barreda et al., 2009), probably during the Late Cretaceous (Antarctica: Barreda et al., 2015). Increased seasonality during the late Eocene-early Oligocene transition might have facilitated the radiation of Fynbos lineages (Linder, 2005; Linder and Verboom, 2015). Plant macro-fossils from the late Oligocene warm period, c. 30-25 Ma, are represented in southern Africa only by possible ferns and unidentified dicot woods (Bamford, unpublished data; Bamford, 2000). Axelrod and Raven (1978) hypothesized a temperate Podocarpaceae-*Araucaria* rainforest with Gondwanan affinities along the southern coast, and

humid, subtropical woodland to the north during the Rupelian-Chattian. These forests might have been the southern African equivalent of the Palaeo-Antarctic rainforest spanning Australia, New Zealand, Patagonia and Antarctica (Kooyman et al., 2014). Since land bridges between Australasia-Antarctica-South America were present for longer than those with Africa (Hill, 2009), a greater similarity exists between the floras of the aforementioned continents (Axelrod and Raven, 1978). Numerous components of the Gondwanan flora have vanished from Africa, but still survive in the modern floras of Australia, New Zealand and Patagonia (Kooyman et al., 2014, Macphail, 1999, Macphail, et al., 1993, 1995). Cowling et al. (2005) suggested that the Oligocene vegetation of the Cape comprised a mosaic of subtropical thicket and Proto-Fynbos on coastal plains, Proto-Fynbos on the Cape Fold belt and warm-temperate thicket in the interior.

Marine records, although giving a limited insight into onshore vegetation, are invaluable since terrestrial Neogene pollen archives in southern Africa are scarce and insufficiently dated (Linder, 2003; van Zinderen Bakker, 1984; Dupont et al., 2005, Udeze and Oboh-Ikuenobe, 2005). Terrestrial Neogene sites in the Cape region (Knysna, Langebaanweg, Rondeberg, Noordhoek), suggest humid, subtropical forests, not unlike those growing today on the humid subtropical east coast of the subcontinent. Podocarpaceae, Arecaceae, Sapotaceae, Sapindaceae, Myrtaceae, and Myricaceae (Neumann and Bamford 2015), as well as Casuarinaceae, Chloranthaceae and Winteraceae, the latter three families presently extinct in the Cape, were all seemingly abundant during the Miocene (Coetzee and Praglowski, 1984; Coetzee and Muller, 1984). During the Miocene, rainfall was higher than today at Langebaanweg, and probably less seasonal (Sciscio et al., 2013). The chronological position of the Elandsfontyn Formation within the Miocene is uncertain, but Roberts et al. (2011, 2013) suggest an early-middle Miocene age. After the opening of the Drake Passage and development of the Antarctic ice sheet in the late Miocene-Pliocene (Shackleton and Kennet, 1975; Uenzelmann-Neben et al., in press), the cold Benguela Current strengthened (Siesser, 1980). In

the Cape, resulting development of temperate winter-rainfall favoured Fynbos development, while northwards under drier conditions karroid and desert vegetation developed (Linder and Verboom, 2015; Neumann and Bamford, 2015). Here we address the timing and evolution of the coastal landscape around the study area and its vegetation in the frame of a geological, geochemical and palaeontological study of core SBQW4/23.

3. MATERIALS AND METHODS

3.1 Marine geophysics – sub-bottom profiling

Twenty-seven profiles of single-channel, high-resolution seismic reflection data were acquired in Saldanha Bay covering 2 km². Two profiles are presented here (line numbers 10, 16), which intercepted the closest location of borehole SBQW4/23 (Figure 3). The boomer system was triggered every 650 ms at an energy level of 1000 J; the seismic data were acquired by an 8 element Design Projects hydrophone array and recorded on an Octopus 760 seismic processor using a sampling rate of 24 kHz and a sweep period of 75 ms. Processing of the reflection seismic data involved application of time-varied gain, a bandpass filter (optimised at 450 to 1800 Hz), swell filter and seabed tracking. Constant sound velocities through water and sediment were set at 1500 and 1650 m s⁻¹ to constrain time-depth conversions.

3.2 Core logging, sampling and generation of 3D models

Core SBQW4/23 was part of an offshore geotechnical investigation by Fairbrother Geotechnical Engineering cc (Figure 1, 3, 4), in which twenty-three boreholes were drilled. For the 3D models produced in this work, contours indicating the depth to granite were digitised in ArcGis from onshore boreholes (Rogers, 1980). Contour heights were combined with the point values interpreted from offshore seismic datasets. In areas where the granite outcrops values were used, the elevation above Mean Sea Level were extracted from the 90 m shuttle radar topography mission (SRTM) data. For the offshore area, seismic profiles were

digitised to basement. XYZ points were merged with onshore data and gridded by Kriging in Surfer (cell size 800 m), to create a seamless surface to use as a base for model extrapolation. Contours lines of values +5 m (sea level high stands during the early-middle Miocene), -20 m (intermediate sea levels during the terminal Oligocene and early Miocene) and -40 m (low sea levels during the early-middle Oligocene) were extracted from the surface and were converted to regions that were overlaid on the granite surface in ArcScene 3D Analyst to create the final images (Figure 5).

3.3 Palynology

Twenty-two samples were processed with HCl, 40% HF, Schultze's solution, KOH and heavy-liquid separation (density 2.0) (Wood et al., 1996). Residues were sieved to obtain particles <250 and >6 µm, mounted in glycerol jelly and stored at Forschungsstelle für Paläobotanik, Münster. Palynomorphs were identified with a light microscope (×400, ×1000) following, e.g., Coetzee 1978, 1981; Coetzee and Rogers, 1982; Coetzee and Praglowski, 1984; de Villiers, 1997; de Villiers and Cadman, 1997; Scott, 1982; Kalgutkar and Jansonius, 2000; Stuchlik et al., 2001, 2002, 2009, 2014, Raine et al., 2011, Zonneveld et al., 2013, Powell, 1986a,b, 1992; Sluijs et al., 2003; and Fauconnier et al., 2004, as well as palynological reference collections at Forschungsstelle für Paläobotanik, Münster, and University of the Free State, Bloemfontein. Around 400 terrestrial pollen grains were counted per sample. Black, angular fragments were grouped into categories according to longest axis length; 10–50, 51–100 µm (microscopic charcoal) and >100 µm (Mooney and Tinner, 2011). Since palynological processing involves centrifuging, charred particles might become fragmented and some bias must be considered also due to sieving. Pollen diagrams were constructed with TILIA 1.7.16, using the terrestrial taxa as pollen sum (Figure 7, 8). In order to show fluctuations of forest and woodland vs. open land vs. wetland indicators, a stacked diagram was calculated using terrestrial taxa and wetland indicators as pollen sum (Figure 8). Pollen zonation used CONISS (stratigraphical constrained

cluster analysis, total sum of squares, TILIA 1.7.16). The percentages of pollen and spore types were used for principal components analysis (PCA) on a correlation matrix using PAST (Hammer and Harper, 2006) after discarding those that had 10 or less specimens in the sequence. The PCA summarises the general trend in the pollen flora and allows the investigation of possible environmental conditions. However, limited knowledge of the ecological requirements of extinct types and taphonomical factors like palynomorph source areas and transport distances must be considered.

3.4 Elemental concentrations and stable isotope analyses

Freeze-dried, homogenized samples were encapsulated in tin cups and total organic carbon (TOC), total nitrogen (TN) and $\delta^{13}\text{C}_{\text{TOC}}$ determined using an ANCA GSL elemental analyser interfaced to a continuous-flow isotope-ratio mass spectrometer. Analyses were carried out in triplicate, with typical precision better than 0.1 ‰ for $\delta^{13}\text{C}$. Major element (Si, Al, Fe, K, Na) and trace metal (U, Th, V, Cr, Mo, Sr) concentrations were measured by X-ray fluorescence (Panalytical PW2400). Measurement accuracy was checked against a range of local and USGS rock standards, with analyses within 2% of accepted values.

3.5 Mineralogy

Mineralogical investigations were performed by X-ray diffraction (XRD) on unorientated powder samples using a Bruker D2 Phaser with monochromated $\text{CoK}\alpha$ radiation (7 to $50^\circ 2\theta$). Semi quantitative estimates of the gypsum content were made by comparing characteristic peaks against in-house (University of the Witwatersrand) gypsum standards.

3.6 Biogeochemistry

Initial characterisation of organic matter composition was provided by pyrolysis-GC/MS (py-GC/MS) analysis of four samples (18,50 m, 19,95, 21,50 m and 25,30 m). This fragments

macromolecular organic matter to produce lower molecular weight products amenable to GC/MS analysis. The resulting pyrolysis products are used to reconstruct likely macromolecular progenitors, providing a semi-quantitative assay of organic matter composition (Saiz-Jimenez and de Leeuw, 1986). Samples were pyrolysed at 610°C using a CDS 1000 pyroprobe, interfaced with a Perkin Elmer Clarus 500 GC/MS system (Carr et al., 2010b). Compounds were identified based on mass spectra and retention times.

4. RESULTS AND DISCUSSION

4.1 Sedimentology

4.1.1 Seismic stratigraphy and sedimentology

The offshore stratigraphy and sedimentology of Neogene to Quaternary sediments was revealed by drill holes (Figure 3, 4), exemplified by SBQW4/23. Correlation of seismic units (Figure 4B, Supplement 1) to these borehole data and to the regional stratigraphy of the West Coast, implies that **Seismic Unit i** represents the Cape Granite Suite while **Seismic Units ii – v** represent the Sandveld Group (Roberts et al., 2006).

Seismic Unit i, the acoustic basement, shows wavy internal reflectors and a hard, undulatory surface, expressed in the topography, which ranges from the seafloor to a depth of up to 100 m below the seafloor.

The unit is interpreted as Neoproterozoic granites (Roberts and Siegfried, 2014, Figure 4). The uppermost surface of the otherwise fresh, undeformed Cape Granite is weathered. The freshness of the granite, which weathers readily in warm, humid climates, suggests that the observed topography may have been due to fluvial incision (Figure 3). Where these depressions within the Cape Granite exist, **Seismic Units ii –v** are preserved and reach a thickness of up to 100 m.

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301 **Figure 3.** Boomer seismic lines (10, 16), overlain on basal granite surface in Saldanha Bay. Inset 3D model

302 illustrates undulatory nature of granite. Grey surface represents present-day harbour floor.

(2-column fitting, colour)

Figure 4 A. Stratigraphic column derived from borehole SBQW4/23, Saldanha Bay. B, C. Representative seismic profiles from Saldanha Bay, showing five units present in sedimentary succession. Sandveld Group deposits represent Elandsfontyn Formation, Varswater Formation, Velddrift Formation, Holocene fine sands.

(2-column fitting, colour)

Seismic Unit ii reaches a maximum thickness of 70 m and contains reflectors which truncate against the steep flanks of **Seismic Unit i**. The unit is composed of sub-parallel sigmoidal reflectors, characterised by retrograding reflectors and downlap nearer the base of the unit and aggradational parallel clinoforms nearer the top.

The unit is interpreted as Elandsfontyn Formation. The contact between this unit, and granite is in our core marked by a veneer of small pebbles, evidencing an unconformity and passing upwards into the coarse, angular quartz sands (Roberts et al., 2006; Roberts et al., 2011). The quartz sand, clay and silt layers within the Elandsfontyn Formation imply meandering rivers depositing sediments near a transgressing shoreline (Roberts et al., 2006; Figure 5). This is confirmed in the seismic stratigraphy by the presence of channel-infill units. Retrograding reflector geometry and sigmoid-oblique clinoforms indicate rising sea level (Catuneanu et al., 2009). A fining upward motif of the Elandsfontyn Formation is evident; culminating in a succession of organic rich, clayey silts (figure 4A, Supplement 1).

A prominent surface separates **Seismic Unit ii** from **Seismic Unit iii** (middle Miocene Varswater Formation), described in the current core logs to contain large pebbles. For details on the post-Elandsfontyn seismic stratigraphy see Supplements 1, 2.

4.1.2 Fluvatile-lacustrine depositional style

The Elandsfontyn Formation sediments are characterised by sands at the bottom and followed by silty and clayey sediments towards the top of the section (Figure 4A). Only the section between 18,73 and 28,73 m, which was predominantly clayey and more suitable for the preservation of palynomorphs, was sampled for this study. The sediment texture was measured by finger-testing (Figure 4A). Sediment colour varies between Dark Yellow Brown (10YR 4/2, Munsell, 2014) and Dusky Yellowish Brown (10YR 2/2, Munsell, 2014). Organic-rich, silty clay prevails in the upper 5m of the sampled sequence. At 23,76 m fine sand in an overall clayey matrix occurs; until 25,36 m the still organic-rich samples contain more silt. Below that,

organic-rich silty clay was predominant to 28,73 m. At ~29 m the sediments are increasingly sandy (Figure 24A).

We interpret the sediments as coarse-grained, quartzose channel fill sands, interfingering with and overlain by overbank/back swamp fines/organics. Two categories of Miocene fluvial systems (possibly ranging back to latest Oligocene) were identified for the southern South African west coast (Figure 3; Roberts et al., 2013):

1) Meandering, suspension load/lacustrine/paludal systems dominated by fines, situated on a low-relief coastal plain at an altitude of 80–130 m asl and

2) Anastomising mixed bedload and suspension-load rivers with shallow lakes whose deposits extended below present sea level in coastal embayments.

The core sediments resemble the latter system. Continuity with the onshore component of the Elandsfontyn Formation lithology and sedimentation patterns is given. Upward fining (Figure 4A) might indicate lateral channel migration, or a decline in slope with basin infill (Roberts et al., 2011). Seismic profiling reveals a pronounced relief in the granite (Figure 4A, B) and the Elandsfontyn Formation thins or pinches out over basement highs (Figure 4A). The depressions in the Cape Granite were not entirely infilled until the Quaternary, and consequently termination of fluvio-lacustrine sedimentation was not controlled by loss of accommodation space. In all drill holes in the Saldanha Bay region, the organic-rich paludal facies of the Elandsfontyn Formation is best developed at the top of the succession (Rogers, 1980; Cole and Roberts, 1996, 2000; Roberts et al., 2011; Sciscio et al., 2013). The poorly sorted, angular, oligotrophic basal sands of the Elandsfontyn Formation suggest first cycle material derived from weathering of the granite hills. Based on a 3D model

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361 5), a provenance source in the northeast is suggested. Short-headed streams
 362 from the granite highlands coalesced in basement lows to form alluvial fans which bordered the
 363 Atlantic Ocean (Roberts et al., 2013). No evidence of wave reworking is apparent, suggesting
 364 a low-energy setting, probably relating to a protected enclave analogous to modern Saldanha
 365 Bay and /or a system of offshore bars. This depositional setting was also proposed for the
 366 Miocene fluvial wedge at Noordhoek (Sciscio et al., 2016). Thus the paludal facies blankets the
 367 entire region where the Elandsfontyn Formation is developed in the Saldanha Bay region
 368 (Figure 1, 3). All fluvial deposits grade upwards and down-dip into marginal marine/estuarine

sediments (Figure 5), reflecting rising glacio-eustatic sea levels presumably during the Oligo-Miocene (Roberts et al., 2013). Rising sea levels would have exerted a damming effect on groundwater, causing a water table rise, which nurtured wetlands around Saldanha (analogous to Noordhoek) (Figure 5). To the north of the study site, marine ingressions at the top of the Langebaanweg sequence (i.e. Elandsfontyn Formation) were inferred from microfossils (Sciscio et al., 2013). The rate of sea level rise eventually exceeded the fluvial deposition rate; transgression terminated organic accumulation. This transgressive model implies that the paludal facies is diachronous in character, younging up-dip by an amount that hinged on the rate of marine transgression. Overlying non-organic clayey sediments are considered to represent estuarine or back-barrier conditions. The 3D model provides three time slices with sea levels relative to the present at -40 m, -20 m and +5 m, respectively (Figure 5). The Palaeo-Berg River seemingly bifurcates as a function of palaeotopography. Stranded depressions are envisaged to become choked with sediments during transgressions.

Figure 5. Modelled surface, shown as depth to granite, prior to deposition of Sandveld Group. **A.** Exposure of DEM surface, with modern coastline. **B.** Coastal configuration during Early/Middle Oligocene, with 40 m lower than present sea level. **C.** -20 m sea level associated with Late Oligocene warming and intermediate levels during the early Miocene when site of borehole SBQW4/23 was probably associated with stranded lake. **D.** Represents early/middle Miocene, when sea level was + 5 m above present. Light blue lines: likely position Palaeo-Berg River.

(1.5, 2-column fitting, colour)

4.2 Palynology and Biostratigraphy

4.2.1 Inferred biostratigraphy

Seventeen dinoflagellate taxa were identified. Stratigraphically significant are *Distatodinium craterum*, *Chiropteridium lobospinosum*, *Homotryblum plectilum*, *Impagidinium paradoxum*, and *Cordosphaeridium minimum* (Figure 6). We infer the Saldanha Bay samples to be of terminal Oligocene or early Miocene age due to the co-occurrence of *Distatodinium craterum* with *Chiropteridium lobospinosum*. *Impagidinium paradoxum* supports an Aquitanian or Burdigalian age, whereas *Cordosphaeridium minimum* has the first appearance date (FAD) in the Chattian (Powell, 1986b; Figure 6). Willumsen et al. (2014) had posited that *Distatodinium paradoxum* whose FAD falls below *Distatodinium craterum*, could be used as a regional indicator of Chattian strata in Angola, while *D. craterum* ranges into the Burdigalian. For details see Supplement 3.

The dinoflagellate-based biostratigraphy is supported by pollen indicators: *Mutisiapollis viteauensis* occurs from the late Oligocene in the Southern Hemisphere (Barreda et al., 2010). However, in South Africa, similar pollen are detected in probably Palaeocene and Eocene strata (De Villiers and Cadman, 2001; Scott et al., 2006, *Tubulifloridites viteauensis*; see Barreda et al., 2010). *Baumannipollis variaperturatus* is known from Oligocene-Miocene strata of Patagonia whereas *Glencopollis ornatus* occurs in the Miocene section of the Chenque Formation (Barreda, 1993). *Glencopollis ornatus* is recorded from Miocene deposits off the west coast of Africa (Partridge, 1978) where pollen probably belonging to Mutisioideae also occur (Barreda et al., 2010).

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Numerical age (Ma)	37,8	33,9	28,1	23,03	20,44	15,97	13,82
Series/Epoch	Eocene <i>upper</i>	Oligocene <i>lower upper</i>		Miocene <i>lower middle</i>			
Stage/Age	Priabonian	Rupelian	Chattian	Aquitanian	Burdigalian	Langhian	Serravalian
<i>Chiropteridium lobospinosum</i> * ₁							
<i>Cordosphaeridium minimum</i> * ₂							
<i>Spiniferites mirabilis</i> * ₃							
<i>Homotryblium plectilum</i> * ₄							
<i>Operculodinium centrocarpum</i> * ₅							
<i>Spiniferites ramosus</i> * ₆							
<i>Spiniferites pseudofurcatus</i> * ₇							
<i>Impagidinium paradoxum</i> * ₈							
<i>Distatodinium craterum</i> * ₉							

420 *₁Powell, 1986a, 1992; Fauconnier et al., 2004, 1992; Williams, 1975, Williams and Brideaux, 1975; Edwards, 1986421 *₂Powell, 1986b; Benedek and Sarjeant, 1981; Dybkjær and Piasecki, 2010422 *₃Zonneveld and Pospelova, 2015423 *₄Powell, 1986a; Edwards, 1986; Stover et al., 1996424 *₅Powell, 1992; Zonneveld and Pospelova, 2015425 *₆Powell, 1992; Zonneveld and Pospelova, 2015426 *₇Powell, 1992427 *₈Powell, 1992; Zonneveld and Pospelova, 2015428 *₉Powell, 1992; Fauconnier et al., 2004

429

430 **Figure 6.** Inferred biostratigraphy based on dinoflagellate cysts at Saldanha Bay

431 (1.5, 2-column fitting, B&W print version; online: colour)

432

433 **4.2.2 Vegetation History**

434 Two-hundred-and-twenty-one palynomorph taxa comprising pollen of angiosperms and

435 gymnosperms, spores of cryptogams, fungal and algal remains, dinoflagellate cysts and

436 microforaminiferal linings were identified (Supplement 4). Palynomorph preservation is good

437 to excellent. Pollen zonation yielded three palynomorph zones (Figure 7, Supplement 5). These

438 represent changes in the AP/NAP ratio (arboreal pollen/nonarboreal pollen), as well as changes

439 in the relative frequency of individual taxa. Zone 1 a and b shows a forested environment, while

440 open vegetation and wetland indicators gradually increase in Zone 2 (Figure 8). An overview

of the most common and stratigraphically/ecologically important types, as well as their proposed botanical affinity is given in Supplement 6. Important palynomorphs are depicted in Figures 9 and 10.

Due to our interpretation and references botanical affinities of fossil pollen and spore species are inferred to fall into moderately distinct ecological groups (Figures 7, 8): **1)** subtropical forest with **a)** gymnosperms, **b)** monocotyledons including palms, as well as **c)** arboreal dicotyledons, **2)** mangrove communities, **3)** thicket and woodland communities that occupied well-drained soils, **4)** vegetation elements with Fynbos affinities, **5)** herbs and shrublets, **6)** aquatics and swamp plants, **7)** cryptogams, **8)** fungi, **9)** freshwater phytoplankton, and **10)** marine-brackish phytoplankton.

The generally well preserved terrestrial palynomorphs suggest no oxidation of sediments and/or no abrasion during sediment transport. Possible biases due to the sources of many pollen types are unknown and reconstruction of the zonal vegetation is tentative, but species dwelling along water courses, as well as marsh/wetland elements like Sparganiaceae are probably overrepresented.

PCA values of the first factor (PC 1, with the highest Eigenvalue 13.3%) reflect the most prominent trend in pollen composition and this probably has environmental implications while the other lower order factors (Supplement 7A1, A2) are more difficult to evaluate. PC1 shows strong positive loadings for forest taxa, e.g., *Podocarpidites* spp., *Araucariacites* spp., *Araliaceoipollenites* spp., *Parthenopollenites* spp., *Zonocostites ramonae*, whereas some Arecaceae/monocotyledons including *Liliacidites minutes*, wetland elements such as Cyperaceae, Sparganiaceae and *Cupuliferoipollenites oviformis*, exhibit negative loadings (Supplement 7B). The PC1 score curve therefore demonstrates a general trend from a forested to a swampy environment.

4.2.2.1 Vegetation history during Zone 1 a, b and Zone 2

1a) In **Zone 1 a, b** the forest is dominated by *Podocarpidites* spp. (30-50%) including *P. torquatus* and *Microcachrydites antarcticus* (botanical affinity: *Microcachrys*, Podocarpaceae) (Figure 7). Podocarpaceae pollen is overrepresented due to their prolific pollen production and wide dispersal. Another Podocarpaceae, known from Gondwana regions like New Zealand (McIntyre and Norris 1966), is cf. *Dacrydiumites* sp., also identified in the Knysna lignite (Thiergart et al., 1963) and at Arnot Pipe (Scholtz, 1985). *Araucariacites australis* (botanical affinity: *Araucaria*) is prominent. Moisture-demanding *Araucaria* has limited pollen dispersal (Paez et al., 2001), therefore Araucariaceae might have grown close to the site. The taxon is common in Cretaceous sediments from the east coast of South Africa (Scott, 1976; McLachlan and Pieterse, 1978) and during the Paleogene at Arnot Pipe (Scholtz, 1985), but unknown from the South African Neogene (Thiergart et al., 1963; Coetzee, 1981, Sciscio et al., 2016). *Zonalopollenites* sp. (botanical affinity: *Tsuga* sp.) occurs in southern African Cretaceous and Paleocene sites (Scott, 1976; Scholtz, 1985; Sandersen et al., 2013). The Saldanha Bay specimens represent the youngest record in South Africa.

In **Zone 2** most taxa from Zone 1 persist, but a gradual change from a forested to a swampier environment takes place ~22,7 m upwards. *Podocarpidites* spp. decreases from ~35% at the bottom to <20% at the top. Other Podocarpaceae, especially cf. *Dacrydiumites* and *Microcachrydites antarcticus*, and Araucariaceae retreat whereas Cupressaceae/Taxodiaceae increase and reach a maximal abundance at ~21 m. While *Podocarpus*-forests require well-drained soils, Taxodiaceae prefer swampy conditions (Stuchlik et al., 2002).

Figure 7. Pollen diagram of core SBQW4/23 in Saldanha Bay, most significant pollen shown; terrestrial elements including CONISS zonation (2-column fitting)

Figure 8. Pollen diagram of core SBQW4/23 in Saldanha Bay, most significant palynomorphs shown; aquatic/marine elements including PC1

(2-column fitting)

1b) In **Zone 1** pollen of Arecaceae/monocotyledons are abundant and diverse but show no significant trends. *Arecipites* spp., (e.g. *A. plectilimuratus*), *A. cf. otagoensis* (a possible swamp forest species, Hendey, 2014), and *Monocolpopollenites* spp., were produced by Arecaceae and probably other monocotyledons (Couper, 1960; McIntyre, 1968; Scholtz, 1985). Palms are currently absent from the Cape, but occur from South Africa's southeastern seaboard northwards. They are associated with warm, frost-free environments with abundant rainfall or riparian habitats (Coates-Palgraves, 2002). *Liliacidites* spp. is observed, including *Liliacidites minutes*, which shows similarities with Arecaceae pollen but is assigned to Liliaceae (Takahashi, 1997). Hoffmann and Zetter (2010) suggest an affinity of *L. minutes* to Orontioideae, especially the wetland element *Symplocarpus foetidus* and *Pothos* spp., a genus of tropical-subtropical hemi-epiphytes which are distributed from China to Australia and Madagascar (Boyce, 2009).

In **Zone 2**, *Liliacidites minutes* is most abundant at ~21m, which supports interpretation of this pollen being produced by a wetland element like *Symplocarpus foetidus*. *Arecipites* spp. benefits from the retreat of the podocarpaceous forest, as these palms may have preferred brackish conditions and high water tables.

1c) In **Zone 1** *Myricipites* spp., especially *M. harrisii*, are common. *M. harrisii* (*Triorites harrisii*, Thiergart et al., 1963) is either related to Myricaceae or Casuarinaceae. Coetzee and Praglowski (1984) suggest a strong similarity to Casuarinaceae pollen, which might point to rainforest (Coetzee, 1980). Subtropical families include Sapotaceae, e.g. *Tetracolporopollenites sapotoides* (botanical affinity: *Mimusops*). *Mimusops* spp. grow in southern Africa today on coastal dunes, and in riparian habitats and swamps (Coates-Palgraves,

2002; Stuchlik et al., 2014). Myrtaceae (i.e. *Myrtaceidites parvus*, De Villiers and Cadman, 2001) may represent a dry element. In contrast *Syzygium* spp. and *Metrosideros angustifolia*, which have similar pollen, today prosper in riverine and coastal forests in southern Africa (Coates-Palgrave, 2002). Present at Saldanha Bay are Aquifoliaceae (e.g., *Ilexpollenites margaritatus*), *Cupanieidites* spp., and Cupuliferoideae (*Cupuliferoipollenites oviformis*). *Cupuliferoipollenites oviformis* shows similarities to pollen of *Lithocarpus*, *Castanopsis* and *Castanea* (Stuchlik et al., 2014) and might correspond to the small Cupuliferae-like pollen observed in the Knysna lignites (Thiergart et al., 1963: Leguminosae) and at Koingnaas, Namaqualand (DeVilliers and Cadman, 1997: *Cupuliferoipollenites liblarensis*). De Villiers and Cadman (1997) found the taxon restricted to peat and accordingly the species might be associated with river banks and wetlands. Cf. *Byttneripollis* sp., identified in Palaeogene palaeochannel deposits (De Villiers and Cadman, 1997) and Cretaceous offshore sediments of South Africa's west coast (Sandersen et al., 2011), appears regularly. It is not likely to be *Byttneria* (pers. comm. Jaramillo 2015) and the botanical affinity is uncertain. *Baumannipollis variaperturatus* (Malvaceae) regularly appears, although this taxon shows similarities to *Echiperiporites* (Coetzee, 1980). Vines might have belonged to the families Araliaceae - represented by *Rhoipites couperi* and *Araliaceipollenites reticuloides* (Pocknall, 1985; Raine et al., 2011; Stuchlik et al., 2014) - , Arecaceae, Sapindaceae (*Cupanieidites* spp., Supplement 6) and Vitaceae (*Parthenopollenites marcodurensis*, *P. formosa*, *P. neshobensis*, Stuchlik et al., 2014, stacked in figure 8). *Rhoipites* spp. including *R. pilatus* (synonym of *R. couperi*) is known from the Miocene and Paleogene of South Africa (Sciscio et al., 2013). Although *Parthenopollenites* spp. is hitherto unknown in South Africa, other Vitaceae with similar pollen types, e.g., *Rhoicissus* and *Cyphostemma*, are today widespread in southern African forests and thickets (Retief et al., 2001; Cowling et al., 2005). *Clavatipollenites* sp. (botanical affinity: Chloranthaceae) and *Pseudowinterapollis couperi* (botanical affinity: Winteraceae: *Drimys*, *Zygogynum*) are identified in southern African Paleogene and Neogene deposits; these basal

angiosperms are now extinct at the Cape. Thiergart et al. (1963) identified Fagaceae, e.g., *Tricolporopollenites microhenrici* from the Knysna lignites; we confirm Fagaceae at the Cape (among others *Quercopollenites* cf. *asper*, pers. comm. Worobiec 2015; all species stacked as *Quercopollenites* spp.). More research is necessary to assess their diversity. *Momipites* sp., produced by a member of the Juglandaceae, appear in low numbers (Figure 7, Supplement 6). De Villiers and Cadman (1997, 2001) noted *Momipites* sp. at Koinaas.

In **Zone 2** few changes are detected, but moisture-indicating *Cupuliferoipollenites oviformis* increase. *Myrtaceidites parvus* reaches a maximum, probably suggesting local moisture or disturbances.

2) In Zone 1 *Zonocostites ramonae*, affiliated to Rhizophoraceae, indicates the presence of mangroves. Paleogene-Neogene mangroves are reported as far south as offshore Angola (Willumsen et al., 2014) but were previously unknown from South African sites.

In **Zone 2** mangrove elements (Rhizophoraceae undifferentiated) are less abundant when podocarps decrease. *Zonocostites ramonae* is absent from 21,5 m, which indicates lower mangrove production, probably due to drowning of the mangal coastline during a transgression (Tyson, 1995; Krauss et al. 2008 and references therein). Mangrove vegetation cannot tolerate sea level increase that exceeds 9mm/10 years (Ellison, 1993).

3) In Zone 1 a sub-humid woodland-thicket element is implied by *Peregrinipollis nigericus* (botanical affinity: *Brachystegia*), *Rhoipites alveolatus* (botanical affinity: Euphorbiaceae), Combretaceae, *Tricolporopollenites marginatus* (botanical affinity: Euphorbiaceae), *Commiphora*-type (Burseraceae, component of African Paleogene vegetation, Dupéron-Laudoueneix and Dupéron, 1995), *Simpsonipollis grandis* (botanical affinity: *Bauhinia*, Caesalpiniaceae, known from Arnot Pipe, Scholtz, 1985; De Villiers, 1999). Combretaceae/Terminalia, Caesalpiniaceae, Burseraceae (Axelrod, 1979), as well as many Euphorbiaceae (Krutzsch et al., 1992), which are today found in seasonally arid landscapes like savannas (Coates-Palgraves, 2002) and the spiny thickets of southwestern Madagascar (Cornet

and Guillaumet, 1976). Their presence at Saldanha Bay implies summer rainfall. Savannas have a grass cover, but Poaceae are scarce at Saldanha Bay suggesting these elements formed a subtropical thicket (Cowling et al., 2005), which might have been the forerunner of the first savannas that developed during the Miocene (Cowling et al., 2005; Schrire et al., 2005).

In **Zone 2** some palaeotropical thicket elements, e.g., Caesalpiniaceae, decrease and *Peregrinipollis nigericus* is absent from the zone, which may indicate fewer well-drained soils close to the site due to inundation.

4) In Zone 1, Cape clades Ericaceae, Proteaceae and Restionaceae at Saldanha Bay are suggestive of Proto-Fynbos. Invoking contemporary Fynbos, this vegetation may indicate seasonally inundated or well-drained sites, oligotrophic sands, and exposure to fire (Cowling and Holmes, 1992). Unlike Langebaanweg (Coetzee and Rogers, 1982; Sciscio et al., 2013), Ericaceae pollen is common at Saldanha Bay (e.g., *Ericipites callidus*-type). Restionaceae pollen account for 5–10%. Assuming that Restionaceae partly favoured paludal conditions, this is consistent with sedimentological evidence for higher groundwater levels up core (but: see discussion below). *Psilatricolporites quenua* shows similarities to pollen of extant *Cliffortia* sp. (Scott, 1982), where several species are common along streams and marshes (Coates-Palgrave, 2002). Proteaceae, diverse at Saldanha Bay, appear more regularly >25,3 m. Common are *Proteacidites* spp., e.g. *Proteacidites bakkeri granulatus* and *Propylipollis meyeri* (botanical affinity: subfamilies Grevilleoideae, Persoonioideae, genera *Lomatia*, *Leucospermum* (Proteoideae)). *Triporopollenites namaquensis*, probably produced by Grevilleoideae (Supplement 6), and also identified at Arnot Pipe (Scholtz, 1985), is rare. A similar form, *Triporopollenites ambiguus*, is known from the Paleogene and Neogene of New Zealand (Raine et al., 2011) and, as *Proteacidites* sp. A, from the Oligocene of Tasmania (Hill and MacPhail, 1983). Grevilleoideae, represented by a single species in modern southern Africa, are diverse in Australia. Neuradaceae, also identified at Saldanha Bay, are suggestive of dry seasons (Krutzsch et al., 1992). *Grielum* (Neuradaceae, Polevova et al., 2010) presently

grows in Fynbos and Succulent Karoo (Neumann et al., 2011). *Anthospermum*-like pollen (*Rhoipites arnotiensis*, Scholtz, 1985; Sciscio et al., 2013) is common.

In **Zone 2** most taxa with an assumed Fynbos affiliation do not show any major change in comparison to Zone 1.

5) In Zone 1 Asteraceae, well-represented in contemporary Fynbos, and other vegetation communities, are diverse (among others *Artemisiaepollenites* spp, *Tubulifloridites antipodica*, *T. anthemidearum*, *Senecio*-type, *Mutisiapollis viteauensis*). *Mutisiapollis viteauensis* belongs to Mutisiaceae, an Asteraceae subfamily (Barreda, 1993). *Tubulifloridites antipodica* is known from Koingnaas and shows similarities to pollen of primitive taxa of the Asteraceae, esp. to Barnadesioideae (De Villiers and Cadman, 2001; Zavada and Lowrey, 2010). Poaceae are more abundant than Asteraceae, with *Graminidites* cf. *crassiglobosus* (Stuchlik et al., 2009) being most prominent. Possible members of the Valerianaceae or Verbenaceae (*Spinatricolpites* spp. including *S. jennerclarkei*, Scholtz, 1985; Quattrocchio et al., 2005) are observed. Open vegetation indicators are <20% during Zone 1, owing to the prevalence of a closed forest canopy.

In **Zone 2** Asteraceae decline, probably in connection to inundation whereas pollen of most other herbs and shrublets do not show significant changes.

6) In Zone 1 Cyperaceae including *Cyperaceaepollis piriformis*, which resembles recent pollen of *Cladium*, *Bulboschenus* and *Eleocharis* (Stuchlik et al., 2009), reach 5-8%. Like Cyperaceae, the continuous presence of *Sparganiaceapollenites barungensis* (botanical affinity: *Sparganium*) indicates a locally high groundwater table. At the top of Zone 1, the taxon reaches c. 15% but normally stays < 10%. Rare wetland elements include *Glencopollis ornatus* (botanical affinity: Polygonaceae/*Polygonum amphibium*, Raine et al., 2011) and *Hygrophila* sp., a pan-tropical, mostly aquatic genus, presently widespread in East Africa (Furness, 1994). Wetland elements are minor and less diverse than terrestrial elements. They were probably restricted to a narrow reed belt, with Poaceae, Cyperaceae, Restionaceae

and *Sparganiaceapollenites barungensis*. The low abundance of wetland elements might be explained by the ancient topography which restricted wetland developments due to steep slopes close to the site (Figure 13).

In **Zone 2** swampier conditions are implied by an increase of Cyperaceae pollen and *Sparganiaceapollenites barungensis* from 22,7 m. *Sparganiaceapollenites barungensis* reaches ~35% at the top of the zone suggesting an increasing reed belt (Figure 7).

7) In Zone 1 abundant pteridophyta spores include rare forms resembling extant *Mohria* sp. (*Mohria*-type) and warm-temperate *Cryptogrammasporis* sp. (botanical affinity: Pteridaceae, *Cryptogramma*, Stuchlik et al., 2001). Terrestrial, pantropical families are dominant, often preferring moist forests. *Camarazonosporites bankiensis* may belong to the Lycopodiaceae (Scholtz, 1985). *Microfoveolatosporis fromensis* is similar to extant Colombian or Brazilian *Schizaea pennula* (Scholtz, 1985; Stuchlik et al., 2001) and might have been a more widespread palaeotropical element during this time. *Leiotriletes* spp. has a botanical affinity to *Lygodium* spp., tropical climbing ferns presently widespread in southern African moist forests (Frederiksen, 1985; Stuchlik et al., 2001; Roux, 2001). *Leiotriletes wolffii*, the most dominant spore type, reaches ~40% at the beginning of Zone 1, drops to c. 5% at 27,2 m and recovers again to > 35% at the end of the zone. Abundant are *L. maximus* and *L. maxoides*, very robust and large spores, which are probably autochthonous. Spores of *Lygodium* and *Acrostichum* cannot be differentiated from each other. *Acrostichum* is a fern genus associated with brackish water and mangroves (Frederiksen, 1985). Gleicheniaceae, often vines (Frederiksen, 1985), are a palaeotropical element, represented by *Gleicheniidites* sp. (similar to *Neogenisporis crassicus*, Stuchlik et al., 2001 and *Gleicheniidites* sp. identified at Koingnaas, De Villiers and Cadman, 1997). *Verrucatisporites alienus* was probably produced by Davalliaceae, tropical ferns (Stuchlik et al., 2001). Families with wide climatic preferences are underrepresented: Pteridaceae (palaeotropical, arctotertiary, Stuchlik et al., 2001) are represented by *Polypodiaceoisporites* sp., Polypodiaceae (Paleotropical, Arctotertiary, Stuchlik et al., 2009)

by *Laevigatosporites haardtii*, and Dennstaedtiaceae by *Verrucatosporites favus* (tropical-temperate, Stuchlik et al., 2001). Marattiaceae spores look similar to extant *Christensenia* spores, which grow in shaded riparian habitats (Rolleri, 1993). *Baculatisporites* spp. are associated with Osmundaceae, temperate-tropical ground ferns (Stuchlik et al., 2001).

In **Zone 2** the spore composition and abundance in general prevails. The retreat of *Leiotriletes wolffii* might be due to more brackish conditions. *Cyathidites australis* (botanical affinity with Cyatheaceae: *Cyathea*, Scholtz, 1985; and Dicksoniaceae (De Villiers and Cadman, 1997) or Schizaeaceae (Raine et al., 2011)) increase slightly in occurrence. *Cyathidites* was observed in the Miocene sediments of Noordhoek (Sciscio et al., 2016).

8, 9, charred particles) In **Zone 1** fungal remains often increase when ferns decline as observed (e.g., at 17,15 m), but the reason for this is unclear. *Tetraploea*, *Involutisporis* and *Brachysporisporites* are rare. Fungal remains are often those of epiphyllous Microthyriaceae, including germlings and mature fruiting bodies (e.g., *Trichothyrites* cf. *ostiolatus*; Worobiec and Worobiec, 2013). However, it was not possible to attribute most fungal remains to taxa; these were lumped as fungi undifferentiated, or hypha. Freshwater indicators are colonial algae *Botryococcus* sp., which also dwells in brackish water, *Ovoidites* sp., and *Zygnema* sp. Charred particles imply recurrent wild fires, the earliest evidence for these in the Cape.

In **Zone 2**, the spread of marshy elements, signaling rising water tables, is accompanied by an increase in charred particles signaling wild fires in a more open, marshy habitat, with increasing disturbance indicators and a retreat of the fire-sensitive forest fringe. Strong fungal activity, accompanied by a decline of most fern spores, indicates enhanced decay of biomass. Fungal hypha are most prominent from ~22 m, probably determining soil development, when fungal ascospores are prominent and charred particles increase. Van Geel (1978) connects fungal ascospores with local bog fires.

10) In **Zone 1** (also in Zone 2) *Spiniferites ramosus*, *S. pseudofurcatus*, *S. mirabilis* (latter restricted to zone 1b), *Impagidinium paradoxum*, *Homotryblum plectilum*, and *Distatodinium craterum*, microforaminiferal linings and *Pterospermella* spp. indicate marine influence. *Spiniferites pseudofurcatus* is associated with marginal marine environments and *S. ramosus* with neritic conditions (Wrenn and Kokinos, 1986; Zevenboom et al., 1994, Jaramillo and Oboh-Ikuenobe, 1999).

In **Zone 2** moderate numbers of *Spiniferites ramosus*, *Glaphyrocysta* sp., *Spiniferites pseudofurcatus*, *Distatodinium craterum*, *Homotryblum plectilum*, *Cordosphaeridium minimum*, *Operculodinium centrocarpum*, *Impagidinium paradoxum* (the latter: single specimen) and few cysts of freshwater algae were recorded throughout the zone. The assemblage indicates sediment deposition that fluctuated between shallow marine to estuarine conditions with frequent freshwater incursions, but higher values of microforaminiferal linings and dinoflagellates from 21,75 m suggest gradual transgression. The uppermost sample at 18,73 m, singled out by cluster analysis, is characterised by the dinoflagellate cyst *Operculodinium centrocarpum*. *Spiniferites* spp. are missing and *Homotryblum plectilum* and *Chiropteridium lobospinosum* are moderately abundant. A further indicator for a transgression is the increase of spiraled microforaminiferal linings belonging to benthic forms.

4.2.2.2 Principal Components Analysis

In **Zone 1** the curve of PC1 does not show any significant trends, but fluctuates between -0.3 and 5.58 (Figure 8), reflecting the strong positive loadings of forest elements like Podocarpaceae, *Araucariacites* spp., *Araliaceoipollenites* spp., *Zonocostites ramonae*, thicket/woodland elements like *Caesalpinaceae*, *Combretaceae*, *Euphorbiaceae* and some Fynbos taxa like *Restionaceae* and *Proteaceae*. The strong positive loading of *Parthenopollenites* spp. (Supplement 7B), together with many subtropical trees, supports the

assumption that those taxa are associated with dense forests. Those taxa are abundant during Zone 1a, b and show a stable and densely forested environment.

In **Zone 2** PC1 shows a significant decrease with values of 1.86 at 23,35 m and the lowest values (-6.61) at the top of the profile at 18,73 m. This is explained by the decrease of Podocarpaceae and other forest and thicket/woodland elements relative to *Cupressacites* sp. (Cupressaceae/Taxodiaceae), *Cupuliferoipollenites oviformis*, *Liliacidites minutes* and wetland elements like Sparganiaceae and Cyperaceae, which benefit from a higher water table. A slight increase of open vegetation is also indicated by the spread of Poaceae (*Graminidites* spp.) which also contribute through their high negative loading to the downward trend of PC1. *Myrtacidites parvus*, more abundant in Zone 2, is strongly negatively loaded, supporting an association with wetland elements like Sparganiaceae. Also indicative of a high water table are *Cupuliferoipollenites oviformis* as well as *Psilatricolporites quenua*, supporting assumptions that these taxa are linked to wetlands and river banks. In contrast Restionaceae, often assumed to present paludial environments, is positively loaded and retreats towards the top of the sequence. Restionaceae may not be a wetland indicator at the study site. The decrease of PC1 during Zone 2 clearly underlines the vegetation response to the gradual sea-level transgression.

Figure 9: **A** *Podocarpidites torquatus*, **B** cf. *Dacrydiumites* sp., **C** *Araucariacites australis*, **D** *Zonalopollenites* sp., **E** *Arecipites* cf. *otagoensis*, **F** *Liliacidites minutes*, **G** *Cupuliferoipollenites oviformis*, **H** cf. *Byttneripollis* sp., **I** *Araliaceipollenites reticuloides*, **J** *Rhoipites couperi*, **K** *Baumannipollis variaperturatus*, **L** *Momipites* sp., **M** *Myricipites harrisii*, **N** *Pseudowinterapollis couperi*, **O** *Parthenopollenites marcodurensis*, **P** *Parthenopollenites neshobensis*, **Q** *Quercopollenites* cf. *asper*, **R** *Tetracolporopollenites sapotoides*, **S** *Zonocostites ramonae*, **T** *Rhoipites alveolatus*, **U** *Peregrinipollis nigericus*, **V** *Commiphora*-type, **W** *Simpsonipollis grandis*
(2-column fitting, colour or b&w)

Figure 10: **A** *Psilatricolporites quenua*, **B** *Ericipites callidus*, **C** *Triporopollenites namaquensis*, **D** *Propylipollis meyeri*, **E** Neuradaceae (*Grielum*-type), **F** Restionaceae, **G** *Artemisiaepollenites* sp., **H** *Tubulifloridites antipodica*, **I** *Mutisiapollis viteauensis*, **J** *Graminidites* cf. *crassiglobosus*, **K** *Spinitricolpites* sp., **L** *Cyperaceapollis piriformis*, **M** *Glencopollis ornatus*, **N** *Baculatisporites* sp., **O** *Camarazonosporites bankiensis*, **P** *Cyathidites australis*, **Q** *Leiotriletes wolffii*, **R** *Christensenia*-type, **S** *Gleicheniidites* sp., **T** *Microfoveolatosporis fromensis*, **U** *Polypodiaceoisporites* sp., **V** *Involutisporis* sp., **W** Fungal fruit body: *Trichothyrites* cf. *ostiolatus*, **X** *Pseudoschizaea* sp., **Y** *Pterospermella* sp. 1, **Z** *Pterospermella* sp. 2, **Za** *Chiropteridium lobospinosum*, **Zb** *Cordosphaeridium minimum*, **Zc** *Homotryblum plectilum*, **Zd** *Impagidinium paradoxum*, **Ze** *Spiniferites mirabilis*, **Zf** *Distatodinium craterum*

(2-column fitting, colour or b&w)

4.3 Biogeochemistry

The curves of TN (%), TOC (%), $\delta^{13}\text{C}_{\text{TOC}}$ (‰) and the ratio TOC/TN show similar trends. Percentages of total nitrogen (TN %) are low between ~26,2 m depth and increase towards a depth of ~25 m. A minor peak at a depth of ~25,5 m depth characterises the curve of TOC/TN whereas the curves of TOC (%) and $\delta^{13}\text{C}_{\text{TOC}}$ (‰) feature a brief peak at ~25,1 m (Figure 11, Supplement 8). Up to ~23 m values of all biogeochemical proxies show few fluctuations, but increase sharply towards the top, parallel to the downward trend of PC1.

We interpret the results as follows: Higher TOC values suggest increased organic matter preservation/production, consistent with swampier conditions. There is good correlation between increased organic preservation, transgression and anoxic conditions, likely attributed to the development of high surface productivity on the flooded shelf (Myers, 1996 and references therein). Experiments on recent fungi show that fungal growth in wet environments and soils correlate positively with low pH (6.5-4.5) and high TOC and TN, whereas the optimal C/N ratio depends on the fungal species (Fransson et al. 2007, De Ruiter et al., 1993; Six et al., 2006). A comparison between TOC and fungal growth (abundance of fungal remains) shows an excellent correlation; high percentages of fungal remains at 27,15 m, 25,02 m, 20,55 m and 19,45 m are mirrored by peaks in TOC. The correlation between fungal remains, TOC/TN and TN is only apparent above ~23 m when the abundance of fungal remains increases. These relationships are clearly connected to higher water tables and the spread of swamp plants, which were likely associated with more anoxic conditions and a lower Ph, leading to an increase and/or a better preservation of biomass. Although TOC contents are highest at the top of the profile, marine ingressión probably inhibited fungal activity, triggering the decrease of the fungal remains in the palynological record. The shift in $\delta^{13}\text{C}_{\text{TOC}}$ is minor (0.5 ‰), while values of -26‰ are consistent with pollen and pyrolysis data in indicating a largely terrestrial C_3 vegetation organic matter source. The trend to marginally higher $\delta^{13}\text{C}$ above a depth of ~23 m may be linked to an increased input of marine-derived organic material

in an estuarine setting (Raymond & Bauer, 2001). This is in good accordance with the trend of PC1 during Zone 2.

The pyrolysis-GC/MS analyses produce superficially comparable programs for all analysed samples (Supplement 9). Each pyrolysate comprises a sequence of homologous *n*-alkane/*n*-alkene doublets to at least C₂₅ chain lengths, accompanied by a secondary long chain length *n*-alkane peak from C₂₃ to C₃₃, with odd over even chain length preference, dominated by the C₂₇ and C₂₉ *n*-alkanes. The latter are probably leaf waxes (probably thermally extracted in the analysis). Other components of significance include prist-1-ene and prist-2-ene (products of chlorophyll, Höld et al., 2001) and several sulphur-containing compounds. The latter are dominated by dimethyl disulphide, and include 2 and 3-methyl thiophene, and 2,5, 2,4, 2,3 and 2-4 dimethyl thiothene. Along with the leaf waxes several other terrestrial plant-derived pyrolysis products were identified, including the sesquiterpenoids cadalene and α -calacorene as well as guaiacyl units of lignin including guaiacol and methyl, ethyl and *p*-vinyl guaiacol. Low abundances of bacterially-derived hopanes were detected. The proportions and chain length distributions of the aliphatic components of the pyrograms are largely invariable. However, the relative abundance of sulphur-containing pyrolysis products is highest in the uppermost samples. Such a trend is also seen in the relative abundance of dimethyl disulphide (Supplement 9), represented by the thiophene ratio (2, 3 dimethyl thiophene/ (1,2 dimethyl benzene + *n*-1-nonene); Sinninghe-Damsté et al., 1992) which increases from 0.3 at 21.5 to 0.47 at 18,5 m. The relative abundance of phenol and several methyl phenols is also higher at 18,5 m, particularly in comparison to 25,3 m. These are often correlated with lignin pyrolysis products and may be derived from degraded lignin macromolecules (Carr et al., 2010a).

These data are interpreted as follows: the origin of the shorter *n*-alkane/*n*-alkene doublets, which are also abundant in the Kynsna lignites (Carr et al., 2010a) could represent leaf cuticle macromolecular cutin (Logan et al., 1993), particularly given the shallow burial and presumed lack of heating of this kerogen (cf. Gupta et al., 2007). The increased abundance of

methyl phenols and lignin pyrolysis products (e.g. increased abundance of guaiacyl units in the upper most sample) is suggestive of better preservation, and in the case of lignin is usually promoted by anoxic conditions, consistent with other evidence. The increased thiophene ratio to 18,5 m suggests an increased abundance of organically-bound sulphur, which is similarly consistent with an anoxic environment and/or an enhanced marine influence (Sinninghe-Damsté et al., 1992; Carr et al., 2015). Overall, the pyrolysis data imply a dominantly terrestrial plant-derived organic matter composition, within an increased incorporation of reduced sulphur into the macromolecular organic matter and potentially better organic matter preservation with fungi as decomposers in the upper-most sediments.

Figure 11: Down-core variations in total nitrogen, total organic carbon, TOC/N and $\delta^{13}\text{C}$ (1.5-column fitting)

4.4 Inorganic geochemistry

To compare element distributions and investigate changes in sediment characteristics, geochemical data were normalised relative to aluminum. Ratios of Si/Al and Fe/Al are constant, but show a positive excursion at ~25 m and distinct deviations >22 m (Figure 12, elemental data see Supplement 10). The Sr/Al ratio increase from <4 at the bottom to ~8 at the top of the profile, whereas Th/Al shows high ratios between ~28 m and ~24 m. The ratios of U/Al, Cr/Al, V/Al and Mo/Al fluctuate strongly, but show similar upward trends from ~23 m as well as sharp positive excursions at ~25 m.

We interpret a decrease in Si/Al ratios coupled with increases in Fe/Al to indicate a low energy environment that favoured fine clastics. The downcore trend in U/Al ratios reveals enrichment at ~25 m, attributed to the reduction of U(VI) to U(IV) under anoxic conditions. This interpretation is supported by corresponding increases in other redox sensitive elements (V, Cr, Fe and Mo) at this depth as well as higher TOC and TOC/TN values and enhanced fungal growth, indicating biomass enrichment. The onset of reducing conditions is interpreted to mark a transient stage between fluvial conditions and a more marine influenced environment. Thorium is more enriched in freshwater relative to seawater and a marked decrease in Th/Al from ~24 m supports an increase in marine inputs. Synchronous increases in Sr/Al, organically-bound sulphur and $\delta^{13}\text{C}_{\text{TOC}}$ values corroborate this interpretation. Subsequent increases in Mo/Al ratios at ~21 m suggest the development of an increasingly reduced and sulfidic environment (cf. Tribovillard et al., 2006). The uppermost sample shows high Mo/Al and U/Al values, implying anoxic conditions during a transgressive stage (Myers, 1996).

Figure 12: Downcore variation in metal/Al ratios

(1.5 column fitting)

4.5 Mineralogy

4.5.1 Gypsum and pyrite

Notable but variable quantities of CaSO_4 appear in all samples, and are most abundant (up to 4%) in the upper succession, pyrite is common in all samples (Supplement 11).

Gypsum currently occurs in economic quantities along the West Coast, in back-barrier facies, where the marine influence supplies the necessary S, and the shelly material the Ca (Cole and Roberts, 2000). Evaporative conditions are required for gypsum precipitation, currently met by the region's Mediterranean climate. The abundance of gypsum supports periodic marine influence, with highest quantities at the top coinciding with the increase of marine microfossils and marshland/wetland elements. This is consistent with the trends in the abundance of sulphur-containing pyrolysis products which might indicate the incorporation of

846 sulphur into the organic matrix during early diagenesis. Pyrite signals anoxic conditions, which
847 is consistent with other indicators for a high water table at the top of the sequence.

849 **5. SYNTHESIS**

850 **5.1. Implications for sea level fluctuations**

851 The Elandsfontyn Formation is preserved at Saldanha Bay where it was
852 deposited into basins, likely during the Oligocene glacio-eustatic lowstands (Coetzee and
853 Rogers, 1978; Rogers, 1980, 1982; Cole and Roberts, 1996, 2000; Roberts et al., 2011, compare
854 Haq et al., 1987; Zachos et al., 2001; Pälike et al., 2006). Major erosional unconformities on
855 continental shelves suggest a -100 m Oligocene lowstand depth (Schlanger and Silva, 1986).
856 Siesser and Dingle (1981), however, proposed that an Oligocene lowstand exceeded 200 m
857 metres off South Africa. From global isotope data, a regression of ~55 m was inferred (Miller
858 et al., 2005b), while early to middle Miocene glacio-eustatic regressions were transient and
859 amounted to a few tens of metres (Miller et al., 1987). We suggest a sea level-lowstand of -100
860 m by the presence of fluvio-lacustrine deposits of the Elandsfontyn Formation at this depth at
861 Saldanha. This probably represents major Oligocene glaciations, rather than one of the more
862 modest Miocene events (cf. Miller et al., 1987; Pälike et al., 2006). The role of regional uplift
863 or subsidence of the land is not known. We report a subsequent transgression supported by
864 various palynological, sedimentological and geochemical proxies as outlined above, either
865 during the Chattian or during the early Miocene as indicated by dinoflagellate indicator taxa.
866 This transgression is also notable on the sea-level curve of van Sickle (2004; Figure 2).

868 **5.2. Environment of deposition**

869 The topography inferred from the seismic data, as well as the sedimentology and
870 palynology of the core, imply an estuarine-lagoonal environment. Oxygen deficiency, which
871 often accompanies marine transgressions (Batten, 1996; Myers, 1996), and deposition in

troughs account for excellent palynomorph preservation. Abundant pyrite also evidences anoxic conditions (Supplement 11). Predominantly terrestrial input of palynomorphs is supported by dominance of plant-derived compounds identified by pyrolysis (leaf waxes; directly lignin derived [guaiacol]; potentially lignin derived [methyl phenols]; potentially cutin [long chain *n*-alkene/*n*-alkane doublets] and several sesquiterpenoids). Abundant large, ornamented spores like *Mohria*-type, the highly diverse, large pollen, abundant fungal remains and phytoclasts, infer a near-shore environment close to a river mouth (Tyson 1995). Considering the coastal character of the deposits, it seems that fungi are abundant when phytoclasts are high, due to degradation of leaf detritus (shown by abundant cuticles). Abundant fungal spores point to delta top facies or lagoonal environment (Muller, 1959; Oboh, 1992). The upward increase in Cyperaceae, aquatics, fungi and a decrease in *Podocarpidites* spp. suggest higher water tables consistent with better preservation of organic matter (Kuhry et al. 2010).

Gypsum, while being variable throughout the succession is notably higher in the upper part, coinciding with a pronounced increase in charcoal, which points to a higher frequency of fires and seasonal aridity, with drying of overbank fines. The rate of sea level rise accelerated, eventually exceeding the rate of sedimentation, inundating the wetland with estuarine/marine waters. This is supported by the higher diversity and stronger occurrence of neritic dinoflagellates and microforaminiferal linings especially in the uppermost sample, as well as by an increase in Sr/Al, $\delta^{13}\text{C}$ and thiophene ratio/decline in Th/Al ratio.

Mixing and possible local over-representation of elements from intrazonal (azonal) formations, riparian forests, swamp forests, and mangroves with marginal freshwater/brackish wetland/aquatic vegetation complicate the reconstruction of the zonal vegetation. Abundant *Podocarpidites* spp. might be indicative of zonal subtropical forests. Thicket with Combretaceae and *Brachystegia* may have fringed the drier inland margin of riverine forests and occurred as bush clumps on the granite inselbergs and plain (Figure 13). Pollen associated to *Brachystegia* is not known from other Paleogene-Neogene South African

898 sites, but shows a possible link to Neogene forests in tropical Africa, e.g. Nigeria (Clarke,
899 1966). Proteoid/ericoid/restioid Fynbos might have emerged. Evidence for fire is crucial for
900 understanding the vegetation. There must have been plants with sufficiently fine fuel loads and
901 seasonal drying to carry a wildfire (Burger et al., 2015; Calitz et al., 2015). These were most
902 likely Restionaceae and ericoid shrubs (Ericaceae, *Cliffortia*) as there is no evidence for a high
903 abundance of grasses. Marshlands were probably less combustible, being fringed by
904 inflammable forest and water.

905 The low variation in pollen spectra at Saldanha Bay contrasts with studies at
906 Langebaanweg and Noordhoek (Coetzee and Rogers 1978; Sciscio et al. 2013, 2016). This may
907 be explained either by a combination of palynomorph mixing in the estuarine environment, the
908 weaker contribution of wetland elements like Sparganiaceae in Saldanha Bay and the stronger
909 effect of local successional changes on pollen deposition of marshy vegetation at Noordhoek
910 and Langebaanweg. The observed change between Zones 1 and 2 is a result of a gradual marine
911 transgression.

912 The sediments represent distal (marginal marine) alluvial fan sedimentation, as
913 indicated by underlying, coarse, unsorted sands/ gravels (proximal fan), the presence of marine
914 fossils as well as the occurrence of mangroves. Additionally, PC1 shows a clear decrease from
915 ~23 m, underlining the marine transgression. The rising sea level probably caused drowning of
916 the mangrove fringe. Scourse et al. (2005) note, by studying a late Quaternary pollen record
917 from the Congo fan, that *Rhizophora* pollen are already in decline once sea level high stand is
918 attained. The topography at Saldanha Bay implies the presence of a barrier separating the
919 marine environment from the palaeo-lakes or estuarine environments (Figure 13). This
920 interpretation is bolstered by an upward increase in marine fossils, e.g. microforaminiferal
921 linings and to a certain degree, dinoflagellates with indicators for a more distal setting in the
922 uppermost sample, e.g., *Operculodinium centrocarpum* and a decrease of *Spiniferites* spp. The
923 assumption is supported by trace elements like Mo, Sr and Th which have much higher

concentrations in seawater and the eventual transition from an organic-rich distal fan to estuarine sedimentation.

The dinoflagellate cyst assemblage indicates shallow to marginal marine environments. As the abundance of dinoflagellate cysts is low, the results are ambiguous and discrepancies, due to the presence of species indicating near-shore environments and others pointing to off-shore environments, might be clarified in the frame of a more extensive study of the dinoflagellate record. Further considerations regarding the interpretation of the dinoflagellate record are given in Supplement 12.

Figure 13. Schematic synthesis for Saldanha Bay during deposition of Elandsfontyn Formation, including hypothesised vegetation (2-column fitting, colour)

5.3. Paleoclimatic implications

Coetzee (1980) inferred cool periods during the South African Paleogene-Neogene to have been characterised by podocarpaceous temperate forests, whereas warmer periods were dominated by palm-dominated vegetation. This may be too simplistic. In Quaternary pollen data from the Indian Ocean coastal belt of South Africa, *Podocarpus*-pollen occurs in coastal, subtropical environments, but it is mixed with a diverse, palm-rich angiosperm flora, as well as mangrove elements (Scott et al., 1992; Oschadleus et al., 1996; compare Neumann et al., 2010; Coates-Palgraves, 2002). *Podocarpus* currently has a montane distribution in southern Africa, but *Afrocarpus falcatus* grows in coastal lowlands in eastern South Africa, probably as a relict of cooler periods during the Pleistocene. Pollen of *Podocarpus* and *Afrocarpus* cannot be differentiated (Adie & Lawes, 2011). At Saldanha Bay the presence of ferns, which probably have a subtropical affinity, underlines the warm-humid character of the vegetation and the probable absence of frost. Some other elements at Saldanha Bay, such as Casuarinaceae or *Cupanieidites*, are thermophilic (Pole, 2014). Several ancient elements, now regionally extinct (e.g., Araucariaceae, Winteraceae, Chloranthaceae, Casuarinaceae), are present. Sciscio et al. (2016) conclude, based on the co-occurrence of *Casuarina/Morella* pollen and *Sparganiaceapollenites*, that Casuarinaceae and Myricaceae are linked to high water tables. The palynoflora at Saldanha Bay is diverse (Supplement 4). Considering that forests in warm and wet conditions are more diverse than cool or dry ones, it implies rather humid, subtropical conditions. The presence of *Rhizophora* spp., the most probable producer of *Zonocostites ramonae*, points to an estimated minimal mean annual temperature (assuming that the climate was permanently wet) of ~19 °C (Germeraad et al., 1968; Quisthoud et al., 2012). This would place the climate during the deposition of the Saldanha Bay sediments within a clearly meso/megathermal, subtropical regime (Pole, 2014). Mangroves also point to high sea surface temperatures (Vogel, 2003). The limits of mangroves coincide with the 20°C isotherm of seawater (Duke et al. 1998). Based also on the occurrence of mangroves, the Benguela

Current was not active. This is consistent with evidence from the South Atlantic marine record indicating the Benguela Current was established during the middle or late Miocene (see below), and underlines the importance of the mangrove taxa. Dry elements like Burseraceae, Caesalpiniaceae, Combretaceae/Terminalia, Myrtaceae and Euphorbiaceae, indicate seasonal aridity and might be linked to summer rainfall. The onset of the Benguela Upwelling System has influenced the depositional regime in the Atlantic Basin and has long been applied in studies on the Neogene evolution of climate and the circulation systems (Bolli et al., 1978; Wefer et al., 1998; Weigelt and Uenzelmann-Neben, 2007). During this time, gradual closure of the exchange between tropical Atlantic and Pacific water masses established the present day oceanic circulation, with a stronger influence of North Atlantic Deep Water on global circulation (Marlow et al., 2000; Weigelt and Uenzelmann-Neben, 2007). Enlargement of the Antarctic ice sheet during the middle Miocene (13 Ma, Zachos et al., 2001) intensified trade winds and caused the corresponding southwest Atlantic upwelling regime to develop (Berger and Wefer, 2002). Rommerskirchen et al. (2011) suggested establishment of Benguela upwelling at ~10 Ma, but Weigelt and Uenzelmann-Neben (2004; 2007) proposed an earlier (~14 Ma) commencement based on reflection seismic stratigraphy, and a gradual development until ~1.5 Ma. Uenzelmann-Neben et al. (in press) further suggest that in this region, the most significant modification in the late Neogene occurred during Oligocene/early Miocene, with the onset of an Antarctic Circumpolar Current (ACC) and Atlantic meridional overturning circulation (AMOC), leading to southern-sourced deep and bottom water masses in the western South Atlantic by the middle Miocene. They argue that the opening of Drake Passage in the early Oligocene and the closure of the Central American Seaway at ~6 Ma were the primary drivers for the most significant changes in oceanic circulation in the South Atlantic.

5.4. Correlation of the Elandsfontyn Formation

Inferred palynological ages for the Elandsfontyn Formation at Noordhoek by Coetzee (1978, 1980, 1983) ranged from Oligo-Miocene to Miocene and Pliocene (Coetzee, 1978, 1983) and previously it was only possible to compare the Elandsfontyn Formation at Langebaanweg with Noordhoek (Coetzee, 1983; Sciscio et al., 2016). The difference in elevation due to the more inland (higher) location of Langebaanweg compared to Saldanha Bay suggests the two are not coeval, and that the Langebaanweg deposits are younger (probably middle Miocene, Sciscio et al., 2013). It is possible that Langebaanweg is contemporaneous with Noordhoek although comparison of the palynological results at the latter site is hampered by a high number of unidentified pollen types (Sciscio et al., 2016). This work has therefore allowed access to the older, distal parts of the Elandsfontyn Formation.

6. CONCLUSIONS AND RESEARCH QUESTIONS

6.1 Age and evolution of the Palaeo-Berg River

The current study suggests a terminal Oligocene-early Miocene age for the distal, seaward margin of the Elandsfontyn Formation. Because of its more proximal location, Langebaanweg, where some ancient pollen types of Gondwanan origin are already extinct, is most likely middle Miocene. A fluvial source in the northeast is envisaged and a plain characterised by anastomosing river channels flowed over the granite landscape, bifurcating around the high-relief hills, which reach at least 260 m above modern sea level. Close to the coring location two shallow depressions might have marked the position of lakes (Figure 13). Offshore seismic data illustrate the control of bedrock topography on stratigraphy and match patterns in the sedimentology, suggesting a damming effect prevailing close to the contemporary coast as a function of topography. Oligocene rivers deeply incised into the granite when sea level was ~ - 100 m, and the subsequent transgression was likely relatively slow.

6.2 Palaeo-vegetation and fire history

The 3D model suggests a complex topography allowing distinct micro-climates, diverse hydrology and substrates supporting a wide array of vegetation units. Although the vegetation distribution in the reconstruction is tentative, the following vegetation units are suggested (Figure 13):

Subtropical rainforest, dominated by *Podocarpus*, but also containing conifers with a Gondwana distribution like Araucariaceae, which were not present by the middle Miocene in southern Africa, occupied the coastal plain and the granite hills. Soils associated with granite were likely more fertile than the low-lying depositional environments, as is the case today. In the contemporary Cape, forest development is more rapid on granite than on sandy, infertile substrates where podzolic soils might develop which support acid Fynbos (Fey, 2010). Angiosperms included Arecaceae, Malvaceae, Aquifoliaceae, Cupaniaceae, Myricaceae/Casuarinaceae, Thymeleaceae, Vitaceae, Sapindaceae, Sapotaceae and probably Fagaceae. A palaeotropical character of the vegetation is also shown by diverse, abundant fern spores with *Lygodium*-type spores being most common.

Riparian/swamp forest developed close to the water courses and on the alluvial plains. Although Riparian forests and the subtropical rainforest probably shared many taxa, the producers of *Cupuliferoipollenites oviformis* as well as many Arecaceae, Myricaceae, Myrtaceae and Sapotaceae might be more indicative of riparian/swamp forest.

Subtropical woodland-thickets are not identified at other sites within the Elandsfontyn Formation, e.g. Langebaanweg, Rondebosch and Noordhoek. Euphorbiaceae, Burseraceae, Caesalpiniaceae and Combretaceae indicate seasonal dryness, cold intolerance and are today characteristic of savannas. Since savannas emerged during the Neogene, we assume that in the light of the modest grass component a subtropical thicket existed, which was probably part of a global thicket formation (Schrire et al., 2005). Such a thicket might have

been found on the wide coastal plain or on the drier, north-facing slopes of the hills, or might have fringed the riparian forests towards the inland.

Mangroves, hitherto unknown from the southern African Paleogene and Neogene, are identified at Saldanha Bay. Since mangrove distribution can be favoured by monsoons, e.g., by warm surface water and high precipitation (Meng et al. 2016), it cannot be excluded that such a climate existed at the Cape.

Wetlands and marsh elements, mostly belonging to the families Cyperaceae and Sparganiaceae, are restricted by steep topography.

Proto-Fynbos taxa, including Ericaceae, Proteaceae, Restionaceae and Neuradaceae were present. This is consistent with molecular dating, which suggests Oligocene radiation of edaphically adapted families like Proteaceae and Restionaceae on the oligotrophic, sandy soils of the Cape Fold Mountains (Linder and Verboom, 2015). A mosaic of subtropical thicket and Proto-Fynbos might have existed on coastal, oligotrophic sand plains or granitic hills. Restionaceae and Ericaceae can also be elements in swamps and wetlands. We have to be careful when delineating Proto-Fynbos as an independent vegetation-unit, but suggest a mosaic of Fynbos and thicket as the most probable sand plains vegetation (Figure 13).

The evidence for fire is of global significance and fire-prone Fynbos vegetation – before the onset of summer dry climates on the Cape west coast – indicates the earliest data for fire as an agent of Cenozoic ecosystem change in this region, even under a non-seasonal or summer rainfall regime.

6.3 Chattian/early Miocene transgression

Fluctuations of the pollen spectra at Saldanha Bay do not signal climate change but rather imply a transgression either during the terminal Oligocene or the early Miocene. Increasing marine influence is inferred from dinoflagellates, marine algae, microforaminiferal linings, and geochemistry. The mangroves, as shown by the decline of *Zonocostites ramonae*

(Rhizophoraceae), and Podocarpaceae retreat from the site and wetland elements spread whereas open land indicators only insignificantly increase towards the top of the sequence (Figure 7, 8). Contemporaneously, PC1 declines from ~23m and TOC/TN as well as fungal activity increase, showing a biomass build-up under probably anoxic, low Ph conditions with fine clastics and the genesis of pyrite.

6.5 Future Research Priorities

The Saldanha Bay core study brings new information in connection with the evolution of the landscape and vegetation along the west coast of South Africa but also highlights the need for further research will seek to address the need for wider spatial coverage of Cape flora Neogene records, the use of phytolith/wood/charcoal analysis (particularly the question of palaeo-fire) and the curious question why Ericaceae, a major component of the Cape Flora today, show patchy occurrences in Neogene sites investigated to date.

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