The application of saltmarsh foraminifera in the reconstruction of sea level along the southern African coastline

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Preface

The experimental work described in this dissertation was carried out in the School of Agriculture, Earth and Environmental Science, University of KwaZulu-Natal, Pietermaritzburg, from January 2021 to February 2022, under the supervision of Dr J.M. Finch and Dr L. Pretorius.

The studies represent the original work of the author and have not otherwise been submitted in any form of degree or diploma to any University. Where use has been made of the work of others, it is duly acknowledged in the text.

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Abstract

Accelerations in global sea-level rise are a major concern for coastal areas, but the geographical expression of sea-level variability is poorly constrained, especially in data-scarce far-field locations. Southern Africa is a case in point, where the tide gauge record is limited, and long-term sea level data points are spatially and temporally discontinuous. One technique which has shown promise for producing continuous sea-level records, is the application of intertidal saltmarsh foraminifera, which are widely used as a robust, high precision sea-level proxy in temperate regions. This research uses saltmarsh foraminifera from the Kromme Estuary, to investigate late Holocene sea level on the southern coastline of South Africa. The first paper presents a review of recent sea-level research from southern Africa, with a focus on the Common Era (past 2000 years), to contextualize the second, data-based paper from the Kromme Estuary. Modern saltmarsh foraminifera were sampled across intertidal zone, to establish vertical zonation of foraminiferal assemblages relative to the tidal frame, and ultimately used to develop a transfer function for quantitative sea-level reconstruction. Subsurface marsh sediment was surveyed and used to inform coring locations. The master sediment core was processed for sedimentological and foraminiferal analysis. Six samples of picked plant macrofossils were sent for Accelerator Mass Spectrometry radiocarbon dating, and used to produce a Bayesian age-depth model. The Kromme record extends ~1 000 cal yrs with a hiatus observed from ~400 - 600 cal yrs BP. Calcareous species dominate the basal part of the record, preventing quantitative sea-level reconstruction, however, species assemblages and sedimentology data consisting of low organic content and medium to coarse sand occurring from ~340 cal yrs BP to present, suggest lower than present sea level. Agglutinated species from the upper portion of the core with associated high organic matter and medium sand from ~180 cal yrs BP were used to reconstruct sea level. The quantitative reconstructions spans ~200 years, with the lowest sea-level estimated at 180 cal yrs BP which broadly coincides with the Little Ice Age (~650 - 100 cal yrs BP) and Maunder Minimum (~305 - 235 cal yrs BP), followed by rising sea level till present day level. The sea-level reconstruction from the Kromme Estaury is supported by previously published sea-level studies in southern Africa and provides a detailed reconstruction of sea level that can inform regional sea-level trends, contributing to coastal planning, and provides an opportunity to explore the possible anthropogenic effect on sea-level variability.

Thesis contents

This Masters dissertation consists of an introduction, a review paper, a data paper, and a conclusion.

List of papers

The papers appended in the main body text include:

I. Pillay, T.R. A review of southern African sea-level research and variability from the Holocene to the Common Era: Past trends and future directions. Intended for submission to: *Transactions of the Royal Society of South Africa.*

II. Pillay T.R., Pretorius, L., Barnett, R., Finch, J.M. A late-Holocene sea-level reconstruction using saltmarsh foraminifera from the Kromme Estuary, South Africa. Intended for submission to *Palaeogeography, Palaeoclimatology, Palaeoecology*.

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Introduction

Introduction

The Earth is constantly changing naturally over geological time, with changes in the ocean, land, and atmosphere (Taffs *et al*., 2017). Over recent decades such as the start of the industrial revolution, these natural processes have been affected by anthropogenic activities, which accelerate change (Crutzen 2002). These changes are observed in the accelerated increase of greenhouse gases resulting in land surface temperature increases (Hunt and Watkiss 2011; Taffs *et al*., 2017), warmer oceans, loss of ice sheets, and rising sea level (IPCC 2021; Khan *et al*., 2015; Kopp *et al*., 2019). Global average sea-level rise has greatly accelerated since the 1900s and is still on the rise, with predictions of 1.1 m by the end of the century (IPCC 2021). This rise in sea level is primarily due to thermal expansion and the melting of glaciers and continental ice (Khan *et al*., 2015; Kopp *et al*., 2019). The global average rise in sea level between 2006-2018 AD was recorded at a rate of ~3.7 mm y^{-1} and is projected to rise to 2.5 m by 2100 AD (IPCC 2021). Regional rates of sea level can differ from global trends (IPCC 2021) due to subsidence, water currents, and ocean-atmospheric cycles (Kopp *et al*., 2019). The rates of sea-level variability are also influenced by the location of sites, with near-field sites located close to ice sheets and influenced by isostatic uplift, whereas far-field sites are located away from ice sheets and affected by meltwater effects (Khan *et al*., 2015; Kopp *et al*., 2019). To better understand the differences in sea level over different timescales, local sea-level curves need to be produced (Compton 2001; Cooper *et al*., 2018).

Southern Africa is classified as a far-field site and therefore provides an opportunity to determine eustatic sea-level change, which is a global change of the volume of water in the oceans (Norström *et al*., 2012). Recent evidence of sea-level change can be gathered from instrumental records, including tide gauges and satellite altimetry (Church *et al*., 2008). For a long-term perspective, however, palaeoenvironmental studies can be used to evaluate past sea-level variability and insight into pre- and post-industrial trends (Horton *et al*., 2018; Rautenbach *et al*., 2019). Microfossil proxy data sources such as pollen, diatoms, and foraminifera are used to improve the length of palaeorecords because instrumental records have a limited timeframe (Church *et al*., 2013; Cooper *et al*., 2018; Rautenbach *et al*., 2019). These microfossils capture past climatic conditions over geological timescales providing valuable information on past sea level and climatic conditions (Gordan *et al*., 2012; Ghosh and Filipsson 2017; Scanes *et al*., 2017). Coastal environments such as estuaries preserve microfossils influenced by tidal mechanisms, which track changes in tidal inundation, salinity, and pH, while the estuarine sediments accumulate through time (Scanes *et al*., 2017). Microfossils, such as foraminifera, which are single-celled organisms consisting of calcareous or agglutinated tests. and are found in high abundance in these systems due to their high preservation potential (Edwards and Wright 2015) and have been applied to reconstruct past sea-level both globally (Gehrels *et al*., 2001) and regionally (Compton 2001; Franceschini *et al*., 2005; Strachan *et al*., 2014).

Long-term sea-level record studies can be used to inform future climate planning and policy-making (Horton *et al*., 2018). These datasets provide valuable information for climate models and sea-level projections over different timescales (Barlow *et al*., 2013; Ziervogel *et al*., 2014) and can assist in conservation planning, coastal management, and climate policy-making (Seddon *et al*., 2014). Understanding past environmental changes is key to understanding current and future changes (Ziervogel *et al*., 2014), and by applying the principles of uniformitarianism, the present being a key to the past, the past can provide valuable insight into the future, increasing understanding (Haywood *et al*., 2009). An understanding of preindustrial sea level can help disentangle natural and anthropogenic drivers of sea-level rise (Meyssignac and Cazenave 2012; Kopp *et al*., 2019) as evidence suggests an acceleration in sea-level rise since the industrial era, which is projected to continue (IPCC 2021). It is important to attempt to understand these complexities of natural versus anthropogenic effects and disentangle the climatic signals to provide more accurate projections of sea-level rise and climatic change (Meyssignac and Cazenave 2012; Kopp *et al*., 2019).

The aim of this research is to reconstruct late Holocene sea level in the far-field location of South Africa using saltmarsh foraminifera from the Kromme Estuary. The Kromme Estuary on the southern coastline of South Africa is a permanently open system hosting multiple relatively undisturbed saltmarshes, which allows for long-term eustatic sea-level variability to be examined. The objectives of this study are to: (i) evaluate the vertical zonation of modern surface foraminiferal assemblages across the saltmarsh, (ii) compile a training dataset using modern saltmarsh foraminifera and use this to develop a transfer function, (iii) establish chronological control for a sediment core using radiocarbon dating, and (iv) apply the transfer function developed in (ii) above to downcore foraminiferal assemblages to reconstruct a record of relative sea-level change. Ultimately, this research seeks to explore the application of high-resolution saltmarsh-derived transfer functions in assessing regional sea-level variability and the detection of natural and anthropogenic drivers of change.

Dissertation outline

Paper I presents a review of late Holocene sea-level studies from southern Africa and examines challenges and future prospects for sea-level research in the subregion. Paper II presents a new record of late Holocene sea-level variability from the Kromme Estuary. A final synthesis chapter reflects on the highlights of the study and discusses future research directions.

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'I can do all things through Christ who strengthens me' (Philippians 4:13).

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Paper I

A review of southern African sea-level research and variability from the Holocene to the Common Era: Past trends and future directions

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Abstract

Global sea-level rise is of major concern due to accelerating rise in the 20th century and potential negative impacts on vulnerable coastal regions. Sea level change in southern Africa has been studied using a variety of proxies and methods and provides sea-level change estimates since the Last Glacial Maximum. Southern Africa is a far-field site with many suitable study sites, providing opportunities to gather changes in eustatic sea-level change from palaeoenvironmental data. Sea level studies have progressed from early beachrock and qualitative approaches to the application of various geological, archaeological and biological proxies coupled with quantitative approaches such as transfer functions. The sea-level record of southern Africa broadly agrees with global trends and other southern hemisphere records, however there is some variability in sea-level estimates and timings for the different coastlines of southern Africa. This paper reviews the progression of sea-level research in southern Africa with a focus on the Holocene to the Common Era. Palaeoenvironmental data sources, methodologies and sea-level estimates produced from various studies are explored along with the drivers of sea-level variability. The knowledge gaps and future directions for sea-level research in southern Africa is addressed.

Contents

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1. Introduction

Global sea level has increased twice as fast in the 20th century compared to long-term trends (IPCC 2021). Sea level has increased rapidly in recent periods at an average rate of ~3.7mm y^{-1} between 2006 - 2018 as compared to ~1.3 mm y^{-1} between 1901 - 1971 and has been accelerating since the 1970s, rising more rapidly in the current century when compared to the last 3000 years (IPCC 2021). The rise of global and local sea level is a point of concern due to the impact on vulnerable coastal regions and the associated biodiversity, infrastructure, and human population, under threats of flooding, erosion, loss of habitats, loss of land, and changes in atmospheric processes (Taffs *et al*., 2017; IPCC 2021). Warming of the oceans has resulted in thermal expansion, melting of polar and glacial ice, and unequal distribution of heat around the ocean, atmosphere, and cryosphere (Kopp *et al*., 2019). Earth systems fall out of balance with many processes such as evaporation, runoff, and meltwater effects from loss of the

Greenland and Antarctic ice sheets affecting isostatic and eustatic changes in sea level (Khan *et al*., 2015). Anthropogenic effects can further alter these systems and compound the imbalance in ocean-atmospheric cycles (Ziervogel *et al*., 2014). It is therefore important to improve understanding of these systems to allow for more robust climate models to be developed, and help address the threat of sea-level change. Palaeoecological studies improve long-term understanding of these complex climate systems and help to discern changes globally and locally over different time scales (Taffs *et al*., 2017). These studies aim to understand past sea-level events to allow for future predictions and provide evidence of sea-level change, which can assist threatened coastlines that provide valuable natural and economic resources (Roberts 2008).

In southern Africa research has gathered evidence of long- term sea-level variability from instrumental data and palaeoenvironmental archives and proxies (Cooper *et al*., 2018). Southern Africa is a far-field site, free from isostatic effects, which allows for more accurate representations of changes in sea level as compared to near-field sites, and is therefore a critical location for sea-level research (Khan *et al*., 2015), however, constraints such as the energy of the coastline, accumulation rate of sediment and the accommodation space of sediment must be accounted for, to ensure accuracy (Friess *et al*., 2019). Southern Africa has various relatively undisturbed coastal study sites such as estuaries, saltmarshes and shorelines with studies conducted along the coastline producing successful sea-level reconstructions (Strachan *et al*., 2014) and estimates (Compton 2001; Norström *et al*., 2012; Kirsten *et al*., 2018). This review explores the topic of sea-level research in southern Africa, from the Last Glacial Maximum with a focus from the Holocene to the Common Era (past 2000 years). The methodological approaches taken and the progression of studies conducted along the southern African coastline are explored. I reflect on the current state of sea-level research, the challenges and limitations faced, and explore future prospects for the advancement of sea-level research in southern Africa.

2. Sea level data sources and methodologies

2.1. Palaeoenvironmental data sources

Past sea level has been examined and reconstructed using stratigraphic evidence from coastal sediments collected from intertidal zones (Nelson 2015). The distribution of meltwater from continental ice sheets since the Last Glacial Maximum (22 000 - 19 000 cal yrs BP) has been uneven, and as such, coastal environments have recorded distinctly different relative sea-level changes (Barlow *et al*., 2013; Nelson 2015), with environments experiencing varying degrees of sea-level change due to the influence of the ice sheets (Barlow *et al*., 2013). The freezing and thawing of global ice associated with the respective glacial and interglacial periods have caused sea-level fluctuations globally (Rignot *et al*., 2011). When ice forms on land, it applies weight on the land, depressing the area and, as an effect, raises the surrounding crust resulting in the apparent sea-level rise around that area. As the ice melts, the crust is no longer depressed and rises as the weight above is lessened, causing isostatic uplift (Khan *et al*., 2015; Skilbeck *et al*., 2017). These near field sites are used to reconstruct past ice volume from glacial periods (Rignot *et al*., 2011; Khan *et al*., 2015). During glacial periods, the sea level is lower, which is most apparent at far-field sites that can measure the global sea-level change (Skilbeck *et al*., 2017; Khan *et al*., 2015). Examining these far-field sites requires understanding past eustatic and isostatic processes as they influence the stratigraphic evidence found at these sites (Khan *et al*., 2015; Skilbeck *et al*., 2017). The provenance of a site affects the stratigraphic evidence along with the characteristics used in sea level reconstruction studies, such as location, elevation, age and modern analogues (Barlow *et al*., 2013). Sites must encompass these characteristics and provide records of past environmental conditions with good preservation potential for sea-level proxies. In the following sections I review different sources of palaeoenvironmental information including geological, archaeological and biological evidence which allow for reconstruction of past environmental change that extends beyond the instrumental period.

2.1.1. Geological evidence

Geological evidence including beach rock (Ramsay 1995), aeolianite (Ramsay 1995; Marker 1997) and erosional features (Ramsay 1995; Marker 1997), have been used as indicators of past sea-level change in various studies along the southern African coast. Beachrock is a coastal deposit that forms over decades from carbonate cemented sandstone on the shoreline of beaches (Vousdoukas *et al*., 2007; Mauz *et* al., 2015). Lithification of beachrock takes place in the intertidal zone and combines different types of sediments as horizontal strata (Mauz *et* al., 2015). The cementation of beachrocks can vary due to temperature, tidal level, and tidal energy (Vousdoukas *et al*., 2007; Mauz *et* al., 2015). The activity of the intertidal zone and formation of beachrocks provides an excellent indicator of past sea level due to the continuous rapid formation, which captures environmental conditions (Ramsay 1995; Mauz *et* al., 2015).

Early application of geological proxies improved the resolution of sea-level change data by examining beach rocks and sediment cores taken along the eastern coast (Ramsay 1995) to address minor peaks observed in the data for the last 6000 years (Ramsay 1995; Ramsay and Cooper 2002). The study on beach rocks (Ramsay 1995) identified the most reliable and effective methods of dating marine clastic carbonates under the context of sea-level change along the southeast African coastline. Beach rock formation is restricted to intertidal zones, and when correctly dated using shells from beach rock or entire rocks, the uncertainty of prediction can be reduced. Mauz *et al*. (2015) explored the application of beach rock to reconstruct sea level in far-field sites. Beach rock displays high preservation potential and is free from post-depositional artefacts such as compaction errors which increases the precision of subsequent reconstructions. The study shows that beach rock is a reliable sea-level marker that can be tested against other sea-level records such as corals, with less unquantifiable errors and similar errors to reconstructions that use various other sea-level markers. Optically-Stimulated Luminescence (OSL) dating provides more accurate dates than bulk carbon dating, and thus more accurate sea-level index points (Bosman 2012) as it eliminates the potential of dating reworked, or introduced material. These dates can be further verified by using field evidence such as proximity to erosional features in beach rock and aeolianite deposits. They show the terrestrial limits and intertidal conditions of the environment and can be referenced to modern erosional features (Ramsay 1995; Mauz *et al*., 2015). Further studies (Armitage *et al*., 2006; Pretorius *et al*., 2016) have investigated preserved offshore coastal sediments deposits and seismic records to determine sea level trends. Pretorius *et al*. (2016) investigated the submerged barrier shoreline complex off the coast of Durban, identified from bathymetry and sub-bottom profiles, and used this to provide positions of barriers and inlets, as evidence of past sea level. Seismic stratigraphic sections can also help identify irregularities in erosional surfaces and can be verified using sediment cores and interpreted using modern beach and nearshore deposits (Smith *et al*., 2010). Using erosional markers from these deposits, sea-level change can be inferred as the changes can be observed in the stratigraphy of the shoreline development (Smith *et al*., 2010).

2.1.2. Archaeological evidence

Archaeological evidence of former sea level has been explored around southern Africa (Davies 1973; Carr *et al*., 2016; Cawthra *et al*., 2016; Cawthra *et al*., 2020); however, this form of evidence can be affected by human artefacts due to coastal developments making the provenance harder to establish. Archaeological evidence such as coastal midden sites and submerged coastal landscapes (Cawthra *et al*., 2016). have been used in a few studies locally in the context of sea-level change (Davies 1973; Compton and Franceschini 2005) as archaeological studies are limited on the southern African coastline (Cooper *et al*., 2018). Fixed proxies have been used to determine intertidal zones and past sea level. The terrestrial limit in Knysna Lagoon was determined by using in-situ tree stumps and from this, sea level along with past environmental conditions could be inferred accurately (Marker 1997). Compton and Franceschini (2005) used dated shell middens from the southwest coast of South Africa to determine shoreline progradation which corresponded to drops in sea level around 5 900, 4 500 and 2 400 cal yrs BP. These studies (Davies 1973; Compton and Franceschini 2005) produced human artefacts; however, they were able to produce useful results in reconstructing patterns of beach progradation.

2.1.3. Biological evidence

Biological evidence includes microfossils preserved in sediments such as diatoms (Kirsten *et al*., 2018), foraminifera (Strachan *et al*., 2014) and pollen grains (Baxter and Meadows 1999; du Plessis 2015). Estuaries have been identified as natural sedimentary archives that preserve microfossils due to their low energy environments and marine and freshwater interface, allowing proxy data to be gathered on past sea-level change (Cooper 2001; Ghosh and Filipsson 2017; Scanes *et al*., 2017). The intertidal zone is the most active coastal subenvironment due to the different processes from water level changes, temperature, and sedimentological processes (Scanes *et al*., 2017). Flora and fauna that inhabit this zone are resilient to these changes and have adapted to the influences of the intertidal zone (Strachan *et al*., 2016). These adaptations and tolerances particularly affect the distributions of flora and fauna in the intertidal saltmarshes, and most noticeably, form vegetation bands across the marsh (Maree 2000; Strachan *et al*., 2016, Strachan *et al*., 2017). When using proxies from estuarine systems, it is important that the provenance of these sites is taken into account as any allochthonous material may cause anomalous data and negatively impact chronology (Compton 2001; Cooper *et al*., 2018).

In southern Africa, in situ shells and shells fixed to substrates and bulk organic matter have been dated and used as past sea-level indicators (Botha *et al*., 2018). However, the reworking, preservation, bioturbation and seasonal influence of the samples in coastal sediments can affect the reliability of the dated material and results obtained (Strachan *et al*., 2016; Cooper *et al*., 2018). These coastal sediments are subject to sedimentological processes, which are determined by environmental conditions such as tidal inundation, fluvial processes, and atmospheric forcing (Scanes *et al*., 2017). The sediments record environmental conditions, which can be studied by examining the succession in the stratigraphy of these sites and using these to infer past conditions (Cooper *et al*., 2018). In the Lake St Lucia area, shells were recorded above the modern Mean High Water (MHW), indicative of higher sea level (Botha *et al*., 2018). Norström *et al*. (2012) used diatoms in southern Mozambique to determine sea-level change. A similar study conducted by Sitoe *et al*. (2017) used diatoms in a study at Lake Lungué Mozambique, with different sea level recorded compared to Norström *et al*. (2012). The differences in records can be attributed to temporal and spatial variations and isostatic effects of interglacial periods, especially when compared globally and to the Caribbean Islands with similar trends (Ramsay and Cooper 2002; Sitoe *et al*., 2017). Studies conducted in Langebaan Lagoon (Franceschini *et al*., 2005), Kariega Estuary (Strachan *et al*., 2014), and Eilandvlei Basin (Kirsten *et al*., 2018) observed foraminiferal zonation from lake sediments and was able to reconstruct Holocene sea level. Studies using diatoms in Macassa Bay (Norström *et al*., 2012) and Princessvlei (Kirsten and Meadows 2016) used trends in species distributions for past sea-level predictions. This combination of proxies can be seen in a study at Eilandvlei Basin, where diatoms, ostracods and foraminifera were used to investigate sea-level changes along the southern Cape coast. The microfossils were classified according to salinity and temperature, and species were distributed according to tidal and marine influence and captured a range of past environmental conditions (Kirsten *et al*., 2018). The study emphasizes the many factors such as oceanic exchange, water conditions, and cycles such as the Gleissberg and De Vries that can result in fluctuations in sea level and progression in ecosystems (Kirsten *et al*., 2018).

For palaeoecological data to be statistically analysed, there needs to be a quantitative approach to allow for proxy data to be verified for reconstructions and serve as an analogue of palaeoenvironments (Barlow *et al*., 2013). Transfer functions have developed from the early qualitative approach of working with palaeoecological data (Kemp and Telford 2015; Scott and Medioli 1978; Scott and Medioli 1986) to using modern quantitative approaches (Gehrels *et al*., 2001; Strachan *et al*., 2014). Transfer functions assume uniformitarian principles for the environment in question and apply numerical techniques to environmental variables to produce an output that quantifies the modern and fossil proxies as numerical representations (Kemp and Telford 2015; Morrison and Ellison 2017). Transfer functions require first developing a modern training set of microfossil assemblages such as diatoms (Zong and Horton 1999; Woodroffe and Long 2010) and/or foraminifera (Gehrels 1994; Gehrels *et al*., 2001; Strachan *et al*., 2014) and the corresponding environmental data for both the modern and fossil proxies (Kemp and Telford 2015). Foraminifera-derived transfer functions have provided reliable sea-level reconstructions (Gehrels 1994), which have shown promise in southern Africa (Strachan *et al*., 2014). Diatom studies have been conducted in southern Africa (Kirsten *et al*., 2018), however, diatom-based transfer functions have not been applied to reconstruct sea level in southern Africa, with only foraminifera-based reconstructions successfully applied (Strachan *et al*., 2014).

The successful application of foraminifera as sea-level proxies requires that limitations and errors are considered to produce reliable datasets (Murray 2006). The reliability of foraminiferal datasets is dependent on the robustness of the relationship between species distributions and the environmental variable being examined, such as elevation, temperature, pH, or salinity (Murray 2006). It is important to ensure that foraminiferal material is autochthonous and has not been altered after deposition. This is also recommended for training sets as variability between modern and fossil assemblages should not exceed one another. This can be avoided by collecting training set samples from the same site or region (Murray 2006). However, it is important to note the seasonal variability in foraminiferal assemblages when collecting training set data (Horton and Edwards 2003). Therefore, a robust training set is required to account for variability and keep errors minimal in sea-level models (Horton and Edwards 2006). It is important to take note of the preservation of foraminiferal assemblages in sediment layers to ensure that preservation errors do not create false signatures of sea-level change (Edwards and Wright 2015). These are often due to taphonomic processes associated with the foraminiferal assemblages and sediment layers (Murray 2006). Foraminiferal tests can undergo oxidation of the cementing structure of organic tests or dissolution of calcareous tests (Edwards and Wright 2015). The oxidation or dissolution of tests can affect fossils assemblages and subsequently the sea level interpretations inferred from the data (Edwards and Wright

2015). Agglutinated tests can be destroyed by bacterial or chemical decay, with bacterial action higher in warmer environments and during sample preparation (Murray 2006; Edwards and Wright 2015). Agglutinated test preservation has been observed to be good in the fossil records of previous studies, especially with high sediment accumulation rates (Murray 2006). Calcareous tests are susceptible to the corrosive properties of marine water, which can etch the surface of the test or completely dissolve it (Edwards and Wright 2015). This can present an issue of species being absent from sea-level reconstructions, negatively affecting the data. It is important to consider these limitations when using foraminifera as a proxy, as this will greatly improve the accuracy and reliability of relative sea-level reconstructions (Scott and Medioli 1986; Edwards and Wright 2015).

Foraminiferal-based techniques have been widely applied in temperate environments, including USA (Gehrels 1994; Kemp *et al*., 2013) and the UK (Edwards and Horton 2000). Similarly, a study using saltmarsh foraminifera in South African estuaries as sea-level indicators was conducted based on zonation (Strachan *et al*., 2017). These studies successfully carried out the respective objectives, using the intertidal and elevation zonation of estuaries as a basis for having captured past environmental records (Gehrels 1994; Strachan *et al*., 2017). A similar foraminiferal approach was used in mangroves from KwaZulu-Natal using vertical distributions (Strachan *et al*., 2017). However, mangroves present challenges and limitations for foraminiferal studies due to the effects of bioturbation, microfossil preservation, and post-depositional transport (Strachan *et al*., 2017), with similar challenges identified by Sefton and Woodroffe (2021), using mangrove pollen as past sea-level indicators in Mahé, Seychelles. These coastal sites provided stratigraphic records of past environmental conditions with good preservation potential for proxies as an archive (Barlow *et al*., 2013). Horton and Edwards (2003) highlight the value of these coastal environments that capture past records as well as seasonal distributions to allow for the application of uniformitarian principles. Living foraminifera are included in datasets to capture seasonal distributions; however, this can affect training set accuracy when comparing data to fossil assemblages (Kemp *et al.*, 2020). Dead foraminifera are representative of environments without the effect of seasonal influence and provides higher accuracy for comparison between the training set and fossil foraminifera (Kemp *et al.*, 2020). Franceschini *et al*. (2005) explored foraminiferal distribution at Langebaan Lagoon, Western Cape, South Africa. This study found that assemblages showed vertical zonation associated with elevation above mean sea level. The elevational range of foraminifera species was used to reconstruct relative sea level for the southern coast of South

Africa using an exposed succession at Monwabisi, Western Cape, South Africa. This was an early South African application of foraminifera as biological proxies for sea-level reconstruction, which paved the way for advanced statistical applications of proxies such as foraminifera. Strachan *et al*. (2014) conducted a study at Kariega Estuary, Eastern Cape, South Africa. The study developed a chronology using radiocarbon dates and gathered corresponding foraminifera samples from saltmarsh cores collected on-site. A transfer function was applied to fossil foraminifera to reconstruct late Holocene sea level for the eastern coast of South Africa. The application of the transfer function was the first successful in a local context. The reliability, reproducibility and preservation potential of estuaries and their associated habitats can be confirmed by the various studies (Compton 2001; Gehrels *et al*., 2001; Franceschini *et al*., 2005; Norström *et al*., 2012; Strachan *et al*., 2014) conducted at these sites using different proxies, producing similar outcomes as when applying foraminiferal techniques.

2.1.4. Dating considerations

The Holocene global mean sea-level record shows partial similarity in the global and local context. However, higher-resolution studies are required to address the fluctuations observed in the data, allowing for accurate reconstructions of sea-level change over shorter timescales (Compton 2001; Ramsay and Cooper 2002; Barlow *et al*., 2013). The type of dating has also differed, but this is dependent on the type of material that is being sampled (Cooper *et al*., 2018). Additional constraining of dates by better selection material, and the use of abundant material for dating to increase the number of reliable dates returned. This will improve the resolution of age-depth models and allow for reliable comparisons between datasets that can inform one another and fill in age data gaps (Strachan *et al*., 2014; Cooper *et al*., 2018). Sitoe *et al*. (2017), Kirsten *et al*. (2018), Compton and Franceschini (2005), Roberts *et al*. (2016) and Cooper *et al*. (2018) have also identified the need to separate environmental factors, natural phenomena and anthropogenic effects from sea-level records. These sea-level variations can often be observed regionally and globally but must be corrected for when reconstructing former sea level, which can be assisted by instrumental and proxy records (Meyssignac and Cazenave 2012). However, anthropogenic effects on these variations are often addressed in global sea level trends but overlooked finer scales, which can affect local sea level predictions (Meyssignac and Cazenave 2012). The anthropogenic influence of sea-level change, especially at local scales, has yet to be addressed (Becker *et al*., 2014). This signature can be difficult to disentangle and track as reliable information is often lacking about the effect of anthropogenic activities. There are many opportunities to improve sea-level studies through the use of reliable proxies, accurate dating methods and precise sampling techniques. This can provide high resolution and longer timescales of sea level data which can assist in disentangling natural versus anthropogenic forcing on sea-level variability.

2.2. Instrumental data sources

The modern sea-level record is limited, with local tidal gauge data spanning back to the 1960s (Church *et al*., 2013; Rautenbach *et al*., 2019). Instrumental evidence can be used to validate proxies such as foraminifera and diatoms (Jury 2013). Prior to the year 1993, sea-level change was monitored using tide gauges, however these tide gauges often had calibration errors (Mather 2007; Mather *et al*., 2009). With the development of technology, satellite data is more widely available, encompassing a larger geographical range, better accuracy and reliability when the instruments are accurately calibrated to prevent unreconciled errors (Mather *et al*., 2009; Smith *et al*., 2010). This advancement has promoted reconstructions and accurate climate models from 1900 - 2100 (Jury 2013) and the calibration and validation of tidal data for use in modelling and sea-level reconstruction (Rautenbach *et al*., 2019).

Altimetric data collected from satellites from 1993 - 2006 reported a rate of sea-level rise of 3.1 mm yr^{-1} in oceans located between latitudes 66° N and 66° S (Church *et al*., 2008). Global satellite data suggest a rise of ~3 mm yr^{-1} with patterns being irregular (Church *et al*., 2008; Cazenave *et al*., 2018). Satellite data provide two reasons for sea-level rise, those being the thermal expansion of water bodies and the melting of land-based ice due to increases in temperature (Church *et al.*, 2008). This instrumental data is used to feed various models which simulate environmental conditions and provide projections of future change (Church *et al.*, 2008; Cazenave *et al*., 2018; IPCC 2021). These models are constantly developing and improving, which provide longer records of projection as well as higher confidence intervals, provided the input data is reliable (Church *et al*., 2008; Mcleod *et al*., 2010). Southern African applications of climate modelling by Jury (2013) indicate an acceleration of warming between + 0.01 - 0.02°C y^{-1}, affecting rainfall, sea level, and subtropical atmospheric processes. Longer records with increased accuracy are important to progress the quality of model projections, and this stems from data provided from instruments and proxies (Church *et al*., 2008; Mather and Stretch 2012; Cazenave *et al*., 2018).

3. Review of southern African sea-level variability

3.1. Sea level change since the Last Glacial Maximum

The Last Glacial Maximum (LGM) occurred between 22 000 - 19 000 cal yrs BP (Lambeck and Chappell 2001). Sea level variability since the LGM occurred due to global ice sheet activity and periods of global cooling and warming (Nelson 2015). At the end of the LGM, global ice volume decreased over time, with sea level rising ~15 mm y^{-1} until ~9 000 cal yrs BP and modern sea level being reached ~7 000 cal yrs BP (Lambeck and Chappell 2001). Southern Africa has recorded sea-level trends since the LGM through biological proxies, sedimentological features and terrestrial and marine limiting (Cooper *et al*., 2018). Sea level has been constrained to within 2 m, with sedimentological evidence estimating fluctuations of 1-3 m above present sea level (Cooper *et al*., 2018).

3.2. Sea level change in the Holocene

Sea-level records along the southern African coastline (Fig. 1; Fig. 2) have shown much fluctuation during glacial and interglacial periods (900 - 250 ka) (Compton 2011). Southern Africa is relatively tectonically stable, with only six minor earthquakes recorded in the last 350 years at magnitudes of 5.5 - 6.3, making effects on sea level in the region unlikely (Compton 2001). Evidence from terrestrial and marine limiting points, beach rock and biological proxies (Table 1) on the southern African coastline suggests a Mid-Late Holocene level of approximately + 3.8 m between 6.5 - 5.5 ka BP, followed by a fall to present sea level (Cooper *et al.*, 2018). The sea-level reconstruction fluctuations are about 1 m above or below the current sea level (Cooper *et al*., 2018). Over the last hundred years, sea level has not fluctuated more than 3 m, and late Holocene sea level showed variability between 1 - 2 m (Norström *et al*., 2012). The southern coastline of South Africa has the mixing of the Benguela and Agulhas currents, which cause variable sea surface temperatures (Mather *et al*., 2009). Sea-level records along the southern coastline are more numerous than the western and eastern coastlines for the late Holocene, making changes hard to discern and the fluctuations difficult to study at a regional scale due to dating considerations, methods and proxies used (Cooper *et al*., 2018).

Figure 1. Late Holocene sea-level study sites along the southern African coastline

Beach rocks analysed from the eastern coastline at different sites in St Lucia Estuary and Kosi bay, provided sea-level estimates of + 1.5 m at ~500 cal yrs AD, indicative of a highstand (Ramsay 1995). Diatoms from Macassa Bay Estuary, Mozambique, were analysed for evidence of sea-level change along the coast (Norström *et al*., 2012). The results suggest higher than present sea level ~4 350 cal yrs AD and between ~2750 - 950 cal yrs AD based on marine evidence (Norström *et al*., 2012). Similarly, a study at Lake Lungué, Mozambique, suggest sea level higher than present between ~740 - 910 cal yrs AD based on diatoms and radiocarbon dated shells (Sitoe *et al*., 2017). The study also suggests lower sea level between ~1 130 – 1 360 cal yrs AD based on the freshwater conditions (Sitoe *et al*., 2017). Siesser (1974) conducted studies on the eastern coast beach rock near Vilankulos in Mozambique and suggested sea level ~842 cal yrs BP were similar to present-day sea level. Findings on the western coastline contradict this, as lowstands were observed between ~700 - 400cal yrs BP in magnitude of -0.5 to -1 m compared to present sea level using sediment from Langebaan Lagoon (Compton 2001). A study at Knysna Estuary on the southern coast using in situ tree stumps recorded lowstands at approximately 682 cal yrs BP (Marker 1997). Sea level ~300 - 400 cal yrs BP have shown a gradual rise to present sea level based on records from the Kariega Estuary and Langebaan Lagoon (Compton 2001; Strachan *et al*., 2014). The study by Norström *et al*. (2012) at Macassa Bay also suggests this gradual rise but at the start of ~700 cal yrs BP.

Sea level oscillations were observed ~300 cal yrs BP (Compton 2001; Strachan *et al.*, 2014) and may influence the timings of the recorded rise in sea level to the present (Norström *et al.*, 2012).

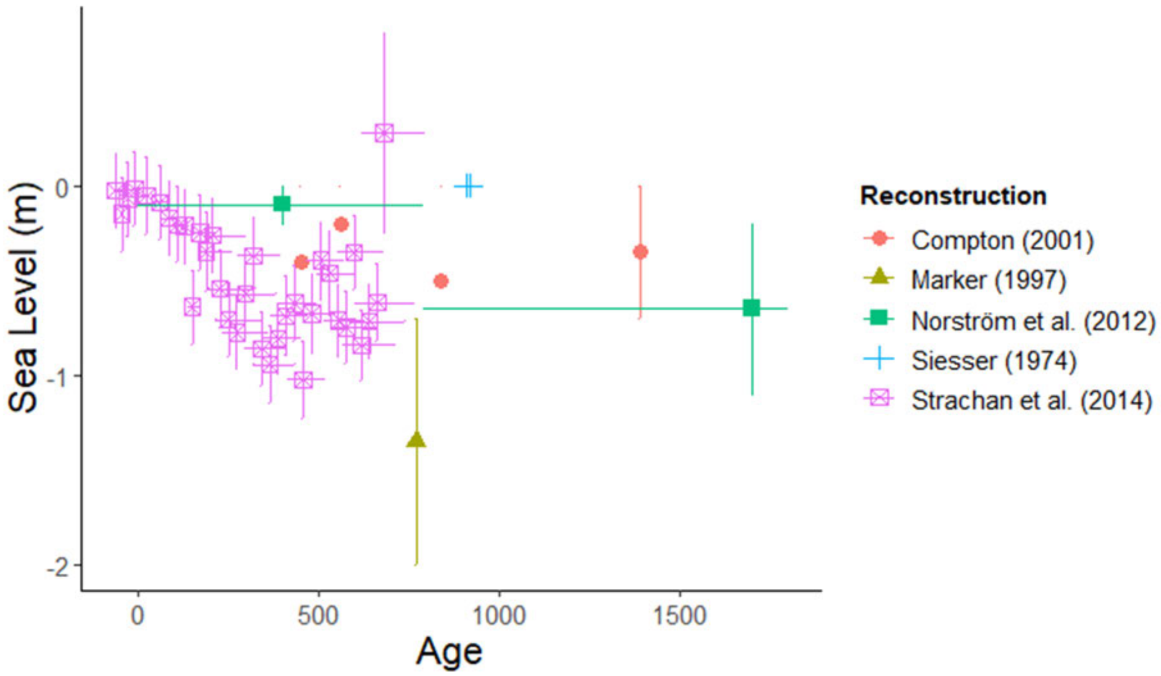

Figure 2. Comparison of Late Holocene sea level from various studies conducted along the southern African coastline

Table 1: Late Holocene sea-level studies conducted along the southern African coastline

Study	**Location**	**Proxy**
Siesser (1974)	Vilankulos	Beach rocks
Ramsay (1995)	St Lucia Estuary, Khosi Bay	Beach rocks
Marker (1997)	Knysna Estuary	Tree stumps
Compton (2001)	Langebaan Lagoon	Sediments
Norström *et al.* (2012)	Macassa Bay	Diatoms
Strachan *et al.* (2014)	Kariega Estuary	Foraminifera
Sitoe *et al.* (2017)	Lake Lungué	Diatoms
Kirsten *et al.* (2018)	Cape Aghulas	Diatoms

3.3. Recent trends from instrumental data

Tidal records of southern Africa indicate an increase of + 1.87 mm y^{-1} for the west coast, an increase of + 1.48 mm y^{-1} for the southern coast, and an increase of + 2.74 mm y^{-1} on the east coast between 1959 - 2006 (Mather *et al*., 2009). Similarly, these increasing trends have been recorded at other southern hemisphere study sites such as Australia and New Zealand, which recorded 4.2 ± 0.1 mm y^{-1} between 1900 and 1950, and 0.7 ± 0.6 mm y^{-1} during the 20^{th} century (Church *et al*., 2006; Gehrels *et al*., 2012). Barometric pressure has been dropping on the western coast at a rate of 1.63 hPa per decade, with a rise of 0.30 hPa on the southern coast (Mather *et al*., 2009). Trends after correcting for barometric pressure and crustal movements indicates sea level trends of + 3.55 mm y^{-1} along the eastern coast, + 1.57 mm y^{-1} along the southern coast and + 0.42 mm y^{-1} along the western coast (Mather *et al*., 2009). Relative sea level has increased at a higher rate along Africa's margins over the last three decades, as compared to the rest of the globe (IPCC 2021). This rise is projected to continue under scenarios of the latest IPCC report based on the latest satellite altimetry and tide gauge data to + 2.5 - 6.5 m until the year 2046 (IPCC 2021).

4. Drivers of sea-level change

4.1. Sea-level fingerprinting

The global mean sea level follows the Earth's geoid and is affected by changes in ice volume and water (Adhikari *et al*., 2019). These changes affect local sea surface height, which determines current sea level and is essential in understanding global sea-level variability (Rignot *et al*., 2011; Kopp *et al*., 2015). Monitoring and modelling gravitational, rotational and hydrological mass changes have become essential in tracking sea-level change and provides evidence of "sea level fingerprints" (Kopp *et al*., 2015; Adhikari *et al*., 2019). These fingerprints are observable due to the transportation of water between ocean and land masses and gravitational attraction due to geodynamics (Adhikari *et al*., 2019). These processes can occur over different scales with events such as the Little Ice Age (LIA) and Maunder Minimum, as well the northern and southern oscillations (Sundqvist *et al*., 2013; Adhikari *et al*., 2019). The Gravity Recovery and Climate Experiment (GRACE) mission data provides valuable data to study climatic changes over decadal time scales, in particular ice mass loss and sea-level rise (Adhikari *et al*., 2019). The data is robust but requires longer, more accurate records to increase reliability and filtering of data when modelling sea level (Adhikari *et al*., 2019). The data can produce global trends clearly, but finer scales can prove challenging due to a lack of data and complex climatic processes (Kopp *et al*., 2015; Adhikari *et al*., 2019).

In southern Africa, there is evidence of cooling between 1690 - 1740 AD based on dated oxygen isotope stalagmite records from the summer rainfall regions of South Africa (Sundqvist *et al*., 2013). Temperatures were approximately 1.4°C colder than the present, with cycles of 22, 11 and 4.8-years showing oscillations based on solar magnetic cycles and El Niño-Southern Oscillation (Sundqvist *et al*., 2013). The observation from Sundqvist *et al*. (2013) are close in timing with the Maunder Minimum ~1645 - 1710 AD and can provide possible evidence from drivers of sea-level change over decadal and interannual climate variability regionally, as well as provide a regional fingerprint for sea level (Sundqvist *et al*., 2013; Kopp *et al*., 2015). Similar records were observed in southern African baobab carbon isotope records between 1600 - 2000 AD. Solar periodicities identified were the ~11-year Schwabe cycle, ~22-year Hale cycle and 80–110-year Gleissberg cycle, with the effect of the Maunder Minimum observed on the Schwabe and Hale cycles (Kotze 2020). Stalagmite records from Makapansgat, South Africa, observe cooling during the LIA ~320 - 220 cal yrs BP with a drop in ~1°C compared to present temperatures (Tyson *et al*., 2000). Further evidence of this cooling event was observed in southern African tree rings (Dunwiddie and LaMarche 1980), oxygen isotopes (Talma and Vogel 1992) and pollen sequences (Scott 1996). This event provides regional as well as global evidence and significance of sea-level variability and can provide further evidence for local sea level fingerprints if these signals can be accurately identified (Tyson *et al*., 2000; Rignot *et al*., 2011).

4.2. Natural versus anthropogenic influences

Sea level variation has been a natural phenomenon occurring over geological time scales and was primarily due to tectonic processes, formation of the ice sheets and periods of warming and cooling (Meyssignac and Cazenave 2012; Becker *et al.*, 2014). Over shorter time scales, sea-level variability is driven by natural forcing and ocean-atmospheric processes (Meyssignac and Cazenave 2012). However, since the start of the industrial era (1760 AD), sea level has been affected by anthropogenic climate forcing (Meyssignac and Cazenave 2012; Kopp *et al*., 2019). The global acceleration in sea-level rise observed in recent times has been attributed to thermal expansion, loss of land-based ice and accelerated greenhouse gas emissions (Khan *et al*., 2015). These changes are clearly observed through the natural consequences; however, the effect of anthropogenic activities on these changes are uncertain (Kopp *et al*., 2012; Becker *et al*., 2014). Despite a clear increase in climatic change since the 1700s due to anthropogenic activity such as the production of greenhouse gases, there remains no clear way to disentangle natural and anthropogenic signatures (Meyssignac and Cazenave 2012). Therefore, models and projections of sea level consider different scenarios of greenhouse gas emissions based on human activity as a method to account for this anthropogenic signal, as seen with IPCC models (Jevrejeva *et al*., 2010; Kopp *et al*., 2019; IPCC 2021). The acceleration from the industrial era is clearly observed, yet the separation of natural versus unnatural causes remain questionable, with the closest degree of estimation being carbon emissions (Kopp *et al*., 2019).

5. Future Directions

5.1. Knowledge gaps

Past sea-level variability has been studied using proxy data, with more recent time periods using proxy data and instrumental data due to the limited, discontinuous instrumental record of less than 60 years of data (Rautenbach *et al*., 2019). Proxy data which is more far-reaching, helps extend the sea-level record and improve the available data (Church *et al*., 2013). Despite the long-term records this approach provides, sea-level variability has been greatly affected since the industrial era, with a rapid acceleration in sea level recorded in the post-industrial era, and projected to continue to rise (IPCC 2021; Church *et al*., 2013). The instrumental record captures the post-industrial changes, however, there is no data available for pre-industrial changes (Meyssignac and Cazenave 2012). Sea-level change in the 20th century compared to the late Holocene was influenced by different conditions, with the latter experiencing more natural conditions. Sea-level rise in the 20th century is a product of natural and anthropogenic factors, however, it is difficult to disentangle natural versus anthropogenic signals of sea-level change (Meyssignac and Cazenave 2012). There is a lack of a baseline of sea-level conditions to which sea-level can be compared against from recent time periods. Global sea level estimates have been produced, however, these models remove complexities to generate a generalized trend, causing regional and local trends to vary from global estimates (Barlow *et al*., 2013; Horton *et al*., 2018). To investigate the difference in trends, studies can provide detailed regional and local data that can be compared to global trends and provide an improved interpretation of the noted variability (Mather and Stretch 2012). These regional and local studies can provide high-resolution sea-level records that capture the variability, and can allow for anthropogenic signals to be detected (Meyssignac and Cazenave 2012; Horton *et al*., 2018). These records need to be robust and reliable and can be improved by the implementation of dating controls ((Barlow *et al*., 2013; Cooper *et al*., 2018) for improved error estimation, and statistical approaches used to increase the reliability of reconstructions (Barlow *et al*., 2013; Cooper *et al*., 2018). However, quantifying errors can be difficult due to environmental complexity (Meyssignac and Cazenave 2012) and the difference in sea level methodologies used to gather data (Cooper *et al*., 2018). Methods can be developed to assess the reliability of reconstructions such as dissimilarity coefficients, as sea-level studies can be limited by the material available (Barlow *et al*., 2013).

5.2. Future challenges

Rising sea level present a major ecological and economic risk; to address this, the geological record needs to be examined and inform future planning (Horton *et al*., 2018). The anthropogenic influence on natural systems has added further complexity to these, and requires finer resolutions to disentangle natural versus anthropogenic forcing (Kopp *et al*., 2012; Horton *et al*., 2018). Sea-level records require a higher spatial and temporal resolution to provide more reliable data which will improve the validity of interpretations (Cooper *et al*., 2018), and can provide larger databases of sea-level records, which future studies can use as a tool for verification. This will improve data accessibility and assist in quantifying errors, further constraining sea level estimates (Cooper *et al*., 2018). There is a need to combine tide gauge and satellite altimetry data (Rautenbach *et al*., 2019) which can provide good comparisons of recent sea-level estimates. This has been partially addressed by the Permanent Service for Mean Sea Level (PSMSL), which provides a global database for sea-level change through tide gauge records (Woodworth and Player 2003). The limiting factor is the difference in the length of tide gauge and altimetry data gathered due to the availability of equipment and skills globally (Rautenbach *et al*., 2019). Opportunities lie in assessing what local and regional sea level trends contribute to the global sea level trends and finding underlying signatures based on solar periodicities, anthropogenic influences, or natural outcomes (Fitchett *et al*., 2017). This can be achieved by the identification of key study sites (Cooper *et al*., 2018), proxies and debates surrounding the current applications of sea-level research in an effort to advance research and build upon existing work (Barlow *et al*., 2013; Fitchett *et al*., 2017).

6. Conclusions

Southern Africa is an excellent region to study global sea-level changes as there is an abundance of suitable far-field sites and proxies along the coastline. These sea-level proxies have been used successfully, globally and locally, to elucidate past sea level and broadly consist of archaeological, geological and biological proxies. These proxies allow for past environmental conditions to be explored through uniformitarian principles. Qualitative sea-level reconstructions of sea level have progressed to quantitative reconstructions of sea level. This was possible due to the progression in the application of sea-level proxies such as diatoms and foraminifera, which allow for statistical analysis of data through transfer functions. The application of high-resolution transfer functions over longer timescales locally has advanced the reliability and robustness of sea-level reconstructions and provides further paths for sea-level research to progress in southern Africa. The sea-level proxy record of southern Africa is diverse and provides an opportunity to build on existing studies as well as apply new proxies to infer past sea level. The increase in sea level data can provide a baseline for comparison and verification with proxy studies and help extend the limited instrumental record and provide a more detailed reconstruction of sea-level change in southern Africa. Advancement in dating techniques alongside the progression of sea-level research will ensure more accurate dating methods, tide gauge data and reliable proxy data for models. These improvements can fill gaps in the southern African sea-level record and constrain estimates of existing studies and future studies to provide us with a better understanding of recorded highstand and lowstand events. Tracking these changes can provide possible explanations for variability in the sea-level record and can lead to attempts at quantifying these variations to determine if the cause is natural or anthropogenic. There is much uncertainty surrounding the anthropogenic effects and solar periodicities of sea-level variability, which can affect future sea-level projections. There is a need for local and regional data and studies that address these finer scales of sea-level variability, which can help with uncertainties and improve the reliability of sea-level projections. There is much potential for sea-level research in southern Africa, with studies building upon early research to improve sea-level estimates and provide a larger database of southern African sea-level change.

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Paper II

A late-Holocene sea-level reconstruction using saltmarsh foraminifera from the Kromme Estuary, South Africa

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Abstract

Global mean sea level has greatly accelerated in the 21st century and is projected to continue to rise to the end of the century, presenting socio-economic threats to coastal areas and damage to natural ecosystems such as flooding, erosion and the destruction of infrastructure. Southern Africa is a far-field site with abundant saltmarsh environments that provide an opportunity to gather evidence on past sea-level changes to better understand sea-level variability and inform future projections. This study investigates late Holocene sea level from the Kromme Estuary along the southern coastline of South Africa, using saltmarsh foraminifera derived from intertidal sediment deposits. Modern foraminiferal surface samples were collected at two marsh sites and used to develop a training set for a sea-level transfer function based on vertical zonation of modern foraminiferal assemblages. Intertidal stratigraphic transects were used to determine locations for coring. The master sediment core was analyzed for loss-on-ignition, grain size, and bulk density, which were used to select sample depths for Accelerator Mass Spectrometry (AMS) radiocarbon dating. Radiocarbon age determinations were used to produce a Bayesian age-depth model, spanning the past ~1 000 cal yrs BP, with a hiatus in the record from ~400 - 600 cal yrs BP. Downcore foraminiferal analysis revealed that calcareous species dominate the basal part of the record from, precluding quantitative sea-level reconstruction. These calcareous assemblages combined with low organic content and medium to coarse sand from ~340 cal yrs BP, suggest a marine environment. Agglutinated assemblages dominate the upper portion of the core with high organic matter and medium sand from ~180 cal yrs BP, and are used to reconstruct a quantitative sea-level curve for the past ~200 years. The lowest reconstructed sea level at ~180 cal yrs BP coincides broadly with the Little Ice Age (LIA; ~650 - 100 cal yrs BP), with the Maunder Minimum falling within the LIA (~305 - 235 cal yrs BP), when low solar activity and an expansion in global ice volume would have lowered global average sea level. This sea level minimum was followed by a rising trend which steadily increased to reach present day levels. The Kromme sea-level reconstruction is supported by

existing studies from southern Africa and captures recent increases in sea level, and the possible influence of the LIA climates on regional sea-level change.

1. Introduction

Global sea level is on the rise, with models projecting approximately 15 - 30 cm global average sea-level rise by the middle of the century under the SSP5-8.5 scenario (IPCC 2021). Increases in ocean temperatures causing thermal expansion, melting of glaciers and ice sheets have caused sea level increases at different spatial scales (Khan *et al*., 2015). The loss of the Greenland and Antarctic continental ice causes meltwater effects which further increases sea level (Khan *et al*., 2015; Kopp *et al*., 2019). Sea level rise is a major concern for coastal areas, as these areas will be affected by flooding, storm surges, and face the destruction of infrastructure and ecosystems (Horton *et al*., 2018; Kopp *et al*., 2019). The disturbance of these coastal ecosystems is expected to cause major economic, social and ecological losses, making it important to manage and mitigate this threat (IPCC 2021; Horton *et al*., 2018; Kopp *et al*., 2019). Developing regions, such as southern Africa, are vulnerable to the risk of these negative impacts due to the dependence on coastal regions as centers of economic activities; which is further exacerbated by highly populated and vulnerable coastal communities (Leck and Simon 2018).

There is a need to understand long-term sea-level variability and gather evidence to assist in mitigation and prepare for negative consequences to address the threats associated with sea-level rise. This can be achieved by studying and observing archaeological sites, geomorphology, proxies, and archives, as well as more recent instrumental records from tide gauges and satellite altimetry (Cooper *et al*., 2018). Estuarine systems are excellent natural archive locations to gather information on past sea level (Edwards and Wright 2015). These systems are exposed to tidal mechanisms, which influence floral and faunal distributions (Edwards and Wright 2015). These sites can be used to gather proxy evidence from areas such as saltmarshes which preserve microfossils well and can be used for biological proxy sampling (Scanes *et al*., 2017). Saltmarsh foraminifera are a widely used proxy for past environmental conditions and sea-level changes (Scott and Medioli 1986; Gehrels 1994; Barlow *et al*., 2013). These organisms are environmentally sensitive and secrete tests that preserve well in sediments and build up over time, thereby capturing palaeoenvironmental conditions (Ghosh and Filipsson 2017). Saltmarsh foraminifera provide a key biological proxy for studying, hindcasting, and reconstructing relative sea level, underpinned by the vertically zoned relationship of these organisms with elevation (Gehrels 1994). This technique uses transfer function models obtained from modern foraminiferal-elevation relationships to create past sea-level change models and assist in extending instrumental records further back in time (Barlow *et al.*, 2013; Cooper *et al.*, 2018). Foraminifera have been successful in assessing past sea-level changes as the technique has been successful in the global (Scott and Medioli 1986; Gehrels 1994; Gehrels *et al.*, 2001) and local contexts (Franceschini *et al.*, 2005; Strachan *et al.*, 2014; Strachan *et al.*, 2015, Strachan *et al.*, 2016).

Proxy data gathered from natural archives such as saltmarshes are valuable when coupled with instrumental data such as tidal gauges and satellites. In southern Africa, prior to 1993, sea-level variability was tracked with tide gauges that produced data with calibration errors, making it hard to reconcile with other records. Satellite data have notably improved the accuracy and reliability of tidal data (Mather *et al.*, 2009; Cooper *et al.*, 2018). Tidal records of southern Africa spanning the 20^{th} century until the present show an increase of + 1.87 mm y^{-1} for the west coast, an increase of + 1.48 mm y^{-1} for the southern coast, and an increase of + 2.74 mm y^{-1} on the east coast (Mather *et al.*, 2009). Similar trends have been documented at other southern hemisphere sites such as New Zealand (Gehrels *et al.*, 2012) and Australia (Church *et al.*, 2006). These differences have been attributed to northern hemisphere ice melt and changes in barometric pressure, indicative of changes in temperature, and subsequently sea surface temperatures (Mather *et al.*, 2009; Gehrels *et al.*, 2012). Meyssignac and Cazenave (2012) have recognised that anthropogenic forcing can play a significant role in these variations and global trends as opposed to strictly regional trends, and local scales at which the effects can be noticeable. However, these effects on local scales have yet to be addressed due to the difficulty in disentangling the signatures (Becker *et al.*, 2014) and the limited length of the instrumental record (Rautenbach *et al.*, 2019). Continuous instrumental data is available for more recent time periods, with older time periods showing inconsistencies and gaps in the records due to challenges with tide gauge data (Jury 2013; Rautenbach *et al.*, 2019). Palaeoecological data has been used in hindcasting to increase the temporal range of these records as well as improve the confidence of these models to better understand sea-level variability at different scales (Jury 2013; Cooper *et al.*, 2018; Rautenbach *et al.*, 2019) and explore the effect of anthropogenic forcing on sea-level variability (Meyssignac and Cazenave 2012).

Sea level change studies are well documented and conducted globally (Gehrels 1994; Gehrels *et al*., 2001) but are limited in the southern hemisphere and, more specifically, the southern African context (Cooper *et al*., 2018). The southern African coastline is a promising region to study sea-level change as it is a far-field site that has been tectonically stable and is situated far from major ice sheets, allowing for eustatic sea-level changes to be recorded (Norström *et al*., 2012; Khan *et al*., 2015; Cooper *et al*., 2018). Local sea-level research (Cooper *et al*., 2018) has been successfully conducted and has progressed from early beach rock studies (Ramsay 1995; Ramsay and Cooper 2002) to the use of various proxies such as diatoms (Norström *et al*., 2012; Kirsten and Meadows 2016; Sitoe *et al*., 2017; Kirsten *et al*., 2018), pollen (Baxter and Meadows 1999), stratigraphy (Compton 2001) and foraminifera (Franceshini *et al*., 2005; Strachan *et al*., 2014). Through the progression of these techniques, more robust and long-term evidence regarding past sea-level changes is attained. This will help inform and economise climate planning and climate system modelling at various scales (Ziervogel *et al*., 2014). Studies have used proxy techniques to build transfer functions from palaeoenvironmental data to reconstruct past sea level at s local scales (Strachan *et al*., 2014). This approach offers an opportunity to reconstruct past sea-level using proxies such as foraminifera (Strachan *et al*., 2014), however, higher resolution studies, an extension of the available record, and an increase in accuracy to understand the nature and drivers of sea-level variability is required. There is also a need to further constrain dates from previous studies to reduce variations in reconstructions, as seen with the discrepancies in the timing of a Mid-Late Holocene highstand (Cooper *et al*., 2018). Current sea-level studies suggest a highstand of ca. + 3.8 m between 6.5 and 5.5 ka BP, decrease to present levels with a positive oscillation around ca. 1.5 ka BP (Cooper *et al*., 2018). To further constrain these figures, data with reliable vertical control and dated material are needed to improve these predictions and explain the Mid-Late Holocene fluctuations.

By utilising long-term, high-resolution records, natural long-term sea-level variability can be compared to post-industrial sea-level variability to disentangle anthropogenic effects and help predictive models for future climate planning and policymaking, thus assisting southern Africa for future sea-level changes. There is an opportunity to expand and contribute to this research with regard to foraminiferal proxies from palaeorecords. This research investigates late Holocene sea level at the Kromme Estuary, South Africa, using foraminifera derived from saltmarsh sediment. Intertidal stratigraphic transects were used to determine locations for coring and modern surface foraminifera used to build a transfer function. A sea-level reconstruction is produced and compared with regional data from the southern African coastline.

2. Study site

The Kromme Estuary (34°08'S, 24°51'E) is classified as a permanently open estuary, with the mouth in St Francis Bay, located approximately 55 km west of Gqeberha, in the Eastern Cape (Fig. 1a). The estuary has a length of ~14 km (Baird and Heymans 1996; Wooldridge 2007). Major tributaries entering the Kromme river include the Geelhoutboom, Sand River and the Dieprivier. Tides are semi-diurnal, with a mean spring tidal range of 1.75 m and a neap tide range of ~0.57 m (Baird and Heymans 1996; Wooldridge 2007). A flood tide delta extends ~5 km from the mouth of the estuary, with high wave energy conditions prevailing in this area (Woolridge 2007). Saltmarshes make up an area of 100 ha, with the largest contiguous marsh, approximately 90 ha, located on the northern bank, 1.8 km upstream from the tidal inlet (Heymans and Baird 1995).

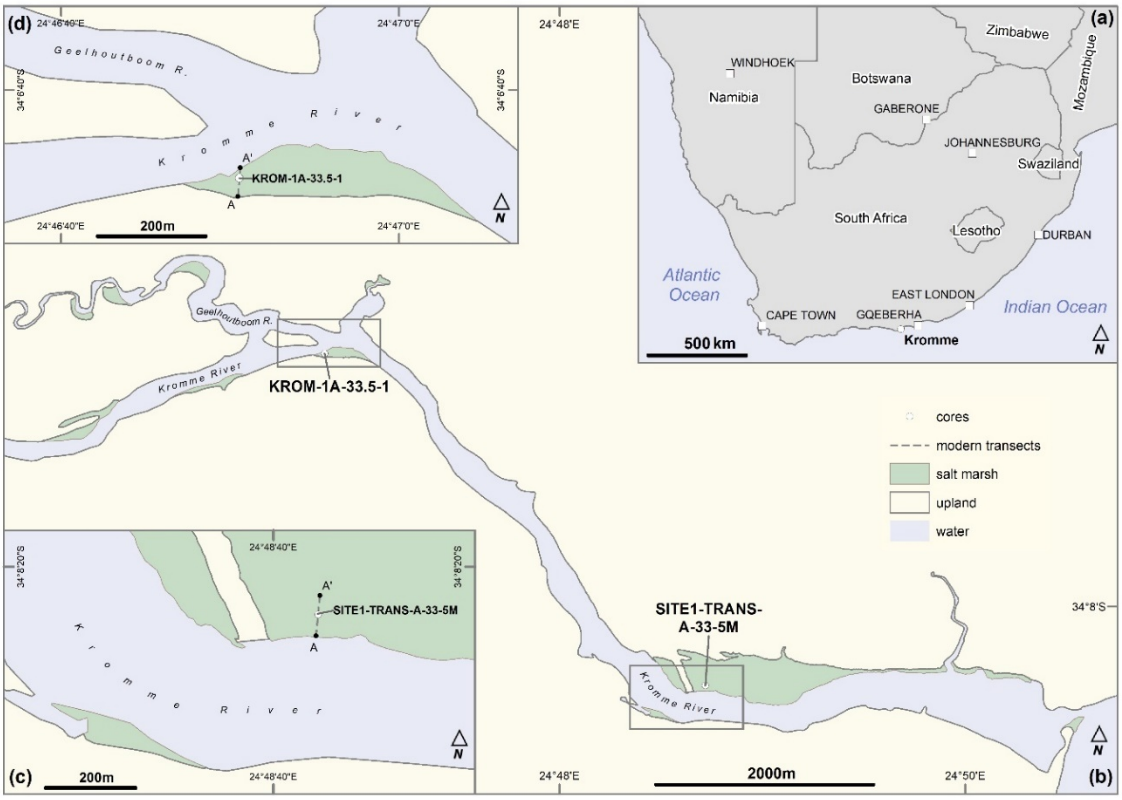

Figure 1. Map of (a) South Africa and locations of the (b) Kromme Estuary and sampled site one (c) and site two (d).

There is no industrial or waste disposal activity evident in close proximity to the Kromme Estuary. The Kromme River has the Kromme Dam constructed in 1943 and the Mpofu Dam constructed in 1984 (Woolridge 2007). Agricultural activities in the catchment area include livestock farming and grain cultivation (Sale *et al*., 2009). A road bridge bisects the saltmarshes approximately 3 km from the sea near the estuary mouth (Fig. 1b). Waterfront housing and private land are located away from the saltmarshes (Baird *et al*., 1981).

3. Methods

3.1. Field sampling

Transects were orientated channel-perpendicular in order to capture the full environmental gradient of the saltmarsh, from the high marsh to the intertidal mudflats. Elevation changes were surveyed along the transects using a dumpy level and related to differential GPS data (Trimble Pro XRT). Vegetation was recorded at 1 m intervals along the transects using the Braun-Blanquet method (Poore 1955) scale (Fig 2.). Surface sediment samples were collected at every 5 cm change in elevation using a 10cm diameter Pitman corer, together with corresponding pH, temperature and salinity readings, using a conductivity and pH meter. Collected surface samples were subsampled via volumetric displacement within 24-hours, removing 5 cm^3 from the top 1cm of each surface sample and placed it into a buffered Rose Bengal-ethanol solution, diluted with 20% distilled water. Stratigraphy of the saltmarsh sites was surveyed at 4 m intervals along the transect using a 20 mm gouge auger and classified using the Troels-Smith (1955) classification system. An intertidal stratigraphic transect was sampled at site one only (Fig.1c). A master sediment core was collected (KROM-1-A-33.5), reaching a depth of 165 cm using a 56 mm gouge auger, along with five replica cores and a corresponding GPS point. Core KROM-1-A-33.5 was analysed for foraminifera, sedimentology, and chronology.

3.2. Laboratory analysis

Core KROM-1-A-33.5 was subsampled at 1 cm intervals for sedimentological analysis, collecting 5 cm^3 sediment per subsample. Samples were weighed before being placed in an oven at 100°C for approximately 8 hours to dry. Samples were left to cool and weighed after being placed in the oven for dry mass and dry bulk density calculations. Samples were placed in a furnace at 550°C for ~16 hours, left to cool, and weighed again. Core samples were analysed for loss on ignition (LOI) by determining the difference in dry mass after being placed in the furnace, indicative of the organic content lost (Zhang *et al*., 2014). Laser Diffraction Analysis (LDA) was run on sediment from the remaining inorganic fractions using a Malvern Mastersizer 2000.

The core was subsampled at 4 cm intervals extracting ~5 cm^3 of sediment, yielding 41 samples referred to as fossil foraminifera, which were processed for foraminiferal analysis following Scott and Medioli (1986). Samples were sieved using aperture sizes of 63 µm and 500 µm. Samples fractions between 63 - 500 µm and >500 µm were retained for analysis and volumetrically divided into eight aliquots using a wetsplitter. The samples were then transferred into 5 ml Eppendorf vials using a buffered alcohol solution.

A Leica (Leica EZ4) stereomicroscope was used for counting and identifying foraminifera at a magnification of 60X, 80X, and 100X. Fossil foraminifera minimum counts were 250 individuals per sample, and aliquots were counted and identified to completion. The recommended minimum count size was 75 - 100 individuals for a stable Holocene paleo-marsh and subsequent relative sea-level reconstruction (Kemp *et al*., 2020). Identification guides were used to classify foraminifera (Murray 1971; Murray 1979).

The Constrained Incremental Sum of Squares (CONISS) (Grimm 1987) technique was applied to sedimentological and foraminiferal data and used to identify important stratigraphic bounds for Accelerator Mass Spectrometry (AMS) dating (Olsen *et al*., 2017). Six samples for dating were prepared. Plant macrofossil remains, including leaves, seeds, wood, and charcoal, were manually picked under a dissecting microscope to reach a minimum dry mass of 300 mg for AMS dating at Beta Laboratories (Florida, USA).

3.3. Data analysis

Radiocarbon age determinations were calibrated using the SHCal 20 calibration curve (Hogg *et al*., 2020), and modern ages were calibrated using postbomb Southern Hemisphere curve, zones 1 - 2 (Hua *et al*., 2016). A Bayesian age-depth model was established for the sediment using Bacon source code (Blaauw and Christen 2011) in the R Software environment.

Downcore foraminiferal abundance was plotted against depth data to produce stratigraphic diagrams that included mean grain size and LOI using R Software and the Rioja package (Juggins 2020). A modern foraminiferal training dataset was used to run ordination and regression analyses. The minimum modern foraminiferal counts were 40 individuals and comprised dead assemblages with < 5% of rare species removed to create a suitable training dataset that excluded seasonal influence (Kemp *et al*., 2020). The training set comprised 41 samples. The modern analogue technique using R Software and the Rioja package (Juggins 2020) was used to assign dissimilarity coefficient (MinDC) values to all fossil samples. Cut-off and percentile values for analogues follow those of Watcham *et al*. (2013), the 5th percentile represents a good modern analogue, samples exceeding the 5th percentile represent a close analogue, and samples exceeding the 20th percentile represent a poor analogue.

Detrended correspondence analysis (DCA) was used to determine the environmental gradient length of the modern foraminiferal data set in standard deviation (SD) units (Ter Braak and Prentice 1988). Gradient lengths < 2 SD indicate species respond linearly to the environmental variable, and > 2 SD indicate species respond non-linearly to the environmental variable (Ter Braak and Prentice 1988; Palmer 2004). The modern data had a length of 2.2 SD units, and therefore a unimodal regression model was suitable for developing a transfer function (Gehrels 1999; Kemp and Telford 2015). R Software and the Rioja package (Juggins 2020) was used to develop a Weighted Average Partial Least Squares Regression (WAPLS) and Weighted Average (WA) transfer function with bootstrapping cross-validation with 1 000 bootstrapping samples. The transfer function was applied to foraminiferal and environmental data to produce a mean sea-level reconstruction, which was plotted against interpolated ages derived from the Bayesian age-depth model.

4. Results

4.1. Modern foraminifera and saltmarsh vegetation

Vegetation was recorded along the transects, with dominant vegetation types noted. For KROM 1A, the high marsh consisted of *Juncus kraussii* and *Sarcocornia sp*. The middle marsh consisted of *Chenolea diffusa* and *Sarcocornia perennis*. The lower marsh consisted of *Sarcocornia perennis*, *Spartina maritima*, and *Zostera capensis* (Fig. 2). For KROM 2A, the high marsh consisted of *Limonium scabrum* and *Sarcocornia perennis*. The middle marsh consisted of *Sarcocornia perennis* and *Triglochin striata*. The lower marsh consisted of *Spartina maritima* (Fig. 2).

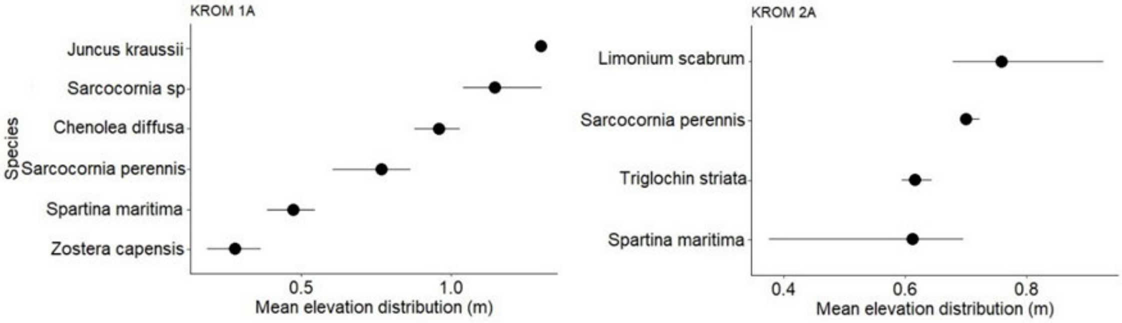

Figure 2. Optimal elevation tolerance of saltmarsh vegetation at Kromme Estuary for transects KROM 1A and KROM 2A. The black dot represents the midpoint of tolerance for each species.

Modern foraminifera were well preserved along the KROM 1A, and KROM 2A transects, with all tests identified and intact with little to no damage. A total of five species were identified for both transects. These included agglutinated species *Trochammina inflata*, *Jadammina macrescens*, *Miliammina fusca,* and calcareous species *Quinqueloculina sp.* and *Ammonia sp*. (Fig. 3). These species made up the modern training set for the transfer function, with the exception of *Quinqueloculina sp.,* which was absent from the fossil dataset. Species *M. fusca* and *T. inflata* were found in high marsh niches, *J. macrescens* in middle marsh zones, *Quinqueloculina sp.* in low marsh niches or near the estuary mouth, and *Ammonia sp.* in the low marsh and tidal flat niches. Agglutinated species dominated the assemblages along the modern transects, with *T. inflata* the most dominant, followed by *M. fusca* for KROM 1A and *J. macrescens* for KROM 2A. *Ammonia sp.* comprised the lowest percentage of the total species counts species for KROM 1A but had higher counts in KROM 2A (Fig. 3). *Quinqueloculina sp.* was only observed from the middle to low marsh towards the lower marsh, with sporadic abundance for both transects. In the low marsh to middle zones, *Ammonia sp*. was the most dominant species, together with less frequently occurring *T. inflata* and *Quinqueloculina sp.* (Fig. 3). KROM 1A living and dead species show similar distributions and counts. However, dead *Ammonia sp*. counts are noticeably higher than living counts for the transect. KROM 2A living and dead species distributions and counts were similar. However, dead *M. fusca* counts were noticeably higher than living counts. Agglutinated species showed a decreasing trend closer to the lower marsh, with calcareous species increasing. The transition to the low marsh and intertidal zones showed a significant decrease in agglutinated species and an increase in calcareous species for both transect KROM 1A and KROM 2A.

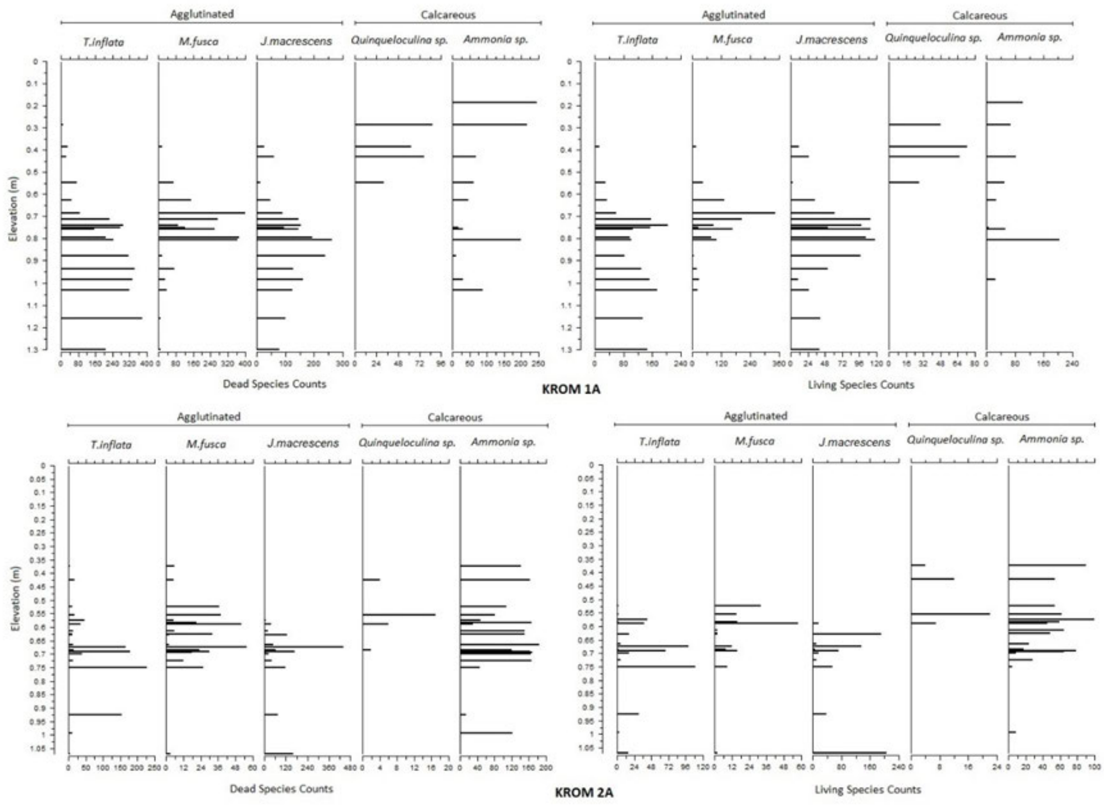

Figure 3. Living versus dead species counts of modern foraminifera from the Kromme Estuary for site one, transect KROM 1A and site two, transect KROM 2A.

4.2. Stratigraphy

The sediment core extended to a depth of 163 cm and was subdivided into six lithological units based on Troels-Smith sediment descriptions (0 - 22 cm, 22 - 55 cm, 55 - 67 cm, 67 - 82 cm, 82 - 110 cm, 110 - 163 cm) (Fig. 4). Core KROM-1-A-33.5 was subdivided into F1 (163 - 96.5 cm) and F2 (96.5 - 0 cm) based on CONISS analysis of foraminiferal assemblage data (Fig. 5). Mean grain size, LOI, and bulk density were analysed for each of these sedimentological units.

The lowest unit, F1, had a very low organic content, with LOI values fluctuating between 4 - 1.5% (Fig. 5). The mean grain size rangeed between 1.4 - 0.7φ (medium sand to coarse sand) and remained relatively consistent throughout the unit (Fig. 5). The bulk density fluctuated between 2.9 - 1 g/cm^3 (Fig. 4).

The upper unit, F2, showed a trend of increasing organic matter toward the top of the unit, with LOI values ranging between 1 - 19% (Fig. 5). The mean grain size ranged between 1.3 - 0.4φ (coarse sand) and fluctuated, with a trend of decreasing mean grain size toward the top of the core, with 1 - 6 cm, having the largest grain sizes (coarse sand to medium sand) within the unit (Fig. 5). Similarly, the bulk density fluctuated with an increasing trend toward the upper limit of the core ranging between 4 - 1 $g/cm^{3,}$ with a minimum of 0.91 g/cm^3 occurring between 1 - 5 cm (Fig. 5). The uppermost portion of F2 had high organic matter with LOI values of ~21%, marking the highest organic content of the core (Fig. 5). The mean grain size ranged between 1.6 - 0.9φ (coarse sand) (Fig. 5). The bulk density was the lowest at ~0.8 g/cm^3, compared to the rest of the core (Fig. 5).

4.3. Chronology

AMS radiocarbon age determinations and their calibrated ages are presented in Table 1, with the corresponding Bayesian age-depth model (Fig 4.) The accumulation rate was an average of 5 cm y^{-1}. A hiatus was designated at a depth of 131 cm between ~400 - 600 cal yrs BP, based on CONISS results, the difference in date at 128 cm (~390 cal yrs BP) compared to the basal date of ~1 000 cal yrs BP, and the difference in accumulation rates from 0 - 130 cm of 3.06 cm y^{-1} compared to the accumulation rates from 130 - 163 cm of 9.15 cm y^{-1}

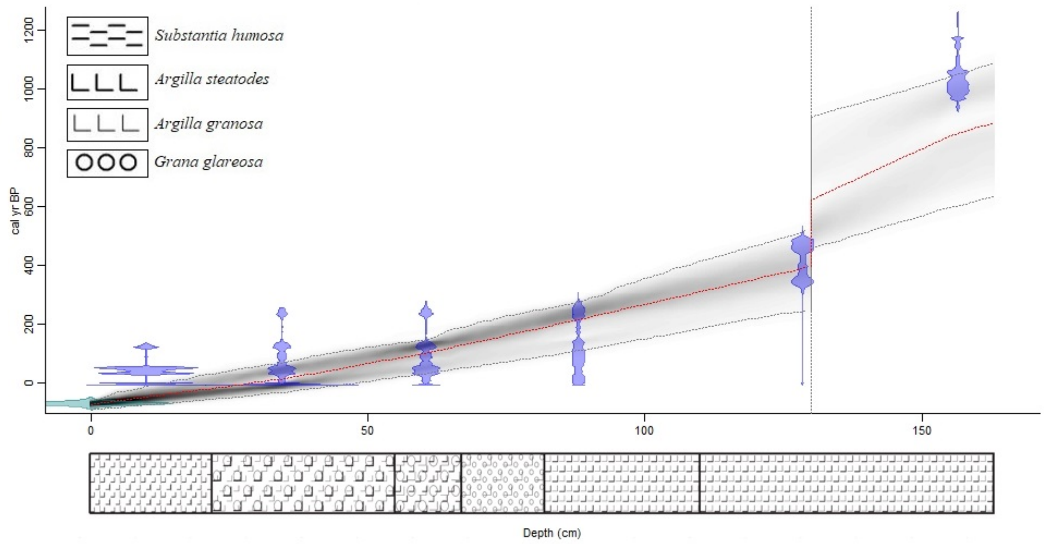

Figure 4. Chronostratigraphy from core KROM-1-A-33.5 core one with associated Troels-Smith stratigraphic description and calibrated age-depth model. The dotted line at 131 cm indicates the position of the hiatus.

Table 1: Radiocarbon results for sampled KROM-1-A-33.5 with calibrated and uncalibrated ages.

Lab Code	Depth (m)	Material	$^{13}C/^{12}C$ (‰)	^{14}C year BP	Cal years BP (2 SD)
Beta-595414	9.5-10.5	Rhizome nodules, stems and leaves	-24	109.38 ± 0.41 pMC	-49 - -53 (93.9%)
Beta-595413	34-35	Stems, charcoal, rhizomes, wood chips and seeds	-27.6	30 ± 30	70 - 24 (74.5%
Beta-595412	60-61	Stems, charcoal and wood chips	-23.8	90 ± 30	140 - 4 (85.4 %)
Beta-602318	88-89	Wood chips and charcoal	-27.1	160 ± 30	151- Post BP 0 (68.6 %)
Beta-602319	128-129	Wood chips and charcoal	-28.5	410 ± 30	499-435 (52.2 %)
Beta-602320	155-156	Woody material	-28.3	1180 ± 30	1078-956 (90.1%)

4.4. Fossil foraminifera

A total of four species were identified from sediment core KROM-1-A-33.5, *Trochammina inflata*, *Jadammina macrescens*, *Miliammina fusca,* and *Ammonia sp*. The average foraminifera test concentration for the core was 82.92 cm^3 with low concentrations (< 40) at depths of 20 - 32 cm, 68 - 108 cm, and 140-152 cm. The CONISS zones mark changes in foraminiferal species assemblages with the depth of the core. Agglutinated foraminifera consist of *T. inflata*, *J. macrescens,* and *M. fusca*, with *Ammonia sp*. defining the calcareous component of the foraminifera species assemblage. Agglutinated species were dominant in the top depths of the core at F2 and gradually decreased down the core intercalated with the low concentration depths identified. Overall, *M. fusca* made up the lowest percentage of the agglutinated assemblage at 12%, with the highest, *J. macrescens* at 48% and the remaining 40% made up by *T. inflata*. Calcareous *Ammonia sp*. species dominated the lower portion of unit F1, and from 112 m, comprised 100% of the species assemblage (Fig. 5).

The 5th percentile was used as a cut-off for a good modern analogue with a coefficient value of 0.04 (Fig. 5). Samples exceeding the 5th percentile are deemed a close analogue (Fig. 5). Of the 14 samples analysed, 1 sample was a poor analogue with a coefficient value of 0.07 at 0 m. The remaining 13 samples had favourable coefficient values and were deemed as good modern analogues (Fig. 5).

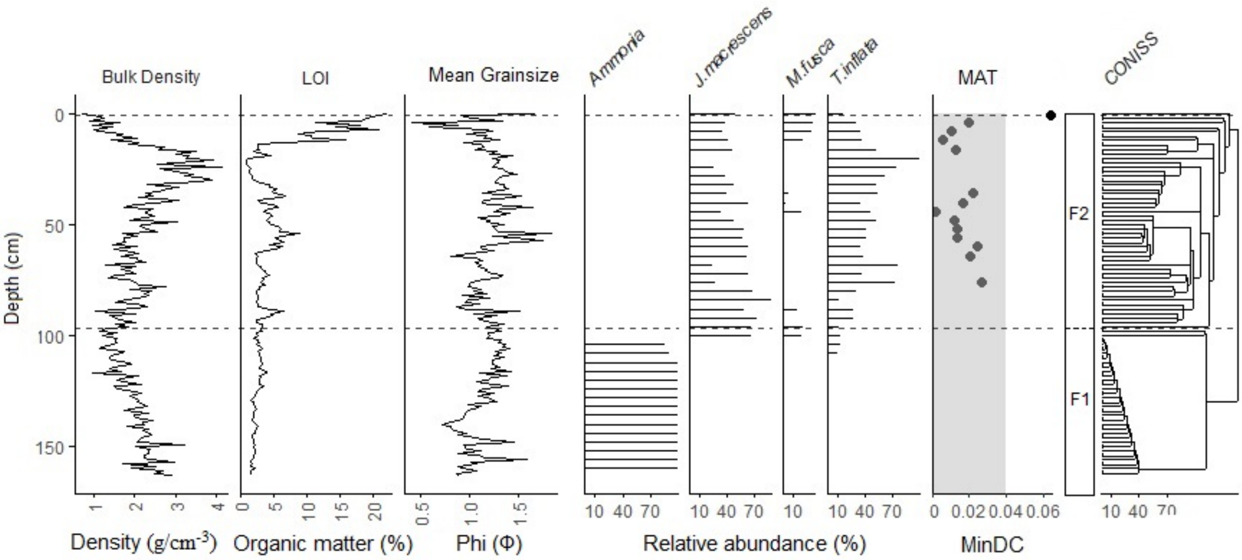

Figure 5. Foraminiferal species assemblages represented at 4 cm intervals, and associated bulk density, LOI, and mean grain size represented at 1 cm intervals. The shaded portion for the modern analogue (MAT) indicates a good analogue and the unshaded a close analogue. Indicated in the figure are the CONISS derived zones (F1-F2) from foraminiferal assemblages.

4.5. Transfer Function

Summaries of model performances applied to the transfer function were compared (Table 2). The observed and predicted values for the different models used were compared (Fig. 6). The Weighted Averaging Monotonic and Weighted Averaging Monotonic Tolerance-down-weighted models had the best model performance of $r^2 = 0.5813$ and $r^2 = 0.5257$, respectively (Table 2). The correlation between the Weighted Averaging Monotonic and Weighted Averaging Monotonic Tolerance-down-weighted was relatively similar and showed a deviation compared to the other models (Fig. 6). The Weighted Averaging Monotonic model predicted and observed variables showed the least deviation for a good correlation compared to other models, with Weighted Averaging Monotonic Tolerance-down-weighted relatively close. The other models had a relatively poor model performance with a higher deviation of predicted and observed variables.

Table 2: Performance statistics of tested models. Weighted Averaging Partial Least Squares Regression (WAPLS), Weighted Averaging Classical (WA_cla), Weighted Averaging Classical Tolerance- down-weighted (WA_cla_tol), Weighted Averaging Inverse (WA_inv), Weighted Averaging Inverse Tolerance-down-weighted (WA_inv_tol), Weighted Averaging Monotonic (WA_m) and Weighted Averaging Monotonic Tolerance-down-weighted (WA_m_tol).

Model	**Model Performance**			**Cross-Validation**		
	RMSE	**r^2**	**Max Bias**	**RMSE**	**r^2**	**Max Bias**
WAPLS	0.1740	0.4084	0.3570	0.2047	0.2685	0.4097
WA_cla	0.2960	0.3689	0.2205	0.3277	0.3552	0.2324
WA_cla_tol	0.2787	0.3973	0.2249	0.3009	0.3708	0.2212
WA_inv	0.1798	0.3689	0.4193	0.1983	0.2763	0.4568
WA_inv_tol	0.1757	0.3973	0.3971	0.1967	0.2931	0.4432
WA_m	0.1467	0.5813	0.2859	0.1928	0.3875	0.3555
WA_m_tol	0.1560	0.5257	0.2798	0.1952	0.3602	0.3609

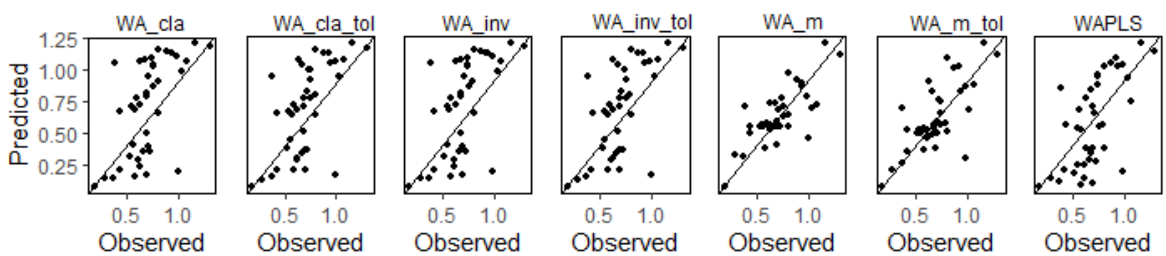

Figure 6. Comparison of predicted versus observed data for implemented models.

4.6. Reconstruction

Indicative meanings of palaeomarsh surface elevations were converted into sea-level index points (SLIP's) following the methods of Gehrels (1999). The formula was:

$SLIP = H - D - I$

where H is the modern sample height relative to current mean sea level in meters, D is the depth of the fossil sample from the sediment core in centimetres, and I is the indicative meaning of palaeomarsh surface elevations in meters.

The transfer function was applied to the screened fossil foraminifera data to generate a sea-level curve and associated errors for each point (Table 3). Each sample was chronologically constrained using interpolated dates from the Bayesian age-depth model with associated asymmetrical minimum and maximum errors due to the use of a t-distribution to calculate errors.

Table 3: Results from the Weighted Averaging Monotonic transfer function applied to the fossil data.

Depth (cm)	Median Modelled Age (cal yrs BP)	Minimum Age Error (yrs)	Maximum Age Error (yrs)	Indicative Meaning (m above MSL)	Sea Level Error (± m)	Sea Level (m)
0	-73,6	-93.4	-60.1	0,7410535	0,414825992	-0,0770535
4	-68,2	-87.4	-51.5	0,7582096	0,422666816	-0,1342096
8	-63,1	-81.9	-39.7	0,7613298	0,424067744	-0,1773298
12	-55,3	-76.3	-22.8	0,7679984	0,427702834	-0,2239984
16	-44,1	-70.7	3.1	1,0264862	0,551326935	-0,5224862
36	18,7	-6.2	82.3	0,9502101	0,511474557	-0,6462101
40	33,5	-2.5	92.9	0,8892326	0,48874495	-0,6252326
44	52,9	6.9	105.9	0,7803525	0,43255545	-0,5563525
48	68,4	12.2	117.8	1,0247246	0,550471235	-0,8407246
52	83,2	19.9	128	0,9552966	0,519068437	-0,8112966
56	100,4	27.1	138.7	0,9568842	0,519748302	-0,8528842
60	121,7	40.4	152	0,9191912	0,503853615	-0,8551912
64	133,9	48.3	175.3	0,9287849	0,507860261	-0,9047849
76	184	86.6	239.3	1,1612745	0,62821105	-1,2572745

112	345,5	241.7	413.7	-	-	-
116	362,5	255.6	433.6	-	-	-
120	381,8	273.8	448.9	-	-	-
124	403,4	285.3	462	-	-	-
128	439	319.7	483.6	-	-	-
132	917,1	749.9	1093.7	-	-	-
136	931,9	792.6	1108	-	-	-
156	1023,6	945.3	1178.7	-	-	-
160	1043,1	969.2	1203.9	-	-	-

The reconstructed sea-level curve for Kromme Estuary (Fig. 7) shows a gradual increase in sea level (-1.26 m) from ~180 cal yrs BP, followed by a sudden increase in sea level from -0.84 m ~68 cal yrs to -0.56 m around 53 cal yrs BP. A minor decrease of sea level between ~30 - 20 cal yrs BP is observed, followed by a rapid and steady increase until present sea level. Species assemblages from 112 cm to the bottom of the core were only calcareous, preventing a quantitative inference on sea level. The calcareous assemblages from ~345 cal yrs BP are indicative of a marine environment.

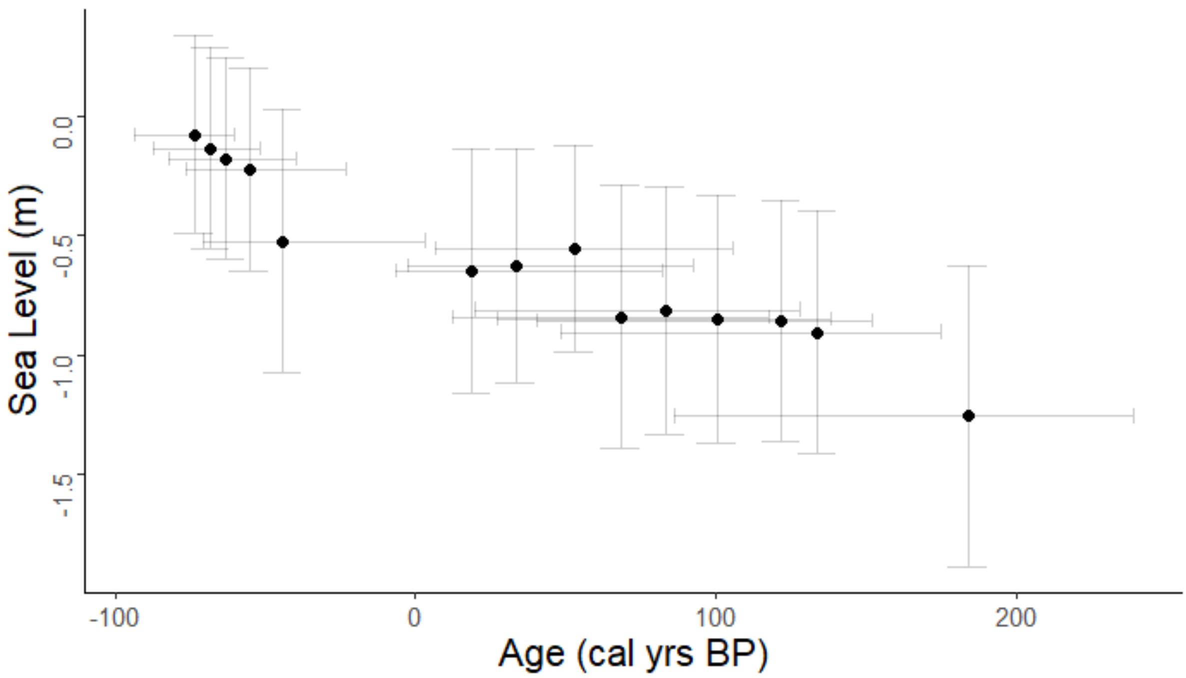

Figure 7. Reconstruction of relative sea-level change for the Kromme Estuary.

5. Discussion

Core KROM-1-A-33.5 shows a high abundance and low diversity of foraminiferal species. The bottom zone, F1, is dominated by calcareous species, namely *Ammonia sp*., indicating low marsh and tidal flat environments, which are dominated by marine conditions (Scott and Medioli 1978; Gehrels *et al*., 2001; Strachan *et al*., 2017). The upper zone (F2) is dominated by agglutinated species, namely *M. fusca, J. macrescens*, and *T. inflata*. These species are indicative of high marsh and vegetated zones (Scott and Medioli 1978). The observed diversity of four species is lower when compared to previous studies conducted along the southern African coastline with eight (Franceshini *et al*., 2005) and thirteen (Strachan *et al*., 2014) recorded species. However, the high abundance ensures that assemblages are adequately characterised to produce a statistically robust transfer function and subsequent reconstruction (Kemp *et al*., 2020). The similarity of the sampled transects for each site, KROM 1A and KROM 2A, indicate that modern foraminifera used for the training set reliably represent the modern-day marsh conditions. Differences in living and dead species counts can be attributed to seasonal influence (Kemp *et al*., 2020). However, dead assemblages were only used in this study, eliminating any biases of seasonality on the training set. Transfer functions are driven by the most abundant species in the dataset, with scarce species often excluded to influence the model to a lesser extent (Kemp *et al*., 2020). *Quinqueloculina sp.* was excluded from the transfer function due to the species absence in the fossil dataset. The Weighted Average transfer function applied is driven by abundant species rather than rare species (Kemp *et al*., 2020). Therefore, it is unlikely that the exclusion of *Quinqueloculina sp.* would affect palaeomarsh estimates.

The mean grain sizes of core KROM-1-A-33.5 show a trend of progressively decreasing size up the core, with organic matter increasing up the core. These trends are similarly observed in the Troels-Smith interpretation of the stratigraphy with lower units comprised of larger particles and fewer organics, compared to upper units with smaller particles and higher organics. This is indicative of a decrease in environmental energy from the intertidal zone, progressing to the middle to higher marsh, and is supported by foraminiferal species present (Strachan *et al*., 2017). Bulk density increases up the core except for an initial maximum recorded at 24 cm from the surface of the core. This supports the implied trend of progression from an intertidal environment to low marsh and high marsh environments, progressing to the top of the core (Scott and Medioli 1978; Gehrels *et al*., 2001; Franceshini *et al*., 2005). The intertidal conditions can be supported by the presence of calcareous species from a depth of 112 cm to the bottom of the core, dated at ~345 cal yrs BP in the Kromme record.

The reconstruction of sea level from the Kromme Estuary shows that from ~345 cal yrs BP, species are only calcareous. This is indicative of higher than present sea level from ~345 cal yrs BP till the end of the Kromme record at ~1 000 cal yrs BP. A study conducted on beach rock on the east coast of southern Africa by Siesser (1974) observed modern beach rock in Mozambique. The beach rocks were radiocarbon dated at 910 - 920 ± 140 cal yrs BP. It is suggested that sea level around 842 ± 215 cal yrs BP were equivalent to present-day sea level (Siesser 1974; Strachan *et al*., 2014). These findings differ compared to Compton (2001) as the west coast study observed lowstands between 700 - 400 cal yrs BP between -0.5 to -1 m to present mean sea level using radiocarbon dated bulk organic. A study at Knysna Estuary shows a similar lowstand trend reported on the southern coast (Marker 1997). In-situ tree stumps were used to determine these changes and were dated at approximately 682 ± 54 cal yrs BP (Marker 1997; Strachan *et al*., 2014). Marker (1997) observed the recorded lowstands coinciding with low sea surface temperatures oscillating between 1 - 3°C of the mean temperature at ~500 - 400 cal yrs BP, which may have contributed to a decrease in sea level. In the Kromme record, the lower than present sea level recorded by studies (Marker 1997, Compton 2001; Strachan *et al*., 2014) can be supported by the indicative marine environment between ~345 – 1 000 cal yrs BP (Fig. 8). Strachan *et al*. (2014) records dominant calcareous assemblages from ~1150 - 1490 cal yrs BP for which marine conditions were inferred. The timing of the calcareous assemblage dominance differ between the Kromme and Kariega records (Strachan *et al*., 2014) differ (Table 4). However, the Kariega record show sea level below present from ~330 cal yrs BP (Fig. 8), similar to the inferred marine environment from the Kromme record from ~345 cal yrs BP (Strachan *et al*., 2014).

At approximately 180 cal yrs BP, sea level is recorded at -1.3 m below present sea level. The ^{14}C date obtained at ~180 cal yrs BP coincides with lower than present temperatures, which can be attributed to the effects of the Little Ice Age (LIA) when glacial expansion would have lowered sea level (Marker 1997; Tyson *et* al., 2000). The LIA is defined broadly as a ~500-year period (~650 - 100 cal yrs BP) and the effects may not be captured by a short sea-level record (Jones *et al*., 2001; Matthews and Briffa 2005). However, the Maunder Minimum, a cold period that falls within the timing of the LIA, occurred between ~305 - 235 cal yrs BP, and coincides with low solar activity (Jones *et al*., 2001). The low sea level recorded at 180 cal yrs BP in the Kromme record broadly fall within the LIA, and follow the end of the Maunder Minimum.

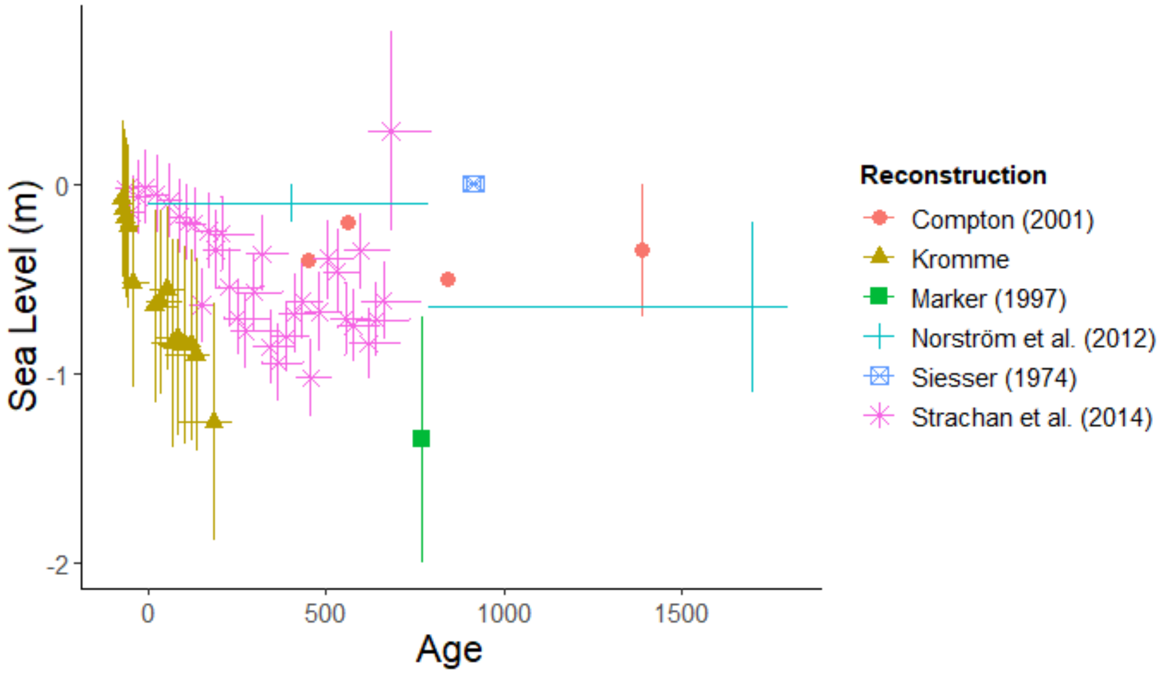

Figure 8. Reconstructed sea level from Kromme Estuary compared with previous sea-level evidence from the southern African coastline.

Stalagmite records from Makapansgat, Limpopo, South Africa, record cooler periods ~320 - 220 cal yrs BP with a drop in daily maximum temperature of approximately 1°C, as well as oxygen isotope records from Madagascan coral, which record a similar decrease in temperature (Tyson *et al*., 2000). This cooling was observed in tree rings from south western records of Cedarberg (Dunwiddie and LaMarche 1980) and eastern records of Karkloof (Tyson *et al*., 2000), which recorded changes in precipitation and temperatures which affected tree ring records. These cooling events can be observed in local patterns of climatic variability such as the Makapansgat and Madagascar records as well as global records of the Greenland oxygen isotope record, Canadian tree ring records and New Zealand tree ring records (Tyson *et al*., 2000). The Kromme record provides high-resolution changes in sea level during this period, further linking findings of both the southern and northern hemispheres, which can be used to further constrain the timing of the LIA and Maunder Minimum events and the effect on sea level (Marker 1997; Tyson *et al*., 2000).

Following the decreasing trend at ~180 cal yrs BP, there is a rapid and steady increase of sea level until the present. The trends of the increasing sea level of the Kromme record show similarity with the trends observed at Kariega Estuary (Fig. 8), with sea level approximately -0.2 - 0 m (Strachan *et al*., 2014). Compton (2001) and Strachan *et al*. (2014) have shown sea-level oscillations before 300 cal yrs, followed by a rapid increase in sea level as seen in the Kromme record from ~100 cal yrs BP to present. The Langebaan record (Compton 2001) suggests a rise from 400 cal yrs BP, and the Macassa Bay record (Norström *et al*., 2012) indicates a rise from 700 cal yrs BP from initial lower sea level. Recent sea-level rise from ~20 cal yrs BP present a rises rapid increase to current sea level.

Sea level estimates from recent time periods can be affected by natural variability and anthropogenic factors. The Kromme Estuary had the Mpofu Dam (1984) and Kromme Dam (1943) constructed with changes in freshwater inflow dropping from 117 x 10^6 m^3-a^{-1} to less than 2 x 10^6 m^3-a^{-1} after the dam construction (Baird and Heymans 1996), affecting sediment loads (Woolridge 2007). The salinity gradient changed from between 35 - 15 psu to a constant 35 psu, the system changed from plankton dominated system to a submerged benthic vegetation system (Baird and Heymans 1996), and there was a reduction in nutrient and sediment loads (Snow and Adams 2006). The effect of these changes has been explored for diatoms and algae (Bate and Adams 2000; Snow and Adams 2006); however, this has not extended to other micro-organisms such as foraminifera. Examination of the Kromme record shows no evidence of anomalous changes in foraminifera assemblages and the sediment record. The recent sea-level increase recorded by the Kromme record can be affected by the changes in species responses to salinity, sediment, vegetation and nutrient status, which could have affected species distribution after the construction of the dams. This can be explored by tracking the management of the dams and assessing environmental changes after the construction, and compare data to pre-construction environmental conditions. Possible changes resulting from the dam construction can introduce unknown variables in the estimates of the sea-level reconstruction and subsequently record this as an over-estimation or under-estimation of sea-level variability over the record. Quantifying any changes in sea level from older sea-level estimates to relatively modern estimates can yield data to discern possible anthropogenic effects on the system.

Table 4: Summary of sea-level estimates for southern Africa. An (*) indicates interpolated ranges from Strachan *et al*. (2014)

Age (cal yrs BP)	Sea Level Relative to Present (m)	Material	Site	Reference
910 ± 120	0	Beach rocks	Vilankulos	Siesser (1974)
910 ± 140	0	Beach rocks	Vilankulos	Siesser (1974)
770 ± 50	-2 to -0.7	Tree stumps	Knysna	Marker (1997)
450 ± 70	-0.4	Shell material	Langebaan	Compton (2001)
560 ± 45	-0.2	Shell material	Langebaan	Compton (2001)
840 ± 45	-0.5	Shell material	Langebaan	Compton (2001)
1390 ± 50	0 to -0.7	Shell material	Langebaan	Compton (2001)
*0-790 (2 SD)	-0.2 to 0	Shell material	Macassa Bay	Norström *et al*. (2012)
*4700-790 (2 SD)	-1.1 to -0.2	Diatoms, mineral magnetic properties and stable carbon and nitrogen isotopes	Macassa Bay	Norström *et al*. (2012)
-60 ± 22.5	-0.024 ± 0.198	Foraminifera	Kariega	Strachan *et al*. (2014)
-19 ± 35	-0.149 ± 0.196	Foraminifera	Kariega	Strachan *et al*. (2014)
29 ± 70	-0.067 ± 0.196	Foraminifera	Kariega	Strachan *et al*. (2014)
83 ± 100	-0.016 ± 0.198	Foraminifera	Kariega	Strachan *et al*. (2014)
121 ± 120	-0.055 ± 0.203	Foraminifera	Kariega	Strachan *et al*. (2014)
171 ± 145	-0.089 ± 0.198	Foraminifera	Kariega	Strachan *et al*. (2014)
209 ± 155	-0.173 ± 0.197	Foraminifera	Kariega	Strachan *et al*. (2014)
245 ± 170	-0.206 ± 0.200	Foraminifera	Kariega	Strachan *et al*. (2014)
295 ± 195	-0.213 ± 0.196	Foraminifera	Kariega	Strachan *et al*. (2014)
338 ± 205	-0.641 ± 0.195	Foraminifera	Kariega	Strachan *et al*. (2014)
373 ± 215	-0.250 ± 0.200	Foraminifera	Kariega	Strachan *et al*. (2014)
404 ± 220	-0.350 ± 0.212	Foraminifera	Kariega	Strachan *et al*. (2014)
436 ± 230	-0.264 ± 0.198	Foraminifera	Kariega	Strachan *et al*. (2014)
470 ± 240	-0.544 ± 0.208	Foraminifera	Kariega	Strachan *et al*. (2014)
499 ± 245	-0.708 ± 0.198	Foraminifera	Kariega	Strachan *et al*. (2014)
532 ± 255	-0.774 ± 0.194	Foraminifera	Kariega	Strachan *et al*. (2014)
564 ± 260	-0.572 ± 0.209	Foraminifera	Kariega	Strachan *et al*. (2014)
603 ± 275	-0.369 ± 0.201	Foraminifera	Kariega	Strachan *et al*. (2014)

629 ± 275	-0.861 ± 0.193	Foraminifera	Kariega	Strachan *et al*. (2014)
664 ± 280	-0.945 ± 0.202	Foraminifera	Kariega	Strachan *et al*. (2014)
696 ± 285	-0.806 ± 0.189	Foraminifera	Kariega	Strachan *et al*. (2014)
732 ± 290	-0.688 ± 0.208	Foraminifera	Kariega	Strachan *et al*. (2014)
766 ± 295	-0.622 ± 0.197	Foraminifera	Kariega	Strachan *et al*. (2014)
807 ± 310	-1.025 ± 0.202	Foraminifera	Kariega	Strachan *et al*. (2014)
834 ± 310	-0.675 ± 0.210	Foraminifera	Kariega	Strachan *et al*. (2014)
865 ± 305	-0.395 ± 0.204	Foraminifera	Kariega	Strachan *et al*. (2014)
889 ± 305	-0.463 ± 0.220	Foraminifera	Kariega	Strachan *et al*. (2014)
923 ± 310	-0.713 ± 0.194	Foraminifera	Kariega	Strachan *et al*. (2014)
956 ± 310	-0.748 ± 0.194	Foraminifera	Kariega	Strachan *et al*. (2014)
998 ± 315	-0.352 ± 0.198	Foraminifera	Kariega	Strachan *et al*. (2014)
1036 ± 320	-0.843 ± 0.188	Foraminifera	Kariega	Strachan *et al*. (2014)
1062 ± 315	-0.717 ± 0.196	Foraminifera	Kariega	Strachan *et al*. (2014)
1101 ± 320	-0.618 ± 0.207	Foraminifera	Kariega	Strachan *et al*. (2014)
1123 ± 310	0.28 ± 0.525	Foraminifera	Kariega	Strachan *et al*. (2014)

6. Conclusion

Saltmarsh foraminifera analysed from the Kromme Estuary, supported by a ~1 000 cal yrs BP sediment record based on Bayesian modelled AMS radiocarbon dates, identify continuous 20th century sea-level rise at an average rate of 1.7 mm y^{-1}. The Kromme record provides regional sea-level data for the eastern coast with major trends clearly observed. This data is supported by the qualitative data of the site's foraminiferal assemblages and sedimentology. The increase in sea level from ~180 cal yrs BP, as well as inferred marine conditions from ~345 – 1 000 cal yrs BP, is supported by previous studies. The increase in sea level from around ~180 cal yrs BP is also supported by local and existing southern hemisphere sea-level studies. The reconstructed sea-level curve captures the influence of the LIA event on global sea-level change and provides high-resolution estimates for the rate of recent sea-level change for ~180 cal yrs BP. The Kromme palaeo and sedimentary record can further contribute to local records, as well as inform global records of the timing and magnitude of the LIA event. This can assist in attempting to disentangle the anthropogenic effects of sea-level variability over recent timescales. To improve future studies, more research sites can be investigated to build a regional database to assist in future reconstructions and provide an opportunity for higher resolution reconstructions. This robust approach can help provide data on regional sea level data, observe oscillations and improve accuracy, provided the data shows good chronological constraints. The results of this study demonstrate potential for further high-resolution reconstructions of recent sea-level change to address finer scale changes such as LIA effects, anthropogenic signals and a comparison pre- and post-industrial sea level trends.

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Synthesis

Synthesis

Sea level rise is expected to continue accelerating in the coming decades, posing a major concern for the world's coastlines (IPCC 2021). The scale and magnitude of regional sea-level change is difficult to predict due to geographical variability present across different parts of the world (Church *et al*., 2013). The differences in sea-level rise need to be quantified to improve sea-level projections (Horton *et al*., 2018). Instrumental datasets help provide short-term insights into the regional manifestation of sea-level change, thereby helping to improve sea-level projections. To gain a longer-term perspective on sea-level variability, and insights into pre- and post-industrial trends in sea level, palaeoenvironmental studies are required. Palaeoenvironmental proxy data can be used to reconstruct long-term sea-level records as far back as the glacial and interglacial periods, which allows for a greater temporal range and resolution of sea-level variability to be examined (Scanes *et al*., 2017). Saltmarsh environments preserve proxies such as foraminifera that provide information on sea-level variability (Ghosh and Filipsson 2017). The relationship between the preserved proxies and elevation is quantified and applied as a transfer function to fossil assemblages present in the sediment record to reconstruct past sea level (Gehrels *et al*., 2001). The relationship observed can be used to reconstruct past sea level and constrain the sea level estimations to time periods by using calibrated radiocarbon dates (Gehrels *et al*., 2001; Strachan *et al*., 2014).

In this study, intertidal saltmarsh foraminifera from the Kromme Estuary in South Africa were used to investigate late Holocene sea level. Modern species distributions were examined relative to intertidal elevational gradients to assess the vertical zonation of foraminiferal assemblages. The modern dead assemblage response to elevation was used to develop a training set for a sea-level transfer function, which was applied to downcore assemblages. Sea-level estimates were chronologically constrained using Bayesian radiocarbon age-depth model to interpolate the timing of sea-level variability. Sea-level index points were plotted against radiocarbon age interpolations to create a sea-level reconstruction for comparison with previously published literature on southern African sea level. Following a late Holocene highstand at ~1 500 – 1 200 cal years BP (Strachan *et al*., 2014), southern Africa experienced a gradual rise in sea level from ~900 cal yrs BP to the present day (Siesser 1974; Strachan *et al*., 2014). A study at Langebaan Lagoon on the West Coast, using sediment records, observed lowstands between ~700 - 400 cal yrs BP of -0.5 to -1 m compared to present sea level (Compton 2001). Records from the South Coast (Marker 1997; Strachan *et al*., 2014) report lowstands ~500 - 300 cal yrs BP as well as lower sea surface temperatures of 1 -3°C, which may have played a role in the lower sea level reported (Marker 1997). These differences in records can be due to local-scale processes such as ocean-atmospheric forcing, sedimentation rates, sea surface temperatures, and the southern oscillation El Niño (Church *et al*., 2008; Cooper *et al*., 2018). The Kromme record extends ~1 000 cal yrs with a hiatus observed from ~400 - 600 cal yrs BP. Calcareous species dominate the basal part of the record, preventing quantitative sea-level reconstruction, however, species assemblages and sedimentology data consisting of low organic content and medium to coarse sand occurring from ~340 cal yrs BP to the end of the record, suggest lower than present sea level. Agglutinated species from the upper portion of the core with associated high organic matter and medium sand from ~180 cal yrs BP were used to reconstruct sea level. The quantitative reconstructions spans ~200 years, with the lowest sea-level estimated at 180 cal yrs BP which broadly coincides with the Little Ice Age (~650 -100 cal yrs BP) and Maunder Minimum (~305 - 235 cal yrs BP), followed by rising sea level till present day levels. The Kromme record reports the lowest sea level of -1.26 m at ~180 cal yrs BP, which broadly coincides with the Little Ice Age event (~650 - 100 cal yrs BP) and the Maunder Minimum (~305 - 235 cal yrs BP), with associated decreases in temperature of 1°C (Tyson *et al*., 2000), similar to the sea-level records of Marker (1997) at an earlier timing. The decrease in temperature during the LIA and Maunder Minimum is supported by studies in southern Africa (Dunwiddie and LaMarche 1980; Scott 1996; Tyson *et al*., 2000), suggesting that northern hemisphere cooling affected environmental conditions, and caused subsequent changes in sea level and precipitation in the southern hemisphere (Tyson *et al*., 2000). From ~180 cal yrs BP to the present, there is a rapid and steady increase in sea level reported from the Kromme record, supported by Strachan *et al*. (2014), Compton (2001), and Norström *et al*. (2012).

Foraminiferal-based research provides reliable reconstructions; however, the application of quantitative transfer function-based reconstructions in southern Africa is still progressing. There is scope to apply this technique in future sea-level studies to further develop the application in southern Africa. The current research was foraminifera-based, and the sea level reconstruction agreed with previously conducted sea level data for the southern African coastline (Strachan *et al*., 2014). However, reconstructions can be improved by taking a multiproxy approach (Kirsten *et al*., 2018) to increase the data available and compare the environmental responses to improve reliability, accuracy, and robustness of sea-level estimates (Cooper *et al*., 2018). This can also assist in creating a database of sea-level estimates for the southern African coastline, which will allow for a baseline for comparisons for future studies and provide easily accessible data for informing sea-level projections.

Future sea-level studies can benefit from advances in dating techniques used. Cooper *et al.* (2018) stressed the need to provide more constrained dates for sea level data. This can reduce uncertainties in chronologies and provide more accurate timings of changes in sea level, allowing for greater accuracy and the potential ability to cross-check data from studies. Dating can be restricted due to the type of material and techniques, such as ^{14}C dating. Plant macrofossils or terrestrial samples can be limited in sedimentary records, presenting a challenge in proving adequate material for dating. An alternative approach such as ^{210}Pb dating can prove useful when organic material is limited in samples. Global studies (Barnett *et al.*, 2019) have used ^{210}Pb dating, but this method has not been applied in southern Africa. This method can be used in conjunction with ^{14}C dating to populate missing data points in chronologies and thus increase the precision of reconstructions.

Sea level rise in the 20th century has increased at a rate higher than previous centuries (IPCC 2021). There has been an increase in anthropogenic effects on the natural functioning of ecosystems, which needs to be quantified. However, this has proven difficult due to the complexity of ecological responses (Meyssignac and Cazenave 2012). Coastal sites have been altered by dams, recreation, development, and pollution, which can affect ecosystems (Turpie *et al.*, 2002), and subsequently, the data gathered from these sites. The Kromme Estuary is relatively undisturbed, providing accurate natural datasets. Future studies must consider the setting of the study site and the effects of disturbance on data gathered. Southern African estuaries are threatened (Turpie *et al.*, 2002), and this reduces the study sites available for sea-level research. Alternatively, if anthropogenic signals can be quantified from disturbed sites and compared to undisturbed sites, the effects can be corrected for in reconstructions and provide further insight into sea-level variability that may be natural, anthropogenic, or a combination of both.

Sea level research in southern Africa has expanded from an early focus on geological proxies such as beach rocks (Ramsay 1995) to include biological proxies such as diatoms and foraminifera (Franceschini *et al.*, 2005; Norström *et al.*, 2012; Strachan *et al.*, 2014). Foraminifera are widely considered as reliable high-resolution proxies of past sea-level variability (Horton and Edwards 2006), and are able to extend sea-level reconstruction beyond instrumental datasets, thereby reducing uncertainty in projections (Edwards and Wright 2015).

This research demonstrates the effectiveness of foraminifera-based sea-level research, producing a high-resolution continuous sea-level reconstruction for the past ~200 years from far-field South Africa, where such data are currently lacking. This can offer further insight into local sea-level variations and the forcing thereof, providing more reliable information for climate planning as compared to using global datasets. In conclusion, saltmarsh foraminifera are considered reliable proxies for quantitative sea-level reconstruction in the southern African context, thereby advancing our understanding of regional sea-level variability, which can in turn be used to inform future sea-level projections.

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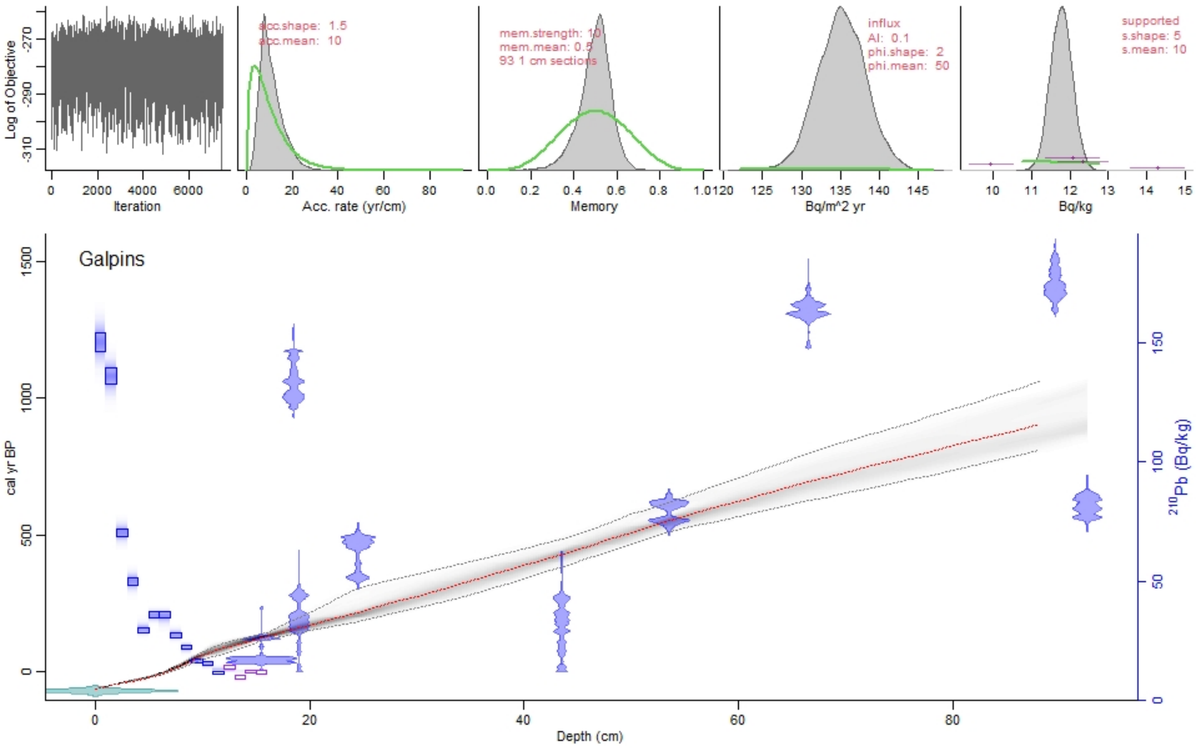
Appendix A

Galpins age-depth model



Appendix B

^{14}C and Pb-210 dates for Kariega

C-14							
Lab ID	Dating method	Sample Depth (cm)	Material	13C/12 C (	14 C year	Cal years BP (2 SD)	
Beta-590076	AMS	15-16	Plant macrofossils - stems and seeds	-15,6	119.78 +/-	-10 - -12 (45.7%)	
Beta-334778	AMS	18-19	Organic sediment (bulk)	-20,5	1200 ± 30	970-1142 (92.1%)	
Beta-584415	AMS	18.5-19.5	Charcoal	-13,7	230 ± 30	228-140 (68.3%)	
Beta-587652	MS-AMS	23.5-25.5	Charcoal and plant macrofossils	NA	440 ± 30	511 - 440 (72.6%)	
Beta-587653	AMS	42.5-45.5	Plant macrofossils -stems and seeds	-13,3	200 ± 30	285-136 (73.6%)	
Beta-301135	AMS	53-54	Organic sediment (bulk)	-20,8	620 ± 30	591-638 (49.7%)	
Beta-334779	AMS	66-67	Organic sediment (bulk)	-19,8	1460 ± 30	1281-1363 (95%)	
Beta-334780	AMS	18-19	Organic sediment (bulk)	-19	1570 ± 30	1331-1424 (69.6%)	
Beta-3301136	AMS	92-93	Shell	1,5	673 ± 30	557-654 (95%)	
Pb-210							
Sample ID	Sample Depth (cm)	Dating method	Pb-210 activity (Bq/kg)	±	Age (Yrs)	Year (AD)	±
1	0-1	Pb-210 - Alpha	150,1417394	3,981195	6,068582	2005,348	1,110921
2	1-2	Pb-210 - Alpha	135,968763	3,276763	13,73969	1997,677	1,546775
3	2-3	Pb-210 - Alpha	70,32538957	1,765843	22,79321	1988,624	1,821046
4	3-4	Pb-210 - Alpha	50,02988203	1,670298	31,12289	1980,294	2,044106
5	4-5	Pb-210 - Alpha	29,42765636	1,084996	39,71457	1971,702	2,289902
6	5-6	Pb-210 - Alpha	35,92610554	1,23334	48,32506	1963,092	2,601652
7	6-7	Pb-210 - Alpha	36,1248898	1,200805	63,54312	1947,874	3,288339
8	7-8	Pb-210 - Alpha	27,44671598	0,993377	76,12524	1935,292	3,616526
9	8-9	Pb-210 - Alpha	22,35123901	0,902138	92,7763	1918,641	5,017908
10	9-10	Pb-210 - Alpha	16,88948565	0,748081	113,7859	1897,631	7,860823
11	10-11	Pb-210 - Alpha	15,49337946	0,745014	132,8621	1878,555	12,03146
12	11-12	Pb-210 - Alpha	11,84675494	0,613521	156,8315	1854,585	22,66163

Appendix C

Stratigraphy of the Kromme saltmarsh

Depth		Physical Features							Components (Total = 4)																
		0-4																							
Upper	Lower	Darkness	Stratification	Elasticity	Dryness	Colour (Munsell)	Structure	Upper Boundary	Mosses (Tb)	Woody Plants (Tl)	Herbs (Th)	Woody Detritus (Dl)	Herb Detritis (Dh)	Fine Detritus (Dg)	Charcoal	Organic Lake Mud	Humus (Sh)	Organosilicates (Lso)	Carbonates (Lc)	Iron Oxides (Lf)	Clay (As)	Silt (Ag)	Sand (Gg)	Gravel (Gg)	Comments
0	13	3	0	1	3	10YR-3/2	Homo	/						++			1				3				UNIT 4
13	22	2	0	2	3	10YR-3/1	Homo	Gr												+	1	2	1		UNIT 3
22	55	2	0	2	2	10YR-3/1	Homo	Gr						+							2	1	1		UNIT 3
55	67	2	0	4	1	10YR-2/1	Homo	Gr														1	3		UNIT 2
67	82	2	0	3	2	10YR-3/1	Homo	Gr						+							2	2	+		UNIT 1
82	110	2	0	3	2	10YR-3/1	Homo	Gr						+							2	2	+		UNIT 1
110	140	CORE LOSS																							Lense
END																									0 m
0	56	2	0	1	2	10YR-3/1	Homo	/						+			+			+	4				UNIT 4 (Detritus)
56	64	2	0	2	2	10YR-3/1	Homo	Gr													3	1			UNIT 3 (Silt)
64	103	CORE LOSS																							
103	113	2	0	3	2																				UNIT 1
113	206	CORE LOSS																							
END																									18 m

Depth		Physical Features							Components (Total 4)																
		0-4																							
Upper	Lower	Darkness	Stratification	Elasticity	Dryness	Colour (Munsell)	Structure	Upper Boundary	Mosses (Tb)	Woody Plants (Tl)	Herbs (Th)	Woody Detritus (Dl)	Herb Detritis (Dh)	Fine Detritus (Dg)	Charcoal	Organic Lake Mud	Humus (Sh)	Organosilicates (Lso)	Carbonates (Lc)	Iron Oxides (Lf)	Clay (As)	Silt (Ag)	Sand (Gg)	Gravel (Gg)	Comments
0	15	3	0	2	2	10YR-2/2	Homo	/									+				4				UNIT 4
15	21	2	0	3	2	10YR-4/6	Homo	Gr												1	1	2			UNIT 4/3 (Oxidized Horizon)
21	69	3	0	2	2	10YR-2/1	Homo	Gr						+			+				4				UNIT 2
69	103	3	0	2	2	10YR-3/1	Homo	Gr													3	1			UNIT 2
103	116						Homo	Gr																	UNIT 1
116	200						Homo	Gr																	UNIT 1
200	206	CORE LOSS																							
END																									16 m
0	15	3	0	1	3	10YR-3/2	Homo	/						+							4				UNIT 4
15	30	2	0	3	2	10YR-3/1	Homo	Gr													1	1	2		UNIT 3 (Sandy Layer)
30	82	2	0	2	2	10YR-3/1	Homo	Gr													3	1	+		UNIT 2
82	103	2	0	3	3	10YR-3/1	Homo	Gr													1		3		UNIT 1
103	206	2	0	3	3	10YR-3/1	Homo	Gr													1		3		UNIT 1

Depth		Physical Features							Components (Total 4)																
		0-4																							
Upper	Lower	Darkness	Stratification	Elasticity	Dryness	Colour (Munsell)	Structure	Upper Boundary	Mosses (Tb)	Woody Plants (Tl)	Herbs (Th)	Woody Detritus (Dl)	Herb Detritis (Dh)	Fine Detritus (Dg)	Charcoal	Organic Lake Mud	Humus (Sh)	Organosilicates (Lso)	Carbonates (Lc)	Iron Oxides (Lf)	Clay (As)	Silt (Ag)	Sand (Gg)	Gravel (Gg)	Comments
0	5	CORE LOSS																							
5	27	3	0	2	2	10YR-2/1	Homo	/													4				UNIT 2
27	206	3	0	2	2	10YR-2/1	Homo	Gr													2	1	1		UNIT 1
END																									42 m
0	57	3	0	2	2	10YR-2/1	Homo	/													4	1			UNIT 2
57	100	3	0	2	2	10YR-2/1	Homo	Gr													2	1	1		UNIT 1
103	206	3	0	2	2	10YR-2/1	Homo	Gr													2	1	1		UNIT 1
END																									50 m

Appendix D

Loss-on-ignition and bulk density of the Kromme saltmarsh

Depth	LOI %	Mean Grainsize	Bulk Density
0	22,18302	1,675601225	0,70865
1	20,93895	0,913371575	1,00005
2	19,28271	1,008170163	1,2589
3	18,17983	1,332553663	0,91475
4	11,44746	0,403291736	1,63355
5	18,05197	0,874785546	0,9697
6	14,33373	0,591593413	1,45775
7	20,94186	1,158195126	1,00015
8	12,3259	1,236771596	1,14515
9	8,87139	0,973996292	1,7207
10	10,69958	1,17922258	1,5538
11	10,98057	1,149272438	2,0641
12	15,88483	1,310091837	1,41015
13	6,335297	0,93588264	2,0883
14	2,609898	1,118599251	1,8449
15	2,717101	1,152258444	2,71245
16	3,012338	1,060407133	2,59765
17	2,071383	1,274305034	3,49525
18	3,865644	1,213300242	2,9995
19	4,627882	1,444182579	3,31145
20	1,171267	1,230777536	3,24435
21	1,016273	1,307155407	3,91135
22	0,972948	1,302587453	2,99605
23	1,039424	1,266460625	2,5543
24	1,307537	1,232528383	4,13755
25	1,538315	1,336399893	2,61975
26	1,478351	1,36378412	2,9932
27	1,658307	1,491965407	3,41915
28	1,717516	1,335430132	3,2285
29	1,85115	1,293579206	3,82735
30	2,365916	1,281298149	3,90335
31	3,022366	1,265127852	3,1118
32	4,327944	1,348917072	2,3071
33	4,467449	1,35813979	3,0767
34	5,617738	1,398811893	2,80985
35	4,870771	1,230489831	2,5807
36	5,309735	1,140018832	2,28825
37	6,763344	1,531359275	2,4411
38	6,138949	1,434131145	2,09645
39	2,749638	1,146670969	3,07495
40	3,176407	1,133521952	2,50755
41	5,192256	1,224418673	2,03765
42	5,773738	1,653313445	1,7493
43	4,38398	1,328458007	2,45325
44	3,561855	1,243904754	2,2755
45	4,380207	1,414471321	2,26245
46	4,916456	1,279877645	2,4957
47	4,355467	1,086714766	2,24775
48	4,104	1,212612709	1,875
49	4,500856	1,174802557	3,0372
50	4,710916	1,34861488	2,18535
51	5,662009	1,243614003	2,1397
52	6,146433	1,259056423	2,2932
53	5,869586	1,302736073	2,55725
54	8,932262	1,843913034	1,6933
55	6,294548	1,237336521	2,0764
56	5,346887	1,46386888	1,7412
57	5,942255	1,75168169	1,7283
58	6,707524	1,47207948	1,7704
59	4,494879	1,218896921	1,46945
60	6,357087	1,12530123	2,0544
61	5,374804	1,129634677	1,50145
62	4,010525	1,249300581	1,7292
63	2,287341	1,005481603	2,10725
64	2,710627	0,806550539	1,6712
65	2,448606	1,05265986	2,07465
66	2,522308	1,138582723	2,10125
67	2,490977	1,056528439	2,25815
68	2,62554	1,124609191	1,28545
69	3,139321	1,088635745	2,04025
70	3,346551	1,183001586	1,6644
71	3,675478	1,157423445	1,88955
72	3,918426	1,237446594	2,0276
73	4,347826	1,336322577	1,5295
74	3,391527	1,296598159	1,34895
75	3,508296	1,150484518	1,8442
76	3,144207	1,020005014	2,04185
77	3,717712	1,003219331	2,08865
78	2,934047	0,98558841	2,7641
79	2,856533	1,125432012	1,8729
80	2,478397	1,046266338	2,41285
81	2,493345	1,17790181	2,254
82	2,630958	0,931674929	2,33185
83	2,662007	1,211881722	2,08865
84	2,749044	0,98862841	1,76425
85	2,568604	0,961377361	1,5378
86	2,738635	1,096140575	2,0722
87	2,624918	0,866254605	2,2915
88	4,664615	0,968733421	1,625
89	6,602254	1,513546608	1,0557
90	4,653672	1,042280922	2,03925
91	4,897428	1,28553913	1,3844
92	3,609186	1,081950519	1,56545
93	2,496085	1,124969136	1,62855
94	2,565881	1,21807613	2,0188
95	3,359139	1,361064825	1,5242
96	3,277577	1,170259623	1,84435
97	3,027585	1,261474274	1,3377
98	3,300589	1,318801492	1,14525
99	2,377205	1,193335798	1,55645
100	2,682867	1,20277709	1,2263
101	2,138038	1,181428742	1,57855
102	2,748449	1,324491863	1,53905
103	2,847851	1,302640541	1,58365
104	2,569947	1,362242263	1,51365
105	3,208887	1,334215914	1,2107
106	3,378261	1,410160867	1,15
107	2,756662	1,262327462	1,74305
108	2,825482	1,321815002	1,7236
109	2,976293	1,250300221	1,44475
110	3,099774	1,350358955	1,39365
111	3,072016	1,242178551	1,44205
112	3,289058	1,239341198	1,8972
113	3,350651	1,234912351	1,9056
114	2,953516	1,310827436	1,48975
115	2,883266	1,217882057	1,38905
116	4,014423	1,428833128	1,664
117	4,014599	1,096426987	0,9864
118	2,906462	1,384338184	2,08845
119	3,171051	1,223467033	1,8322
120	2,80978	1,192506548	1,5624
121	2,821343	1,07778293	1,7598
122	2,909225	1,233019392	2,1724
123	3,583942	1,398422387	1,49835
124	2,970234	1,148870717	1,5588
125	2,511766	1,093527412	2,0185
126	2,55327	1,249257418	2,16585
127	2,179915	1,08667198	1,90145
128	2,10063	1,187724912	1,9994
129	1,609491	1,250194401	2,10315
130	2,078093	1,281575837	2,04755
131	2,108798	0,988551378	2,2335
132	2,210556	1,113983887	2,30485
133	2,423543	1,03988821	1,9063
134	2,256495	0,981850554	1,75715
135	2,085379	0,955370829	2,3425
136	2,05993	0,962168966	1,98065
137	1,945018	0,946406218	2,0334
138	1,88005	0,901847862	2,4627
139	1,970028	0,804562832	2,1954
140	2,389412	0,724074314	2,2516
141	2,584257	0,809741173	1,8129
142	2,545857	0,81817426	2,34695
143	2,359133	0,848808041	2,2042
144	2,296248	0,972915113	2,36255
145	1,907846	0,882102463	2,4242
146	1,903495	1,074671741	2,1802
147	2,088449	1,126348645	2,13795
148	2,05633	1,462823958	2,0522
149	2,227484	0,93493312	3,2099
150	1,990505	0,950663212	2,0221
151	2,242171	0,964691232	2,38385
152	2,279766	1,125376403	2,3248
153	2,271128	0,885783963	2,34465
154	2,081744	1,089066125	2,2289
155	1,985106	1,158244624	2,24925
156	1,822605	1,597415396	2,38395
157	1,66801	1,012590659	2,9766
158	1,771005	1,066629684	1,6996
159	1,670588	0,885008694	2,52905
160	2,327209	0,924188665	1,92935
161	1,66797	1,074506085	2,6859
162	1,560466	0,869804022	2,49605
163	1,794216	0,891710638	2,95115

Appendix E

Fossil foraminifera counts of the Kromme saltmarsh

Sample	*T.inflata*	*M.fusca*	*Quin.*	*J.mac*	*Amm.*	Total
KROM 1A-0	62	129	0	187	0	378
KROM 1A-4	92	93	0	116	0	301
KROM 1A-8	95	82	0	94	0	271
KROM 1A-12	118	65	0	129	0	312
KROM 1A-16	132	0	0	116	0	248
KROM 1A-20	9	0	0	0	0	9
KROM 1A-24	3	0	0	1	0	4
KROM 1A-28	16	0	0	10	0	26
KROM 1A-32	11	0	0	10	0	21
KROM 1A-36	170	18	0	124	0	312
KROM 1A-40	92	5	0	164	0	261
KROM 1A-44	116	49	0	82	0	247
KROM 1A-48	134	0	0	119	0	253
KROM 1A-52	112	0	0	153	0	265
KROM 1A-56	108	0	0	146	0	254
KROM 1A-60	95	0	0	167	0	262
KROM 1A-64	36	0	0	59	0	95
KROM 1A-68	16	0	0	5	0	21
KROM 1A-72	10	0	0	17	0	27
KROM 1A-76	29	0	0	11	0	40
KROM 1A-80	6	0	0	13	0	19
KROM 1A-84	3	0	0	23	0	26
KROM 1A-88	10	5	0	21	0	36
KROM 1A-92	6	0	0	16	0	22
KROM 1A-96	3	5	0	16	0	24
KROM 1A-100	3	4	0	14	0	21
KROM 1A-104	2	0	0	0	12	14
KROM 1A-108	2	0	0	0	18	20
KROM 1A-112	0	0	0	0	44	44
KROM 1A-116	0	0	0	0	65	65
KROM 1A-120	0	0	0	0	79	79
KROM 1A-124	0	0	0	0	110	110
KROM 1A-128	0	0	0	0	433	433
KROM 1A-132	0	0	0	0	361	361
KROM 1A-136	0	0	0	0	111	111
KROM 1A-140	0	0	0	0	38	38
KROM 1A-144	0	0	0	0	24	24
KROM 1A-148	0	0	0	0	36	36
KROM 1A-152	0	0	0	0	33	33
KROM 1A-156	0	0	0	0	64	64
KROM 1A-160	0	0	0	0	58	58

Appendix F

Modern foraminifera counts of the Kromme saltmarsh (KROM 1A)

Sample	*T.inflata*		*M.fusca*		*Quin.*		*J.mac*		*Amm.*	
	L	D	L	D	L	D	L	D	L	D
KROM 1A - 4M	146	208	2	10	0	0	40	80	0	0
KROM 1A-8M	134	377	2	10	0	0	41	100	0	0
KROM 1A-9M	175	318	21	38	0	0	25	125	2	88
KROM 1A-12M	152	331	27	32	0	0	11	163	25	30
KROM 1A-15M	130	342	20	75	0	0	52	128	0	0
KROM 1A-17M	82	315	5	17	0	0	98	239	0	10
KROM 1A-19M	92	244	3	5	0	0	118	262	0	0
KROM 1A-25M	98	209	78	372	0	0	105	195	0	0
KROM 1A-27M	101	149	100	364	0	0	115	104	203	199
KROM 1A-28M	107	157	166	261	0	0	112	147	53	30
KROM 1A-32M	156	277	26	124	0	0	52	95	7	18
KROM 1A-33M	203	289	87	92	0	0	99	153	0	0
KROM 1A-34M	158	226	205	274	0	0	111	147	0	0
KROM 1A-35M	59	88	343	399	0	0	62	90	0	0
KROM 1A-36M	34	50	133	151	0	0	34	48	28	46
KROM 1A-38M	30	75	45	69	28	32	3	12	52	61
KROM 1A-40M	0	26	0	0	66	77	26	62	83	68
KROM 1A-41M	12	33	15	17	73	63	12	26	0	0
KROM 1A-47M	0	12	0	0	48	87	0	0	69	216
KROM 1A-53M	0	0	0	0	0	0	0	0	103	246

Appendix G

Modern foraminifera counts of the Kromme saltmarsh (KROM 2A)

Sample	*T.inflata*		*M.fusca*		*Quin.*		*J.mac*		*Amm.*	
	L	D	L	D	L	D	L	D	L	D
KROM 2A-1M	31	155	0	0	0	0	38	76	0	14
KROM 2A-2M	3	11	0	0	0	0	2	2	9	123
KROM 2A-3M	109	228	9	26	0	0	56	118	4	46
KROM 2A-4M	17	40	0	0	0	0	16	25	9	164
KROM 2A-6M	68	179	16	30	0	0	72	172	79	163
KROM 2A-12M	100	167	12	56	0	0	135	440	0	0
KROM 2A-18M	16	5	2	3	0	0	207	161	0	0
KROM 2A-28M	17	10	2	2	0	0	192	128	0	0
KROM 2A-34M	2	15	8	23	0	2	7	64	18	121
KROM 2A-39M	5	14	0	12	0	0	10	43	28	167
KROM 2A-41M	5	13	0	2	0	0	11	52	24	184
KROM 2A-50M	0	0	0	18	0	0	1	7	65	168
KROM 2A-52M	0	10	2	32	0	0	0	2	49	151
KROM 2A-56M	2	3	16	21	0	0	0	0	59	167
KROM 2A-60M	0	14	2	6	0	0	3	21	65	151
KROM 2A-70M	38	36	58	52	7	6	18	40	45	30
KROM 2A-80M	42	46		5	0	0	3	9	100	48
KROM 2A-86M	2	18	15	38	22	17	2	4	62	82
KROM 2A-87M	2	11	32	37	0	0	2	6	54	108
KROM 2A-88M	0	18	0	5	12	4	0	0	54	162
KROM 2A-89M	0	5	0	6	4	0	0	0	90	141

Appendix H

Modern field data collection from the Kromme saltmarsh (KROM 1A)

Transect Number	A	Height of Dumpy Above Ground	1,175			
Low Tide Mark	53m	Aerial Height Top (m)	1,945			
High Tide Mark	40m	Aerial Height Bottom (m)	1,94			
Length (m)	53m					
Surface Sample (x)	Transect (m)	Elevation (m)	pH	°C	Salinity	Notes
	1	1,245				
	2	1,26				
	3	1,255				
x	4	1,375	6,8	18,1	1,11	
	7					Debris
x	8	1,475	7,48	17,4	5,75	
x	9	1,605	7,74	19,2	11,52	
	10					
	11					
x	12	7,58	18,7	8,58		
	13					
	14					
x	15	7,36	18,6	8,4		
	16					
x	17	7,4	17,3	9,55		
	18	1,79				
x	19	1,83	7,08	19	19,88	
	20	1,81				
	21	1,8				
	22	1,785				
	23	1,77				
	24	1,82				
x	25	1,84	7,43	20,4	9,19	
	26	1,83				
x	27	1,83	7,26	24,7	10,96	
x	28	1,88	7,4	19,8	9,26	
	29	1,885				
	30	1,91				
	31	1,91				
x	32	1,885	7,39	20,7	16,34	
x	33	1,895	7,1	23,3	10,06	
x	34	1,925	5,84	21,4	18,51	
x	35	1,95	6,76	21,9	8,44	
x	36	2,01	6,27	20,3	11,99	
	37	2,03				
x	38	2,09	7,33	21,9	15,67	
	39	2,105				
x	40	2,205	7,46	22,4	11,31	
x	41	2,25	6,86	21	18,98	
	42	2,27				
	43	2,29				
	44	2,3				
	45	2,33				
	46	2,33				
x	47	2,35	8,02	20,4	16,18	
	48	2,37				
	49	2,37				
	50	2,39				
	51	2,41				
	52	2,425				
x	53	2,45	7,73	21	13,75	

Appendix I

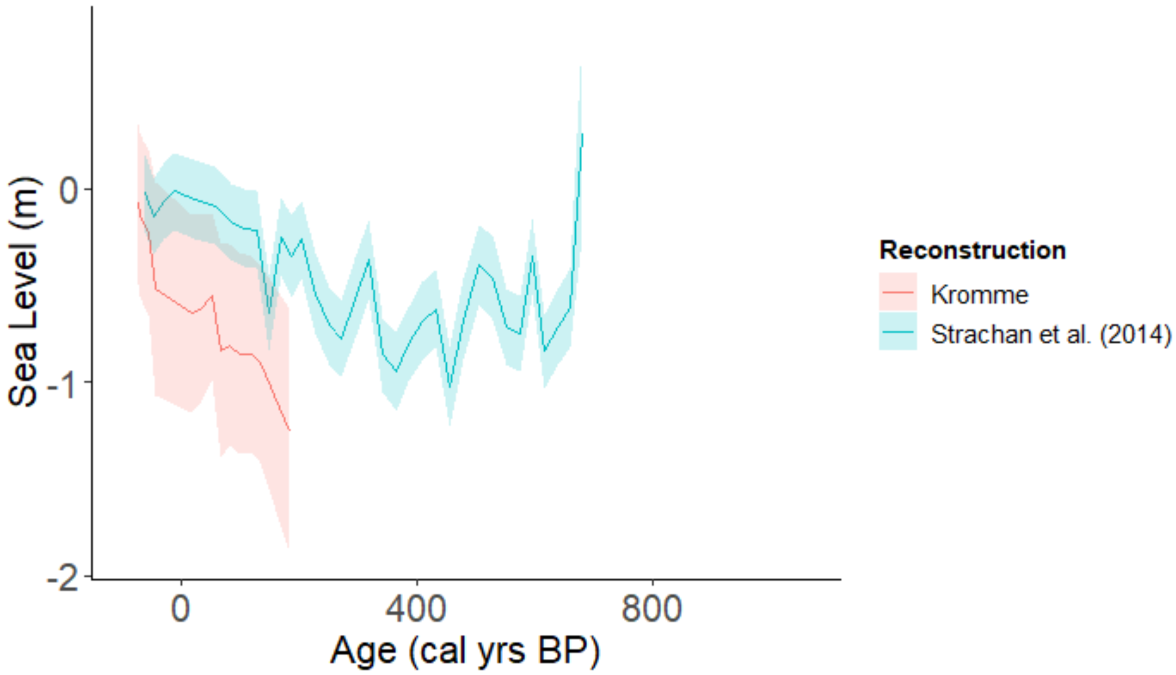
Modern field data collection from the Kromme saltmarsh (KROM 2A)

Transect Number	2A	Height of Dumpy Above Ground	1,35			
Low Tide Mark		Aerial Height Top (m)				
High Tide Mark		Aerial Height Bottom (m)				
Length (m)	89m					
Surface Sample (x)	Transect (m)	Elevation (m)	pH	°C	Salinity	Notes
x	1	1,3	8,51	16,6	0,54	
x	2	1,23	8,85	17,2	0,2	
x	3	1,475	7,48	16,1	3,89	
x	4	1,525	7,7	16,5	5	
	5	1,54				
x	6	1,535	7,51	16,8	1,22	
	7	1,54				
	8	1,525				
	9	1,555				
	10	1,56				
	11	1,56				
x	12	1,55	6,98	15,3	10,22	
	13	1,545				
	14	1,545				
	15	1,53				
	16	1,545				
	17	1,53				
x	18	1,545	7,07	15,4	4,03	
	19	1,53				
	20	1,52				
	21	1,525				
	22	1,53				
	23	1,52				
	24	1,54				
	25	1,54				
	26	1,56				
	27	1,58				
x	28	1,595	6,97	16	11,58	
	29	1,58				
	30	1,57				
	31	1,56				
	32	1,55				
	33	1,53				
x	34	1,54	7,68	16,2	9,58	
	35	1,53				
	36	1,51				
	37	1,54				
	38	1,55				
x	39	1,5	7,37	16,6	9,58	
	40	1,55				
x	41	1,56	7,81	15,8	11,9	
	42	1,55				
	43	1,53				
	44	1,54				
	45	1,525				

	46	1,54				
	47	1,525				
	48	1,525				
	49	1,53				
x	50	1,53	7,88	15,7	6,85	
	51	1,59				
x	52	1,6	7,71	14,3	5,92	
	53	1,61				
	54	1,625				
	55	1,63				
x	56	1,64	7,54	14,6	8,03	
	57	1,62				
	58	1,62				
	59	1,62				
x	60	1,61	7,46	15	10,56	
	61	1,61				
	62	1,61				
	63	1,61				
	64	1,61				
	65	1,615				
	66	1,615				
	67	1,62				
	68	1,63				
	69	1,635				
x	70	1,635	7,04	16	8,32	
	71	1,62				
	72	1,615				
	73	1,62				
	74	1,62				
	75	1,625				
	76	1,615				
	77	1,63				
	78	1,63				
	79	1,63				
x	80	1,65	7,13	14,5	7,66	
	81	1,65				
	82	1,65				
	83	1,645				
	84	1,63				
	85	1,625				
x	86	1,67	7,32	14,2	5,7	
x	87	1,7	7,13	15	6,29	
x	88	1,8	7,89	13,2	7,86	
x	89	1,85	7,86	15,3	8,41	

Appendix J

Kromme and Kariega sea-level reconstruction comparison



Appendix K

Taxonomic list of species

***Quinqueloculina* species** (d'Orbigny 1826):

Description: The walls of the test are porcellaneous with a translucent to opaque appearance. The chambers are coiled on a quinqueloculine plan, with the aperture usually having a tooth (Murray 1979; Horton and Edwards 2006). *Quinqueloculina* usually has an average length of 0.3mm (Horton and Edwards 2006).

Distribution: *Quinqueloculina* are sediment dwelling and colonize mouths of estuaries if the conditions are favourable. They are also commonly found in the inner shelf as well as middle to low marshes and tidal flats (Horton and Edwards 2006).

Ammonia species (Brünnich 1771):

Description: *Ammonia* have calcite tests with radially arranged crystallites and pores. They appear glassy and translucent and can appear brownish in colour. They generally have a flattened dorsal side with the periphery sub-angular to sub-rounded. It is common to see eight to nine chambers on the ventral side (Horton and Edwards 2006).

Distribution: *Ammonia* are commonly found in low marsh and tidal flat environments (Horton and Edwards 2006). They occasionally appear in high abundance (Horton and Edwards 2006).

Miliammina fusca (Brady 1879):

Description: Test walls are agglutinated composed of sand-sized detrital grains, held together by a pale brown in colour organic cement. However, morphology will vary slightly with grain size. The test is elongated and rounded in section. This is made up of many chambers coiled on a milioline plan. Aperture terminal with a tooth (Murray 1979; Horton and Edwards 2006). With an average length of 0.4 mm (Murray 1979)

Distribution: *Miliammina fusca* is a sediment dwelling euryhaline species and is restricted to a narrow elevation zone within brackish lagoons, estuaries and tidal marshes (Murray 1979; Horton and Edwards 2006).

Trochammina inflata (Montagu 1808):

<u>Description:</u> Test is agglutinated and composed of very fine detrital grains with the outer layer being organic cement, brown in colour. The test is trochospirally coiled with globular chambers. The sutures are gently depressed on the spiral side, with the sutures deeply depressed between the inflated chambers on the umbilical side. The aperture is a narrow slit with bordering lip. The average size is 0.4 mm in diameter (Murray 1979; Horton and Edwards 2006).

<u>Distribution:</u> *Trochammina inflata* is a sediment dwelling species, commonly found in higher elevation zones within salt marshes. They are also typically able to survive in environments that vary including periods of little available oxygen (Murray 1979).

Jadammina macrescens (Brady 1870):

<u>Description:</u> Test agglutinated and made up of incredibly fine detrital grains held together by brown in colour organic cement. The walls are particularly thin and when wet are flexible, however when they are dry the chambers tend to collapse. The test is trophospirally coiled and compressed with a shallow umbilicus (Murray 1979; Horton and Edwards 2006). The sutures are slightly raised when the chambers collapse (Murray 1979). The aperture is a slit at the bottom of the apertural face with areal pores spread across the face. The average diameter of *Jadammina macrescens* is 0.3 mm (Murray 1979; Horton and Edwards 2006)

<u>Distribution:</u> *Jadammina macrescens* is one of the most abundant species to be found. They are commonly found around the world in brackish marshes and are able to survive extreme environmental changes (Murray 1979).