A multi-proxy investigation into past and present environmental change at Lake St Lucia

Report to the
WATER RESEARCH COMMISSION

Marc Humphries
School of Chemistry, University of the Witwatersrand, Johannesburg

Andrew Green, Keegan Benallack, Jemma Finch, Ander de Lecea
School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal

Megan Gomes
School of Animal, Plant and Environmental Sciences, University of the Witwatersrand

Kate Strachan
School of Geography, Archaeology and Environmental Studies, University of the Witwatersrand

Kelly Kirsten
Department of Environmental and Geographical Science, University of Cape Town

WRC Report No 2336/1/17
ISBN 978-1-4312-0935-4

Obtainable from:

Water Research Commission
Private Bag X03
GEZINA, 0031
orders@wrc.org.za or download from www.wrc.org.za

EXECUTIVE SUMMARY

Lake St Lucia, the largest estuarine system in Africa, is located in northern KwaZulu-Natal, South Africa. It is enclosed by a 120 m-high compound Quaternary barrier-dune system and comprises several discrete sedimentary basins within a single shallow back-barrier water body. The lake is characterised by extreme natural fluctuations in salinity as a result of variable river inflows and evaporation. Although regarded as a resilient system, Lake St Lucia has, over the past decade, experienced severe periods of prolonged drought, associated with hypersalinity, loss of aquatic habitat and general deterioration in ecological state. Despite the ecological importance of Lake St Lucia, our understanding of the geomorphic evolution of the system, changes in past hydrological regimes, and controls on ecological response remain poor, and largely limited to data collected over a brief period of time. Long-term datasets are needed to aid in understanding the evolution and natural variability of the system, particularly in light of increasing human pressures and predicted future climate change. It is within this context that the present study was undertaken.

This report documents the first high-resolution seismic study and targeted coring programme undertaken at Lake St Lucia. The aims of this study were to:

1. investigate both the long-term and short-term geomorphic and sedimentological evolution of Lake St Lucia, through a combination of geophysical, geochemical and palaeo-environmental techniques;
2. relate these changes to long-term change in climate and lake water chemistry, and shorter-term anthropogenic influences to the system;
3. provide an analysis of climatic controls on the geomorphic and sedimentological evolution of the lake system;
4. inform system management practices using insights gained from a longer-term evolutionary perspective.

The findings

The findings are divided into four sub-components:

Geophysical and sedimentological surveys

This section details the environmental interpretations made from a very high resolution seismic survey and coring programme undertaken in the Lake St Lucia area. The various palaeo-environments of deposition are discussed, paying particular attention to the fill sequence of the palaeochannel system beneath the lake floor. These interpretations are reconciled, where possible, with core data from the False Bay, North Lake and South Lake areas. Investigations reveal that the long-term evolution of the Lake St Lucia system is the product of two periods of major base level fall, one in the Pliocene, the other ~ 18 000 years ago, that resulted in a series of incised valleys forming. Associated with these are two phases of transgressive infilling (Pleistocene and late Pleistocene/Holocene) which follow the typical facies successions of mixed tide- and wave-dominated incised valley fills. As sea levels rose the valleys were filled, the back-barrier responded differently due to the sheltering effects of the Nibela Peninsula which buffered shoreline migration during the transgression. In this context, False Bay appears to have evolved towards an estuarine-lake system earlier than the North Lake depocentre. In general, however, the northern portions of the system (False Bay and North Lake) house the largest relict bayhead deltaic material, whereas the southern areas (South Lake) lack such deposits and are dominated by thick central basin-type infilling. The two areas appear to have evolved separately since the Last Glacial Maximum (LGM), when two discrete and unrelated drainage systems were formed. Subsequently, these were infilled and only became connected as a single system after the closure of the main LGM inlets ~6200 cal. yr BP.

Sediment dating and characterisation

This section presents age-depth models, sedimentation and nutrient accumulation data from a series of long and short sediment cores obtained from Lake St Lucia. Long-term processes are investigated using cores from the three main basins of Lake St Lucia (North Lake, False Bay and South Lake), while short sediment cores, extracted from deltaic deposits near the river inlets, are used to understand short-term processes. Dating provides a chronological framework that allows correlation between lake records and the timing of past changes to be pinpointed. Based on a total of 18 AMS (accelerator mass spectrometry) radiocarbon dates, cores obtained from North Lake (NL-1), False Bay (FB-1) and South Lake (CB-2) reveal Holocene-aged sedimentary sequences, with NL-1 dating back to 7582–7678 cal. yr BP, FB-1 to 8295–8402 cal. yr BP, and CB-2 to 9401–9523 cal. yr BP. The sediment cores capture the most recent lacustrine sedimentary infill and provide a unique opportunity to gain insight into recent environmental changes and development of the system. Derived age-depth models are used in subsequent sections to interpret and compare biological, geochemical and sedimentological proxies.

The North Lake and False Bay basins have filled at similar and relatively constant rates (0.20 cm yr^{-1}) over the last 8000 to 7000 years. However, the most recent 2000 years are characterised by substantially lower rates of accumulation (~0.05 cm yr^{-1}). Sediment accumulation in South Lake shows a distinct decrease ~7000 cal. yr BP, linked to the closure of the palaeochannel near Mission Rocks. Since then, ~2.5 m of sediment has accumulated over 7000 years, an average sedimentation rate of ~0.03 cm yr^{-1}. Notably, the influence of Mfolozi River sediment on infilling within the main lake basins appears to be negligible. We also report no net change in recent sediment accumulation at the main river inlets. Despite concerns regarding increased sediment accumulation within the main basins of Lake St Lucia, our data suggest that increased deposition has not occurred over recent years.

Proxy reconstructions: palaeohydrology and geomorphological evolution

Sedimentary deposits contained within the incised valleys of Lake St Lucia provided an opportunity to investigate complex hydrological and sedimentological processes, and examine sea-level controls governing system geomorphic evolution. In this section, various biological, sedimentological and geochemical proxies are used to reconstruct Holocene environmental change in the northern basins of Lake St Lucia (North Lake and False Bay). Analyses allow the reconstruction of hydrological changes associated with the geomorphic development of the system over the mid- to late Holocene. The sedimentary sequences indicate that St Lucia was a shallow, partially enclosed estuary/embayment dominated by strong tidal flows prior to ~6200 cal. yr BP. Infilling was initiated when sea-level rise slowed and stabilised around present-day levels, resulting in the accumulation of fine-grained sediment behind an emergent proto-barrier. Diatom assemblages, dominated by marine benthic and epiphytic species, reveal a system structured by marine water influx and characterised by marsh and tidal flat habitats until ~4550 cal. yr BP. A shift in the biological community at ~4550 ca. yr BP is linked to the development of a deepening back-barrier water body that supported a brackish community. Marine planktonics and enrichments in $\delta^{34}S$ suggest recurrent, large-scale barrier inundation events during this time, coincident with the mid-Holocene highstand. Periodic marine incursions associated with episodes of enhanced storminess and overwash remain prevalent until ~1200 cal. yr BP, when further barrier construction ultimately isolated the northern basins from the ocean. This provides the first reconstruction of the palaeohydrological environment at Lake St Lucia and highlights the long-term geomorphic controls that have shaped the recent evolution and natural dynamics of the system.

Geochemical characterisation: desiccation cycles and recent evolution

This section presents geochemical data from sediment cores extracted from North Lake, False Bay and South Lake. The sedimentary record documents the evolution of the system from a relatively deep-water, open lagoon to a confined, shallow estuarine lake that today is highly sensitive to changes in freshwater supply. This is particularly evident in the northern portions of the system, where the presence of distinct halite-enriched horizons document episodes of prolonged drought. The lateral persistence of these halite layers, as revealed by seismic profiling, point to a system-wide onset of desiccation associated with a major shift in the regional hydroclimate. The most severe drought events are identified to have occurred within the past 2000 years and are associated with known peaks in El Niño frequency and intensity. Analyses suggest that past cycles of desiccation and hypersalinity have been controlled by climatic changes related to El Niño-Southern Oscillation (ENSO) intensification. The cores from Lake St Lucia provide important new records from a key ENSO-sensitive region of the Southern Hemisphere.

Conclusions

The long-term evolution of the Lake St Lucia system is the product of two periods of major base level fall, one in the Pliocene, the other ~ 18 000 years ago, that resulted in a series of incised valleys forming. Associated with these are two phases of transgressive infilling (Pleistocene and late Pleistocene/Holocene) which follow the typical facies successions of mixed tide- and wave-dominated incised valley fills. As sea levels rose the valleys were filled, the back-barrier responded differently due to the sheltering effects of the Nibela Peninsula which buffered shoreline migration during the transgression. In this context, False Bay appears to have evolved towards an estuarine-lake system earlier than the North Lake depocentre. In general, however, the northern portions of the system (False Bay and North Lake) house the largest relict bayhead deltaic material, whereas the southern areas (South Lake) lack such deposits and are dominated by thick central basin-type infilling. The two areas appear to have evolved separately since the LGM, when two discrete and unrelated drainage systems were formed. Subsequently, these were infilled and only became connected as a single system after the closure of the main LGM inlets ~7500 years ago.

The most recent cycle of sedimentary infill has been strongly influenced by changes in relative sea level and geomorphic processes over the mid- to late Holocene. Systematic changes in foraminifera, diatom assemblages and sulfur isotope geochemistry record changes in basin geomorphology driven by sea level, coupled with barrier aggradation and lagoon development. The Holocene transgression is reflected by initial marine intrusions into the lake basin, followed by barrier development and the gradual transitioning of the system from a shallow, partially enclosed embayment to a brackish back-barrier lagoon. Barrier stabilisation was periodically interrupted by large-scale inundation events linked to the mid-Holocene highstand and episodes of enhanced storminess. St Lucia's present-day configuration was likely only established during the last ~1000 years, driven by further barrier accretion, which ultimately sealed the northern basins from the ocean. Geomorphic rather than climatic controls are identified as the primary forces responsible for governing depositional and hydrological changes within St Lucia over the last ~6000 years.

Sediment accumulation appears to have also played a role in tandem with drier climatic periods. The net shallowing of the system is a continuing process, as evidenced from the ongoing sedimentation within each main lake basin. Even with stable lake levels, Lake St Lucia is on a trajectory that will eventually (possibly within the next two millennia) result in it being transformed into a swamp or wetland due to normal regression of the shorelines and eventual infilling of the available accommodation space. Although the accelerated accumulation of sediment in the lake would artificially shorten the lifespan of the present system, and increasing sediment yields have been a recurrent management concern, cores recovered from all three basins document dramatic decreases in sediment accumulation over recent times. In this light, future desiccation and hypersalinity may be controlled more by climatic changes than by the current catchment management practices.

Global warming is expected to increase the frequency and intensity of droughts over the next century, driven by reduced precipitation and increases in potential evapotranspiration (Cook et al., 2014; Dai, 2013). Projections for southern Africa indicate substantial drying over much of the region and increased climatic variability associated with a greater frequency and/or intensity of ENSO events (Fauchereau et al., 2003; Cook et al., 2014; Gaughan et al., 2016). Such changes will exert a profound influence on regional rainfall and river flow. Precipitation-sensitive systems such as Lake St Lucia will be particularly vulnerable to the impacts of climate variability, which are likely to be exacerbated by population growth and increasing dependence on water resources. Declines in precipitation, accompanied by increases in evaporative demand, will amplify extreme salinity changes within the system, severely altering physicochemical conditions, habitat availability and ecological functioning. Deterioration in the ecological functioning of Lake St Lucia will likely have pronounced impacts on offshore production, through changes in fish recruitment and in the delivery of nutrients to coastal environments. While the protection of natural flow regimes is likely to be the most effective management strategy to maintain estuarine functioning, in light of our findings, predicted climate-induced modifications to the hydroclimate are expected to have severe ramifications for biodiversity, local populations, and ultimately the long-term survival of Africa's largest estuarine system.

ACKNOWLEDGEMENTS

This study was based on research supported and funded by the Water Research Commission (WRC). We thank Dr B. Petja and Dr S. Liphadzi from the WRC, as well as the people who served on our project committee and provided valuable feedback, in particular, Alan Whitfield and Nicolette Forbes.

The iSimangaliso Wetland Park Authority and Ezemvelo KZN Wildlife enthusiastically supported the project and kindly granted us permission to work at Lake St Lucia. In particular, we thank Caroline Fox, Ricky Taylor, Dirk Rossouw and Nerosha Govender.

The National Research Foundation provided funding for students working on aspects of the project and the University of the Witwatersrand provided funding for the purchase of field equipment. Caldin Higgs, Letitia Pillay and Trevor Hill are thanked for assisting in the field.

Any opinion, finding and conclusion or recommendation expressed in this material is that of the authors.
We kindly acknowledge the following Reference Group Members:

Dr Brilliant Petja, Water Research Commission (Chair)
Prof G. Bate, Nelson Mandela University
Dr R.H. Taylor, Independent
Prof A. Whitfield, South African Institute for Aquatic Biodiversity
Dr N. Forbes, Marine and Estuarine Research
Barbara Weston / Mazibuko Molefi Jacob, Department of Water and Sanitation
Dr Colin Everson, University of KwaZulu-Natal
Dr M.D.V. Nakin, Walter Sisulu University
Ms Sue J van Janse Rensburg, South African Environmental Observation Network
Ms N. Govender, iSmangaliso Wetland Park
Dr Karl Reineke, Southern Waters Ecological Research and Consulting cc

Publications and thesis reports emanating from this work

Benallack, K., Green, A.N., Humphries, M.S., Cooper, J.A.G., Dladla, N.N., Finch, J.M., 2016. The stratigraphic evolution of a large back-barrier lagoon system with a non-migrating barrier. *Marine Geology* 379, 64-77.

Humphries, M.S., Green, A.N., Finch, J.M., 2016. Evidence of El Niño driven desiccation cycles in a shallow estuarine lake: the evolution and fate of Africa's largest estuarine system, Lake St Lucia. *Global and Planetary Change* 147, 97-105.

Gomes, M., Humphries, M.S., Kirsten, K.L., Green, A.N., Finch, J.M., de Lecea, A. Diatom-inferred hydrological changes and Holocene geomorphic transitioning of Africa's largest estuarine system, Lake St Lucia. *Estuarine, Coastal and Shelf Science*. In review.

Dladla, N. The geomorphological and sedimentological evolution of Lake St. Lucia, South Africa. School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal. PhD thesis to be submitted December 2017.

Gomes, M., 2016. Diatom-based reconstruction of the Holocene evolution of Lake St. Lucia, South Africa. School of Animal, Plant and Environmental Sciences, University of the Witwatersrand. Unpublished MSc thesis.

Benallack, K., 2014. The seismic stratigraphy and evolution of the False Bay and North Lake basins of Lake St Lucia, northern KwaZulu-Natal. School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal. Unpublished Honours thesis.

Sheik, T., 2014. Fire history of the southern Maputaland Coastal Plain: Implications for fire management in the iSimangaliso Wetland Park, KwaZulu-Natal, South Africa. School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal. Unpublished Honours thesis.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AMS	Accelerator mass spectrometry
Cal. yr BP	Calendar years before present
CONISS	Constrained incremental sum of squares
ENSO	El Niño-Southern Oscillation
HAR	High-amplitude reflector
LGM	Last glacial maximum
LP	Low preservation
XRD	X-ray diffraction

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND TO THE STUDY

Lake St Lucia is regarded as one of the most important estuarine systems in Africa. Covering a surface area of 350 km^2, it is the largest estuarine lake on the continent and encompasses some 80% of the total estuarine habitat in South Africa. The ecological importance of St Lucia is well documented, with the system forming part of the iSimangaliso Wetland Park which gained international recognition when it was listed as a UNESCO World Heritage Site in 1999. While Lake St Lucia has received significant research attention over the past 70 years, few studies have focussed on understanding the geomorphic evolution of the system and the controls governing its response to changing environmental conditions. Lake St Lucia has undergone relatively rapid changes over the last 20 000 years, driven primarily by changing sea level and fluctuating climatic conditions. The present St Lucia system only started forming ~ 6 000 years ago when sedimentation and basin infilling initiated a transition from marine to lagoonal and lacustrine conditions. Today, Lake St Lucia continues to evolve in response to ongoing sedimentary processes that drive the system along a trajectory that will eventually convert the lake into a floodplain wetland. Estuarine systems, such as Lake St Lucia, are thus ephemeral features in the long term, a reality that is often overlooked by scientists and conservation managers.

In addition to the long-term processes that govern their evolution, estuaries are recognised as highly dynamic environments, fluctuating on much shorter timescales. Lake St Lucia is at a point in its geological evolution where it is extremely sensitive to changes in water and sediment supply. The system experiences ecosystem shifts caused by prolonged droughts that result in hypersaline conditions, interspersed by floods that transform the system into an almost entirely freshwater system. This renders St Lucia particularly vulnerable to external influences. The lake is fed by five rivers that drain catchments that have all been influenced by upstream human-induced modifications. Although regarded as a resilient system and characterised by extreme natural fluctuations in salinity, Lake St Lucia has recently experienced severe periods of prolonged drought, associated with hypersalinity, loss of aquatic habitat and general deterioration in ecological state (Whitfield and Taylor, 2009; Cyrus et al., 2010). The most recent events (2002-2012 and 2015-2016), resulted in desiccation of up to 90% of the lake's surface area, severely impacting biodiversity (Pillay and Perissinotto et al., 2008; Whitfield and Taylor, 2009; Cyrus et al., 2010).

Lake St Lucia has experienced numerous anthropogenic impacts over the past century, including freshwater abstraction, catchment development and mouth manipulation. Virtually all research on St Lucia has taken place since 1950 and has therefore dealt with a system that was already severely impacted by human activities and management interventions. Little is known about how the system behaved before this (Taylor, 2013), and attempts to manage the estuary have often been limited by our lack of understanding of the long-term processes that govern change at the regional scale. An understanding of the long-term evolution and functioning of St Lucia is crucial in providing insight into how the system developed, how it used to function, and how it may respond in the future. It is this knowledge that should ultimately underpin future management strategies for the St Lucia ecosystem.

Most South African coastal lake systems evolved from fluvial origins (during the Last Glacial Maximum; LGM ~18 000 BP) that were slowly drowned by the rising sea levels of the Holocene (Wright et al., 2000; Cooper et al., 2012). The infilling of these channels represents a change from early, high-energy deposition to more stable conditions as the system evolved from transitional marine to lagoonal and lacustrine conditions. The accumulation of sediment in these systems is relatively undisturbed and various biological, sedimentological and geochemical proxies associated with these deposits provide a valuable source of information to aid in the understanding of palaeo-environments and geomorphic changes over the Holocene.

Facing issues of drought, catchment deterioration and episodes of recurring hypersalinity, the effective management of the Lake St Lucia system needs to be better informed with basic background geological and sedimentological data concerning its evolution and response to variables such as climate change, sea-level fluctuation and changing sediment supply. It is within this framework that this study was undertaken.

1.2 AIMS OF THE STUDY

- To investigate both the long-term and short-term geomorphic and sedimentological evolution of Lake St Lucia through a combination of geophysical, geochemical, and palaeo-environmental techniques;
- To relate these changes to long-term change in climate, lakewater chemistry, and shorter-term anthropogenic influences to the system;
- To provide an analysis of climatic controls on the geomorphic and sedimentological evolution of the lake system;
- To inform system management practices using insights gained from a longer-term evolutionary perspective.

1.3 THE STUDY AREA

Lake St Lucia is situated in Maputaland on the southern tip of the southeast African coastal plain (Fig. 1). Covering an area of ~ 350 km^2, the system comprises three main lake compartments, viz. False Bay, North Lake and South Lake, which are separated from the ocean by a Pleistocene-Holocene barrier dune complex. The lake's only contemporary oceanic link is via the Narrows, a 21 km-long channel (Wright, 1995) that opens into the Indian Ocean adjacent to the Mfolozi River outlet. The inlet is susceptible to prolonged periods of closure. Tidal effects penetrate 14 km up the Narrows when the inlet is open (Orme, 1975), but the lake itself is not tidal.

The system is underlain by siltstones of the St Lucia Formation (Kennedy and Klinger, 1975). Late Pleistocene sediments (366 to 101 Ka BP) form the core of the main barrier system. Holocene-age dune sands have accreted onto the complex coastal barrier dune cordon at, and immediately inland of, the modern shoreline (Porat and Botha, 2008). The recent Holocene sedimentation within the lake system reflects the transgressive infilling of several incised valleys formed during low sea levels (Van Heerden, 1987). Sea levels have varied significantly in the past (Ramsay and Cooper, 2002). The Last Glacial Maximum (LGM) sea level occurred at a depth of 125 m, ~18 000 yr BP (Fig. 2a). This was responsible for the exhumation and extension of these river valleys across the adjacent northern KwaZulu-Natal continental shelf (Green, 2009). An open ocean connection was present at Leven Point through most of the Late Pleistocene/Holocene transgression (Green, 2009) (Fig. 1). This inlet sustained the lagoon phase of the system before it was sealed and the back-barrier transitioned from lagoonal to lacustrine conditions (Wright et al., 2000).

Lake St Lucia is fed by five rivers, although the Mkhuze River in the north and the Mfolozi River in the south are the largest contributors to freshwater and sediment supply. The rivers are seasonal, flowing during the wet summer, but typically reduced to seepage through bed sediments during winter. Persistent groundwater seepage occurs through shallow coastal plain aquifers, although this contributes only a small component (typically 6-7%) to the overall water balance of the lake (Kelbe et al., 2013). Thunderstorms and mid-latitude cyclone activity are the dominant weather patterns. Rainfall varies from 1200 mm yr^{-1} at the St Lucia estuary mouth to 625 mm yr^{-1} at Lister's Point, although the region is characterised by high inter-annual variability (Mason and Jury, 1997). The lake water level is sensitive to evaporative losses, due to the large surface area to volume ratio, and evaporation accounts for losses up to 397 x 10^6 m^3 yr^{-1} (Begg, 1978). The system is therefore subject to extreme fluctuations in lake level and physicochemical conditions, frequently shifting between freshwater and hypersaline conditions.

For the last 70 years, management at St Lucia has focussed on manipulating the flow of water and sediments, often in response to periods of drought. Significant anthropogenic impacts began in the early 20th century when large areas of the lower Mfolozi floodplain were converted to agriculture, leading to the drainage of swamps, the construction of large levees and partial canalisation of the river. It is widely believed that these changes increased the sediment load transported by the Mfolozi River and resulted in the accumulation of sediment in the St Lucia mouth (Taylor, 2013). In an attempt to address this issue and protect sugarcane farms from back-flooding during mouth closures, the mouth of the Mfolozi River was artificially separated from St Lucia in 1952. After the separation of the Mfolozi River, the St Lucia inlet had a natural tendency to close and active management intervention was required to keep the mouth open. At the time, it was considered desirable to have a continuously open inlet to facilitate biological exchanges between estuary and sea (Kriel et al., 1966). The management strategy to keep the inlets of the Mfolozi and St Lucia systems separate while artificially maintaining an open St Lucia mouth remained in place for the next 50 years. In 2002, the mouth was left to close following the onset of dry conditions. Coupled with persistent dry conditions, this led to the development of extreme hypersaline conditions within the lake and relinking the Mfolozi River with St Lucia become a priority for management (Whitfield and Taylor, 2009). In 2012, a beach spillway was established to facilitate the relinking of the Mfolozi and St Lucia systems. At the time of the study, the system was experiencing a prolonged drought with large areas exposed to subaerial conditions.

CHAPTER 2

GEOPHYSICAL AND SEDIMENTOLOGICAL SURVEYS

A detailed geophysical survey of the Lake St Lucia system was undertaken from a very high resolution seismic perspective. The main aim of this sub-component was to map the incised valleys that underlie the system. These effectively house the main sedimentary infill and provide an archive of the system transition from a fluvial to a lagoonal/lacustrine setting.

This report forms the first high-resolution seismic (and accompanying sedimentological) study of two major depocentres of Lake St Lucia, and investigates their stepwise evolution from a sequence stratigraphic and sedimentological perspective. More broadly, this study investigates the role of barrier sheltering and antecedent conditions on the manner in which back-barrier environments may evolve during similar phases of sea level and sediment supply.

2.1 METHODS

2.1.1 Seismic survey

Approximately 300 line kilometres of single-channel seismic reflection data were collected in June, 2014 (Fig. 1). A 175 J Boomer system was used for the seismic source, coupled with a 24-element hydrophone array. The data were recorded digitally via a National Instruments analogue to digital converter interfaced with the HYPACK^{TM} survey program. Data were collected at a trigger rate of 500 ms and a sweep rate of 100 ms for optimal resolution. All data were integrated with a DGPS feed for positioning. When corrected for layback errors, the data are within ~ 1 m horizontal resolution. The data's vertical resolution is between 30 and 50 cm. The data were processed using in-house designed software where they were bottom tracked and band pass filtered. Time-varied gains and sound velocity corrections were applied to all data prior to exporting in the processed SEG-Y format.

2.1.2 Sediment coring

In January and June, 2014, three continuous sediment cores (NL-1, FB-1 and CB-2) were extracted from the main depocentres of the lake (Fig. 1) using a barge-mounted piston corer coupled to a percussion drill. Cores were sited to intersect the upper incised valley fills identified from an earlier intensive seismic reflection survey (Benallack et al., 2016). Maximum depth of penetration varied between 13 and 16 m, and targeted the entire estuarine-lacustrine succession. Lake water levels at the time of coring were ~1 m. Cores were transported to the laboratory where they were split longitudinally and logged according to standard sedimentological procedures.

2.2 RESULTS

2.2.1 Seismic stratigraphy

Seven seismic units, A-G, were resolved beneath the lake bed within each area, identified on the basis of seismic impedance, reflection termination patterns, internal reflection configuration and bounding acoustic reflectors (Figs 2-8). Sub-units were recognised within each seismic unit and were assigned numbers, e.g. A1, A2 and A3 of Unit A. Each sub-unit is separated by an acoustic reflector (e.g. reflector-ai overlying sub-unit A1). Two master reflectors, reflector SB1 and reflector SB2, are recognised underlying the successions of each area.

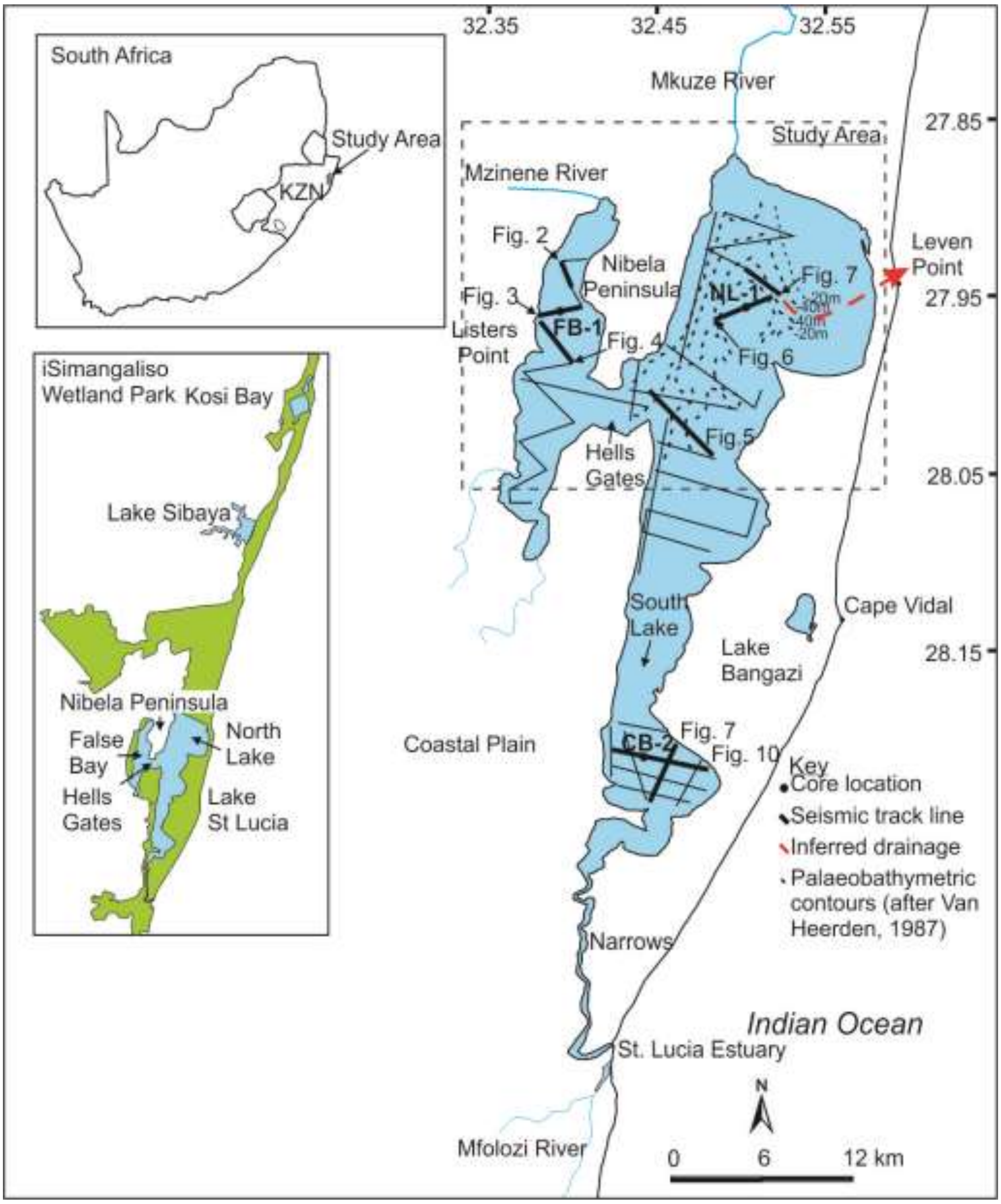


Figure 1. Overview of the spatial distribution of the seismic profiling coverage and core sites (NL-1, FB-1 and CB-2).

Unit A

Unit A is the deepest unit resolved in the study. It is characterised by continuous, sub-parallel to parallel, moderate- to high-amplitude reflectors that dip at approximately 2-3° seawards. These display an overall progradational stacking pattern (Figs. 3-7). The thickness of this unit cannot be calculated directly from the seismic profiles as its basal surface is beyond the penetration depth of the boomer seismic system, but it is greater than 50 m. The upper reflectors of Unit A are erosionally truncated by a very rugged, erosional surface, marked as reflector SB1. This surface is characterised by a number of incisions that vary in width from a few metres to hundreds of metres wide, with highly variable cross sectional profile reliefs. The interpolated colour-contoured plots of this basal-most erosional surface show a meandering form in the North Lake area, that trends towards the southeast (Fig. 8). Drainage, as defined by reflector SB1, appears to be most concentrated in the northern area of the lake system, with little to no connection to the southern areas (e.g. South Lake).

Unit B

Unit B is separated from the underlying Unit A by reflector SB1, and is divided into four distinct sub-units (B1 to B4) which are present to varying degrees throughout the survey area (Figs. 4-7). These comprise either narrow incised valley fills or more laterally extensive packages. Sub-units within this unit are commonly observed as either onlapping or downlapping underlying facies, and are separated by moderate- to high-amplitude erosional surfaces (Reflectors bi, bii and biii) (Figs. 4, 5 and 6).

Sub-unit B1 overlies reflector SB1 and is characterised by moderate- to high-amplitude, chaotic, discontinuous aggrading to prograding reflectors that onlap and downlap onto the underlying surface and may be truncated by an overlying master reflector (Fig. 3). B1 attains an average thickness of 5-7m which varies laterally. Deposits of B1 vary in lateral extent, and may be restricted in occurrence to only the deeply incised valley thalwegs of reflector SB1 in the distal North Lake, while rarely attaining a thickness of more than 12 m throughout.

Sub-unit B2 comprises low- to moderate-amplitude, steeply dipping, prograding oblique-parallel reflectors which onlap valley flanks and downlap reflector SB1 or reflector-bi, forming a valley flank-attached unit which may be attached to either one or both valley flanks (Fig. 6), and in some cases may be absent (Fig. 5). Deposits of B2 occur only within the distal V-shaped incised valleys of reflector SB1.

Sub-unit B3 is the most prominent of the Unit B sub-units, and is separated from the underlying B1 by reflector-bi. This sub-unit appears as a well-developed drape package, typically comprising moderate- to low-amplitude, oblique-parallel to wavy sigmoid continuous reflectors that onlap the valley flanks of reflector SB1 locally (Figs. 4, 6 and 7) or reflector-bii where sub-unit B2 is developed (Figs. 6 and 7). Reflectors may also be truncated in places by reflector SB2. This package averages 8-10 m in thickness in the proximal False Bay, but may attain thicknesses of up to 45 m distally, albeit over a very limited width (Figs. 6 and 7).

Sub-unit B4 is the uppermost facies of Unit B, and overlies reflector-biii. The moderate-amplitude, sub-parallel continuous internal reflectors of B4 exhibit a low angle (3-5°) dip towards the valley thalweg, downlapping the underlying surface, and are erosionally truncated by reflector SB2 (Fig. 3). The thickness of this unit is indeterminate as it is erosionally bound at its lower and upper surface.

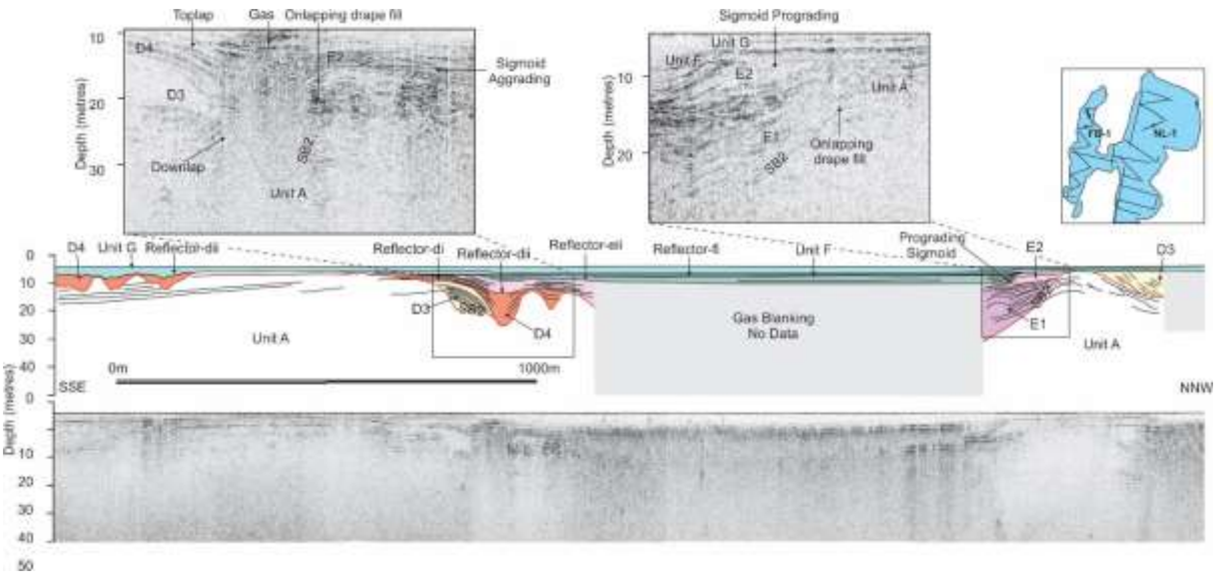


Figure 2. NNW-SSE seismic profile from False Bay displaying interpreted (top) and raw (bottom) seismic data. Unit B is absent from this line, however prominent incisions (SB2) filled by Units D (3 and 4) and E (1 and 2) are apparent. Bold line on inset indicates position of seismic line.

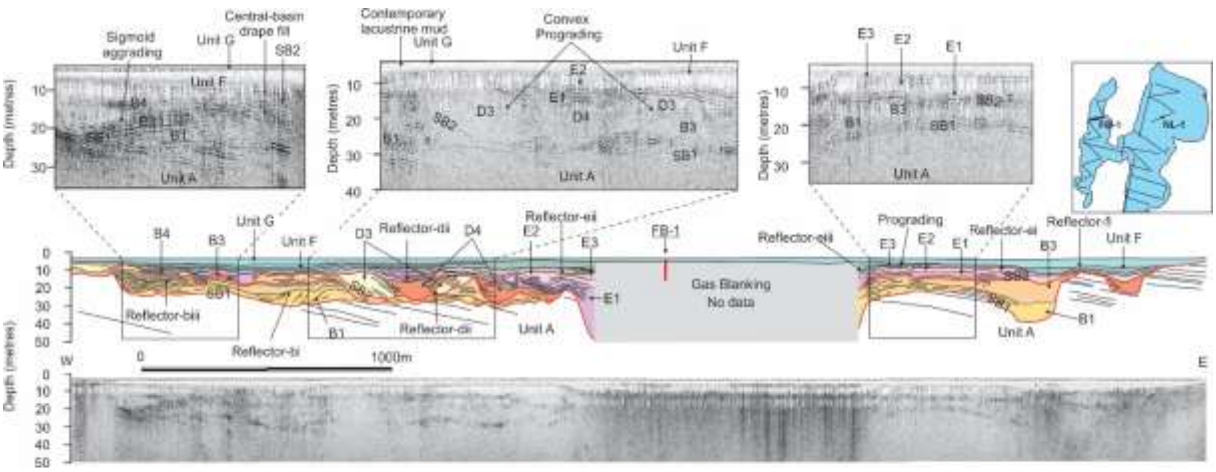


Figure 3. W-E seismic profile from False Bay displaying interpreted (top) and raw (bottom) data, with enlarged raw data detailing the stratigraphic relationships of Units B, D and E. All seismic stratigraphic units from the False Bay area are evident in this section. Units A and B are truncated by a series of incisions within reflectors SB1 and SB2 respectively. Note the strongly prograding reflectors of sub-unit D3. Bold line on inset indicates position of seismic line.

Unit C

Unit C, which is divisible into three sub-units, C1 to C3, constitutes the uppermost unit deposited above reflector SB1, and is restricted to North Lake. The reflectors of Unit C are commonly weakly developed, exhibiting dominantly low to isolated moderate amplitudes. The basal reflectors are partially definable, but pass upwards into chaotic, unstructured semi-opaque packages.

Sub-unit C1 directly overlies reflector SB1 and forms the capping fill for the distal V-shaped valleys incised into reflector SB1. The low-amplitude, draping reflectors of this facies fill these depressions, along with many other minor depressions, onlapping the valley flanks in reflector SB1. This facies reaches up to 20 m thickness within valley margins, while spreading laterally and thinning out to 10 m after overspilling its confining interfluves (Fig. 5). The transition from sub-unit C1 to C3 is represented by reflector-ci, although C1 may be truncated locally by reflector SB2.

Sub-unit C2 is spatially restricted to the Hells Gate area, and comprises convex prograding moderate-amplitude reflectors that downlap the underlying reflector-biii (Fig. 6). These reflectors prograde laterally from north-west to south-east and are confined to the antecedent depression within reflector-biii. The upper surface of C2 is incised by reflector SB2. This lens-like accumulation of sediment thickens to 18 m, pinching out laterally.

Sub-unit C3 is the thickest of the Unit C sub-units and caps the succession, overlying either C1 (Fig. 6) or Unit A (separated by reflector SB1) as shown in Figure 6. This unit represents a vertical continuation from sub-unit C1, but is significantly less organised, with the low-amplitude reflectors appearing chaotic and structureless. C3 occurs over a significant lateral distance and unconfined by valley interfluves (Figs. 5 and 6). It averages a thickness of 25 m.

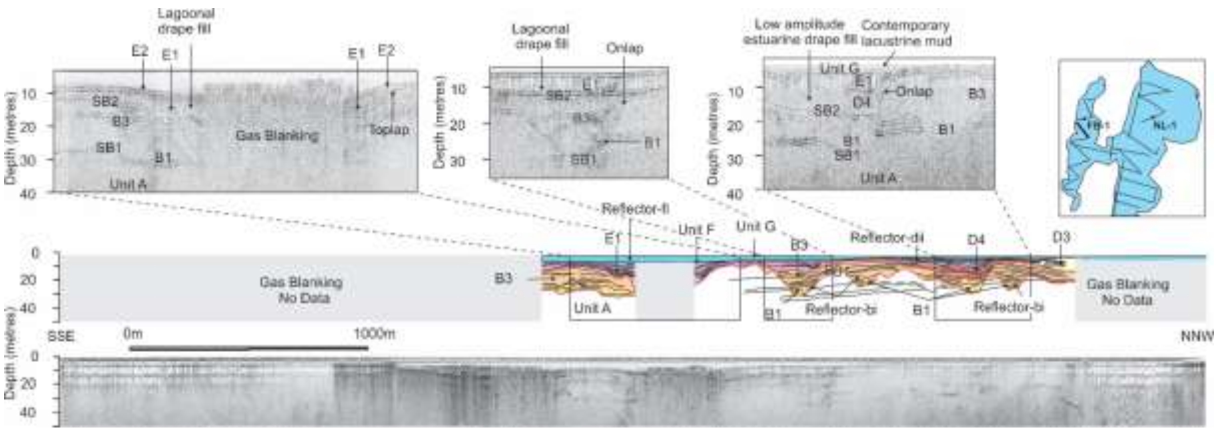


Figure 4. NNW-SSE seismic profile from False Bay displaying interpreted (top) and raw (bottom) data, with enlarged raw data detailing the characteristics of Units, B, D and E. Note the pronounced gas blanking throughout most of the line. Bold line on inset indicates position of seismic line.

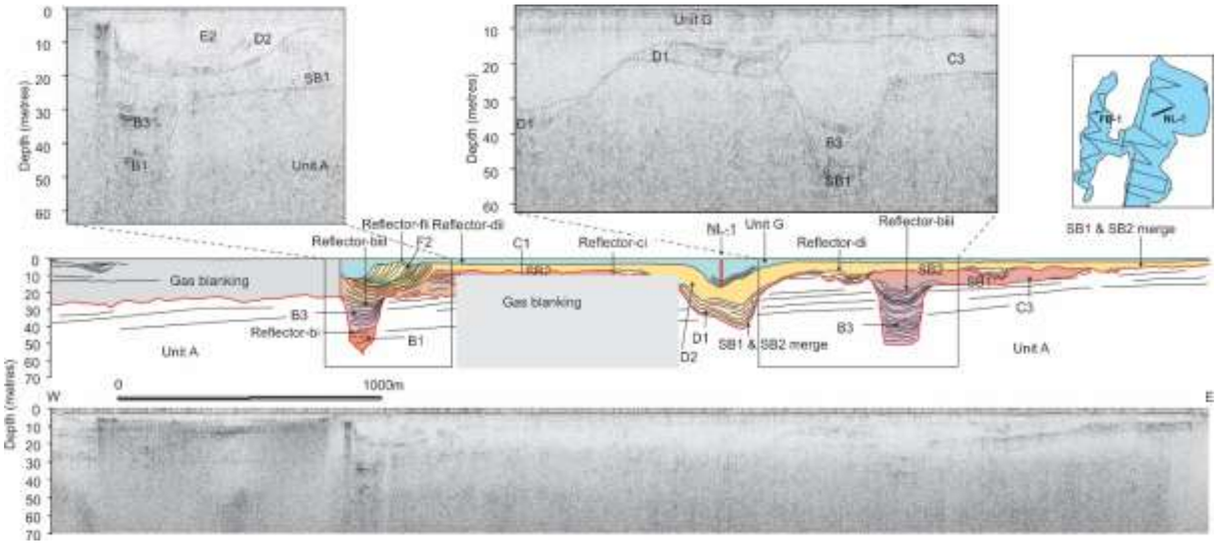


Figure 5. E-W seismic profile from North Lake displaying interpreted (top) and raw (bottom) data, with enlarged raw data. All seismic stratigraphic units are observable in this line. Note the deep V-shaped valleys. Bold line on inset indicates position of seismic line.

Unit D

Unit D directly overlies the undulating, erosive surface reflector SB2 and occurs as a series of low- to moderate-amplitude, sub-parallel, wavy and continuous reflectors that often appear to be draped within the numerous saddles of this reflector. Incisions within reflector SB2 vary from 5 m to 20 m in width (Fig. 8), into which the reflectors of Unit D drape, and may downlap (Figs. 2 and 3) or onlap (Figs. 2, 4 and 5). Reflector SB2 erodes into the underlying units, in places coming into erosional contact with reflector SB1, in which case a composite surface is formed (Fig. 5). Unit D reaches a thickness of ~35 m, and occurs within all seismic lines (Figs. 2-7), extending laterally and filling all depressions within reflector SB2 throughout its entire strike length. Much like Unit C, the reflectors of Unit D grade vertically from definable and structured to very low amplitude, chaotic and structureless in the upper stratigraphy (Figs. 5 and 6).

Distally, sub-unit D1 is the lowermost of the four Unit D sub-units, and comprises a depression bound, 10-17 m thick drape fill succession represented by low- to moderate-amplitude reflectors that onlap the gently undulating valleys of reflector SB2 (Figs. 5 and 6). These reflectors grade vertically into the predominantly acoustically opaque, structureless sub-unit D2, a transition represented by reflector-di. Sub-unit D2 dominates the unit D succession in North Lake, and much like sub-unit C3, occurs over a significant lateral extent, attaining thicknesses of up to 20 m, while thinning to 8 m in places, again visible in all three North Lake seismic lines (Figs. 5 and 6).

In the proximal False Bay area, sub-units D3 and D4 predominate. Sub-unit D3 occurs as a series of moderate- to high-amplitude, prograding convex sigmoid reflectors that onlap valley flanks and downlap the underlying erosional boundary reflector SB1 (Figs. 2 and 3). The reflectors of D3 prograde towards the valley thalweg in all cases and may be present on either one (Fig. 2) or both valley sides (Fig. 3).

Sub-unit D4 comprises low- to moderate-amplitude, sub-parallel to sigmoid-oblique reflectors developed as a thick drape package within the incisions of reflector SB2 that onlap either reflector-di, where D3 is developed (Figs. 2 and 3), or reflector SB2 (Figs. 2 and 4). Sub-unit D4 attains a maximum thickness of 13 m.

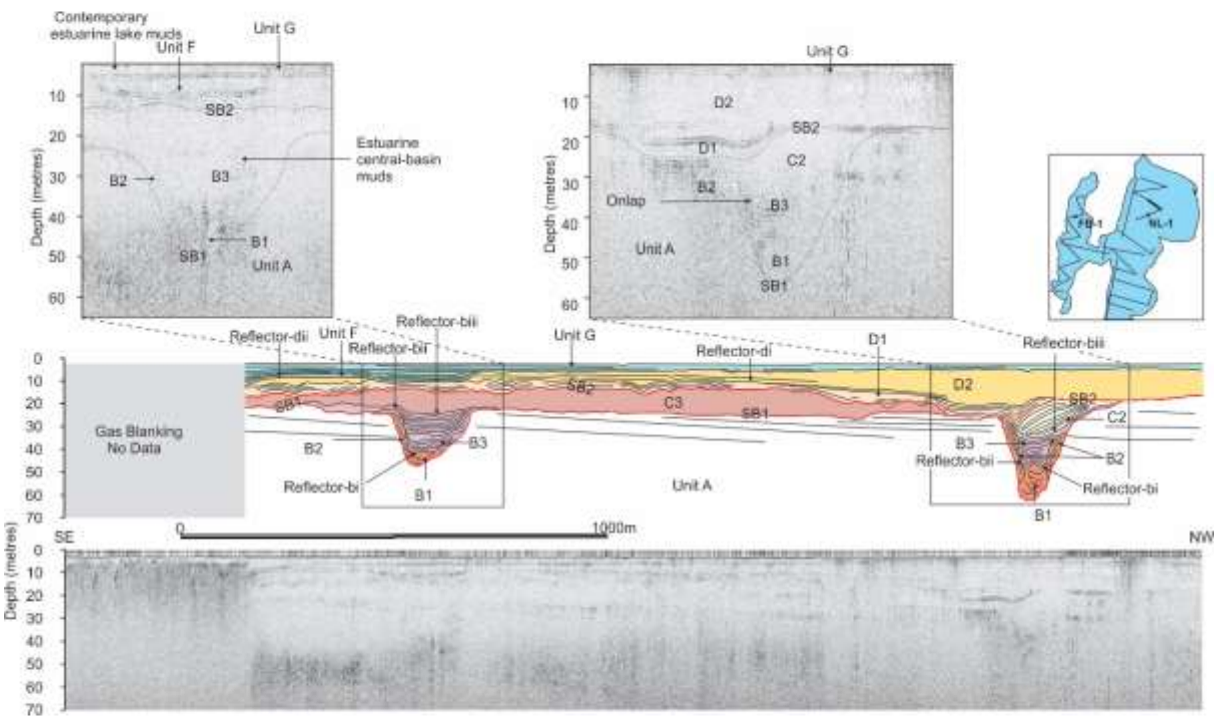


Figure 6. SW-NE seismic profile from North Lake displaying interpreted (top) and raw (bottom) data, with enlarged raw data. Valley fills are prominent here, capped notably by the strongly prograding sub-unit C2. Note the laterally persistent occurrence of Unit D2. Bold line on inset indicates position of seismic line.

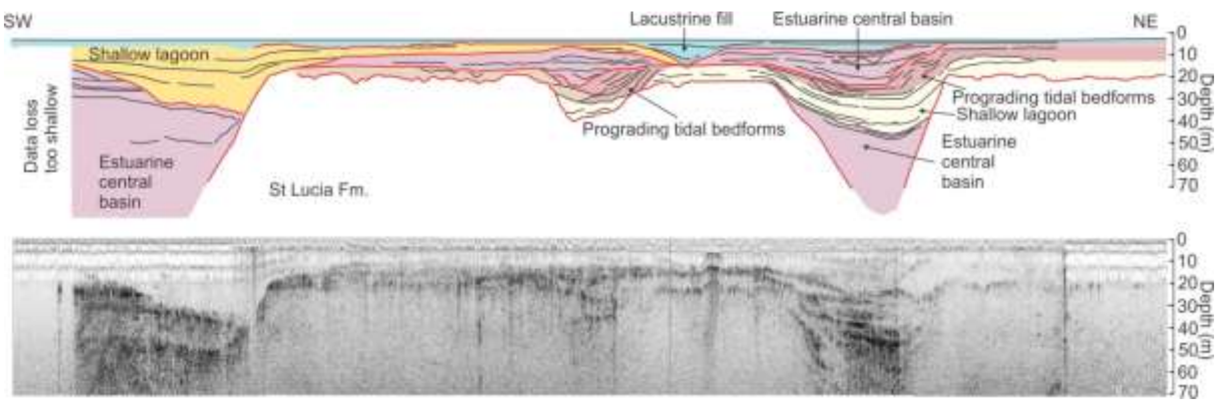


Figure 7. Seismic profile from South Lake.

Unit E

Unit E occurs in the more proximal False Bay area and exhibits three distinct sub-units (E1 to E3) that comprise generally aggrading (Figs. 3 and 4) to prograding (Fig. 2), low- to moderate-amplitude, sub-parallel to oblique wavy reflectors that onlap, downlap and locally toplap their bounding surfaces (Figs. 2-4). These facies may extend laterally as thin ‘fingers’, eventually pinching out or terminating against erosional boundaries (Figs. 3 and 4).

Sub-unit E1 is the lowermost of the three sub-units and directly overlies reflector SB2 (Figs. 2 and 3) or reflector-dii. Internal reflectors comprise moderate-amplitude, sub-parallel and wavy packages and occur as a drape succession that onlaps onto reflector SB2, often filling minor, low-relief depressions (Fig. 3).

Sub-unit E2 is separated from the underlying E1 by reflector-ei, onto which the internal reflectors of this facies downlap and onlap (Figs. 2 and 4). The upper reflectors of this package may in places be erosionally truncated by reflector-eiii (Fig. 2). They are characteristically low- to moderate-amplitude, sigmoid prograding (Figs. 2-4).

Sub-unit E3 is the thinnest and least developed of the three observed sub-units that comprise unit E. The low-amplitude, sigmoid-oblique, prograding reflectors onlap and downlap (Fig. 3) the underlying reflector-eii. E3 is overlain by reflector-eiii, which truncates the prograding reflectors of this package in places (Fig. 3).

Unit F

Unit F comprises two sub-units, F1 and F2 that drape (F1, Figs. 2, 3 and 6) or prograde (F2, Fig. 5) into the depressions of reflector-dii distally or reflector-eiii. This underlying surface displays an erosive topography, similar in nature but on a smaller scale to those of reflectors SB1 and SB2. The reflectors of F1 are low amplitude, typically onlapping the minor depressions of reflector-dii (Figs. 3 and 6), while the reflectors of E2 are of moderate amplitude and are commonly oblique to oblique tangential, downlapping onto reflector-dii (Fig. 5) On average, Unit E displays a thickness of 5-8 m, but where depression-bound may thicken to 14 m.

Unit G

Unit G directly overlies reflector-fi. This unit forms a thin veneer that caps the underlying stratigraphy throughout the entire survey area. The upper surface of Unit G is the present-day lake bed, a predominantly stratiform horizon that displays weak undulation in places. This unit lacks any definite internal configuration, comprising predominantly acoustically semi-transparent reflectors which exhibit an acoustic signature that extends beyond the internal resolution of the boomer seismic system (Figs. 3-5). When definable, Unit G appears to possess parallel, mixed very low to moderate amplitude reflectors that drape the underlying horizon and extend laterally for hundreds of metres (Fig. 2). This unit averages ~6 m in thickness, but is variable over strike length, at times thinning to 2 m as well as attaining maximum thicknesses of up to 12 m.

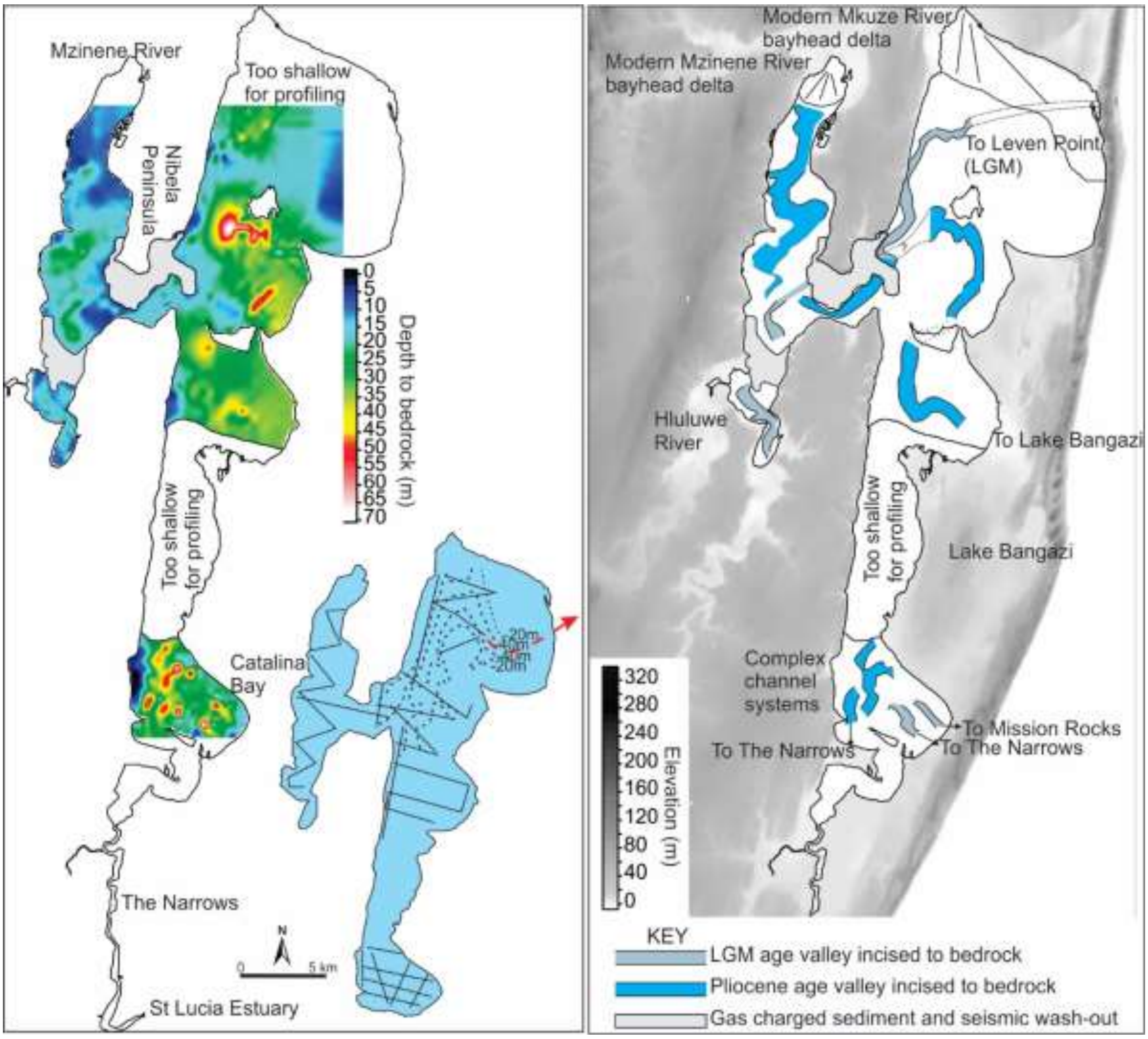


Figure 8. Combined sun-shaded relief surface of the SB1 unconformity and colour-coded depth to bedrock isopach map of the St Lucia system. On the right are the inferred channels from the various seismic units identified in the St Lucia system; grey units depict channels in SB2.

2.2.2 Core lithologies

The position of cores FB-1, NL-1 and CB-1 in the context of the seismic sections are shown in figures 3, 5 and 10, respectively. The ~16 m-long FB-1 (Fig. 9a) comprises predominantly stiff, and in restricted sections, fluid-rich clayey sediment that is interspersed with thin beds of coarser sediment. The core is mostly homogenous clay, with occasional spikes in grain size (Fig. 9c). These layers are typically poorly sorted (Fig. 9d).

NL-1 (Fig. 9b) comprises ~16 m of predominantly (~12 m) stiff, organic-rich, muddy units punctuated by a number of thin (0.3-0.05 m) horizons characterised by an abundance of shell debris. This dominant sequence is underlain by a basal (16-12 m) sandy unit. The lowermost facies comprises a fining upward, medium- to fine-grained, deep brownish-orange, quartz-rich sandy unit with occasional thin (<1 cm) rhythmic mud draping (Fig. 9b). This is sharply overlain by a dark grey, organic-rich, very fine-grained, clayey sand unit approximately 30 cm in thickness, interbedded with thin (<2 cm) quartz-rich sandy horizons (Fig. 9b). This unit grades into a thick (1 m) dark brown (at its base) to dark grey, fine to very fine sandy unit with occasional thin (0.2 cm) mud draping and a notable, ~20%, clay content (Fig. 9c). This is sharply overlain by dark grey to black, mostly clay dominated sediments (Fig. 9b), intermittently interspersed with coarser shell debris-rich layers (Fig. 9c). These are poorly sorted (Fig. 9d).

CB-1 (Fig. 9e) comprises an ~14 m core of predominantly silty sediment. The core intersected the upper tidal bedform package of Unit F2 revealing it to comprise rhythmic draping of mud/sand packages. Unit G had several coarser sandy layers, the most prominent of which was a 12 cm thick package of normally graded medium sand to silt at ~ 7.3 m downcore. Another coarser horizon is found at 2.1 m and comprises quartz and shell debris.

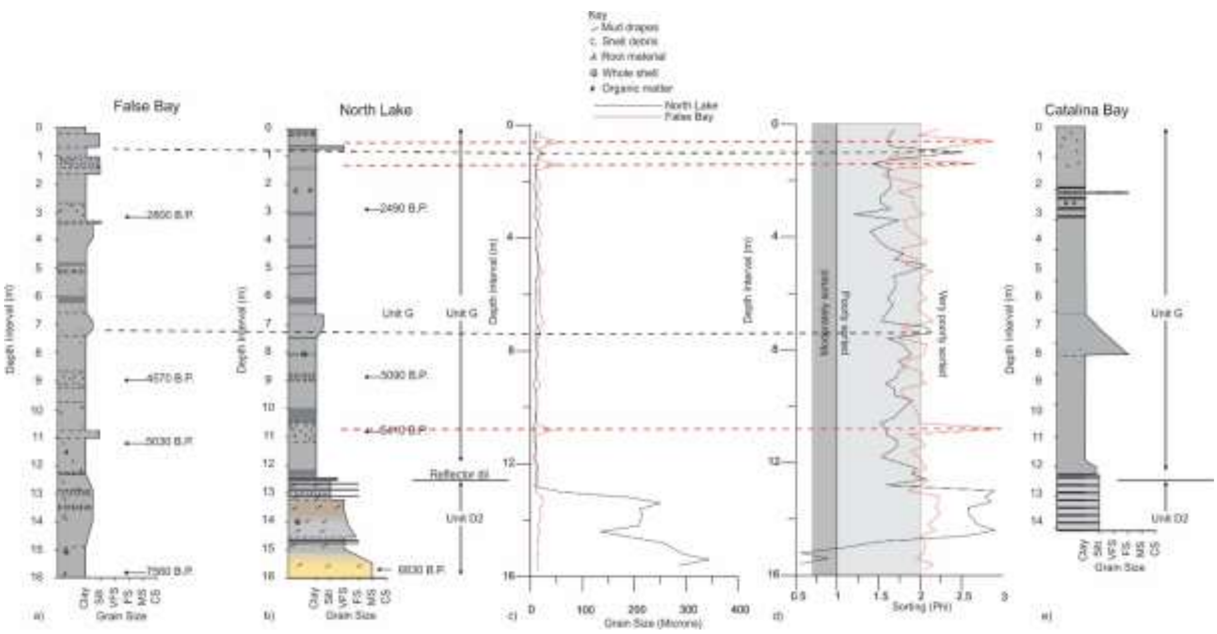


Figure 9. Core logs and key stratigraphic dates (a, b), mean grain size (c) and sorting (d) analyses of cores FB-1 and NL-1.

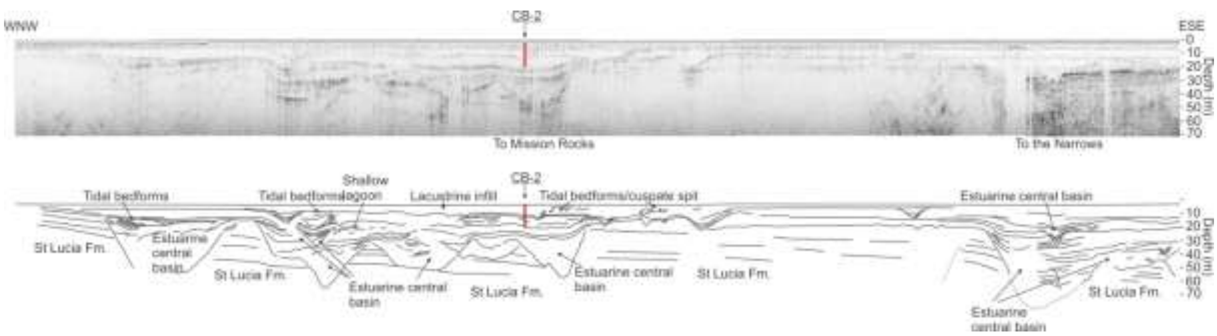


Figure 10. Core log of CB-2 and intersecting seismic line. Note the more complex incisions and the positioning of core CB-2, where it intersects the full lacustrine and upper tidal bedform succession.

2.3 Seismic interpretation and environmental analysis

Underlying the entire study area, and constituting the bedrock that hosts the development of the network of incised valleys, are the parallel to sub-parallel, high-amplitude, gently seaward-dipping reflectors of Unit A. The cliffs around the Nibela Peninsula provide a particularly well-exposed outcrop of the St Lucia Formation deposits (Kennedy and Klinger, 1975). The reflectors of Unit A can be traced into the outcrop of these cliffs, consequently the interpretation of this unit as a subcrop of the St Lucia Formation is particularly robust.

Throughout the study area, the gently seaward-dipping reflectors of seismic Unit A are erosionally truncated by the very rugged, undulating surface of reflector SB1. This surface is characterised by a number of incisions that vary in width from a few metres to hundreds of metres wide, with highly variable cross sectional profile reliefs. The scale and geometry of these incisions and the erosive nature of this surface suggests that its formation may be linked to a period of appreciable fluvial incision and downcutting.

Wiles et al. (2013) related the nearby Tugela submarine canyon (a major slope-hosted erosional unconformity) to several phases of Tertiary (Neogene) hinterland uplift, the largest of which occurred in the late Pliocene. The development of several shelf-impinging submarine canyons directly offshore Leven Point in North Lake was similarly ascribed to the late Pliocene uplift (Green, 2011a). It seems likely that this major base-level change was thus responsible for the initial basal valley incision and agrees with the inferred ages of a series of isolated incised valleys located on the outer shelf of the east coast of South Africa (Green et al., 2013). The drainage pattern established by this palaeo-surface shows no pathway to the ocean other than via one of the seaward fringing disconnected coastal lakes of the system (Lake Bhangazi) (Fig. 8).

The most recent recorded sea-level lowstand occurred ~18 000 yr BP during the LGM (Last Glacial Maximum). Reflector SB2 constitutes the uppermost, and thus youngest, subaerial unconformity and is thus associated with the LGM-age lowstand. This surface is recognised by Green (2009), Green (2011b) and Green et al. (2013) as the most common erosion surface on the southeast South African continental shelf.

Unit B is separated from the underlying unit A by SB1 (Figs. 2-6), and is divided into four distinct sub-units (B1 to B4) that constitute the onlapping or downlapping fills of the observed incised valleys in SB1.

Sub-unit B1

The chaotic, moderate to high amplitude seismic characteristics of B1, coupled with its position directly above the fluvially incised sequence boundary, suggest the deposition of this sub-unit in a high-energy, possibly fluvial environment shortly after the cessation of erosion related to the formation of SB1. Allen and Posamentier (1994), Menier et al. (2006) and Nordfjord et al. (2006) document similar mixed amplitude, chaotic basal units that occur immediately above a regionally developed erosional boundary, and have in all cases suggested a similar depositional environment. Locally, Green (2009), Green and Garlick (2011) and Green et al. (2013) encountered similar packages within incised valleys on the continental shelf offshore of northern KwaZulu-Natal, Durban, and north of Durban, respectively, and interpreted them as fluvial lag deposits in each case.

Sub-unit B2

The flank-attached, progradational nature of sub-unit B2 reflectors (Fig. 6) is suggestive of deposition at the valley margins by backfilling of the newly formed incised valley under transgressive conditions. Within an incised valley, the early phases of transgression are characterised by the landward migration of a zone of fluvial aggradation and tidal influence as base level rises (Dalrymple et al., 1992; Allen and Posamentier, 1994; Zaitlin et al., 1994). Nordfjord et al. (2006) document the development of salt marsh and tidal flats sediments along the margins of incised valleys on the New Jersey continental shelf during similar conditions, which are represented by valley flank-attached reflectors similar to those of sub-unit B2. The deposits of sub-unit B2 are ascribed to deposition in a similar setting, and are consequently allocated to the early phases of transgression, during which valley-confined estuarine deposition backfilled the incised valleys of SB1.

Sub-unit B3

The low to moderate amplitude, sub-parallel, continuous reflectors of Unit B3 typically onlap the SB1 valley flanks, and display striking similarity to features observed by Thomas and Anderson (1994) and Menier et al. (2006), which were interpreted as fine-grained central basin deposits in a wave-dominated estuary. These sediments are deposited during the early transgressive stages of base-level rise as fluvial sediment supply is commonly outstripped by the rate of creation of accommodation space, and a drowned-valley estuary is generated at the seaward end of the incised valley (Dalrymple et al., 1992; Oertel et al., 1992; Zaitlin et al., 1994).

Botha et al. (2013) highlight the role of the Upper Cretaceous linear cliffs of the Nibela Peninsula as a barrier to oceanic activity sometime during the middle to late Pleistocene highstand with False Bay serving as a palaeo-embayment. Cooper et al. (2013) observed several 'stacked shoreline' sequences at the landward edge of False Bay, representing a succession of sea-level highstands within a few metres of the contemporary sea level since late Cretaceous times. The presence of limestone and the absence of clasts or storm beach deposits suggest a protected coastline (Cooper et al., 2013).

The development of sub-unit B3, particularly in the proximal False Bay area, is attributed to sheltering by the Nibela Peninsula. These acted like an estuarine barrier and dampened imposing wave energy. These deposits were likely laid down in a tranquil back-barrier estuarine environment in the early stages of transgression whereby a change in depositional regime from fluvial to estuarine is observed (Ashley and Sheridan, 1994). These constitute the equivalent of Zaitlin et al. (1994)'s central basin deposits.

Sub-unit B4

The restricted occurrence of sub-unit B4 (Fig. 3), combined with an absence of groundtruthing data, inhibits a rigorous evaluation of the unit. The inclined, aggrading to gently prograding, strata, however, are suggestive of a gradual advance in sediment migration towards the valley thalweg. The erosional lower contact is consistent with deposition by the forward advance of sediment within a channelised conduit, gradually incising down into the underlying unit B3.

Nichol et al. (1994) document modern fluvial channel and bayhead delta facies incised into aggraded central basin deposits at the head of the estuary in Lake Calcasieu along the Louisiana coast. This progradational sediment body is attributed to the onset of highstand conditions. These conditions can also prevail if there is sufficient stability in sea level to promote normal regression of the bayhead delta shoreline. Either case may be applicable here.

Unit C occurs only in the distal portions of the system in the North Lake area. The basal reflectors of unit C appear to correlate with the final phase of valley-confined sedimentation, after which rapid transgression and the landward migration of the shoreline resulted in the complete inundation of the incised valley on the landward side of the coastal dune barrier complex which may have been in place at that time (Porat and Botha, 2008). This would have triggered a transition from confined estuarine central basin conditions to more laterally extensive back-barrier lagoonal sedimentation, as barrier confinement served to partially impound the waterbody and promoted the development of a deepening lagoonal environment.

Sub-unit C1
Sub-unit C1 represents the earliest phases of this back-barrier lagoonal sedimentation in a deep back-barrier lagoon, where tidal currents would have been restricted to the deepest tidal channels, and deposition would have been dominated by the suspension settling of flocculated clays and fine silts. This explains the low-amplitude, draped nature of sub-unit C1 reflectors, which aggraded as successive layers of sediment were deposited. These fine sediments may be intercalated with thin sand sheets derived from storm-related barrier washover. These deposits would be proximal to the shoreline and thus explain their presence in the more seaward depocentre in contrast to the False Bay area.

Sub-unit C2
The convex, progradational nature of the sub-unit C2 reflectors, and their location within a channel-like depression (Fig. 6), suggests that this sub-unit may also be considered as a fluvial or tidal channel-hosted bedform. Weber et al. (2004) document similar style sub-units, and similarly attribute them to such an environment. The large scale of the unit’s clinoform structures suggests their deposition by tidal currents associated with a rise in sea level and an increase in tidal regime consistent with an increasing tidal prism and deeper back-barrier conditions.

Sub-unit C3
The chaotic arrangement of low-amplitude sub-unit C3 reflectors may be ascribed to the reworking and re-deposition of the underlying deposits. This would occur in a steadily shallowing lagoonal system where the lagoon floor is raised to an elevation above the wind-wave base (Green et al., 2015). Lagoon shallowing is typically driven by an imbalance between sediment supply and available accommodation space, usually marking periods of stillstand during an overall transgression (Cooper, 1993).

On this basis, it is suggested that the entirety of unit C represents sedimentation in an initially deep transgressive lagoonal system. These conditions were however modified by periods of relative sea-level stillstand, slowing the development of deep back-barrier lagoonal conditions and allowing for lateral sediment accumulation, aggradation and subsequent lagoonal shallowing and wind-wave reworking of the floor.

Unit D occurs as the dominant fill of the incised valleys hosted by SB2, representing a period of lowstand to transgressive sedimentation following the late Pleistocene regression to the Last Glacial Maximum sea levels of -120 m (Ramsay and Cooper, 2002). This unit, much like that of Unit B, onlaps and downlaps the underlying sequence boundary, and is likely representative of a similar cycle of fluvial incision, downcutting and successive transgressive sedimentation.

Sub-units D1 and D2

The similarity of the arrangement of the distal Unit D reflectors of North Lake to those of the underlying Unit C reflectors, suggests that this unit represents another cycle of initially deep, to shallowing lagoonal sedimentation on the landward side of the developing dune cordon, with sub-unit D1 representing deeper, tranquil conditions that promote suspension settling and fine particle flocculation possibly intercalated with sheets of laminated sands derived from storm washover, while sub-unit D2 represents the transition to shallow lagoonal conditions driven by superimposed stillstands in sea level on the overall rapid Holocene transgression.

Core NL-1 (Fig. 9a) intersected unit D2 (Fig. 5). The basal facies of the core is dominated by sandy sediment displaying occasional mud draping, indicative of deposition within a tidal environment in an initially shallow back-barrier setting. Gradual broadening and deepening of the system as sea level rose is reflected by a gradual decrease in grain size and an increase in the finer sediment fraction (Fig. 9). The intercalation of clayey sands and silts with thin quartz-rich sand beds is consistent with storm surge episodes depositing coarser sandy sediments within the back-barrier lagoon (e.g. Davis and Flemming, 1995).

Sub-unit D3

The flank-attached nature of D3's convex sigmoid reflectors, as well as its prograding architecture is similar to the outward building of side-attached channel margin deposits such as fluvial point bars from the insides of meander bends. Coe et al. (2003) describe the architecture of the fluvial component of the Book Cliffs succession, envisaged to have been deposited in a coastal plain setting similar to that of the northern KwaZulu-Natal coastal plain. Sandbodies of 1-4 m thick appear to have been deposited by lateral point bar accretion on the inner bends of meandering rivers, displaying a similar progradational, sigmoidal character to that observed for Unit D3. Weber et al. (2004) document similar isolated flank-attached deposits in the mixed tide- and wave-dominated incised valley of the palaeo-Charente river, and ascribe them to deposition in point bars in alluvial settings.

The preservation of such fluvial deposits may be ascribed to the establishment of a coastal barrier complex on the seaward side of the Nibela Peninsula at that time (see Porat and Botha, 2008) coupled with the impediment of the Peninsula itself, culminating in the retardation of reworking during the ensuing transgression and bayline ravinement.

Sub-unit D4

The predominantly low to moderate amplitude reflectors of sub-unit D4 are characteristically similar to those described for sub-unit B3. The draped nature is again suggestive of deposition within the confines of a low-energy, tranquil setting analogous to that described by Zaitlin et al. (1994) for the central basin portion of a wave-dominated estuary. The restriction of sub-unit D4 within the interfluves of the SB2 hosted incised valleys and their valley flank onlapping nature are supportive of estuarine confinement of the type-deposit, and thus it is suggested that sub-unit D4 constitutes aggradationally accreting beds of muddy to fine sandy sediment developed within the confines of the valley margins.

Sub-unit E1

This sub-unit displays an architecture similar to that described above for sub-unit D4. The moderate-amplitude, sub-parallel wavy reflectors occur as a drape succession that terminate or onlap onto SB2 (Fig. 3), often filling minor, low relief depressions. A difference in reflector geometry with regard the underlying sub-unit D4 is the continuous, unconfined nature of sub-unit E1 reflectors that are observed as overtopping their valley margins. This suggests that sub-unit E1 represents the earliest departure from valley confinement as relative sea level rose beyond the limit of SB2 valley relief, promoting the lateral development of accommodation space and a subsequent adjustment from confined, low-energy depositional conditions to a more laterally extensive zone of deposition. These packages are interpreted as settling packages formed within a tranquil back-barrier lagoonal type setting. Groundtruthing of similar seismic packages in the estuaries of KwaZulu-Natal revealed the presence of stiff clays (Orme, 1973), interpreted by the authors as lagoonal. Sub-unit E1 is likely to have developed as a lagoon within the zone of low-energy landward of the Nibela Peninsula and the early development of the contemporary dune barrier complex (cf. Porat and Botha, 2008).

Sub-unit E2 and E3

The generally prograding sigmoid arrangement of E2 and E3 reflectors and their occupation of minor topographic lows suggests that they may represent prograding subaqueous dune forms deposited by tidal currents active within the lagoon. Ashley and Sheridan (1994) document similarly arranged reflector packages within the Delaware River incised valley fill. These were identified as migrating fine sandy ridges commonly associated with relatively deeply incised tidal channels. The observation of tidalite deposits within core NL-1 bolsters the tidal sand body interpretation, highlighting the intermittent role of tidal deposition within the system.

Unit F's low-amplitude, sub-parallel reflectors occupy shallow depressions within the underlying erosional reflectors-dii and -eiii. This surface is interpreted as a tidal ravinement surface formed by migrating tidal channels as barrier constriction of the lagoon inlet reached an advanced stage. The deposits of unit F are thus interpreted as the final stage of lagoonal deposition prior to the complete impoundment of the coastal lagoon by the seaward dune barrier complex (Porat and Botha, 2008).

Sub-unit F1

The low-amplitude, draped nature of sub-unit F1 reflectors is interpreted as representing stiff lagoonal clays similar to those described by Orme (1973) and Cooper (2001) along the KwaZulu-Natal coastline. These were deposited in the channels and depressions of reflector-dii, and onlap the channel margins, as expected for the deposit type.

Sub-unit F2

The oblique tangential reflection configurations of unit F2 are similar to those recognised by Mallinson et al. (2010) as deposited by the migration of inlet and tidal channels within a barrier island complex. It is accordingly interpreted as such for Lake St Lucia.

The entire False Bay succession is capped by the laterally extensive, very low-amplitude reflectors of Unit G. The underlying reflector-fi is characteristically smooth, reflecting the absence of any major tidal or fluvial influence preceding the deposition of this unit. This suggests that it may be linked to the final impoundment of the lagoonal waters and the onset of the current estuarine-lake conditions. Both core FB-1 (Fig. 9b) and Core NL-1 (Fig. 9a) intersected the sediments of Unit G. The dominance of clays and fine silts is consistent with deposition under the contemporary low-energy conditions, whereby a lack of tidal or fluvial currents promotes primarily tranquil suspension settling. In False Bay, this dates to 8355 cal. yr BP (Fig. 9), whereas in North Lake, this dates to 6830 to 5410 cal. yr BP. The succession is punctuated by coarser-grained, silty facies. Both the sub-basin's extensive surface areas render them vulnerable to desiccation and deflation during extreme drought conditions, or to the effect of wind-wave currents and subsequent reworking of the lake bed sediments by oscillatory wave action, particularly during storm events. Either of these may cause the deposition of coarser debris or leave lag material in the main depocentres. In North Lake, this material is characteristically poorly sorted (Fig. 9), consistent with short-lived, high-energy deposition (possibly related to brief, windy episodes).

It is clear that the transition towards the contemporary lower energy regime was subtle; False Bay appears far more tranquil (based on the dominance of the very fine grain size, the system-wide, together with the accompanying low-amplitude, parallel seismic reflection pattern occurring outside of the main valleys) while the more seaward North Lake reflected a gradually sealing inlet (bedforms overlain by the same parallel, low-amplitude reflector configuration). Total closure of the Leven Point inlet (and any other inlets for that matter) occurred between 7123 and 6235 cal. yr BP. This is at odds with the suggestion of Porat and Botha (2008) that closure at Leven Point and the consequent onset of significantly lower energy conditions occurred approximately 2000 years ago. Our data agree with a major dune building event ~ 6 ka BP, recognised by Botha et al. (2013), and similarly associated with a phase of progradational spit development that further segmented the system.

Catalina Bay differs from the northern portions of the system in that the cut and fill stratigraphy is more complex (Fig. 10). Like the other areas, it comprises a series of regressive-transgressive successions; however, the fluvial systems are more incised; occurring as depressions, larger and wider than any other channel complex in the system. There are up to four cycles of incision and infilling (Fig. 10). Central basin, shallow lagoon and tidal bedform environments dominate the transgressive stratigraphic packages; basal fluvial lags are completely absent in this area.

The tidal bedform environments in Catalina Bay (Fig. 10) are not as well-developed as those in North Lake, suggesting that the tidal prism was not as constricted in the southern areas and the tidal velocities required to build significant subaqueous dunefields were not as frequently experienced. Each transgressive succession is separated by a subaerial unconformity; these get less pronounced as they young towards the top of the stratigraphy (Fig. 8; 10).

The largest incision in the entire system is the Pliocene age subaerial unconformity, which incises beyond the depth of penetration of the system (~100 m) as it enters the Narrows area (Fig. 8). In the Catalina Bay basin, the lacustrine muddy infill is less thickly developed as it is in the northern basins. The coring in Catalina Bay intersected the entire lacustrine succession, in addition to an underlying tidal bedform deposit (Fig. 9e). This corresponded to a late lagoonal phase before the sub-basin's access to the ocean was restricted. The lacustrine infill here appears to be sandier than that of the northern basin.

The seismic and core survey show that False Bay and the northern portion of North Lake have relict bayhead deltas, as would be expected for the main fluvial entry points to the system (Fig. 11). These areas also have the thickest lacustrine deposits. These appear to young seawards, as expected with a concomitant protection of the False Bay area by the Nibela Peninsula during the last transgression. When compared with Catalina Bay, these areas have greater occurrences of lowstand fluvial basal deposits; whereas Catalina Bay is dominated by central estuarine basin fill deposits. In Catalina Bay's case, the drainage channels are very large and these lags may occur below the range of penetration of the seismic system. On the basis of the seismic and core evidence, there is a strong suggestion that the northern and southern domains of Lake St Lucia evolved separately during lowstand conditions and that geomorphological connectivity was likely to have only been established once the main LGM-aged inlets began to close from ~7500 yr ago.

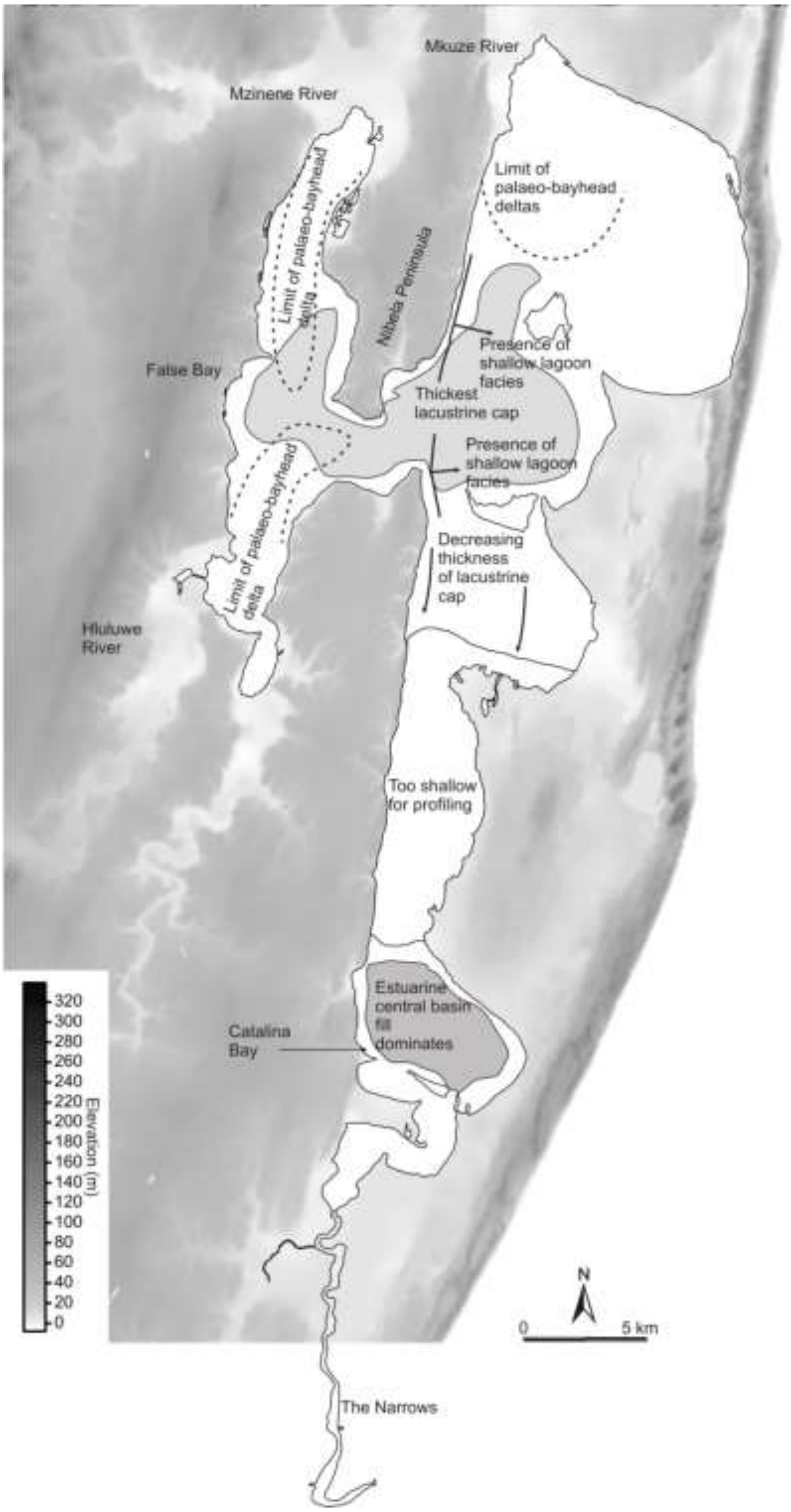


Figure 11. Summary map of basic environmental differences within the Lake St Lucia system

CHAPTER 3

SEDIMENT DATING AND CHARACTERISATION

Accurate dating is a fundamental prerequisite to understanding long-term processes through the use of palaeoreconstruction techniques. This becomes especially important when studying stratigraphic records of environmental change, such as within the field of palaeolimnology. Dating allows for the construction of chronological frameworks or timelines, such that the sequence and timing of past changes can be pinpointed and correlated between records. In this chapter, we present age-depth models, sedimentation and nutrient accumulation data from a series of long and short sediment cores obtained from Lake St Lucia.

Long-term processes are investigated using cores from the three main basins of Lake St Lucia (North Lake, False Bay and South Lake), while short sediment cores extracted from deltaic deposits near the river inlets are used to understand short-term processes. This information provides a useful chronostratigraphic framework against which to compare proxy-based environmental reconstructions (Chapters 4 and 5).

3.1 METHODS

Recently deposited sediments in shallow estuarine systems are difficult to date as wind mixing and bioturbation often results in sediment reworking. The shallow water levels and long wind fetch that characterise the St Lucia environment render sediments from the main lake basins unsuitable for investigating change over short timescales. In order to examine recent sedimentation and nutrient accumulation rates, deltaic deposits near the river inlets were targeted (Fig. 12). These sites represent areas of net sediment accumulation within the lake where reworking is less likely. This approach also allowed spatial differences in accumulation to be investigated.

Sediment cores were obtained from the four main rivers entering the northern basins of Lake St Lucia; the Mkhuze (MK; 85 cm), Mzinene (MZ; 35 cm), Hluhluwe (HL; 82 cm), and Nyalazi (NY; 91 cm) rivers. Cores were collected by manually inserting a clear 72 mm diameter pipe into the sediment. Care was taken to avoid disturbing the sediment–water interface and minimal perturbation of the surface layer was observed in the core barrel during retrieval. Cores were split open in the laboratory and subsampled at 1-cm intervals for radiometric and nutrient analysis.

Figure 12. Map of Lake St Lucia showing the location of core sampling sites from the main lake basins (NL-1, FB-1, CB-2) and river deltas (MK, MZ, HL, NY)

3.1.1 Radiocarbon dating

A series of samples for rangefinder Accelerator Mass Spectrometry (AMS) dating were extracted for each of the long sediment cores (NL-1, FB-1, CB-2) at basal and intermediate levels, including the boundaries of obvious changes in sediment type. These consisted primarily of bulk sediment samples, owing to the apparent lack of plant macrofossil material, with the exception of three shell samples. All AMS analyses were performed at Beta Analytic, Florida (USA). Pretreatment for sediment samples included removal of visible contaminants such as rootlets, drying overnight at 100°C, and a series of acid washes. Shell samples were etched in acid prior to analysis. Results were calibrated to calendar years before present (cal. yr BP), according to the Southern Hemisphere calibration curve (SHCal13; Hogg et al., 2013) using the 'classical' age modelling source code (clam 2.2; Blaauw, 2010) within RStudio 0.98.1091 (R Development Core Team, 2012). In the absence of further research into the marine reservoir correction factor for the southern African east coast, we elected not to correct AMS results according to the ΔR correction factor.

Bayesian age-depth models for NL-1 and FB-1 were developed using Bacon 2.2 (Blaauw and Christen, 2011). A non-Bayesian 'classical' age-depth model (Blaauw, 2010) was developed for CB-2, due to marked changes in sediment accumulation rate in this core and resulting poor fit of the Bacon model. The CB-2 age-depth model was based on linear interpolation between adjacent ages. The CB-2 AMS determination at 100 cm was designated an outlier for the age-depth model based on an age reversal.

3.1.2 Pollen marker analysis

As an independent means of providing age estimates for core tops, targeted fossil pollen analysis was conducted on the upper 20-25 cm of each core. A selection of neophytic (introduced) pollen markers was used as chronostratigraphic markers, and to establish age-equivalence across cores. This technique is not well established in the South African context, with few local applications (e.g. Thamm et al., 1996; Turner and Plater, 2004) and St Lucia provided an opportunity for testing methodological feasibility. Sediment cores were analysed at a 2-cm resolution, using 1 cm^3 sediment samples measured by volumetric displacement, to each of which 1 mL of well dispersed LacCore Microsphere Pollen Spike solution was added for calculating concentrations. Sediment samples were subjected to standard pollen extraction procedures (Faegri and Iverson, 1989), including removal of humic acids and clay materials using NaOH digestion, removal of clastic material through HF digestion, and acetolysis to treat the extraneous organic detritus. Processed samples were mounted using Aquatex aqueous mountant and analysed at 40x – 100x magnification using a Nikon Eclipse E100 compound light microscope. The following types were enumerated: spike, neophyte (*Zea mays*, *Pinus*, *Casuarina* or *Eucalyptus*-type), other pollen, and unknown. Palynomorph concentrations were determined according to Stockmarr's (1971) equation. Pollen stratigraphic profiles were plotted to establish depth of first appearance as a time marker, and ages were assigned accordingly. The earliest age of introduction was selected as a time marker, factoring in a lag phase for planted trees to reach reproductive maturity and produce pollen (Table 1).

3.1.3 Radiometric dating and nutrient analyses

Sediment subsamples from coring sites MK, MZ, HL, and NY were dried at 60˚C and then homogenised to a fine powder using a ball mill. Sedimentation rates were calculated using ^{210}Pb. Measurements of ^{210}Pb were made by gamma ray spectrometry using a low-energy Germanium well type detector system. All gamma data were processed using the HYPERMET software, and all errors were determined from counting statistics and the error associated with the HYPERMET curve-fitting routine (Phillips and Marlow, 1976). Total ^{210}Pb was determined by its emission at 46.5 keV and supported ^{210}Pb determined by measuring the ^{226}Ra activity of the sample via its daughter ^{214}Pb at 352 keV. Excess ^{210}Pb was calculated from the difference between total ^{210}Pb and the supported ^{210}Pb activity. Count times were typically in excess of 48 h, with detection limits of 0.3 dpm g^{-1}. The constant rate-of-supply (CRS) model was used to determine dates and sedimentation rates (Appleby and Oldfield, 1978). A total of 68 samples were selected for total carbon (TC) and total nitrogen (TN) analysis. Concentrations were measured using a Perkin Elmer elemental analyser.

Table 1. Evidence of introduction of exotic trees to Lake St Lucia and surrounds. Maturation time for each genus is: *Casuarina* 6 years (Thamm et al., 1996; Turner and Plater, 2004); *Eucalyptus* 4 years (Skolmen, 1986); *Pinus* 8 years (Thamm et al., 1996; Turner and Plater, 2004).

Neophyte	Date of establishment (AD) [maturity]	Reference
Casuarina	1947 [1953]*	Bainbridge, 1994
	1950 [1956]	Turner and Plater, 2004
	1955 [1961]	Perissinotto et al., 2013
	1969 [1975]	Thamm et al., 1996
Eucalyptus	1905 [1909]*	Turner and Plater, 2004
	1905 [1909]	Thamm et al., 1996
Pinus	1947 [1955]*	Bainbridge, 1994
	1950 [1958]	Turner and Plater, 2004
	1956 [1964]	Perissinotto et al., 2013
	1966 [1974]	Thamm et al., 1996

3.1.4 Carbon and nitrogen isotope analyses

Stable isotope analyses focussed on cores from sites NL-1 and FB-1. The stable carbon isotope composition of total organic carbon ($\delta^{13}C$), percent TOC (%TOC), and stable nitrogen isotope composition ($\delta^{15}N$) of total nitrogen (%TN; used to derive C/N ratios) were determined at a downcore resolution of 20-30 cm (NL-1: 51, FB-1: 78). Samples were dried at 60°C and homogenised using an automated mortar and pestle. Subsamples for $\delta^{13}C$ analysis were acidified using 2 M HCl solution for 24 h to remove any inorganic carbon present, and then rinsed with Milli-Q water and oven-dried at 60°C for another 24 h. Samples were analysed at the Stable Light Isotope Laboratory at iThemba Labs, using a DELTA V Advantage Mass Spectrometer (Waltham, USA) coupled to a Gas Bench II interface. A laboratory running standard (Merck Gel: $\delta^{13}C$ = –20.57‰, $\delta^{15}N$= 6.8‰, %C = 43.83, %N = 14.64) and blank controls were periodically analysed to monitor instrument response. All results were referenced to Vienna Pee-Dee Belemnite for carbon isotope values, and to air for nitrogen isotope values. The analytical precision of the instrument was 0.08‰ for $^{14}N/^{15}N$, 0.06‰ for $^{12}C/^{13}C$ and 0.04‰ for $^{32}S/^{34}S$.

3.2 RESULTS AND INTERPRETATION

3.2.1 Short-term sedimentation rates

Radioisotope profile data for ^{210}Pb are presented in Fig. 13. With the exception of core MK, excess ^{210}Pb profiles showed an expected exponential decay with increasing sediment depth. $^{210}Pb_{ex}$ activity in core MK suggests that the uppermost sediments of this core profile are disturbed, most likely as a result of human activities in the area. A sedimentation rate for this core could therefore not be calculated and no further work on samples from this site was conducted. For the remaining three cores (MZ, HL and NY), sedimentation rates were calculated using the CRS model.

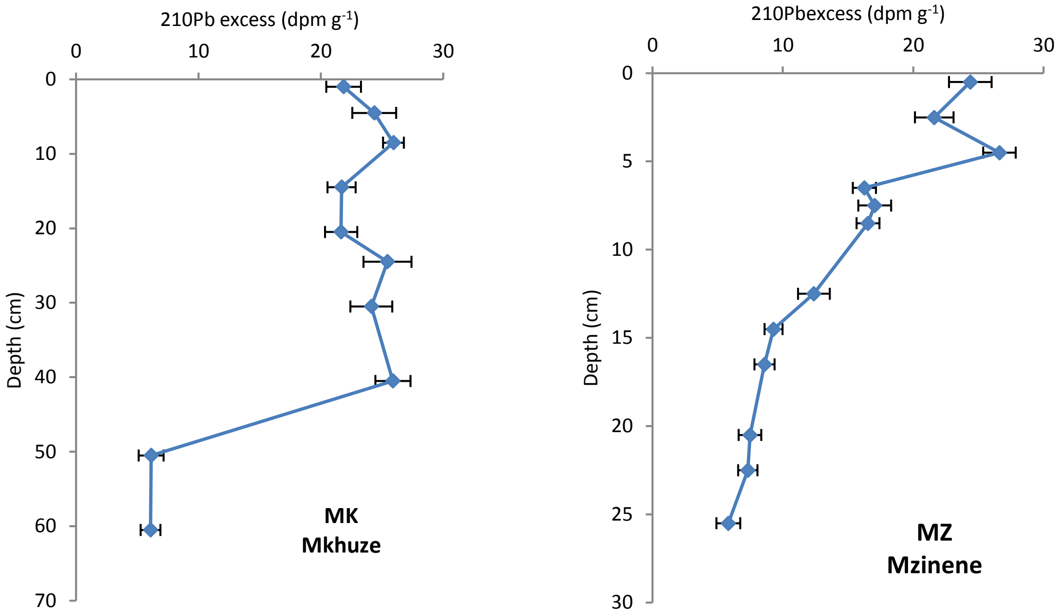
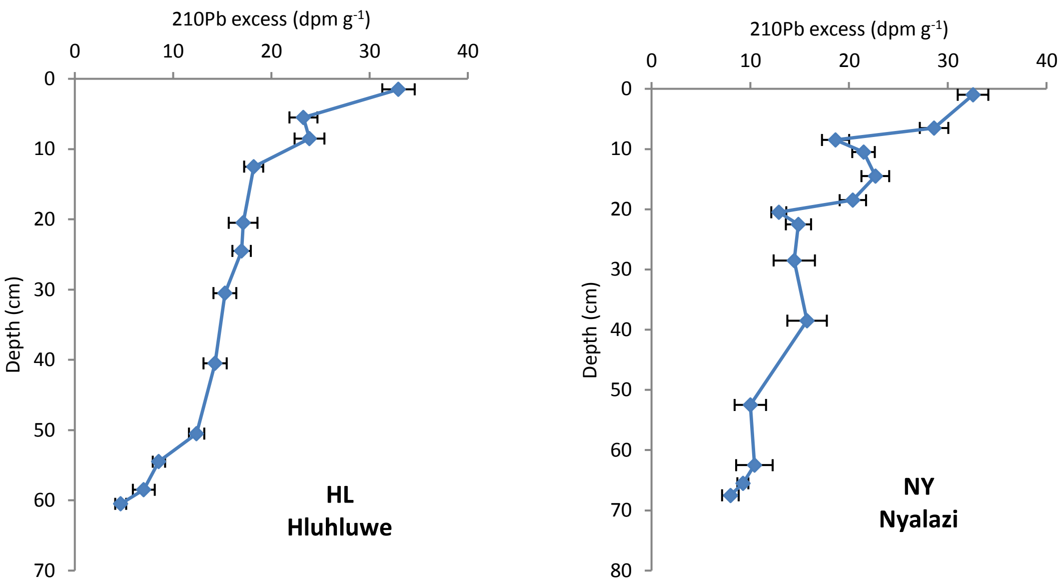


Figure 13. Variation in excess ^{210}Pb with depth in cores MK, MZ, NY and HL

Results reveal significant variation in sedimentation between sites, with rates of 0.6 cm yr^{-1}, 1.7 cm $yr^{-1}$and 2.5 cm yr^{-1}calculated for cores MZ, HL and NY, respectively (Table 2). Sediment mass fluxes for each core were obtained by plotting the linear regression of ln($^{210}Pb_{ex}$) activities against the cumulative dry mass (Fig.14). Despite significant variation in sedimentation rates between sites, all cores indicate that sediment mass accumulations rates have remained fairly constant over the last ~50 years. This suggests that net sediment influx



to Lake St Lucia at these sites has changed little over recent times. Spatial variability in sedimentation accumulation is likely related to river sediment loads, with larger rivers able to transport higher quantities of suspended material. These river catchments are identified as areas that are particularly prone to exerting influence on Lake St Lucia in the future, both in terms of sediment supply and potential nutrient/contaminant loadings.

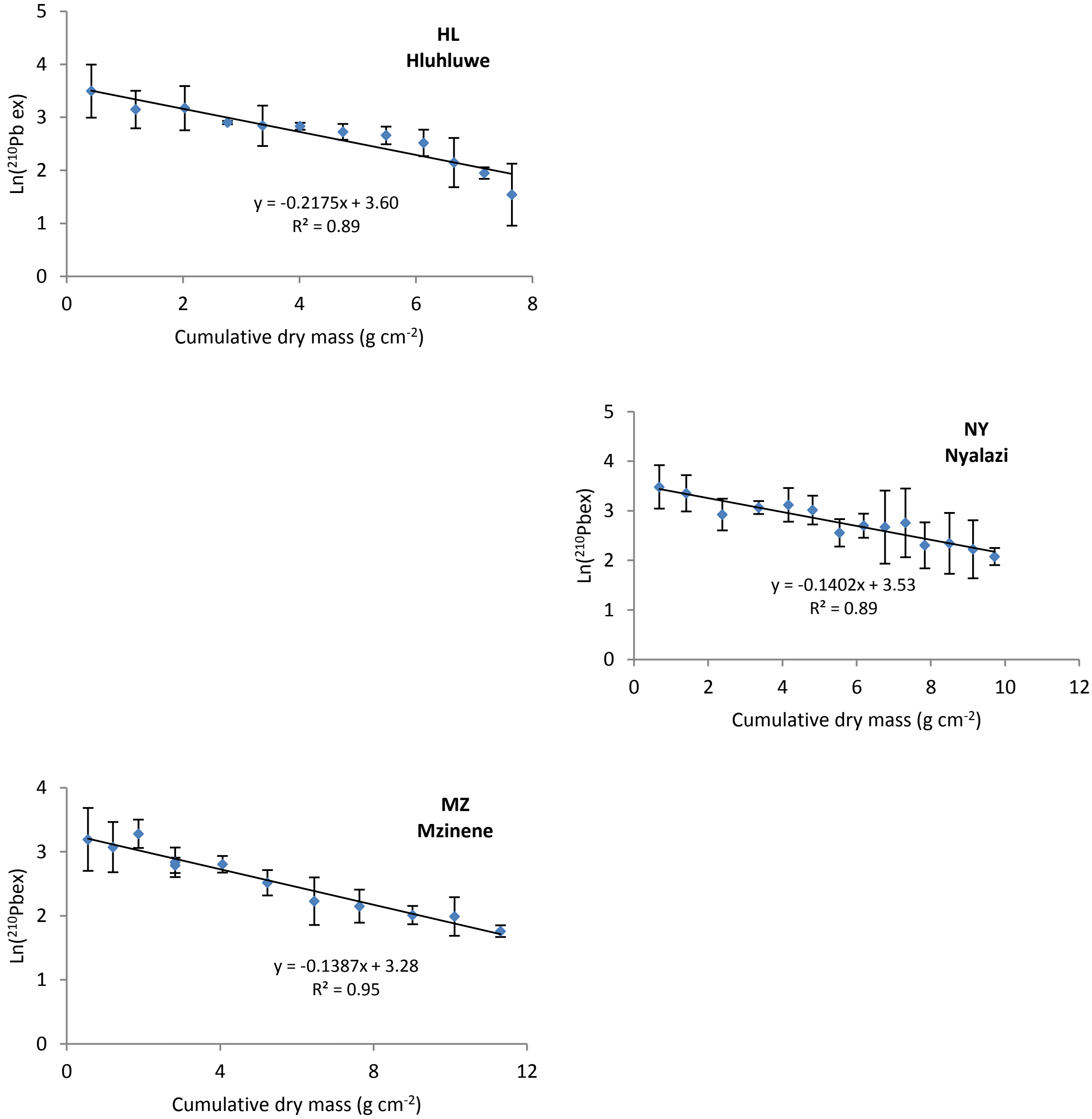


Figure 14. Excess ln^{210}Pb activity versus cumulative dry mass in cores MZ, NY and HL

Table 2: Average sedimentation and nutrient accumulation rates calculated for sites MZ, HL, and NY

Sampling site	Linear sedimentation rate (cm yr^{-1})	Sediment accumulation rate (g cm^{-2} yr^{-1})	Carbon accumulation (mg cm^{-2} yr^{-1})	Nitrogen accumulation (mg cm^{-2} yr^{-1})
Mzinene (MZ)	0.6	0.6	15.6	1.5
Hluhluwe (HL)	1.7	1.2	34.1	3.5
Nyalazi (NY)	2.5	1.7	46.7	5.0

3.2.2 Nutrient accumulation rates

Sediment dating provides a framework for trace metal and organic contamination investigations, affording a historical perspective of recent changes in the catchment. Here, we present reconstructed changes in nutrient (total carbon and total nitrogen) concentrations (Fig. 15). Calculated nutrient fluxes to St Lucia show little temporal variation over the time period investigated. Carbon and nitrogen co-vary through all cores, with slight enrichments in the upper layers likely associated with the deposition of less decomposed organic material.

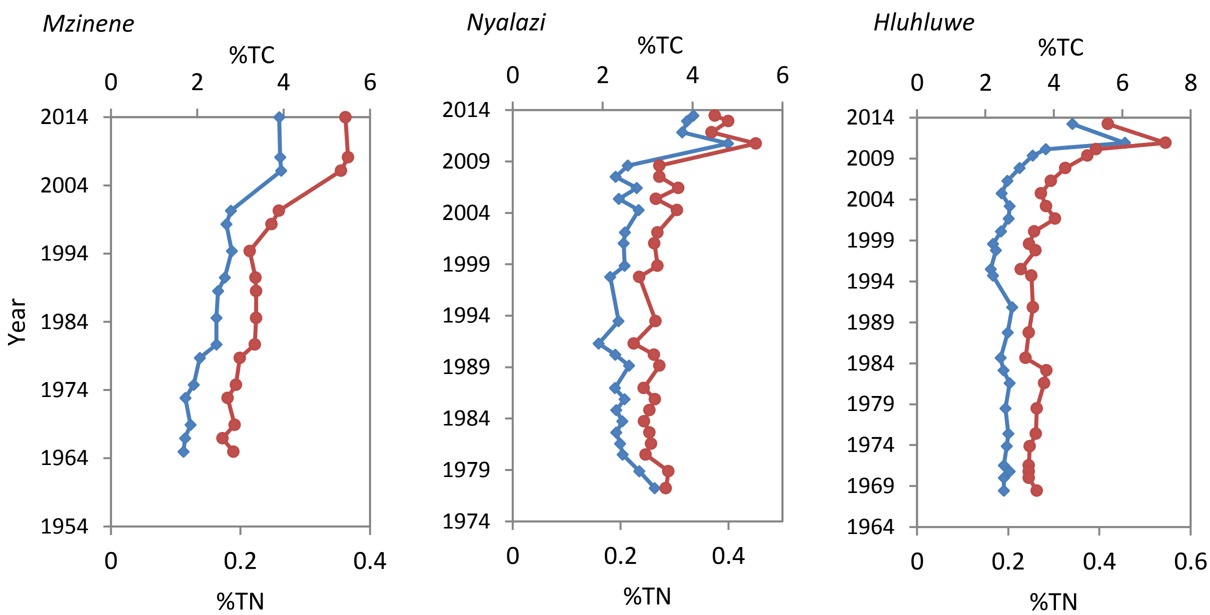


Figure 15. Variation in total carbon (TC) and total nitrogen (TN) concentrations

3.2.3 Long-term sedimentation rates

AMS results for the three long sediment cores reveal Holocene-aged sedimentary sequences, with NL-1 dating back to 7582-7678 (95%), FB-1 to 8295-8402 (82.1%), and CB-2 to 9401-9523 (88.8%) (Table 3). The NL-1 sediment core AMS results are largely stratigraphically consistent. For FB-1, a single inverted age is present at 65 cm. At CB-2, an inverted age at 100 cm is present. Inverted ages which are younger than expected are likely due to mixing of the sedimentary profile linked with bioturbation, storm events or wind-driven currents.

Whereas the age-depth models for NL-1 and FB-1 indicate relatively linear overall sediment accumulation, with similar rates of 0.20 and 0.19 cm yr^{-1}, respectively, CB-2 shows a distinct change in sedimentation rate around 242 cm depth (Table 4). The lower section of the CB-2 core is characterised by a relatively high sediment accumulation rate (0.47 cm yr^{-1}), and the upper section a much lower sediment accumulation rate (0.03 cm yr^{-1}) (Table 4). Notably, the influence of Mfolozi River sediment on infilling within the main lake basins appears to be negligible.

Table 3. AMS dating results from the NL-1, FB-1 and CB-2 sediment cores.

Lab code	Depth (cm)	Material	^{14}C age (yr BP)	Error (±yr)	95% prob. range (cal. yr BP)
North Lake (NL-1)					
Beta-423921	22.5	Sediment	1140	30	953-1060 (91.1%)
Beta-405603	28.5	Sediment	1170	30	957-1074 (95%)
Beta-387868	96	Sediment	1430	30	1271-1351 (95%)
Beta-423923	148.5	Sediment	2220	30	2141-2310 (81.9%)
Beta-386293	290	Sediment	2490	30	2359-2545 (54.9%)
Beta-405604	577	Sediment	3980	30	4281-4445 (80.4%)
Beta-386294	897	Sediment	5090	30	5711-5905 (93.3%)
Beta-373289	1185	Sediment	5410	30	6169-6278 (50.4%)
Beta-405605	1478	Shell	7350	30	8025-8180 (95%)
Beta-386295	1563	Shell	6830	30	7582-7678 (95%)
False Bay (FB-1)					
Beta-423919	30	Sediment	1420	30	1267-1322 (87.8%)
Beta-423920	55	Sediment	1460	30	1283-1362 (95%)
Beta-405600	65	Sediment	1280	30	1069-1188 (72.3%)
Beta-387867	187	Sediment	1870	30	1702-1834 (95%)
Beta-386290	316	Sediment	2800	30	2776-2944 (95%)
Beta-405601	691	Sediment	3830	30	4078-4291 (90.8%)
Beta-386291	896	Sediment	4570	30	5048-5197 (61%)
Beta-373287	1186	Sediment	5030	40	5606-5767 (72.7%)
Beta-405602	1350	Shell	5290	30	5922-6031 (60.4%)
Beta-38629	1591	Sediment	7560	30	8295-8402 (82.1%)
South Lake (CB-2)					
Beta-405598	50	Sediment	1780	30	1578-1717 (95%)
Beta-387866	100	Sediment	1370	30	1185-1253 (50.8%)
Beta-405599	170	Sediment	3570	30	3698-3898 (95%)
Beta-386286	242	Sediment	6400	40	7238-7342 (63.8%)
Beta-386287	541	Sediment	7610	30	8333-8421 (95%)
Beta-423918	718	Sediment	7500	30	8192-8360 (95%)
Beta-386288	945	Sediment	7910	30	8554-8777 (92.7%)
Beta-386289	1254	Sediment	8460	30	9401-9523 (88.8%)

The average linear sediment accumulation rates of the main basin sediment cores are considerably lower than the accumulation rates of the deltaic sediments of the Mzinene, Hluhluwe, and Nyalazi. This is to be expected as most sediment entering Lake St Lucia is likely deposited at the river deltas. However, results suggest no net change in recent sediment accumulation at the main river inlets. Despite concerns regarding increased sediment accumulation within the main basins of Lake St Lucia, the data suggest that increased deposition has not occurred over recent years.

Table 4. Average long-term sedimentation rates based on AMS results

Sampling site / Core section	Linear sedimentation rate (cm yr^{-1})
NL-1	0.20
FB-1	0.19
CB-2	0.13
CB-2 (0-242 cm)	0.03
CB-2 (242-1200 m)	0.47

3.2.4 Pollen markers

Four potential neophytes were targeted as time markers from the St Lucia core tops. However, of these, maize (*Zea mays*) pollen was absent from the sediments analysed, *Casuarina* pollen could not be positively identified, and *Eucalyptus*-type pollen was rejected as a robust time marker as the palynomorph grouping includes other indigenous pollen types such as *Syzygium*. The only time marker found to be viable was pine (*Pinus*), which was fairly abundant in the upper sediments, and could be positively distinguished from the most similar pollen type, *Podocarpus*. The pine pollen profiles revealed an overall trend of absence in the lower profile, and increased abundance towards the core tops (Fig. 16). Depth of first appearance at NL-1 was 16 cm, 18 cm at FB-1, and 6 cm at CB-2. These depths are likely contemporaneous, with the caveat that mixing as a result of bioturbation is a possibility within the lake system. Here we use the pollen markers to assign an age of AD 1955, or −5 cal. yr BP, based on first introduction and maturation rates.

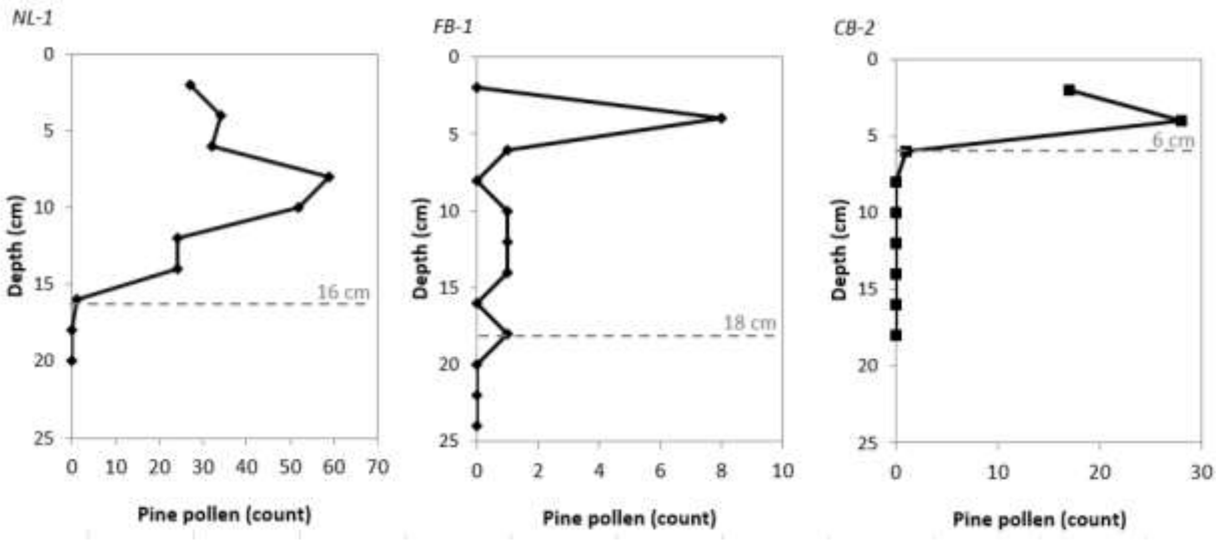
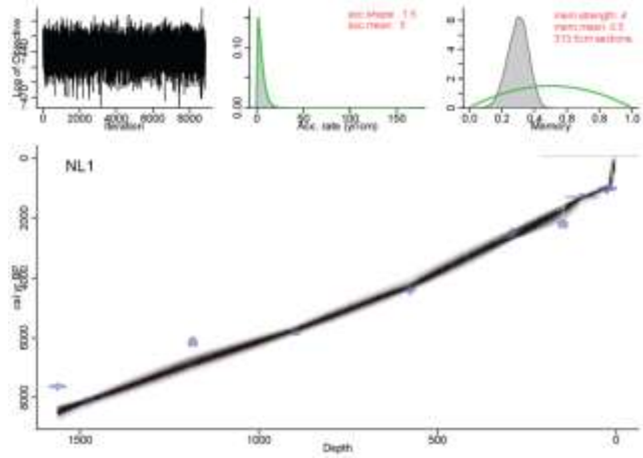
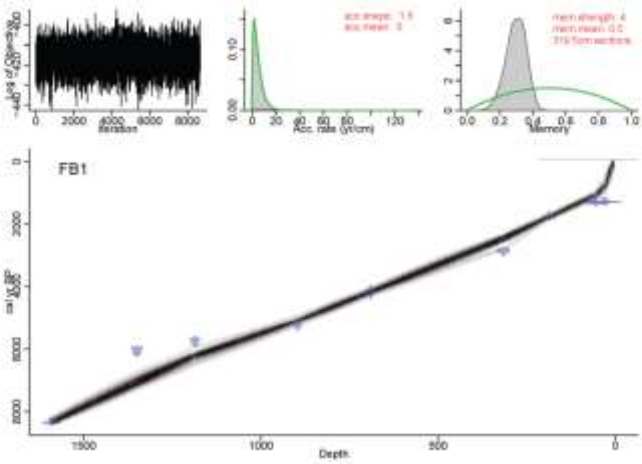


Figure 16. Neophyte pollen profiles for NL-1, FB-1 and CB-2 based on appearance of pine (*Pinus*) pollen in the sediments. The time marker based on first appearance of this pollen type is indicated by a dashed line, and assigned an age of AD 1955, or −5 cal. BP.

a)



b)



c)

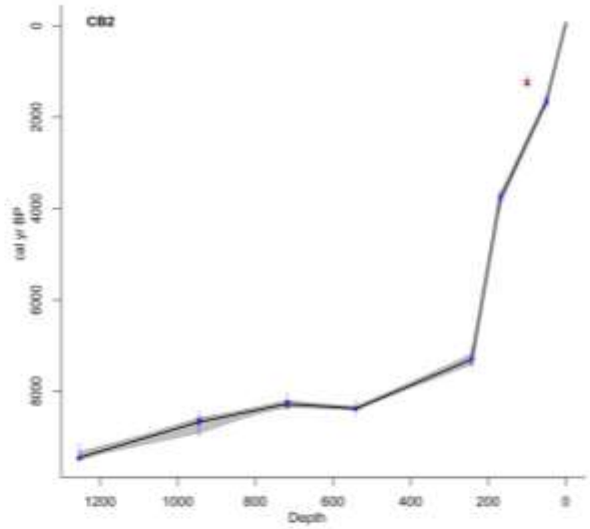


Figure 17. Age-depth models for sediment cores a) NL-1, b) FB-1 and c) CB-2

Comparative recent sediment accumulation rates calculated based on the pine pollen marker are 0.3, 0.3 and 0.1 cm yr^{-1} for NL-1, FB-1 and CB-2, respectively. These rates are comparable with average long-term sedimentation rates obtained from the AMS age-depth models. However, they are considerably lower than results obtained from the river inlet short cores.

The chronology and sedimentation results presented indicate a degree of spatial variability across the lake, both between the main depositional basins, and the river inlet sites. Short cores obtained from deltaic sediments at the inlets of the Mkhuze, Mzinene, Hluhluwe, and Nyalazi rivers were dated using ^{210}Pb, yielding linear sedimentation rates ranging from 0.6 to 2.5 cm yr^{-1}. Nutrient fluxes were calculated for each of the short cores, indicating limited variability over the time period investigated. Carbon and nitrogen were found to co-vary through the short cores, showing enriched values towards the core tops.

All three of the long sediment cores extracted from North Lake, False Bay and Catalina Bay, respectively, are Holocene in age, with age-depth models supporting continuous sediment accumulation throughout this period, and sedimentation rates of 0.13–0.2 cm yr^{-1}. A range of age-depth models were produced and compared for each core, and the most appropriate selected to facilitate interpretation of sedimentation history. The incorporation of pollen time markers as an additional dating tool for the core tops provides insight into the age of recent portions of the age-depth models.

The combination of long- and short-core analysis across the lake system has allowed for comparison of long- and short-term sedimentation processes. The use of three independent dating techniques adds confidence to the results obtained. The age-depth models presented in this report provide a robust chronostratigraphic framework for palaeo-environmental reconstruction, providing a means of comparing changes within the lake, and with other published records of environmental change.

3.2.5 Carbon and nitrogen isotope geochemical characterisation

The NL-1 downcore bulk sediment stable carbon isotope composition ($\delta^{13}C$) varies between –24.9‰ and –17‰ (Fig. 18). Due to their different photosynthetic pathways, different groups of terrestrial plants have distinctive $\delta^{13}C$ signatures, for instance, C3 plant values range between −22 and −33‰ (O'Leary, 1988; Prahl et al., 1980). C4 plant values range from −9 to −16‰, with C/N ratios similar to those for C3 plants (Huang et al., 2000; Lamb et al., 2006). Marine phytoplankton has a much narrower range than terrestrial plants, ranging from −21 to −18‰ (Middelburg and Nieuwenhuize, 1998).

The NL-1 %TOC values fluctuate between 0.7 and 1.9%. $\delta^{15}N$ ratios of 5.5–15.1‰ fall within the usual range for lacustrine systems (–5 to 20‰; Talbot, 2001). These values align with the expected ranges of *ex situ* sources such as terrestrial plants (2–10‰; Talbot, 2001) and soil organic matter contributions (~5‰; Talbot, 2001). %TN values vary between 0.1 and 0.2%.

In addition to the above proxies, C/N ratio values are useful in differentiating between marine and terrestrial sources of organic matter. Terrestrial plants, both C3 and C4 plants, have C/N ratios >12, while marine phytoplankton C/N ratios are usually ~7 or lower due to the high uptake of nitrogen by phytoplankton (Bordovskiy, 1965; Lamb et al., 2006; Owens, 1987; Peters et al., 1978). Values ranging from 10.6 to 18.8 from NL-1 indicate mainly terrestrial sources, although $\delta^{13}C$ values suggest the presence of aquatic-derived organic matter (Fig. 18).

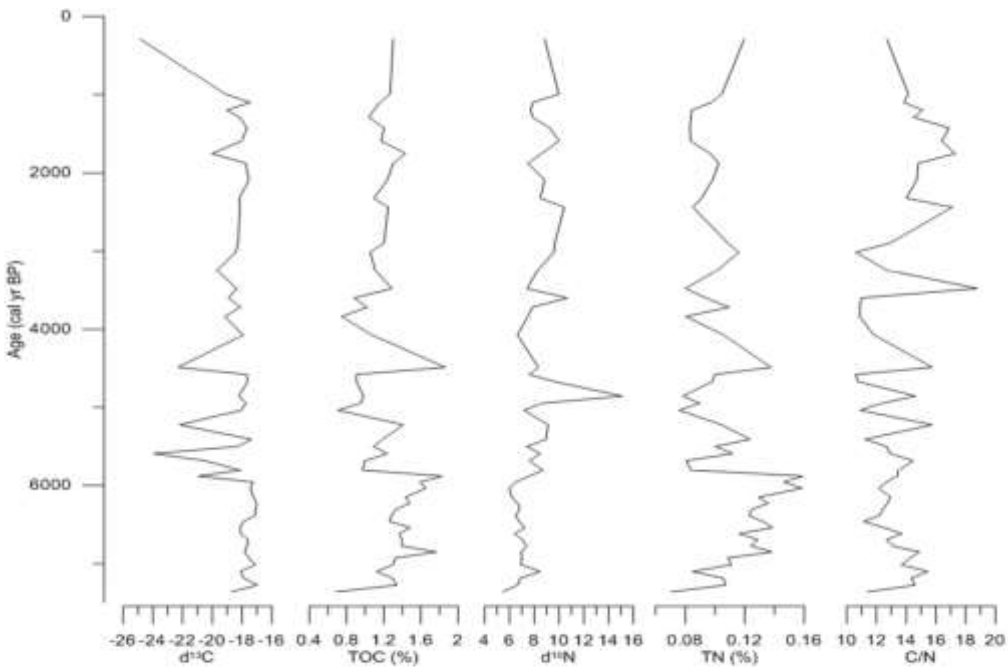


Figure 18. Bulk sediment isotope data for NL-1 plotted against age model interpolated calibrated ages.

A plot of δ^{13}C against C/N ratio can be used to trace changes in organic matter inputs through the core (Fig. 19a; Lamb et al., 2006). Results reflect a mix of aquatic (both freshwater and marine) and terrestrial (both C3 and C4) organic inputs to the system. On average, the δ^{13}C values are more closely aligned with marine than freshwater standard ranges (Lamb et al., 2006). From 7000 to 3500 cal yr BP, the C/N values indicate relatively greater aquatic inputs than the subsequent period from 3500 cal yr BP to the present day, when more terrestrial influence is inferred. A small number of core samples for the periods 6200 to 4550 cal yr BP, and 4550 to 3500 cal yr BP have a lower δ^{13}C than the remainder of the core samples analysed. These are difficult to interpret since they fall ambiguously within both the standard ranges for C3 terrestrial plants and marine dissolved organic carbon (DOC) inputs (Lamb et al., 2006). A plausible explanation is that these samples reflect a greater freshwater DOC input, hence depleting the δ^{13}C of the bulk sediment sample. This is an inherent limitation of analysing bulk sediment geochemical data, which reflect an average of a broad range of inputs to the sample.

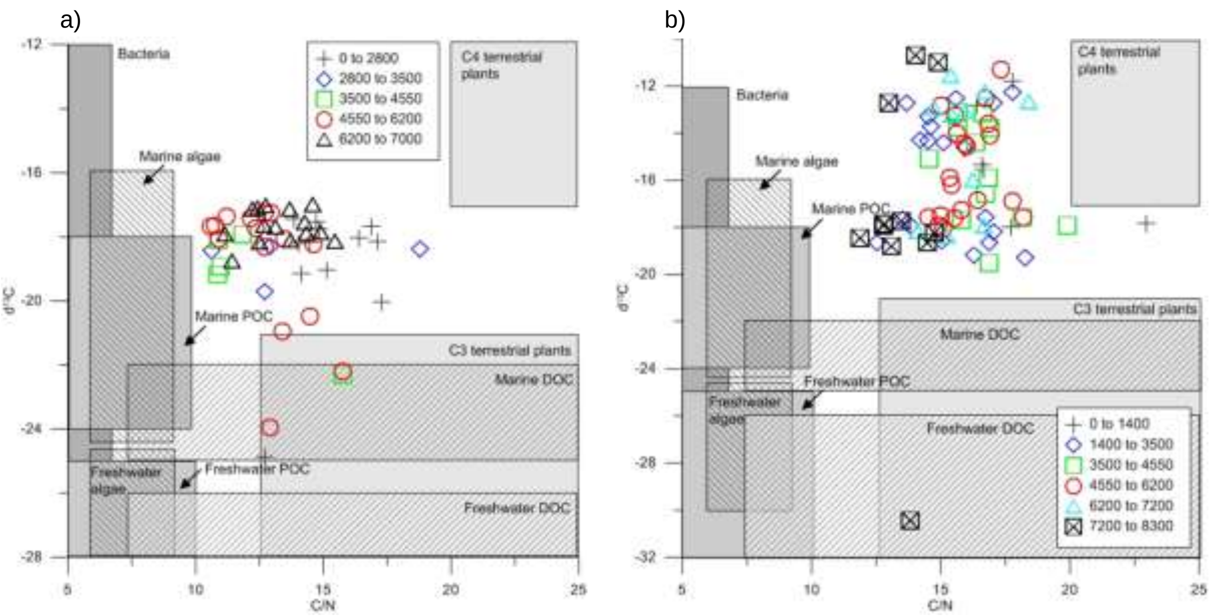


Figure 19. Plot of δ^{13}C (‰) against C/N ratio for a) NL-1 core samples and b) FB-1 core samples. Symbols reflect important calibrated radiocarbon time intervals identified in the microfossil proxy data. Standard ranges for organic inputs to coastal environments are indicated according to Lamb et al. (2006).

For the FB-1 core, δ^{13}C varies from –30.4‰ to –10.7‰ (Fig. 20). %TOC values fluctuate between 0.8 and 7.7%. δ^{15}N ratios are similar to those recorded from NL-1, from 2 to 14.3‰, and correspond with terrestrial plants and soils as major contributors to the sediment. %TN values vary between 0 and 0.3%. C/N values range from 11.9 to 22.9, and fall within the range of mixed aquatic and terrestrial sources of organic matter (Fig. 20).

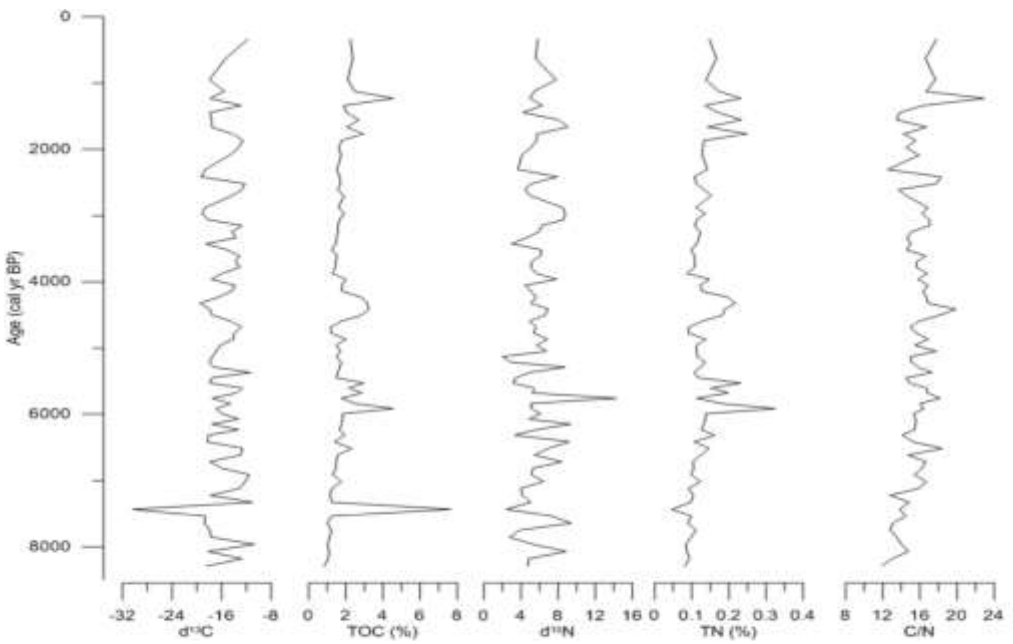


Figure 20. Bulk sediment isotope data for FB-1 plotted against age model interpolated calibrated ages.

Sediment organic matter for the FB-1 core reflects a relatively wider overall provenance than was recorded from NL-1, with higher C/N values suggesting a stronger terrestrial influence, and more enriched $\delta^{13}C$ suggesting a greater proportion of inputs from C4 land plants (Fig. 19b; Lamb et al., 2006). The core data suggest an overall trend of increasing C/N ratios over time, which may reflect a shift from more aquatic inputs in the early part of the record to more terrestrial inputs towards the present day. An exception to this trend is recorded for the period 3500–1400 cal yr BP, when a broad mix of aquatic and terrestrial influences is indicated.

CHAPTER 4

PROXY RECONSTRUCTIONS: PALAEOHYDROLOGY AND GEOMORPHOLOGICAL EVOLUTION

Lacustrine sedimentary archives have the potential to yield valuable records of long-term environmental change. This is achieved through extraction of undisturbed sedimentary sequences, followed by detailed analysis of their physical characteristics, as well as their chemical and biological constituents. These proxy data sources provide indirect evidence of past environmental conditions under which sediments were deposited. By analysing changes in proxy composition along the length of a sedimentary sequence, a record of change over time can be reconstructed and matched to a chronological framework provided by dating methods such as radiocarbon analysis.

The various biological, sedimentological and geochemical proxy records associated with these sequences thus provide a valuable source of information to aid in the understanding of palaeo-environmental and geomorphic changes in coastal systems during the Holocene. Such proxies hold the key to unravelling complex changes in hydroclimate, and examining variations in freshwater inputs, regional climate and sea-level fluctuations. Furthermore, the linkages between hydroclimate and overall geomorphic functioning of these systems can be examined (e.g. Caffrey et al., 2015; dos Santos-Fischer et al., 2016). Despite the importance of Lake St. Lucia, little is currently known about the long-term development and palaeohydrology of this system. While a large number of ecological studies have been conducted on St Lucia (e.g. Cyrus et al., 2010; Lawrie and Stretch, 2011; Carrasco and Perissinotto, 2015), these surveys provide only a snapshot in time of the recent biological and physico-chemical environment. Moreover, such studies have been confined to the past century, during which time the St Lucia system has been subject to large-scale management interventions. Long-term datasets are thus needed to aid in understanding the evolution and natural variability of the system, particularly in light of increasing human pressures and predicted future climate change. This chapter thus aims to reconstruct changes in the hydrological environment at Lake St Lucia over the Holocene using diatom and sulfur isotope data, and examine sea-level controls on the geomorphic evolution of the system.

In this chapter, we combine a range of biological and geochemical proxies to reconstruct Holocene environmental change in the northern basins of the Lake St Lucia system (North Lake and False Bay). Isotope data are used to trace organic matter inputs, and to reconstruct sea-level change. Diatom and foraminiferal assemblage data are used to understand hydrological changes, such as marine, brackish and freshwater influences. A statistical transfer function approach is applied to reconstruct a quantitative palaeosalinity record from the lake system. In an estuarine-lake system such as St Lucia it is useful to understand historical fluctuations in hydrology, marine influences, and their impact on lake biota, to gain a long-term perspective on the range of natural variability within the lake.

4.1 METHODS

Proxy investigations focussed on sediment cores, NL-1 and FB-1 from the northern basins of

Lake St Lucia (Fig. 1).

4.1.1 Diatom analysis

The cores were sampled at 40 cm intervals for diatom analysis, resulting in a total of 76 samples from each core. The laboratory procedure as outlined by Battarbee (1986) was followed to adequately extract the fossil diatoms and obtain representative microscope slides for analysis. This was achieved by chemically treating subsamples with 30% H_2O_2 and 10% HCl to remove organics and carbonates, respectively. Coarse-grained particulates were removed by sieving and then swirling. The resultant residue was repeatedly left to settle and decanted at 8 hr intervals to remove clay particulates. Microscope slides were mounted using Pleurax and examined under a light microscope at a magnification of up to X1000. A minimum count of 300 had to be achieved for the sample to be included in the analysis. Species were grouped based on salinity, namely dilute, brackish, transitional and marine, and displayed using TILIA and TILIAGRAPH (Grimm, 1993). Dilute diatoms include the fresh, fresh-brackish and brackish-fresh species. Transitional species are those that tolerate fluctuating salinities typical of estuarine and lagoonal habitats. TILIA was used to perform a stratigraphically constrained cluster analysis by incremental sum of squares (CONISS) to identify zones within the data (Grimm, 1987, 1993).

4.1.2 Foraminiferal analysis

Subsamples of ~10 cm^3 were extracted from each of the cores at 10 cm depth intervals. Approximately 5 cm^3 of each of these was preserved in 70% ethanol for foraminiferal analysis. A total of 130 downcore samples were used for foraminiferal analysis (NL-1: 81; FB-1: 49). Sample preparation followed Culver et al. (1996) and Gehrels (2002). Each sample was washed over a nest of 500 µm and 63 µm sieves to remove mud and shell fragments. The remaining material in the 63-µm sieve was retained and sub-divided into eight aliquots using a wet splitter (Gehrels, 2002). Each aliquot was air dried and placed into a marked plastic bag. Whenever possible, a total of ~150 foraminiferal tests were counted from each sample, starting with a single aliquot and adding additional aliquots to ensure a minimum count size was reached. In some instances, a count of ~150 was not achieved and a lower count was considered sufficient given the low species diversity (Patterson and Fishbein, 1989). Samples of fewer than 50 tests were removed from the final dataset (Fatela and Taborda, 2002). Foraminiferal identifications follow Debenay (2012). Relative abundances of fossil foraminiferal assemblages for each site were plotted as frequencies against depth using Psimpoll version 4.263 (Bennett, 2005). For each site the foraminiferal abundance is expressed as the number of individuals per 5 cm^3. The constrained incremental sum of squares (CONISS; Grimm, 1987) stratigraphically constrained ordination technique assisted in identifying patterns down each of the cores.

4.1.3 Sulfur isotope geochemistry

Total stable sulfur isotope composition ($\delta^{34}S$) was determined at a downcore resolution of 20–30 cm, yielding 51 and 78 samples from NL-1 and FB-1, respectively. Samples were dried at 60°C and homogenised using an automated mortar and pestle. Samples were analysed using a DELTA V Advantage Mass Spectrometer (Waltham, USA) coupled to a Gas Bench II interface. Blank controls and a laboratory running standard were periodically analysed to monitor instrument response. Analytical precision was typically 0.04‰.

4.2 RESULTS

4.2.1 Diatom stratigraphy

4.2.1.1 North Lake

Based on CONISS, three zones were identified (Fig. 21) for the NL-1 record, namely NL-A (1089–689 cm; ~6500–4500 cal. yr BP), NL-B (649–549 cm; ~4500–4000 cal. yr BP) and NL-C (509–89 cm; ~4000–1300 cal. yr BP). Four periods of low preservation (LP) are observed. Of these, two were extended, *viz.* LP1, from the base of the core until 1149 cm (LP1: base – 6500 cal. yr BP) and LF4, from 49 cm to the surface (~1200 cal. yr BP–present). These periods are either devoid of fossils or are composed of frustule fragments.

Zone NL-A (6500–4550 cal. yr BP)

The zone is primarily dominated by marine and transitional species. The marine species, *Diploneis crabro,* often associated with oligotrophic waters, is most common. Species typical of tidal flat environments are also frequent, such as *Diploneis smithii* and *Giffenia cocconeiformis* (Chiba et al., 2016). Brief periods of low preservation occur at 6400–6300 cal. BP (LP2) and 6050–5650 cal. yr BP (LP3). Marine species decline towards the low preservation zone of LP3, accompanied by rapid rises in transitional taxa, particularly *Nitzschia compressa* (Fig. 21). Dilute taxa, mainly epiphytes, are constantly observed throughout the zone, becoming more frequent post LP3 period and towards the termination of the zone. Notable is the sudden peak in *Cocconeis placentula var. euglypta*, a meso-eutrophic epiphyte, at 4600 cal. yr BP, reaching a maximum of ~33%. The epipelic marine, *Petroneis marina,* occurs persistently during this stage, with greatest abundance (8.1%) at 4500 cal. yr BP.

Zone NL-B (4550–4000 cal. BP)

This brief period shows an abundance in taxa tolerant of saline conditions, such as *N. compressa, Campylodiscus clypeus* and *Melosira nummuloides*. The marine littoral species *Hyalodiscus radiatus* increases coupled by the decline of *D. crabro* (Fig. 21). *Coscinodiscus wittianus* and *Epithemia adnata* are prevalent during the early stages until 4400 cal. yr BP. *E. adnata* occupies the littoral zone, particularly on submerged macrophytes. Low fossil preservation occurs at ~4300 cal. yr BP. The eutrophic, (tyco-)planktonics *Melosira varians* and *Cyclotella meneghiniana* have notable occurrences between 4500 and 4400 cal. yr BP (Fig. 21).

Zone NL-C (4000–1300 cal. BP)

Marine taxa make a recovery during this zone, dominated by the warm water species *D. crabro* and *H. radiatus,* and the cold water diatom, *Paralia sulcata*. *C. clypeus*, typically found in saline waters, remains high in the early stages from 3850–3750 cal. yr BP and again at 1450 cal. yr BP. The fresh-brackish taxon, *Terpsinoe musica* reaches maximum abundance at 3850 cal. yr

BP and between 2700 and 2550 cal. yr BP, accompanied by the planktonic *Stephanodiscus hantzschii* which peaks at 2550 cal. yr BP (Fig. 21). *N. compressa,* although prevalent throughout this period, rises near the close of the zone, increasing to 31% by 1300 cal. yr BP.

4.2.1.2 False Bay

The FB-1 core was divided into three zones according to CONISS (Fig. 22), *viz.* FB-A (1109–789 cm; 6000–4550 cal. yr BP), FB-B (709–549 cm; 4550–3500 cal. yr BP) and FB-C (509–23 cm; 3500–530 cal. yr BP). Three periods of low fossil preservation occurred. Of these, major periods were LP1, from the base of the core until 1128 cm (~8500–6200 cal. yr BP) and LP3, from 22 cm to the surface (~500 cal. yr BP–present).

Zone FB-A (6000–4550 cal. BP)

Marine and transitional species dominate the assemblage. The initial stages of this zone are characterised by high abundances in the marine species *Diploneis crabro* and *Coscinodiscus wittianus* and the marine-brackish species *Giffenia cocconeiformis*, followed by a period of low preservation (LP2) between 5900 and 5600 cal. yr BP. Post LP2, *D. crabro* and *G. cocconeiformis* remain dominant with the inclusion of the marine-brackish species *Grammatophora oceanica*. *P. marina* seems to be limited in its distribution within False Bay, primarily occurring between 5400 and 4900 cal. yr BP with greatest (4.4%) representation at 5150 cal. yr BP. Dilute taxa, *C. meneghiniana*, the benthic, eutrophic *Gyrosigma acuminatum* and epiphytic *Cocconeis placentula* make notable appearances throughout the zone, particularly from 5300 - 4900 cal. yr BP. These species are accompanied by the brackish, epiphyte *Cocconeis discrepans* which peaks at 5150 cal.yr BP before steadily declining to the end of the zone. *G. cocconeiformis* and *D. crabro* make a resurgence in the later phases of FB-A reaching a maximum of 28% by 4600 cal. BP.

Zone FB-B (4550–3500 cal. BP)

Following on from 4600 cal. yr BP in the previous stage, *Campylodiscus clypeus,* coupled with *G. cocconeiformis* and *D. crabro,* are constant features throughout the FB-B zone, particularly from 3800–3500 cal. yr BP. Brackish taxa are well represented *with C. discrepans* and *Diploneis smithii* comprising nearly 20% of the overall community at 4150 cal. yr BP. A brief resurgence in the dilute epiphytes *Diploneis elliptica*, *Epithemia adnata* and *Mastogloia densei* is observed at 4000 cal. yr BP. The marine planktonic *Actinoptychus splendens* progressively increases in representation from 3800 cal. yr BP until the termination of the zone.

Zone FB-C (3500–530 cal. BP)

Marine species and those tolerant of fluctuating salinities are dominant, in particular *N. compressa*, *G. cocconeiformis* and *C. wittianus*. The dilute, planktonic *Thalassiosira weissflogii*, commonly found in nutrient-enriched environments, increases notably at 3250 cal. yr BP. The brackish, benthic *Melosira nummuloides* and *C. wittianus* peak simultaneously

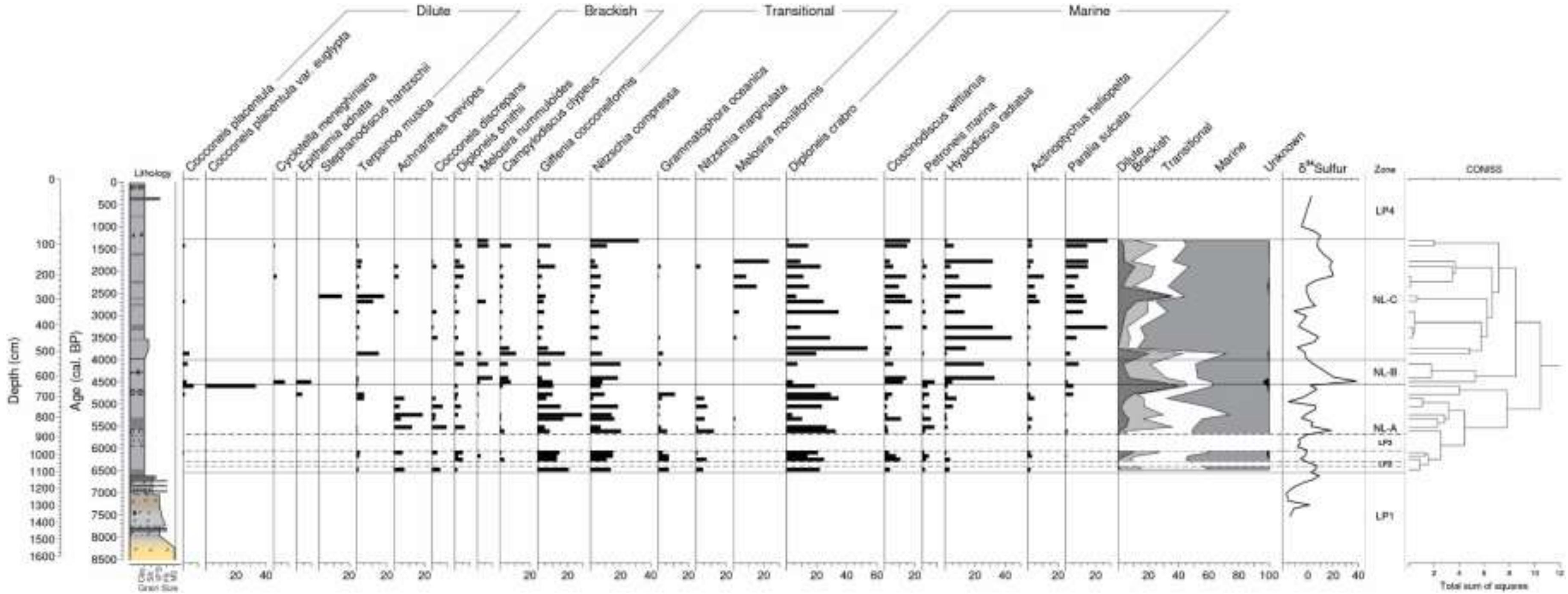


Figure 21. Variation in lithology, $\delta^{34}S$ and relative distribution of selected diatom species from core NL-1 against depth (cm) and age (cal yr BP). Diatom species are grouped according to their salinity preferences.

between ~3100 and 2900 cal. yr BP. At ~2750 cal. yr BP, the marine-brackish *Melosira moniliformis*, *H. radiatus* and *P. sulcata* all peak simultaneously before declining in abundance, although remaining prevalent throughout the zone. A rise in dilute taxa is observed from 2350 cal. yr BP, with *C. meneghiniana* reaching a maximum of 15% at 1900 cal. yr BP. Fossil preservation declines at 1350 and between 650 and 600 cal. yr BP. Prior to a brief period of low preservation at ~1350 cal. yr BP, *N. compressa* and *C. wittianus* reached a maximum of 38% and 23%, respectively.

4.2.1.3 Between core comparison

The North Lake diatom assemblage consists of 97 individual species, with 68% of the community classified as rare (less than 5% occurrence). The False Bay diatom assemblage consists of 87 individual species, with 62% composed of rare species. The most common species shared between both records are those favouring marine and transitional habitats with *D. crabro*, *C. wittianus*, *H. radiatus* and *P. sulcata* from the former, and *N. compressa* and *G. oceanica* from the latter, being the most prevalent. Brackish taxa with a wide salinity tolerance are also common to both sites, predominantly *C. clypeus* and *D. smithii*. Marine, and to a lesser degree, transitional benthics are dominant prior to 4500 cal. yr BP, after which planktonics become the primary life form for these salinity groups. Differences in dilute species composition and abundance between records are observed. For instance, the once-off dominance of *Stephanodiscus hantzschii* during zone NL-C, *C. placentula* var. *euglypta* during zone NL-A and *T. weissflogii* during zone FB-C, suggest major pulses of freshwater into the system. Both records show a system shift at 4500 cal. yr BP, in addition to extended episodes of low preservation of the diatom frustules, particularly prior to ~6000 cal. yr BP, as well as in the more recent sediments (last 1000 years). Although these periods rendered non-viable samples, fragments of heavily silicified diatoms were encountered, mostly consisting of *G. oceanica* and *G. cocconeiformis*.

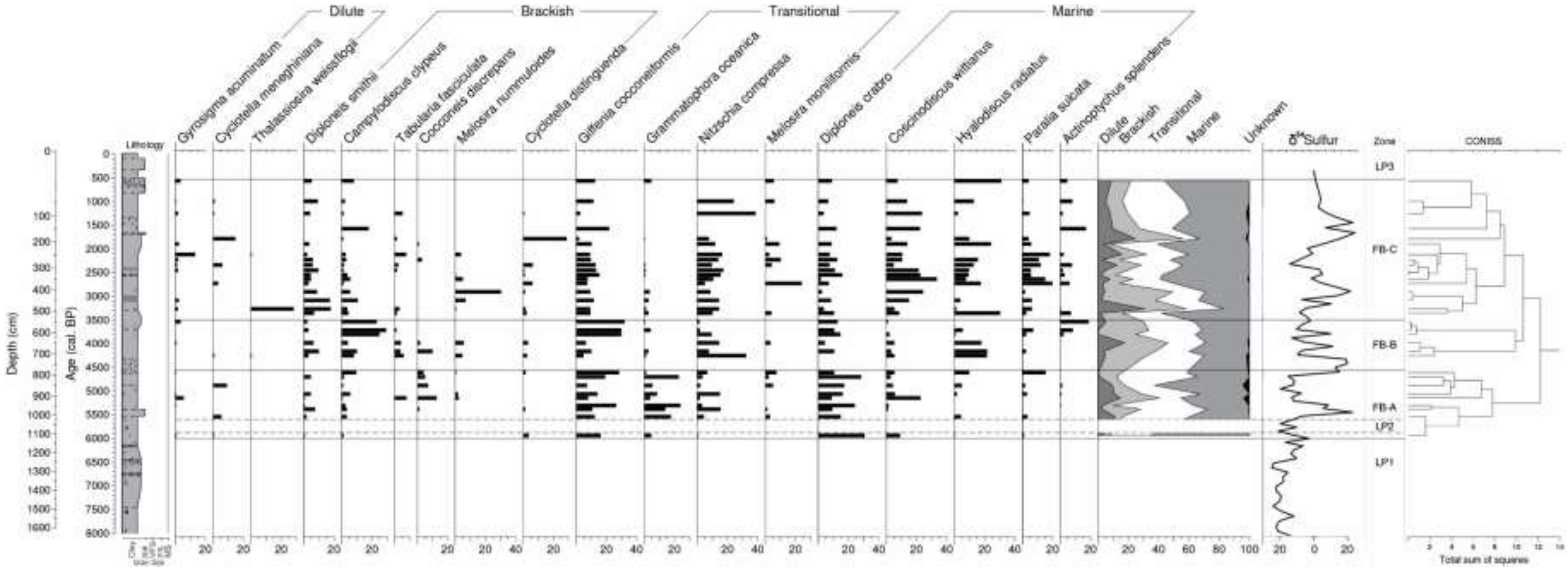


Figure 22. Variation in lithology, δ34S and relative distribution of selected diatom species from core FB-1 against depth (cm) and age (cal yr BP). Diatom species are grouped according to their salinity preferences.

4.2.2 Foraminiferal stratigraphy

4.2.2.1 North Lake

Foraminifera are present in 95% of the samples counted down the length of the NL-1 core, of which all were well preserved. The majority of the tests identified and counted were intact and showed little evidence of corrosion. A total of five agglutinated species and 17 calcareous species were identified (Fig. 23), with the most common species being *Ammonia tepida*. The lowest concentrations of foraminiferal tests are present at 140–180 cm and between 1490 cm and the base of the core. CONISS cluster analysis identified four assemblage zones; N-4 (0–330 cm), N-3 (330–1380 cm), N-2 (1380–1500 cm) and N-1 (1500–1520 cm), differentiating major changes in foraminiferal populations. Calcareous species are dominant down the entire length of the core.

In zone N-1 (1500–1520 cm), the only species present is the calcareous *Spiroloculina spp*, a marine species typically found in lagoons and shallow reef areas. Zone N-2 (1380–1500 cm) is also dominated by *Spiroloculina spp.*; however, at 1500 cm, this species is replaced by *Ammonia tepida,* and to a lesser extent by the agglutinates *Balticammina pseudomcrescens* and *Siphotextularia sp. Ammonia tepida* is the most abundant species in both zone N-3 (330–1380 cm) and N-4 (0–330 cm). However, in the upper section of zone N-3 (~660 cm) the abundance of *A. tepida* decreases and there is a greater presence of other marine calcareous species, including *Haynesina depressula*, Nonion sp. and *Elphidium sp*. Between zones N-3 and N-4, *A. tepida* is replaced by *Triloculina spp.*, a marine species commonly found in lagoonal, shelf and outer reef habitats. Zone N-4 is dominated by *A. tepida*, but also hosts the highest diversity of species present in comparison to the other zones down the core.

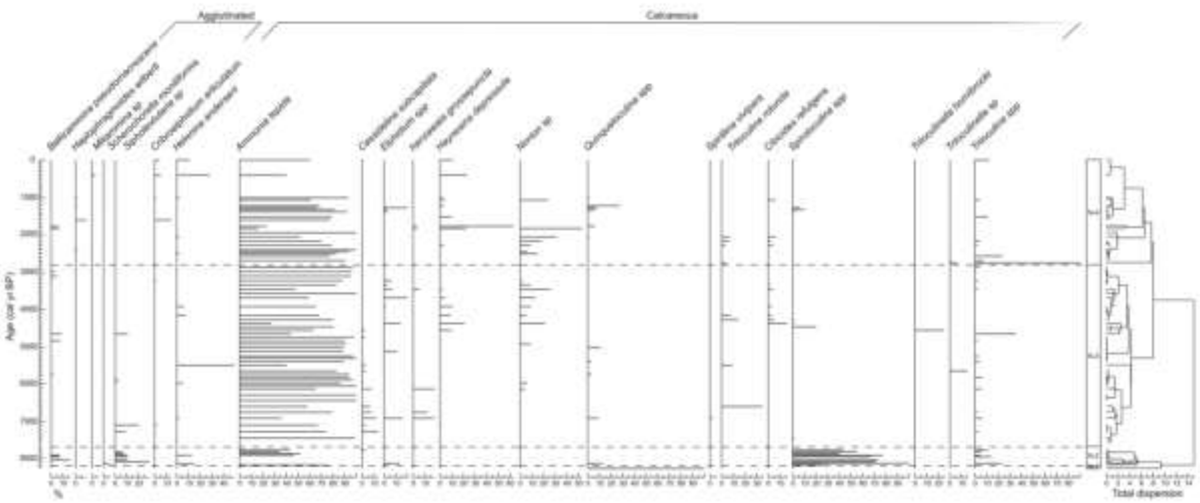


Figure 23. Foraminiferal concentrations down core NL-1, including constrained incremental sum of squares derived zonation.

4.2.2.2 False Bay

A total of 17 species were identified in 49 samples down core FB-1, with an average of ~274 tests per sample. Five zones (Fig. 23) were identified, *viz.* F-1 (1390–1560 cm), F-2 (750–1390 cm), F-3 (110–750 cm), F-4 (90–110 cm) and F-5 (0–90 cm). Foraminifera were abundant throughout the core, with *Ammonia tepida* the dominant species present.

The lowermost section of the core (F-1) has only calcareous species present, along with the greatest abundance of foraminifera. *Spiroloculina spp*., *Triloculina spp*., *A. tepida*, *Cassidelina subcapitata, Eliphidium spp*. and *Quinqueloculina spp*. were recorded in this zone include. Of these, *Spiroloculina spp*., *Triloculina spp*., *Eliphidium spp*. and *Quinqueloculina spp.* are all typically found in water depths of >10 m. Zone F-1 has a significantly lower abundance of *A. tepida* in comparison the rest of the core. In zone F-2, agglutinated species appear, and the abundance of calcareous species is significantly lower than in F-1. Agglutinates are significantly more abundant than calcareous species (with the exception of *A. tepida*) between 900 and 1390 cm. Above 900 cm, agglutinated species decrease to be replaced by calcareous species, especially *Rosalina bradyi*, *Triloculina spp*. and *Quinqueloculina spp*. Zone F-3 recorded a decrease in agglutinated species and a significant increase in calcareous species, *viz. Nonion sp*. and *Haynesina depressula*. Zone F-4 is a narrow zone; however, there is a significant decrease in the abundance of *A. tepida* and a large increase in deep dwelling species such as *Triloculina spp*., *Nonion sp*., *Quinqueloculina spp*. and *Haynesina depressula*. The uppermost section of the core recorded few species, with *A. tepida* dominating.

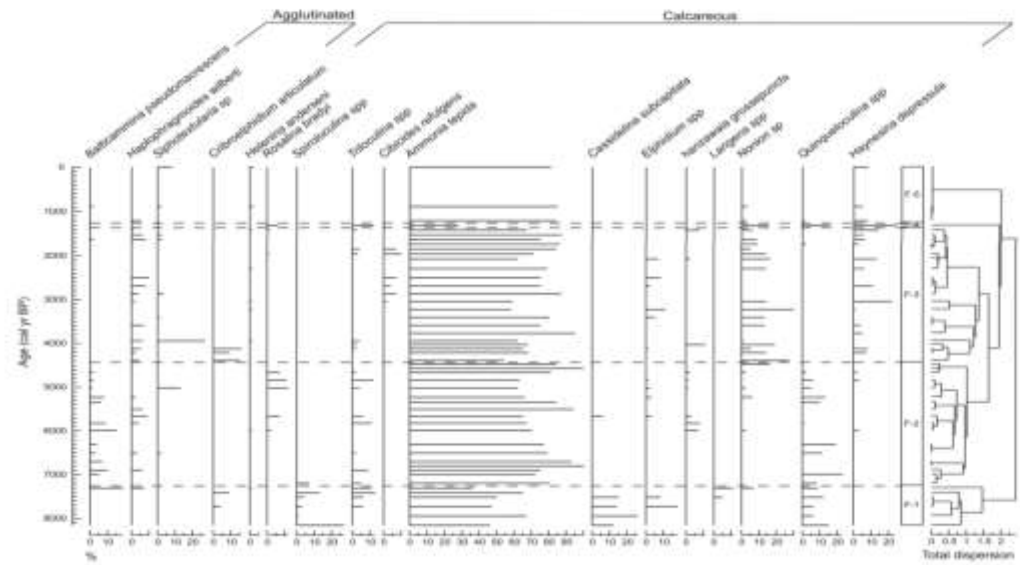


Figure 24. Foraminiferal concentrations down core FB-1, including constrained incremental sum of squares derived zonation.

4.2.3 Sulfur isotope chemistry

Sediment $\delta^{34}S$ values are highly variable, ranging between -16.6 and +38.6‰ in NL-1 (Fig. 21), and between -24.7 and +24.7‰ in FB-1 (Fig 22). The majority of the data are <0‰, indicating that bacterial sulfate reduction dominates in the sediments. The development of anoxia is typical of estuarine water bodies. The reduced sulfur is largely fixed as FeS or FeS_2 and isotopically depleted in ^{34}S relative to seawater sulfate (Thode, 1991). However, a number of notable $\delta^{34}S$ enrichments in both the NL-1 and FB-1 records are evident. These enrichments occur at ~5500, 4500 and 1800–1400 cal. yr BP, and show $\delta^{34}S$ values close to the isotopic composition of sulfate in seawater (+20‰). Given that little or no sulfur fractionation occurs during uptake of sulfate by plankton (Croisetière et al., 2009), it is likely that organic material deposited during these periods originated from marine inputs.

4.3 DISCUSSION

4.3.1 Hydrological reconstruction

The cores extracted from the North Lake and False Bay basins document the most recent infilling cycle that occurred primarily in response to early Holocene sea-level rise. The fine sand present at the base of NL-1 reflects a time when the St Lucia basin was connected to the ocean via an inlet near Leven Point. Foraminiferal evidence supports the interpretation of a direct link to the ocean via Leven Point, prior to ~7600 cal. yr BP, by the abundance and the well preserved tests of *Spiroloculina spp*. This taxon is commonly found in lagoonal and shallow reefal areas (Javaux and Scott, 2003; Debenay, 2012), Poor diatom preservation, numerous fragmented frustules and reworked shells distributed throughout the sand matrix provide evidence for an environment subjected to tidal currents.

A shift from marine sand to silt-dominated sedimentation at ~6200 cal yr BP signifies the establishment of a low-energy environment that promoted the accumulation of finer sediment. A decrease in wave energy and restricted tidal flow supported better preservation of fossil diatoms. The transition to low-energy conditions appears to have occurred earlier (prior to 8300 cal yr BP) in False Bay, an observation that is explained by its relatively sheltered landward position. The presence of marine-brackish foraminifera suggests an estuarine environment. The introduction of *B. pseudomacrescens* and *C. articulatum* provides evidence that False Bay was subjected to a large freshwater supply during this period. The presence of marine foraminifera, particularly *Triloculina spp*., *Trilocilinella sp*. and *Triloculinella horribrooki*, particularly between ~6300 and 5200 cal yr BP in North Lake, suggests a degree of marine influence, likely linked with episodic overwashing.

The diatom assemblages from North Lake and False Bay reveal a system which was structured by the influx of marine waters (Fig. 25). From the initiation of the diatom records until ~4550 cal yr BP, a system that is constantly influenced by marine waters, possibly associated with the aforementioned washover events and marsh and tidal flat habitats, is indicated. The appearance of several diatom taxa restricted to brackish and fresh waters suggests mixing between fluvial and marine sources under a relatively low-energy environment, although zones of low preservation observed in both records may be attributed to high-energy events associated with wind-induced turbulence. The dominance of benthic diatoms in both basins suggests a relatively shallow water environment persisted prior to 4550 cal yr BP.

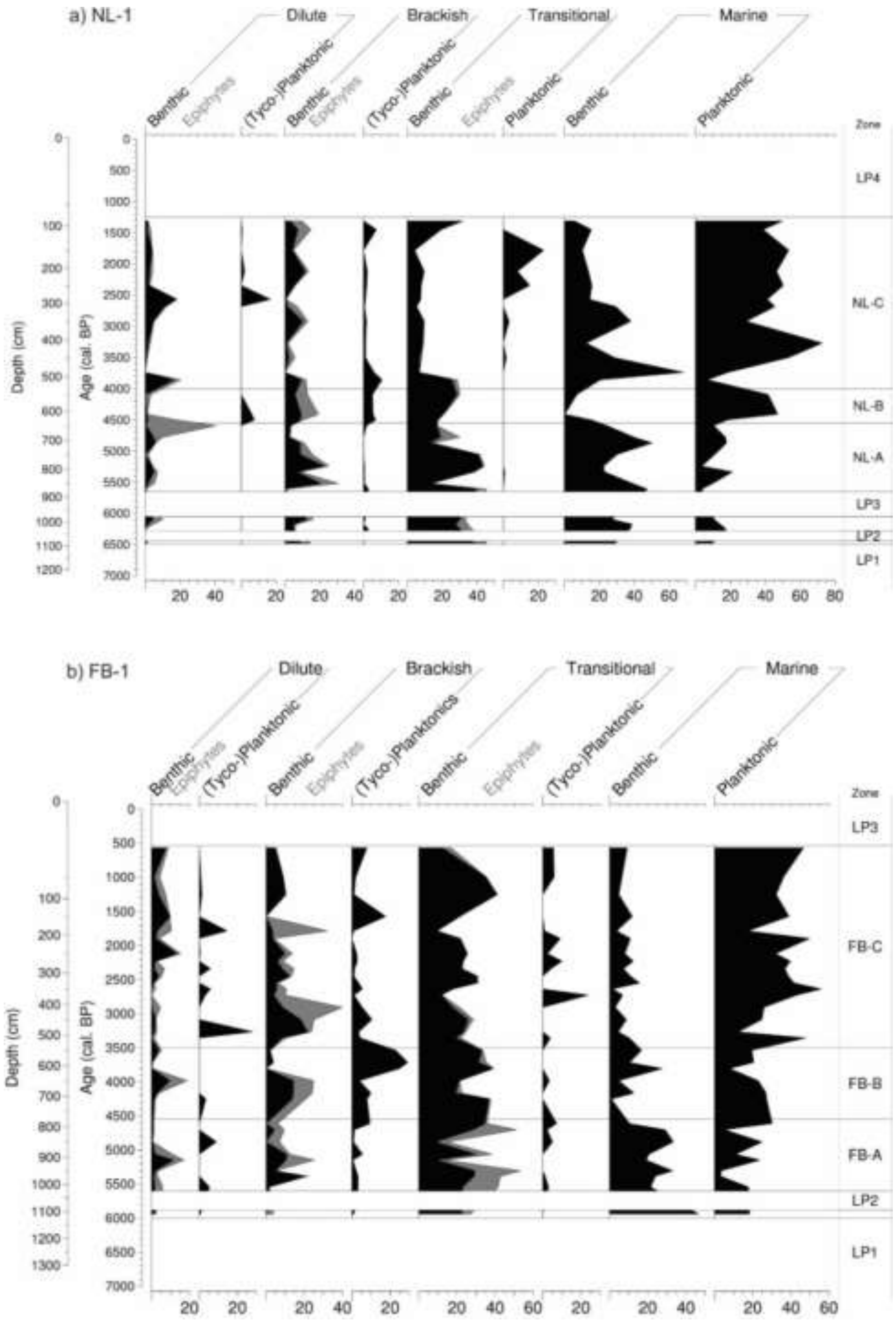


Figure 25. Summary classification of diatom species found in core a) NL-1 and b) FB-1 based on salinity preferences and habitat.

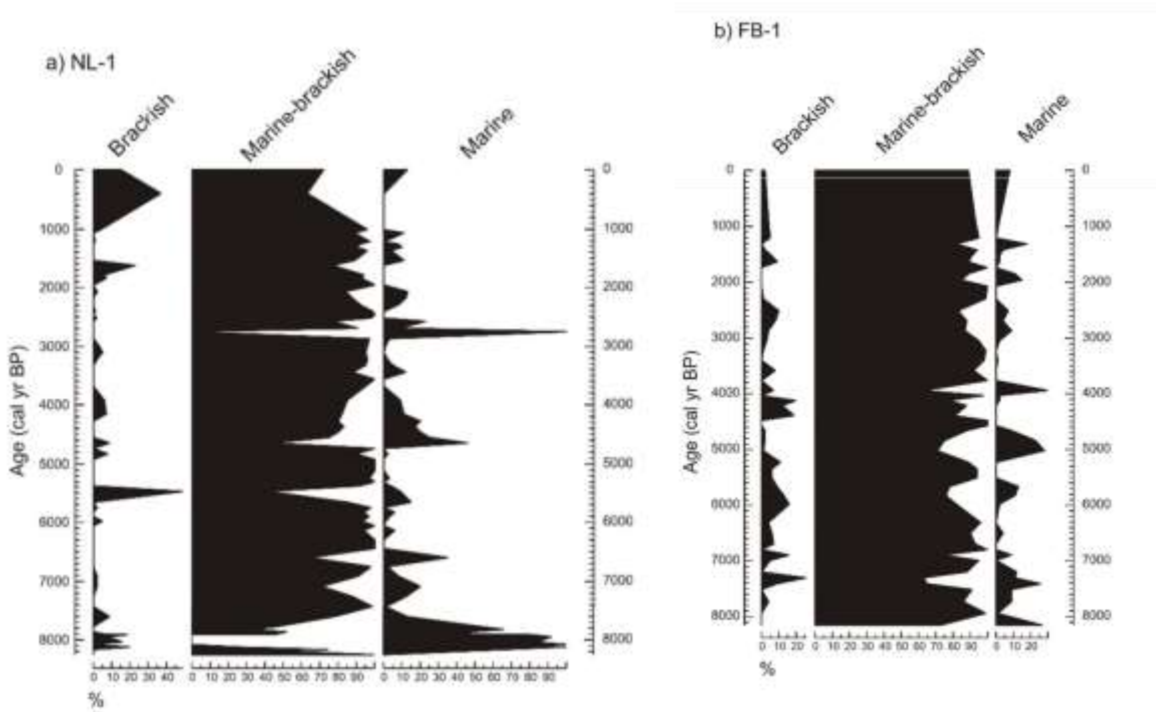


Figure 26. Summary diagram indicating fluctuations in brackish, marine-brackish, and marine foraminifera at NL-1 and FB-1.

A transitional phase in the lake history is suggested by a marked change in foraminiferal composition between 3700 and 4500 cal. yr BP. This is supported by a shift in the diatom community at ~4550 cal. yr BP, signalling a shift from a shallow water environment characterised by benthic and epiphytic species to a deeper water system dominated by planktonic species, notably brackish planktonics from 4550–3500 cal yr BP (Fig. 25). This is further substantiated by the foraminiferal evidence, notably a decrease in the abundance of *A. tepida* and increased presence of *Elphidium spp*., *Haynesina depressula* and *Nonion sp*., with these species preferring deeper waters (Debenay, 2012). This may be attributed to marine inputs via overwash bringing these species into the system. This transition is evident in both NL-1 and FB-1, and points to the establishment of a deepening back-barrier water body associated with the impoundment of water behind an emergent barrier at Leven Point. The input of nutrient-enriched, fresh water supported a habitat favourable for a brackish community. Marine influences, although higher than in previous zones, begin to decline from ~3500 cal yr BP. Between 3500 and 3000 cal. yr BP, there is a rapid decline in foraminiferal species diversity, likely driven by further accretion and stabilisation of the barrier at Leven Point, which limited the frequency of wash over events. The marine diatom group is dominated by planktonics, which are easily transported and point to intermittent seawater intrusions into the system rather than marine water inundation. Warm water marine diatoms typify the assemblage, consistent with the nature of the Agulhas current, although cool water taxa, particularly *P. sulcata* and *Thalassionema nitzschioides*, show peaks in distribution, from 3250 cal yr BP onwards in North Lake and between 2650 and 2100 cal yr BP in False Bay. The likely origin of these cold water species would be the Cape St. Lucia upwelling cell, suggesting period of greater activity in upwelling long the coast. Upwelling in this region is related to storm events and major shifts in the Agulhas offshore. Both basins reveal the presence of mixed diatom communities, suggesting an environment characterised by high salinity variability. The presence of foraminiferal species, *viz. Triloculina spp*., *Elphidium spp., Haynesina depressula* and *Nonion sp*. between ~2800 and 2600 cal. yr BP is a strong marine signal in North Lake attributed to overwash. A marine influence at ~2700 cal. yr BP is supported at False Bay by the marine foraminifera *C. refugen* and *H. depressula* (Fig. 26).

In the upper section of both cores, foraminiferal diversity is low, as are the recorded total assemblage counts, relative to lower down the core. This may be a result of taphonomic factors such as dissolution due to poor preservation conditions for foraminiferal tests. Similarly for the diatom assemblage, low fossil preservation is recorded at the top of both cores, which may point to periods of desiccation (Chapter 5) or frustule fragmentation caused by wind-induced turbulence, as the gradual shallowing of the basins proceeded. Despite poor diatom preservation in the upper sediments, $\delta^{34}S$ values (~0‰) point to an environment that was isolated from direct marine inputs during the last ~1000 years.

4.3.2 Sea-level controls on geomorphological evolution

The diatom reconstruction presented in this study documents the development of the St Lucia basin over the last ~6000 years. The reconstruction allows the influence of regional variations in relative sea level and sediment supply on the geomorphological evolution of the present St Lucia system to be examined. These variations are most strongly reflected in the record obtained from the more seaward depocentre of North Lake.

Initial Holocene marine transgression

The Holocene sedimentary infill from North Lake indicates that St Lucia was a shallow, partially enclosed estuary/embayment dominated by strong tidal flows prior to ~6200 cal. yr BP. Infilling of the basin was initiated when deglacial sea-level rise slowed and stabilised around present-day levels (Fig. 27). Longshore drift provided sediment for the cross-shore growth of the adjoining barriers and the accumulation of sediment within the inlet to form a newly emergent Holocene proto-barrier/spit. Fluvial discharge was unable to complete with spit accretion, restricting the tidal prism. This boundary is clearly preserved in the NL-1 record and is in good agreement with available sea-level data from the east coast of South Africa that suggests a general stillstand at ~ 6200 cal. yr BP (Ramsay, 1995; Fig. 27).

Mid-Holocene highstand

Our sedimentary records indicate a change to low-energy conditions consistent with barrier growth and inlet closure at ~6200 cal. yr BP (Chapter 2). The back-barrier has since been modified by periodic incursions related to sea-level highstands. Evidence of sea-level change from coastal areas of southern Africa generally supports a mid-Holocene highstand, although the timing and amplitude remain uncertain (Miller et al., 1993; Compton, 2006; Ramsay, 1995). Similar trends of higher-than-present Holocene sea level periods have been observed along the Brazilian coast (dos Santos-Fischer et al., 2016), Australia and Argentina (Isla, 1989), and are consistent with global isostatic models (Clark et al., 1978). Preserved beach rock and intertidal zone deposits on the east coast indicate sea-level rise in excess of 3 m between 5200 and 4500 cal. yr BP (Ramsay, 1995). Coincident and recurrent large-scale barrier inundation events are inferred during this time. We base this on the dominance of marine planktonic species and $\delta^{34}S$ enrichment. The occurrence of *Petroneis marina* within the basins during this time is a likely artefact from these washover events, and shows good correspondence with $\delta^{34}S$ (Fig. 5). Evidence of a period of increased storminess through the mid- to late Holocene are recorded elsewhere in a number of global estuarine and coastal sedimentary archives (e.g. Billeaud et al., 2009; Sorrel et al., 2012). A similar record of storminess was found from the south Durban shelf by Dixon (2016), who related these storms to a strongly positive Indian Ocean Dipole anomaly. These in turn are related to warming sea-surface temperatures and the increase in cyclonic intensity and frequency (e.g. Webster et al., 2005).

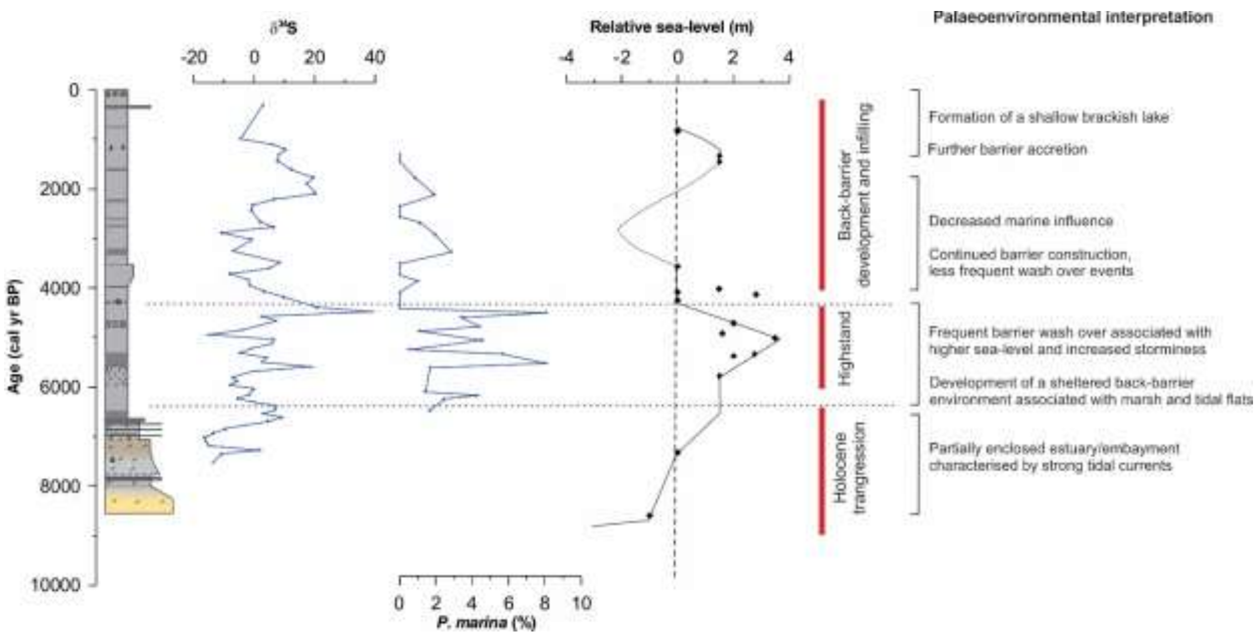


Figure 27. Palaeo-environmental evolution of Lake St Lucia based on sedimentological, geochemical and diatom indicators from core NL-1. Sea level curve from Ramsay (1995); data have been calibrated using ShCal13.

Back-barrier development and infilling

The final phase of geomorphological evolution developed under a gradual decline in relative sea level following the mid-Holocene highstand around 4000 cal. yr BP (Fig. 27). This phase is represented by the progressive decrease in marine influence and reduction in lake surface area as the lake shallowed and segmented. Sandy beach ridge sequences in embayments along sections of the Lake St Lucia shoreline are considered to document the gradually declining water levels and shrinking of area of St Lucia in response to declining sea levels (Botha and Porat, 2013). Periodic marine incursions, associated with storm surges and overwash, remained prevalent until at least ~1200 cal. yr BP. This is supported by the dating of the youngest phase of dune accretion forming the coastal barrier which indicates that this section of the barrier dune was likely still mobile ~2000 years ago (Porat and Botha, 2008). Further barrier construction during a final phase of sea-level rise ~1500 cal. yr BP was likely responsible for permanently isolating the northern basins from the ocean and transforming the system towards its present state. In this instance, the lake hydrology is now mainly controlled by variations in fluvial discharge and evaporation. The adjacent water bodies of Kosi Bay and Lake Sibaya sealed along similar lines; however, they have deeper and larger volume incised valleys (Wright et al., 2000), which have not been infilled by fluvial processes. As a result, they are less likely to be affected by major variations in discharge and evaporation and may host better climate-archives, as opposed to the strong geomorphological archive of St Lucia.

Chapter 5

GEOCHEMICAL CHARACTERISATION: DESICCATION CYCLES AND RECENT EVOLUTION

The occurrence of recent severe drought episodes has largely been attributed to the manipulation of freshwater inflow by anthropogenic activities that have taken place over the last century (e.g. Whitfield and Taylor, 2009). However, our understanding of salinity dynamics at Lake St Lucia is largely based on circumstantial evidence and data collected over a brief period of time. Despite a pressing need to understand the long-term evolution of the system, little research has focussed on understanding the geomorphic evolution of Lake St Lucia and the controls governing its response to changing environmental conditions. In particular, changes in past hydrological regimes and depositional settings of Lake St Lucia remain poorly understood, limiting our understanding of the relationship between system evolution, sedimentary deposition and ecological response. Such information is crucial for understanding the relative influence of human activities on the system's functioning and the response of Lake St Lucia to future climate change.

In this chapter, we present geochemical data from three sediment cores extracted from the main depositional basins of Lake St Lucia. These basins offer potentially useful repositories for environmental study as the geochemical signatures preserved record variations in hydrological, sedimentological, and climatic conditions. It is within this context that we relate cyclical variations in palaeohydrology to regional climate drivers.

5.1 METHODS

5.1.1 Geochemical analysis

Three cores (NL-1, FB-1 and CB-2) were selected for geochemical analysis. Cores were subsampled at 5 cm intervals over the top 2 m, with the remainder of each core then sectioned every 10 cm. Subsamples were dried and ground to a fine powder. Organic content was measured by loss on ignition (LOI) at 550˚C for four hours. Ash residues were then pressed into a pellet and analysed for major element concentrations on an energy dispersive X-ray fluorescence (XRF) spectrometer (S2 Ranger, Bruker). The measurements were calibrated against 14 certified rock standards. The relative standard deviation, based on the repeat analyses of USGS AGV-2, was less than 2% for all elements. To avoid artefacts generated by possible dilution effects and allow for comparison between sediment profiles, elemental ratios rather than absolute concentrations are reported.

5.1.2 Mineralogical analysis

Mineralogical investigations were performed by X-ray diffraction (XRD) on un-orientated powder samples using a Bruker D2 Phaser with monochromated CoKα radiation (7 to 50º 2θ). Scanning electron microscope-energy dispersive X-ray analysis (SEM-EDS) was performed on a FEI Nova 600 microscope. Samples were dispersed in water, mounted onto aluminium stubs and coated with 10 µm Au-Pd prior to examination under the microscope.

5.2 RESULTS

5.2.1 Chronology and core characterisation

North Lake: NL-1

The core extracted from North Lake, NL-1 (Fig. 28a) intersected the last ~7600 cal. yr BP of sedimentary infill. The upper 12 m of the sequence comprises mostly clay dominated sediments, punctuated by a number of thin horizons characterised by coarser grain size and abundant shell debris. These discrete, coarser-grained horizons become more prevalent towards the top of the sequence, particularly over the last 2000 years, where a number of distinct increases in Na/K and Ca/Ti ratios are also observed. The upper 12 m section of NL-1 is characterised by a relatively linear sedimentation rate of ~0.25 cm yr^{-1}, although rates decline sharply to 0.03 cm yr^{-1} over the last 2000 years. This dominant clay sequence is underlain by a basal sandy unit comprising quartz-rich medium to fine sand that is low in organic matter (< 4%). Deposited prior to 6200 cal. yr BP, this material is characterised by elevated Ca/Ti values and is host to a number of bivalve shells, as well as occasional barnacle and oyster fragments. The dating of two intact shell samples from near the base of the core (1478 cm and 1563 cm) yielded similar, although stratigraphically inconsistent, ages, suggesting some sediment reworking.

False Bay: FB-1

The core extracted from False Bay (FB-1, Fig. 28b) consists predominantly of fine silt and clays that are geochemically similar to the muds of NL-1. This clayey sequence is interspersed with a number of coarse sediment horizons and reworked shell fragments that display corresponding increases in Si/Al and Ca/Ti ratios, respectively. Radiocarbon dating indicates a basal age of ~8350 cal. yr BP and a relatively linear sedimentation rate of ~0.23 cm yr^{-1} over much of the succession. The sedimentary profile is stratigraphically consistent, with the exception of a single inverted age at 65 cm, which may indicate a degree of mixing linked to bioturbation or wind-driven currents. As observed in NL-1, the upper 200 cm of the sequence, corresponding to the last ~2000 years, shows discrete enrichments in Na/K that are accompanied by a decrease in sedimentation rate.

South Lake: CB-2

The sedimentary infill of South Lake (CB-2, Fig. 28c) is more complex in comparison to the infilling of the more northern basins. Eight AMS age determinations reveal a basal age of ~9500 years, with an age reversal at 100 cm possibly attributed to sediment mixing (Table 1). The top ~500 cm of the sequence is dominated largely by fine-grained silt and clays that contain occasional shell fragments. This clay sequence shows a distinct decrease in sedimentation rate over the upper ~200 cm, with rates over the last ~4000 years of ~ 0.05 cm yr^{-1}. Unlike NL-1 and FB-1, the upper clay of CB-2 is not interlaminated with coarser horizons and is characterised by substantially lower Na/K ratios. This clay is underlain by a 2 m thick upward fining sand unit that is rich in shell debris.

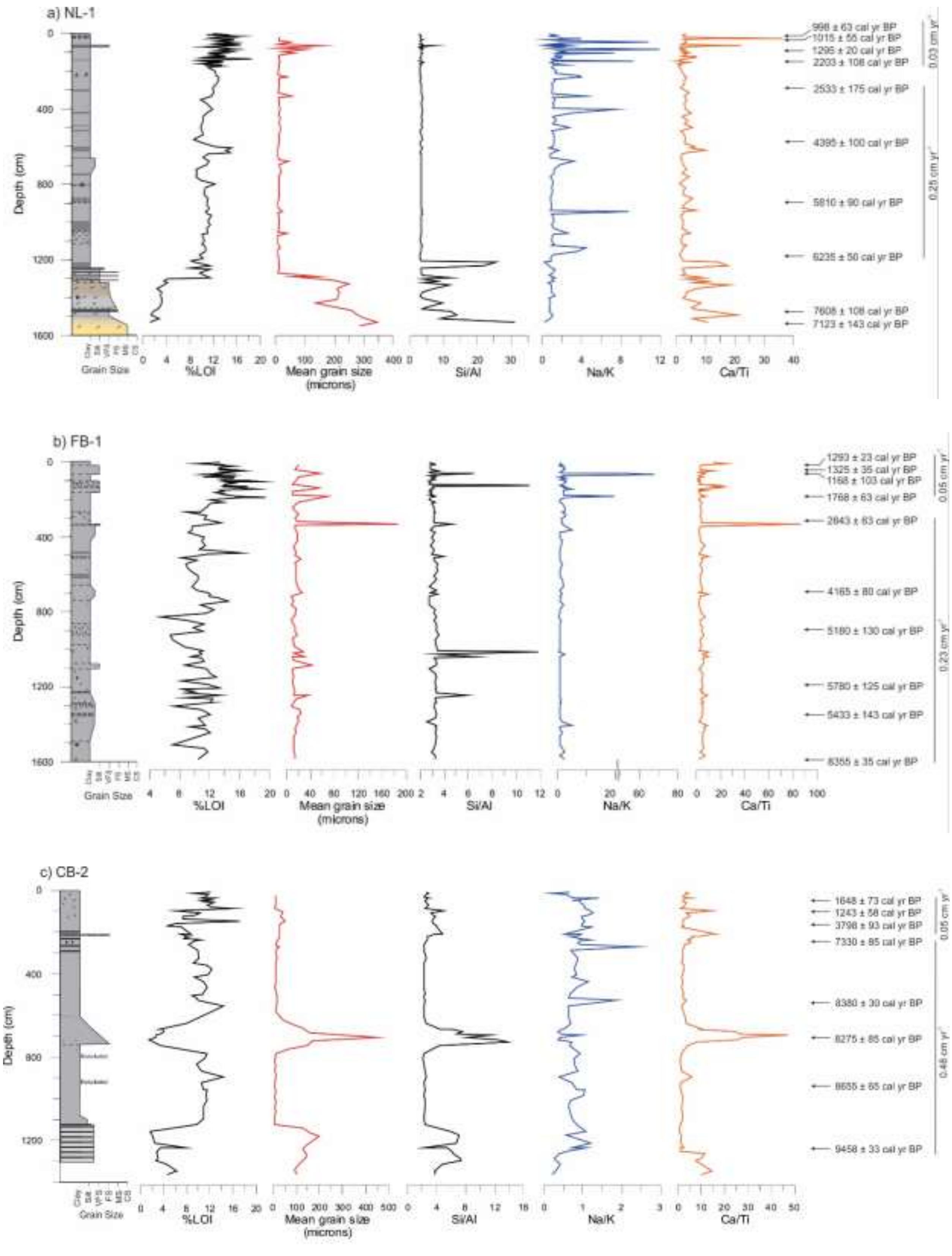


Figure 28. Core logs and selected geochemical data for cores NL-1, FB-1 and CB-2
VFS = very fine sand, FS = fine sand, MS = medium sand, CS = coarse sand

The dates of two samples, taken from 541 and 718 cm, overlap and suggest that this unit was rapidly deposited ~8300 cal. yr BP. Sharply underlying this deposit is a 3.5 m thick, silty, clay unit that was deposited 9500–8300 cal. yr BP and appears to be broadly geochemically similar to muds from the upper section of the sequence. This unit is underlain by coarse, silty sand that contains occasional shell fragments and laminated clay drapes.

5.2.2 Seismic profiles

The upper 10 m of the infill of the system is detailed in Figure 29. The stratigraphy is characterised by horizontal, high-continuity, low-amplitude reflectors with occasional high-amplitude reflectors (HARs). In some places these can undulate and may be marked by occasional shallow depressions. These reflectors extend across the entire system for both the North Lake and False Bay sub-basins. In North Lake, the most prominent enrichment peaks in Na/K (88 and 148 cm downcore) are associated with two very distinct HARs (Fig. 29a and b). The same association within the upper seismic packages is evident from the more proximal coast parallel profiles adjoining Hells Gates (Fig. 29c). Throughout False Bay, peaks in Na/K can be linked with only one HAR (Fig. 29d). A strong enrichment peak at 185 cm is expressed as an undulating high-amplitude reflector, usually associated with extensive gas brightening of the underlying reflectors. Signal washout of the upper layers due to the very shallow nature of False Bay, together with gas obscuration, precludes a more detailed correlation with the upper peaks in Na/K.

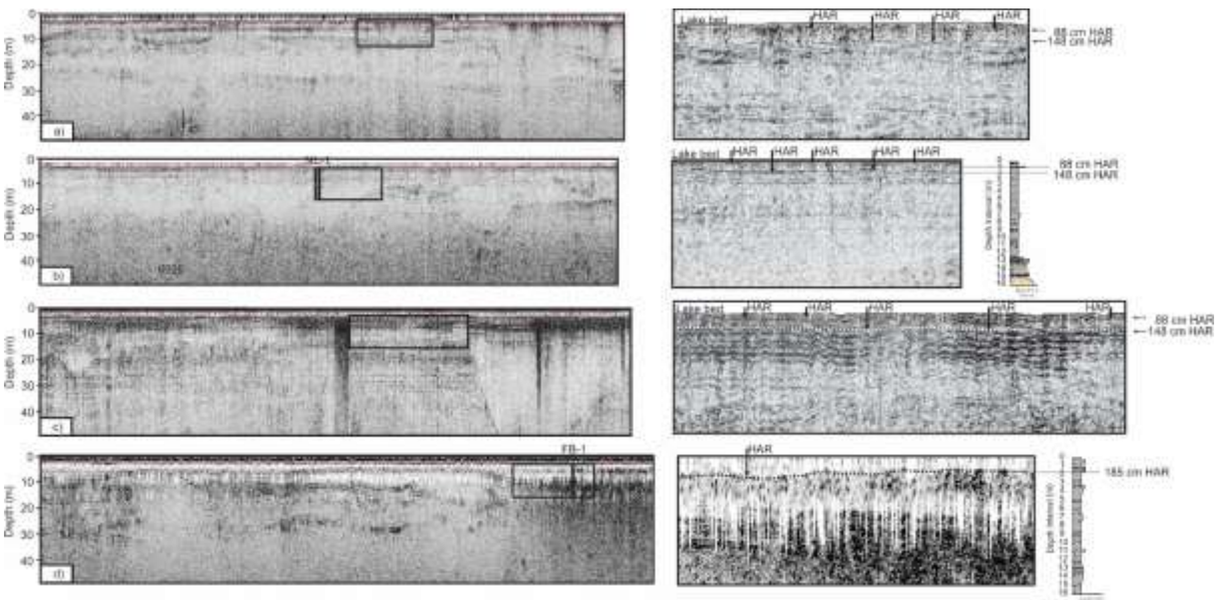


Figure 29. Seismic profiles detailing the upper stratigraphy of the northern portions of Lake St Lucia. a) North Lake. Note the lateral continuity of high-amplitude reflectors (HARs) at depths of 88 cm and 148 cm in the lake substrate. b) North Lake intersecting core NL-1. Note the clear association between intervals in the core that mark enrichments in Na/K (see Fig. 28a) and reflectors at 88 and 148 cm below the lake floor. c) Coast parallel line crossing Hells Gates similarly revealing HARs at equable depth. d) False Bay intersecting core FB-1. Here the upper reflectors are obscured due to the extreme shallowness of the sub-basin, together with extensive gas accumulations in the upper stratigraphy. Note the clear association between a single HAR and the core interval of most enrichment in Na/K (185 cm down core).

5.3 DISCUSSION

5.3.1 Recent depositional history and system evolution

The sedimentary infill of Lake St Lucia documents the transition of the system from fluvial origins to its contemporary estuarine-lacustrine setting. Cores recovered from the three main depocentres of Lake St Lucia reveal sequences capped by mud, reflecting the most recent infill associated with low-energy estuarine/lacustrine conditions. Although the thickness of the mud infill varies between basins, the material is largely homogeneous in nature, comprising predominantly SiO_2 (55 ±6%), Al_2O_3 (16 ±2.6%) and Fe_2O_3 (11.5 ±1.9%). Fe and Al abundances indicate a strong terrestrial influence and, together with the grain sizes, point to the suspension settling of fluvial sediment under low-energy conditions. XRD indicates that the surface sediments of St Lucia are dominated by the clay minerals kaolinite, mica and smectite, with varying amounts of calcite and halite. There appears to be little spatial variation in mineralogical composition, indicating a well-mixed system and drainage of similar catchment geology.

The core from North Lake (NL-1) documents a clear and distinct change in depositional conditions ~6200 cal. yr BP. Coarse, quartz-rich sediments present at the base of the core indicate the prevalence of high-energy conditions and likely represent marine sands, deposited when Lake St Lucia was connected to the ocean via an opening at Leven Point. These sands are characterised by elevated Ca/Ti ratios and reflect the presence of numerous bivalves, barnacles and oyster fragments that would have been deposited under free tidal exchange. The overlying fine-grained silts and clays reflect deposition under more tranquil estuarine-lake conditions, signalling inlet closure and gradual development of a back-barrier environment. Under these conditions, fluvial, organic-rich sediments started to accumulate ~6200 cal. yr BP. Core FB-1, which intersected only the contemporary lacustrine infill (Chapter 2), indicates that the onset of estuarine-lacustrine conditions in the False Bay region of the system occurred prior to 8355 cal. yr BP, earlier than in North Lake. Sediment accumulation in both False Bay and North Lake basins has occurred at similar rates (~0.25 cm yr^{-1}) since the establishment of estuarine-lake conditions, although cores from both basins document a marked decrease in sedimentation rate over the last ~2000 years. Associated with this decrease in sedimentation rate is the presence of a number of distinct coarse-grained horizons, characterised by elevated Na/K ratios. These discrete horizons point to occasional deviations from tranquil lacustrine conditions and shifts in the nature of the material accumulating within the system.

The low-energy, estuarine/lacustrine infill in South Lake (CB-2) is less thickly developed than in the northern basins of the system. The upper clay and silt-dominated sediments are underlain by a sandy unit that is associated with elevated Ca/Ti ratios and likely represents a flood-tide deposit, which formed during a late lagoonal phase when the connection between South Lake and the ocean became restricted. This suggests that South Lake was connected to the ocean via a separate opening that closed permanently around 8400 cal. yr BP. Geophysical mapping in South Lake (Chapter 2) and drilling of the adjacent coastal dune (Meyer et al., 2001) suggest that an oceanic connection in the vicinity of Mission Rocks was likely. With no direct fluvial inputs, closure of this opening severely restricted sediment influx into the basin. In contrast to the northern basins where sediment accumulation via bayhead deltas has actively promoted basin shallowing, sedimentation rates in South Lake have been in the region of 0.05 cm yr^{-1} over the last ~7000 year. Wind-driven currents are known to result in large water exchanges between South Lake and the northern basins of Lake St Lucia (Schoen et al*.,* 2014), with the remobilisation and suspension transport of fine silts and clay likely the main mechanism of sediment transport into South Lake. In addition, there are no true bayhead deltas prograding into the system here; consequently, South Lake today remains the deepest basin of the St Lucia system at ~2 m during normal lake level conditions.

5.3.2 Lake salinity and climate variability

Despite the homogeneous nature of the lacustrine infill, marked variations in Na/K ratios through NL-1 and FB-1 reveal distinct periods of increased salinity, particularly over the last 2000 years (Fig. 30). Several notable phases can be identified in the record from North Lake, two of which (at ~1100 and 1750 cal. yr BP), are also clearly observable in FB-1. Scanning electron microscopy reveals halite as the dominant mineral present in subsamples from these horizons (Fig. 31), suggesting extensive mineral precipitation under dry and evaporative conditions. Additionally, these halite-enriched horizons are commonly associated with discrete increases in grain size, likely attributed to the deflation of coarse-grained material from exposed, sandy shorelines during low or even desiccated lake water conditions. Overlapping radiocarbon dates from the upper sections of both FB-1 and NL-1 point to possible depositional hiatuses, which would support the occurrence of prolonged dry periods, desiccation and associated deflation of the exposed lake floor. Often overlying these coarse, halite-enriched horizons are abundant shell debris accumulations that we attribute to mass die-offs in molluscs during prolonged periods of hypersalinity and/or desiccation.

Substantially higher Na/K ratios (up to six times) in FB-1 suggest that False Bay has likely experienced more severe periods of desiccation compared to North Lake. The Mkhuze River that drains into the northern end of North Lake is host to an extensive bayhead delta-top swamp system that is largely groundwater fed. Freshwater seepage from the swamps likely plays an important role in ameliorating salinity in North Lake, particularly during prolonged dry periods. In contrast, the rivers that drain into False Bay have relatively small catchments and rely predominantly on surface runoff. Unlike the northern basins, the lacustrine muds from South Lake are characterised by substantially lower Na/K values and lack halite-enriched horizons. In addition to South Lake being a deeper basin and therefore less prone to desiccation, the basin also receives substantial groundwater inputs from the Eastern Shores (Taylor, 2006). The lack of such features in South Lake may also be due to its connection to either the estuary via the Narrows, or the palaeo-connection of estuary mouth to the Mfolozi River which may have buffered the southern portions of the system from these desiccation events.

Correspondence between the NL-1 and FB-1 records suggests that these events are driven by system-scale processes operating between each sub-basin. The lateral persistence of these enriched Na/K correlative seismic reflectors points to a system-wide onset of desiccation and a major shift in regional hydroclimate at Lake St Lucia. El Niño-Southern Oscillation (ENSO) activity is known to be the most important mechanism driving inter-annual climatic variability in the Southern Hemisphere (Tudhope et al., 2001).

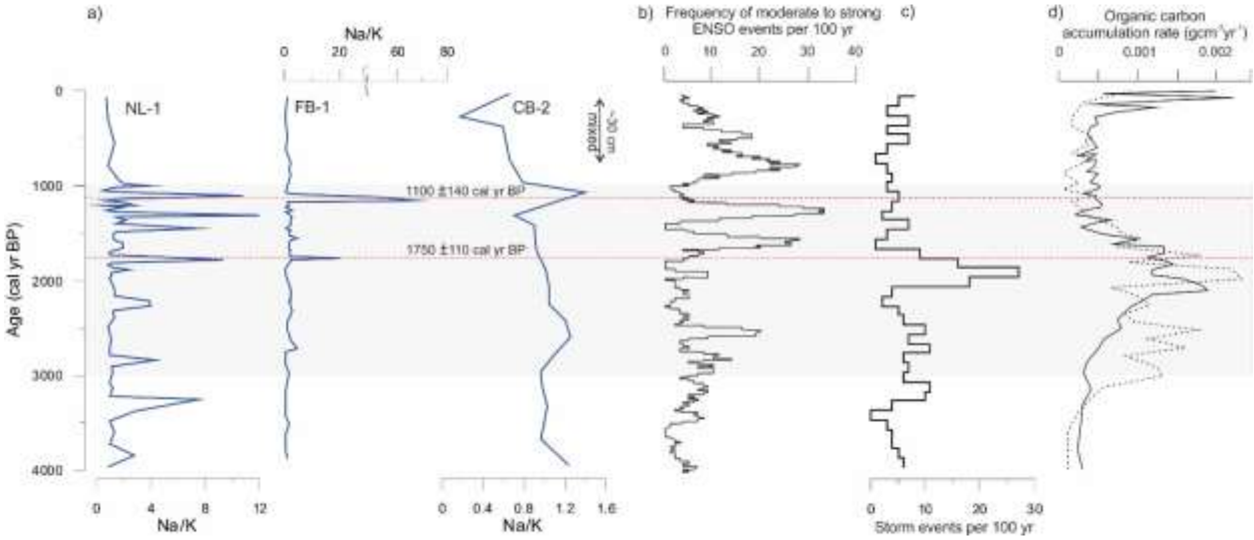


Figure 30. Comparison of the records from Lake St Lucia with other Southern Hemisphere terrestrial palaeo-ENSO proxies. a) Occurrence of salinity phases in sediment cores from Lake St Lucia. b) Reconstructed frequency of moderate to strong ENSO events recorded at Laguna Pallcacocha, Ecuador (Moy et al., 2002). c) ENSO-driven changes in storm activity recorded in the Lake Tutira sediment record, New Zealand (Gomez et al., 2011). d) ENSO associated changes in carbon accumulation rates in sediment cores from Tuggerah Lake, Australia (Macreadie et al., 2015). Grey shading indicates the observed peak period of ENSO intensification.

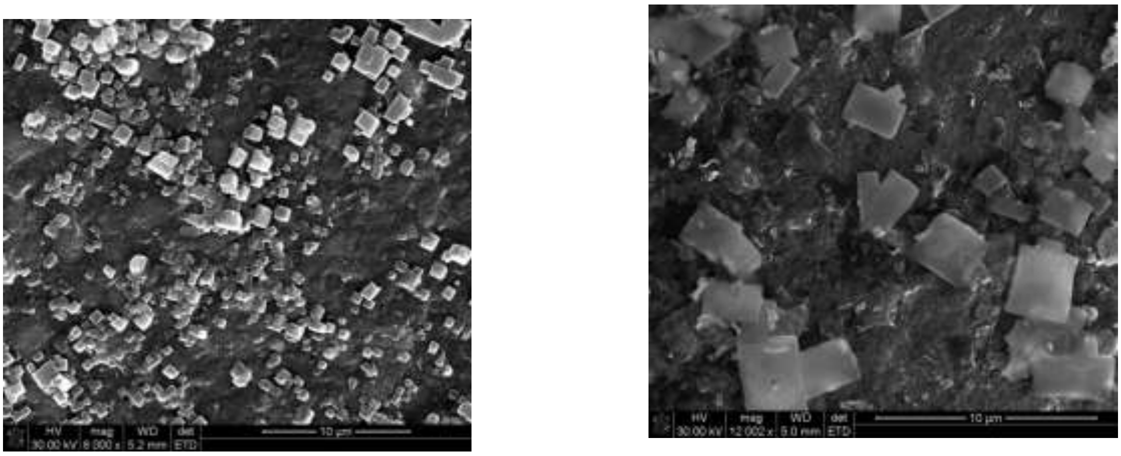


Figure 31. Scanning electron microscope images showing extensive halite precipitation (NL-1, 26-27 cm and 47-49 cm)

Anomalously warm sea-surface temperatures in the southwestern Indian Ocean are typically associated with dry conditions over the summer rainfall region of southern Africa (Mason et al., 1994; Jury, 1996). This shift is coincident with a weaker subtropical high-pressure belt and reduced penetration of moist Indian Ocean trade winds over the southern African plateau (Richard et al., 2000), and consequently, ENSO warm events have frequently been considered the key factor for drought in the region (Richard et al., 2001). We suggest that observed periods of protracted desiccation at Lake St Lucia have been driven by ENSO variability. Palaeo-ENSO records from the Indian Ocean region are scarce and limited largely to analyses of modern corals, which do not extend back much beyond a few hundred years (Neukom and Gergis, 2011). To examine the link between halite layers at Lake St Lucia and longer-term climate variability, we compare our data to available similar estuarine and lake sediment records from the tropical Pacific (Fig. 30). Records from this region indicate a marked increase in El Niño activity ~1000-3000 yr BP that resulted in millennial-scale ENSO intensification known as "super-ENSO" (Gagan et al., 2004; Macreadie et al., 2015). A shift to amplified ENSO variability during the late Holocene is corroborated by a number of coral records from the topical Pacific region (e.g. Woodroffe et al., 2003; McGregor and Gagan, 2004) and is consistent with numerical climate models which suggest that orbitally driven changes in seasonal insolation produced intense and more frequent ENSO events ~3000-1000 cal. yr BP (Clement et al., 2000).

Our data indicate that severe desiccation events at Lake St Lucia occurred ~1100–1700 cal. yr BP, coincident with maximum ENSO activity. Despite uncertainties associated with radiometric dating, age modelling, differences in temporal resolution and inherent variability between records, inferred periods of prolonged drought at Lake St Lucia broadly show good correspondence with peaks in ENSO activity documented in other terrestrial records. The match suggests that protracted dry periods at Lake St Lucia were likely triggered by intensive El Niño events, which produced severe droughts that may have lasted several years. Given the temporal resolution of our records, it is likely that only the most intense El Niño events, which induced large and protracted periods of drought, are identified in this study.

5.3.3 Contemporary desiccation and hypersalinity cycles

Like many estuarine systems worldwide, fresh water reductions and other anthropogenic impacts have influenced the natural functioning of Lake St Lucia over the past century (Whitfield and Taylor, 2009; Lawrie and Stretch, 2011). The most significant alteration to the system occurred in the 1950s when the Mfolozi River was separated from the St Lucia estuary mouth. This management decision was taken in response to the deposition of large amounts of sediment near the estuary mouth that followed the establishment of sugarcane plantations and canalisation of the Mfolozi floodplain.

The Mfolozi River is an essential source of freshwater to Lake St Lucia and its separation resulted in reduced freshwater inflow, which is believed to have contributed to prolonged mouth closure and periods of hypersalinity. Recent drought events have been unprecedentedly severe. The drought that persisted between 2002 and 2012 resulted in extreme hypersalinities and the drying out of large parts of the system, causing the northern basins to become disconnected from South Lake. These conditions resulted in the mass die-off of mollusc species and disappearance of nearly all macro-zoobenthos from the northern areas of the lake (Pillay and Perissinotto, 2008; Mackay et al. 2010; Cyrus et al., 2010). A similar event occurred at the end of 2015, where rapid decreases in water levels resulted in the segmentation of Lake St Lucia, with pockets of water remaining only in the deeper sections of the lake (Fig. 32). When comparing the seismic geometry of the uppermost HARs to the current desiccation surfaces shown from contemporary satellite imagery, a strong similarity in surface morphology is also noted. Both comprise gently undulating surfaces with occasional small gullies formed at the fringes of the basin.

Figure 32. a) Comparative satellite images (Sept 2014 vs Feb 2016) showing the desiccation of large areas of Lake St Lucia and segmentation of the main basins during prolonged dry periods. Note that the False Bay and North Lake basin are largely dry, with water remaining in the system ponding in the deeper basins where the cores were sited. b) Surface halite accumulations and mass mollusc die-offs caused by the recent drought, False Bay 24 November 2015

While recent drought events have largely been attributed to anthropogenic impacts, including freshwater abstractions, catchment development and separation of the Mfolozi River (Whitfield and Taylor, 2009; Lawrie and Stretch, 2011), our analysis suggests that periods of extreme salinity and desiccation have occurred in the past, likely triggered by intensive El Niño events. Lake St Lucia provides one of the longest instrumental lake salinity records in southern Africa, spanning more than 50 years. This provides the opportunity to evaluate the occurrence of high salinity events as a function of decadal climate variability. Salinity records from St Lucia indicate that the False Bay and North Lake basins are highly susceptible to hypersalinity and desiccation, with salinities in False Bay reaching in excess of 150 in recent years (Fig. 33). Contemporary environmental conditions are also less harsh in the southern parts of the lake, with salinities in South Lake typically remaining below 120. South Lake is thought to act as a refuge during drought conditions, from where benthic and macro-zoobenthos recolonisation can take place (Taylor, 2006). Clear similarities thus exist between contemporary spatial heterogeneities in salinity, the present-day functioning of Lake St Lucia, and the cycles reflected in the sediment cores extracted from the lake.

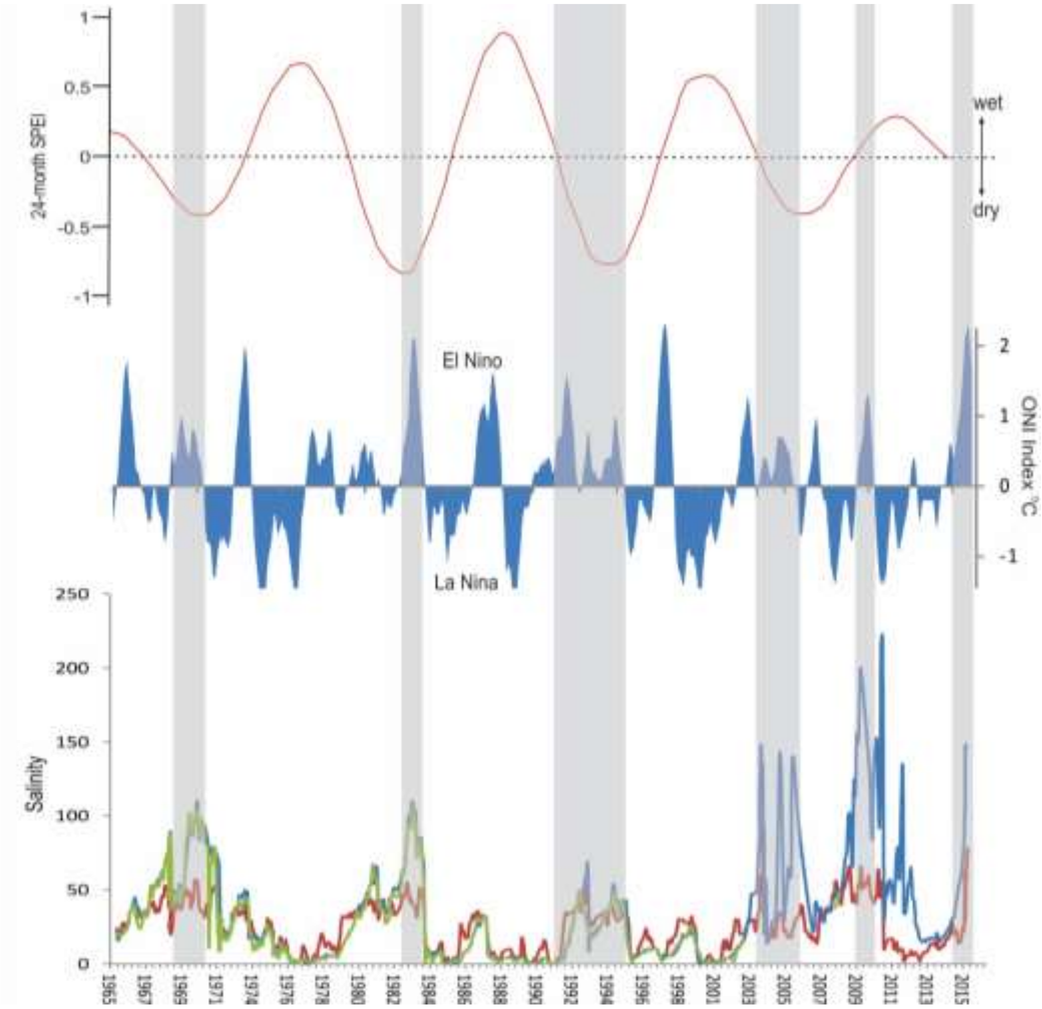


Figure 33. Comparison between the a) variability in the 10–12 year timescale reconstructed Standardised Precipitation Evapotranspiration Index (SPEI, Malherbe et al., 2016), b) Oceanic Niño Index (ONI) based on the running three-month average sea-surface temperature in the Nino3.4 region (NOAA Climate.gov), c) variation in monthly salinity recorded at False Bay, North Lake and South Lake, 1965–2016 (Ezemvelo KZN Wildlife). Note that when decadal dry cycles coincide with El Niño events, increased salinity levels are observed in Lake St Lucia.

The position of South Africa within the subtropical high-pressure belt predisposes the country to large climate variability related to the position and strength of the high-pressure systems over the Atlantic and Indian Oceans (Tyson, 1981; Jury, 1996). Rainfall in the summer rainfall region of South Africa is characterised by decadal variability (Fig. 33a; Malherbe et al., 2016), which has been shown to enhance or oppose the effect of ENSO events (Kruger, 1999). When comparing variations in salinity recorded at Lake St Lucia, it is evident that periods of extreme salinity usually arise when an El Niño event coincides with a dry cycle (Fig. 33). Decadal dry cycles exacerbate the impacts of drought associated with El Niño, while phases of above-normal rainfall have a moderating effect.

5.3.4 The future of Lake St Lucia

The formation of Lake St Lucia is linked to sea-level rise during the Holocene, which triggered coastal barrier accretion and initiated the accumulation of fluvial sediment via bayhead deltas within the lake basins. Since then, the accumulation of sediments has gradually transformed the original deep-water system into a shallow estuarine lake as sediment supply to the system has caught up (e.g. Cooper et al., 2012) with a relatively rapid rise in sea level that initially drowned the system and then began to outstrip the available accommodation space once the northern parts of the system were sealed from oceanic influence. This shallowing process has resulted in the contemporary St Lucia system being extremely sensitive to changes in water supply, particularly the northern portions of the system which rely heavily on groundwater inputs to maintain lake levels. The geochemical records presented here put the recent drought events at Lake St Lucia into perspective. While anthropogenic impacts on water flow may exacerbate current freshwater supply issues, it is clear that episodic and severe drought events have occurred in the past. The cores were sited in areas that have historically been the deepest points of each sub-basin (Chapter 2). These mark areas of bathymetric lows where the last amounts of water would have accumulated before complete desiccation took place. Sediment accumulation appears to have also played a role in tandem with drier climatic periods. The net shallowing of the system is a continuing process, as evidenced from the ongoing sedimentation of each main lake basin. Even with stable lake levels, Lake St Lucia is on a trajectory that will eventually result in it being transformed into a swamp or wetland due to normal regression of the shorelines and eventual infilling of the available accommodation space. While it is difficult to accurately predict future infilling, an approximate timeline can be developed based on current sedimentation rates. Taking an average lake water depth of 1 m and assuming a sedimentation rate of 0.05 cm yr^{-1} (the approximate current rate of accumulation in North Lake, False Bay and South Lake), the main basins could be expected to fill within the next 2000 years. However, as outlined in this chapter, future changes in climate are likely to influence this process.

CHAPTER 6

CONCLUSIONS

The long-term evolution of the Lake St Lucia system is the product of two periods of major base level fall, one in the Pliocene, the other ~ 18 000 years ago, that resulted in a series of incised valleys forming. Associated with these are two phases of transgressive infilling (Pleistocene and late Pleistocene/Holocene) which follow the typical facies successions of mixed tide- and wave-dominated incised valley fills. As sea levels rose the valleys were filled, the back-barrier responded differently due to the sheltering effects of the Nibela Peninsula which buffered shoreline migration during the transgression. In this context, False Bay appears to have evolved towards an estuarine-lake system earlier than the North Lake depocentre. In general, however, the northern portions of the system (False Bay and North Lake) house the largest relict bayhead deltaic material, whereas the southern areas (South Lake) lack such deposits and are dominated by thick central basin-type infilling. The two areas appear to have evolved separately since the LGM, when two discrete and unrelated drainage systems were formed. Subsequently, these were infilled and only became connected as a single system after the closure of the main LGM inlets ~ 7500 years ago.

The most recent cycle of sedimentary infill has been strongly influenced by changes in relative sea level and geomorphic processes over the mid- to late Holocene. Systematic changes in foraminifera, diatom assemblages and sulfur isotope geochemistry record changes in basin geomorphology driven by sea level, coupled with barrier aggradation and lagoon development. The Holocene transgression is reflected by initial marine intrusions into the lake basin, followed by barrier development and the gradual transitioning of the system from a shallow, partially enclosed embayment to a brackish back-barrier lagoon. Barrier stabilisation was periodically interrupted by large-scale inundation events linked to the mid-Holocene highstand and episodes of enhanced storminess. St Lucia’s present-day configuration was likely only established during the last ~1000 years, driven by further barrier accretion, which ultimately sealed the northern basins from the ocean. Geomorphic rather than climatic controls are identified as the primary forces responsible for governing depositional and hydrological changes within St Lucia over the last ~6000 years.

Sediment accumulation appears to have also played a role in tandem with drier climatic periods. The net shallowing of the system is a continuing process, as evidenced from the ongoing sedimentation within each main lake basin. Even with stable lake levels, Lake St Lucia is on a trajectory that will eventually (possibly within the next two millennia) result in it being transformed into a swamp or wetland due to normal regression of the shorelines and eventual infilling of the available accommodation space. Although the accelerated accumulation of sediment in the lake would artificially shorten the lifespan of the present system, and increasing sediment yields have been a recurrent management concern (Taylor, 2013), cores recovered from all three basins document dramatic decreases in sediment accumulation over recent times. In this light, future desiccation and hypersalinity may be controlled more by climatic changes than by the current catchment management practices.

Global warming is expected to increase the frequency and intensity of droughts over the next century, driven by reduced precipitation and increases in potential evapotranspiration (Cook et al., 2014; Dai, 2013). Projections for southern Africa indicate substantial drying over much of the region and increased climatic variability associated with a greater frequency and/or intensity of ENSO events (Fauchereau et al., 2003; Cook et al., 2014; Gaughan et al., 2016). Such changes will exert a profound influence on regional rainfall and river flow. Precipitation-sensitive systems such as Lake St Lucia will be particularly vulnerable to the impacts of climate variability, which are likely to be exacerbated by population growth and increasing dependence on water resources. Declines in precipitation, accompanied by increases in evaporative demand, will amplify extreme salinity changes within the system, severely altering physicochemical conditions, habitat availability and ecological functioning. Deterioration in the ecological functioning of Lake St Lucia will likely have pronounced impacts on offshore production, through changes in fish recruitment and in the delivery of nutrients to coastal environments. While the protection of natural flow regimes is likely to be the most effective management strategy to maintain estuarine functioning, in light of our findings, predicted climate-induced modifications to the hydroclimate are expected to have severe ramifications for biodiversity, local populations, and ultimately the long-term survival of Africa's largest estuarine system.

REFERENCES

Allen, G.P., Posamentier, H.W. 1993. Sequence stratigraphy and facies model of an incised valley fill: the Gironde estuary, France. *Journal of Sedimentary Petrology* 63, 378-391.

Appleby, P.G., and Oldfield, F. 1978. The calculation of lead-210 dates assuming a constant rate of supply of unsupported 210Pb to the sediment. *Catena* 5, 1-8.

Ashley, G.M., Sheridan, R.E. 1994. Depositional model for valley fills on a passive continental margin. In: Dalrymple, R.W., Boyd, R., Zaitlin, B.A. (Eds.), *Incised Valley Systems: Origin and Sedimentary Sequences.* SEPM Special Publication 51. SEPM, pp. 57- 85.

Bainbridge, B. 1994. Lake St Lucia and the Eastern Shores: The Natal Parks Board's role in the Environmental Impact Report. *Natalia* 23/24, 45-60.

Battarbee, R. 1999. The importance of palaeolimnology to lake restoration. *Hydrobiologia* 395/396, 149-159.

Begg, G.W. 1978. The Estuaries of Natal. Natal town and Regional Planning Commission Report, vol. 41. Pietermaritzburg, South Africa.

Bennett, K.D. 2005. Psimpoll. Uppsala Universitet, Villavgen.

Billeaud, I., Tessier, B., Lesueur, P. 2009. Impacts of late Holocene rapid climate changes as recorded in a macrotidal coastal setting (Mont-Saint-Michel Bay, France). *Geological Society of America* 37, 1031-1034.

Blaauw, M. 2010. Methods and code for 'classical' age-modelling of radiocarbon sequences. *Quaternary Geochronology* 5, 512-518.

Blaauw, M., and Christen, J.A. 2011. Flexible paleoclimate age-depth models using an autoregressive gamma process. *Bayesian Analysis* 6, 457-474.

Bordovskiy, O.K. 1965. Sources of organic matter in marine basins. *Marine Geology* 3, 5-31.

Botha, G.A., Porat, N., Haldorsen, S. 2013. Geological history. In: Perissinotto, R., Stretch and Taylor, R.H., (Eds), *Ecology and Conservation of Estuarine Ecosystems: Lake St. Lucia as a Global Model*, Cambridge University Press, UK, pp. 47-62.

Caffrey, M.A., Horn, S.P., Oryis, K.H., Haberyan, K.A. 2015. Holocene environmental change of Laguna Saladilla, coastal north Hispaniola. *Palaeogeography, Palaeoclimatology, Palaeoecology* 436, 9-22.

Carrasco, N.K., Perissinotto, R. 2015. Zooplankton community structure during a transition from dry to wet state in a shallow, subtropical estuarine lake. *Continental Shelf Research* 111, 294-303.

Chiba, T., Endo, K., Sugai, T., Haraguchi, T., Kondo, R., Kubota, J. 2016. Reconstruction of Lake Balkhash levels and precipitation/evaporation changes during the last 2000 years from fossil diatom assemblages. *Quaternary International* 397, 330-341

Clark, J.A., Farrell, W.E., Peltier, W.R. 1978. Global changes in postglacial sea level: a numerical calculation. *Quaternary Research* 9, 265-287.

Clement, A.C., Seager, R., Cane, M.A. 2000. Suppression of El Niño during the mid-Holocene by changes in the Earth’s orbit. *Paleoceanography* 15, 731-737.

Coe, A.L., Bosence, D.W.J., Church, K.D., Flint, S.S., Howell, J.A., Wilson, R.C.L. 2003. *The Sedimentary Record of Sea Level Change*. Cambridge University Press, Cambridge, pp. 288.

Compton J.S. 2006. The mid-Holocene sea-level highstand at Bogenfels Pan on the southwest coast of Namibia. *Quaternary Research* 66, 303-310.

Cook, B.I., Smerdon, J.E., Seager, R., Coats, S. 2014. Global warming and 21st century drying. *Climate Dynamics* 43, 2607-2627.

Cooper, J.A.G. 1993. Sedimentation in a river dominated estuary. *Sedimentology* 40, 979-1017.

Cooper, J.A.G. 2001. Geomorphological variability among microtidal estuaries from the wave-dominated South African coast. *Geomorphology* 40, 99-122.

Cooper, J.A.G., Green, A.N., Smith, A.M. 2013. Vertical stacking of multiple highstand shoreline deposits from the Cretaceous to the present: facies development and preservation. *Journal of Coastal Research* SI 65, 1904-1908.

Cooper, J.A.G., Green, A.N., Wright, C.I. 2012. Evolution of an incised valley coastal plain estuary under low sediment supply: a 'give-up' estuary. *Sedimentology* 59, 899-916.

Croisetière, L., Hare, L., Tessier, A. and Cabana, G. 2009. Sulphur stable isotopes can distinguish trophic dependence on sediments and plankton in boreal lakes. *Freshwater Biology* 54,1006-1015.

Culver, S.J., Woo, H.J., Oertel, G.F. and Buzas, M.A. 1996. Foraminifera of coastal depositional environments, Virginia, USA: distribution and taphonomy. *Palaios,* pp. 459-486.

Cyrus, D.P., Vivier, L., Jerling, H.L. 2010. Effect of hypersaline and low lake conditions on ecological functioning of St Lucia estuarine system, South Africa: An overview 2002-2008. *Estuarine, Coastal and Shelf Science* 86, 535-542.

Dalrymple, R.W., Zaitlin, R.A., Boyd, R. 1992. Estuarine facies models: conceptual basis and stratigraphic implications. *Journal of Sedimentary Petrology* 62, 1130-1146.

Davis, R.A., Flemming, B.W. 1995. Stratigraphy of a combined wave- and tide-dominated intertidal sand body: Martens Plate, East Frisian Wadden Sea, Germany. In: Flemming, B.W., Bartholomä, A. (Eds) *Tidal signatures in modern and ancient sediments*. Spec Publ Intern Assoc Sediment 24,121-132.

Dia, A. 2013. Increasing drought under global warming in observations and models. *Nature Climate Change* 3, 52-58.

Debenay, J.P. 2012. *A guide to 1,000 foraminifera from Southwestern Pacific*: *New Caledonia*, IRD Editions. Publications Scientifiques du Musèum, Marseille.

Dixon, A., 2015. Seismic, geochemical and sedimentological characteristics of storm deposits from the Durban continental shelf, South Africa. Unpublished MSc thesis. School of Agriculture, Earth and Environment Sciences. University of KwaZulu-Natal.

Dos Santos-Fischer, C.B., Correa, I.C.S, Weschenfelder, J., Togran, L.C., Stone, J.R., 2016. Paleoenvironmental insights into the Quaternary evolution of the southern Brazilian coast based on fossil and modern diatom assemblages. *Palaeogeography, Palaeoclimatology, Palaeoecology* 446, 108-124.

Faegri, K., and Iversen, J. 1989. *Textbook of Pollen Analysis* (5th ed.). John Wiley and Sons, New York.

Fatela, F. and Taborda, R. 2002. Confidence limits of species proportions in microfossil assemblages. *Marine Micropaleontology* 45, 169-174.

Fauchereau, N., Trzaska, S., Rouault, M., Richard, Y. 2003. Rainfall variability and changes in southern Africa during the 20th century in the global warming context. *Natural Hazards* 29, 139-154.

Gagan, M.K., Hendy, E.J., Haberle, S.G., Hantoro, W.S. 2004. Post-glacial evolution of the Indo-Pacific warm pool and El Niño-southern oscillation. *Quaternary International* 118-119, 127-143.

Gaughan, A.E., Staub, C.G., Hoell, A., Weaver, A., Waylen, P.R. 2016. Inter- and intra-annual precipitation variability and associated relationships to ENSO and the IOD in southern Africa. *International Journal of Climatology* 36, 1643-1656.

Gehrels, W.R. 2002. Intertidal foraminifera as palaeoenvironmental indicators. In, S.K. Haslett, S.K., (Eds) *Quaternary Environmental Micropalaeontology*. Oxford University Press, London, pp. 91-114.

Gomez, B., Carter, L., Orpin, A.R., Cobb, K.M., Page, M.J., Trustrum, N.A., Palmer, A.S. 2011. ENSO/SAM interactions during the middle and late Holocene. *The Holocene* 22, 23-30.

Green, A.N. 2009. Palaeo-drainage, incised valley fills and transgressive systems tract sedimentation of the Northern KwaZulu-Natal continental shelf, South Africa, SW Indian Ocean. *Marine Geology* 263, 46-63.

Green, A.N. 2011a. Submarine canyons associated with alternating sediment starvation and shelf-edge wedge development: northern KwaZulu-Natal continental margin, South Africa. *Marine Geology* 289, 114-126.

Green, A.N., 2011b. The late Cretaceous to Holocene sequence stratigraphy of a sheared passive upper continental margin, northern KwaZulu-Natal, South Africa. *Marine Geology* 289, 17-28.

Green, A.N., Garlick, G.L. 2011. Sequence stratigraphic framework for a narrow, current-swept continental shelf: the Durban Bight, central KwaZulu-Natal, South Africa. *Journal of African Earth Sciences* 60, 303-314.

Green, A.N., Dladla, N., Garlick, G.L. 2013. Spatial and temporal variations in incised valley systems from the Durban continental shelf, KwaZulu-Natal, South Africa. *Marine Geology* 335, 148-161.

Green, A.N., Cooper, J.A.G., Wiles, E.A., De Lecea, A.M. 2015. Seismic architecture, stratigraphy and evolution of a sub-tropical marine embayment: Maputo Bay, Mozambique. *Marine Geology* 369, 300-309.

Grimm, E., 1993. TILIA: A Pollen Program for Analysis and Display. Illinois State Museum, Springfield.

Grimm, E.C., 1987. CONISS: a FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. *Computers and Geoscience* 13, 13-35.

Hogg, A.G., Hua, Q., Blackwell, P.G., Niu, M., Buck, C.E., Guilderson, T.P., Heaton, T.J., Palmer, J.G., Reimer, P.J., Reimer, R.W., Turney, C.S.M., and Zimmerman, S.R.H. 2013. SHCal13 southern hemisphere calibration, 0-50,000 years cal BP. *Radiocarbon* 55 (4), 1889-1903.

Huang, Y., Dupont, L., Sarnthein, M., Hayes, J.M. and Eglinton, G., 2000. Mapping of C4 plant input from North West Africa into North East Atlantic sediments. *Geochimica et Cosmochimica Acta* 64, 3505-3513.

Javaux, E.J. and Scott, D.B., 2003. Illustration of modern benthic foraminifera from Bermuda and remarks on distribution in other subtropical/tropical areas. *Palaeontologia Electronica* 6, 29.

Jury, M.R., 1996. Regional teleconnection patterns associated with summer rainfall over South Africa, Namibia and Zimbabwe. *International Journal of Climatology* 16, 135-153.

Kelbe, B.E., Taylor, R.H., Haldorsen, S., 2013. Groundwater hydrology. In Perissinotto, R., Stretch, D.D., Taylor, R.H. (Eds). *Ecology and Conservation of Estuarine Ecosystems: Lake St Lucia as a Global Model.* Cambridge University Press, Cambridge. Pp 151-167.

Kennedy, W.J., Klinger, H.C., 1975. Hiatus concretions and hardground horizons in the Cretaceous of Zululand. *Palaeontology* 15, 539-549.

Kriel, J.P., Adler, E., Bayer, A.J.W., et al. 1966. Report of the Commission of Inquiry into the alleged threat to animal and plant life in St Lucia Lake, 1964-1966. Pretoria. Government Printer.

Kruger, A.C. 1999. The influence of the decadal-scale variability of summer rainfall on the impact of El Nino and La Nina events in South Africa. *International Journal of Climatology* 19, 59-68.

Lamb, A.L., Wilson, G.P. and Leng, M.J. 2006. A review of coastal palaeoclimate and relative sea-level reconstructions using d13C and C/N ratios in organic material. *Earth-Science Reviews* 75, 29-57.

Lawrie, R.A., Stretch, D.D. 2011. Occurrence and persistence of water level/salinity states and the ecological impacts for St Lucia estuarine lake, South Africa. *Estuarine, Coastal and Shelf Science* 95, 67-76.

Mackay, F., Cyrus, D.P., Russell, K.-L. 2010. Macrobenthic invertebrate responses to prolonged drought in South Africa's largest estuarine lake complex. *Estuarine, Coastal and Shelf Science* 86, 553-567.

Malherbe, J., Dieppois, B., Maluleke, P., Van Staden, M., Pillay, D.L. 2016. South African droughts and decadal variability. *Natural Hazards* 80, 657-681.

Macreadie, P.I., Rolph, T.C., Boyd, R., Schröder-Adams, C.J., Skilbeck, C.G. 2015. Do ENSO and coastal development enhance coastal burial of terrestrial carbon? *PLoS One* 10(12), e0145136.

Mallinson, D.J., Smith, C.W., Culver, S.J., Riggs, S.R., Ames, D. 2010. Geological characteristics and spatial distribution of paleo-inlet channels beneath the outer banks barrier islands, North Carolina, USA. *Estuarine, Coastal and Shelf Science* 88, 175-189.

Mason, S.J., Jury, M.R. 1997. Climate variability and change over southern Africa: a reflection on underlying processes. *Progress in Physical Geography* 21, 23-50.

McGregor, H.V., Gagan, M.K. 2004. Western Pacific coral δ^{18}O records of anomalous Holocene variability in the El Niño-Southern Oscillation. *Geophysical Research Letters* 31, L11204.

Menier, D., Reynaud, J.Y., Proust, J.N., Guillocheau, F., Guennoc, P., Tessier, B., Bonnet, S., Goubert, E. 2006. Inherited fault control on the drainage pattern and infilling sequences of late glacial incised valleys, SE coast of Brittany, France. In: Dalrymple, R.W., Leckie, D.A., Tillman, R.W. (Eds*), Incised valleys in time and space*. SEPM Spec. Publ. 85, 37-55.

Meyer, R., Talma, A.S., Duvenhage, A.W.A., Eglington, B.M., Taljaard, J., Botha, J.F., Verwey, J., van der Voort, I. 2001. *Geohydrological investigation and evaluation of the Zululand coastal aquifer.* Report to the Water Research Commission, no. 221/1/01. Pretoria, South Africa.

Middelburg, J.J. and Nieuwenhuize, J. 1998. Carbon and nitrogen stable isotopes in suspended matter and sediments from the Schelde Estuary. *Marine Chemistry* 60, 217-225.

Miller D, Yates R, Jerardino A, Parkington J., 1995: Late Holocene coastal change in the southwestern Cape, South Africa. *Quaternary International* 29, 3-10.

Moy, C.M., Seltzer, G.O., Rodbell, D.T., Anderson, D.M. 2002. Variability of El Nino/Southern Oscillation activity at millennial timescales during the Holocene epoch. *Nature* 420, 162-165.

Neukom, R., Gergis, J. 2011. Southern Hemisphere high-resolution palaeoclimate records of the last 2000 years. *The Holocene* 0, 1-24.

Nichol, S.L., Boyd, R., Penland, S. 1994. Stratigraphic response of wave-dominated estuaries to different relative sea-level and sediment supply histories: Quaternary case studies from Nova Scotia, Louisiana and Eastern Australia. In: Dalrymple, R.W., Boyd, R., Zaitlin, B.A. (Eds.), *Incised Valley Systems: Origin and Sedimentary Sequences.* SEPM Special Publication 51. SEPM, pp. 264-283.

Nordfjord, S., Goff, J.A., Austin, J.A., Gulick, S.P.S. 2006. Seismic facies of the incised valley fills, New Jersey continental shelf: Implications for erosion and preservation processes acting during the latest Pleistocene-Holocene transgression. *Journal of Sedimentary Research* 76, 1284-1303.

Oertel, G.F., Kraft, J.C., Kearney, M.S., Woo, H.J. 1992. A rational theory for barrier-lagoon development. In: Fletcher, C.H., and Wehmiller, J.F. (Eds), *Quaternary Coasts of the United States: Marine and Lacustrine Systems.* SEPM Spec. Publ. 48: 77-87.

O'Leary, M.H. 1988. Carbon isotopes in photosynthesis. *Bioscience*, 328-336.

Orme, R., 1973. Barrier and lagoon systems along the Zululand Coast, South Africa. In: Coates, D.R. (Ed.), *Coastal Geomorphology*, pp. 181-217.

Orme, A.R. 1975. Late Pleistocene channels and Flandrian sediments beneath Natal estuaries: a synthesis. *Annuals of the South African Museum* 71, 77-85.

Owens, N.J.P. 1987. Natural variations in 15N in the marine environment. *Advances in Marine Biology* 24, 389-451.

Patterson, R.T. and Fishbein, E. 1989. Re-examination of the statistical methods used to determine the number of point counts needed for micropaleontological quantitative research. *Journal of Paleontology* 1, 245-248.

Perissinotto, R., Stretch, D.D., and Taylor, R.H. 2013. *Ecology and Conservation of Estuarine Ecosystems: Lake St Lucia as a Global Model*. Cambridge University Press, Cambridge.

Peters, K.E., Sweeney, R.E. and Kaplan, I.R. 1978. Correlation of carbon and nitrogen stable isotope ratios in sedimentary organic matter. *Limnology and Oceanography* 23, 598-604.

Phillips, G. W., and Marlow, K. W. 1976. Automatic analysis of gamma ray spectra from germanium detectors. *Nuclear Instruments and Methods* 137, 525-536.

Pillay, D., Perissinotto, R. 2008. The benthic macrofauna of the St Lucia Estuary during the 2005 drought year. *Estuarine, Coastal and Shelf Science* 77, 35-46.

Porat, N. and Botha, G.A. 2008. The luminescence chronology of dune development on the Maputaland coastal plain, southeast Africa. *Quaternary Science Reviews* 27, 1024-1046.

Prahl, F.G., Bennett, J.T. and Carpenter, R. 1980: The early diagenesis of aliphatic hydrocarbons and organic matter in sedimentary particulates from Dabob Bay, Washington. *Geochimica et Cosmochimica Acta,* 44: 1967-1976.

R Development Core Team 2012. R: a Language and Environment for Statistical Computing. R Foundation for Statistical Computing: Vienna. Available at: www.r-project.org/.

Ramsay, P.J. 1995. 9000 years of sea-level change along the southern African coastline. *Quaternary International* 31, 71-75.

Ramsay, P.J., Cooper, J.A.G. 2002. Late Quaternary sea-level change in South Africa. *Quaternary Research* 57, 82-90.

Richard, Y., Fauchereau, N., Poccard, I., Rouault, M., Trzaska, S. 2001. 20th century droughts in southern Africa: spatial and temporal variability, teleconnections with oceanic and atmospheric conditions. *International Journal of Climatology* 21, 873-885.

Richard, Y., Trzaska, S., Roucou, P., Rouault, M. 2000. Modification of the southern African rainfall variability/ENSO relationship since the late 1960s. *Climate Dynamics* 16, 883-895.

Schoen, J.H., Stretch, D.D., Tirok, K. 2014. Wind-driven circulation patterns in a shallow estuarine lake: St Lucia, South Africa. *Estuarine, Coastal and Shelf Science* 146, 49-59.

Sorrel, P., Debret, M., Billeaud, I., Jaccard, S.L., McManus, J.F., Tessier, B. 2012. Persistent non-solar forcing of Holocene storm dynamics in coastal sedimentary archives. *Nature Geoscience* 5, 892-896.

Stockmarr, J. 1971. Tablets with spores used in absolute pollen analysis. *Pollen et spores* 13, 615-621.

Talbot, M.R. 2001. Nitrogen isotopes in palaeolimnology. In: W.M. Last and J.P. Smol (Eds.), *Tracking Environmental Changes Using Lake Sediments: Physical and Chemical Techniques*. Kluwer, Dordrecht, pp. 401-439.

Taylor, R.H. 2006. Ecological responses to changes in the physical environment of the St Lucia Estuary. PhD thesis, Norwegian University of Life Sciences, Department of Plant and Environmental Sciences, Norway.

Taylor, R.H. 2013. Management history. In Perissinotto, R., Stretch, D.D., Taylor, R.H. (eds). *Ecology and Conservation of Estuarine Ecosystems: Lake St Lucia as a Global Model.* Cambridge University Press, Cambridge. Pp 21-44.

Thamm, A.G., Grundling, P., and Mazus, H. 1996. Holocene and recent peat growth rates on the Zululand coastal plain. *Journal of African Earth Sciences* 23, 119-124.

Thode, H.G. 1991. Sulphur Isotopes in nature and the environment: An overview. In: Krouse, H.R. & Grinenko, V.A. (Eds). *Stable Isotopes in the Assessment of Natural and Anthropogenic Sulphur in the Environment.* John Wiley & Sons, pp 1-25.

Thomas, M.A., Anderson, J.B. 1994. Sea-level controls on the facies architecture of the Trinity/Sabine incised-valley system: Origin and sedimentary sequences. SEPM Special Publication 51, pp. 63-83.

Tudhope, A.W., Chilcott, C.P., McCulloch, M.T., Cook, E.R., Chappell, J., Ellam, R.M., Lea, D.W., Lough, J.M., Shimmield, G.B. 2001. Variability in the El Nino-Southern Oscillation through a glacial-interglacial cycle. *Science* 291, 1511-1517.

Turner, S. and Plater, A. 2004. Palynological evidence for the origin and development of Late Holocene wetland sediments: Mdlanzi swamp, KZN, SA. *South African Journal of Science* 100, 220-229.

Tyson, P.D. 1981. Atmospheric circulation variations and the occurrence of extended wet and dry spells over southern Africa. *International Journal of Climatology* 1, 115-130.

Van Heerden, I.L. 1987. Sedimentation in the Greater St Lucia complex as related to palaeo sea-levels. 6th National Oceonographic Symposium, Stellenbosch.

Weber, N., Chaumillon, E., Tesson, M., Garlan, T. 2004. Architecture and morphology of the outer segment of a mixed tide and wave-dominated-incised valley, revealed by HR seismic reflection profiling: the palaeo-Charente River, France. *Marine Geology* 207, 17-38.

Webster, P. J., Holland, G. J., Curry, J. A., Chang, H.R. 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* 309, 1844-1846.

Whitfield, A.K., Taylor, R.H. 2009. A review of the importance of freshwater inflow to the future conservation of Lake St Lucia. *Aquatic Conservation: Marine and Freshwater Ecosystems* 19, 838-848.

Wiles, E.A., Green, A.N., Watkeys, M.K., Jokat, W., Krocker, R. 2013. The evolution of the Tugela canyon and submarine fan: A complex interaction between margin erosion and bottom current sweeping, southwest Indian Ocean, South Africa. *Marine and Petroleum Geology* 44, 60-70.

Woodroffe, C.D., Beech, M.R., Gagan, M.K. 2003. Mid-late Holocene El Niño variability in the equatorial Pacific from coral microatolls. *Geophysical Research Letters* 30, 1358.

Wright, C.I., Miller, W.R., Cooper, J.A.G. 2000. The late Cenozoic evolution of coastal water bodies in northern KwaZulu-Natal, South Africa. *Marine Geology* 167, 207-229.

Wright, C.I. 1995. The sediment dynamics of the St Lucia and Mfolozi estuary mouths, Zululand, South Africa. *Council for Geoscience Bulletin* 109, 61 pp.

Zaitlin, B.A., Dalrymple, R.W., Boyd, R. 1994. The stratigraphic organization of incised valley systems associated with relative sea-level change. In: Dalrymple, R.W., Boyd, R., Zaitlin, B.A. (Eds.), *Incised Valley Systems: Origin and Sedimentary Sequences.* Society for Sedimentary Geology. Spec. Publ., 51. SEPM, pp. 45-60.