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Marc Humphries
University of the Witwatersrand

Kelly Kirsten
University of Cape Town

Jemma Finch
University of KwaZulu-Natal

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Diatom-inferred hydrological changes and Holocene geomorphic transitioning of Africa's largest estuarine system, Lake St Lucia

M. Gomes [a], M.S. Humphries [b, *], K.L. Kirsten [c], A.N. Green [d], J.M. Finch [e], A.M. de Lecea [d]

[a] School of Animal, Plant and Environmental Sciences, University of the Witwatersrand, South Africa
[b] Molecular Sciences Institute, School of Chemistry, University of the Witwatersrand, South Africa
[c] Department of Environmental and Geographical Science, University of Cape Town, South Africa
[d] Geological Sciences, School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, South Africa
[e] Geography, School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, South Africa

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ABSTRACT

The diverse lagoons and coastal lakes along the east coast of South Africa occupy incised valleys that were flooded during the rise and subsequent stabilisation of relative sea-level during the Holocene. Sedimentary deposits contained within these waterbodies provide an opportunity to investigate complex hydrological and sedimentological processes, and examine sea-level controls governing system geomorphic evolution. In this paper, we combine diatom and sulfur isotope analyses from two sediment cores extracted from the northern sub-basins of Lake St Lucia, a large shallow estuarine lake that is today largely isolated from direct ocean influence behind a Holocene-Pleistocene barrier complex. 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. 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. BP. A shift in the biological community at ~4550 cal. BP is linked to the development of a back-barrier water body that supported a brackish community. Marine planktonics and enrichments in δ^{34}S suggest recurrent, large-scale barrier inundation events during this time, coincident with a mid-Holocene sea-level highstand. Periodic marine incursions associated with episodes of enhanced storminess and overwash remained prevalent until ~1200 cal. BP, when further barrier construction ultimately isolated the northern basins from the ocean. This study 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. Unlike most coastal lake systems, this system is particularly effective as an archive of geomorphological change. Systems driven by back-barrier modifications, such as Lake St Lucia, highlight how geomorphological changes driven by sediment-supply, climate and sea level can be distributed unevenly over several isolated back-barrier basins.

1. Introduction

The postglacial Holocene transgression produced a series of coastal waterbodies along the south-eastern coastline of Africa. The majority of these waterbodies evolved from fluvial systems that were drowned by rising sea levels, a process recorded in the accumulation of incised valley fill deposits that mark changes in the rate of sea level rise, together with evolving environmental conditions (Cooper et al., 2012; Benallack et al., 2016). 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 the coastal systems during the Holocene. Such proxies hold the key to unravelling complex changes in hydro-

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* Corresponding author.
E-mail address: marchump@gmail.com (M.S. Humphries).

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climate, and examining variations in freshwater inputs, regional climate and sea-level fluctuations. Furthermore, the linkages between hydro-climate and overall geomorphic functioning of these systems can be examined (e.g. Caffrey et al., 2015; Dos Santos-Fischer et al., 2016).

Lake St Lucia (Fig. 1), on the east coast of South Africa, is Africa's largest estuarine lake and forms the largest protected estuarine environment for fish, hippopotamus, crocodiles and aquatic birds on the continent (Porter, 2013). Covering a surface area of ~350 km^2, the site represents over 80% of the estuarine habitat in southern Africa, and forms part of the iSimangaliso Wetland Park, one of only two World Heritage Sites within the Indian Ocean region. Despite the importance of this system, little is currently known about the long-term development and palaeohydrology of Lake St Lucia. While a large number of ecological studies have been conducted on St Lucia (e.g. Cyrus et al., 2010; Lawrie and Stretch,

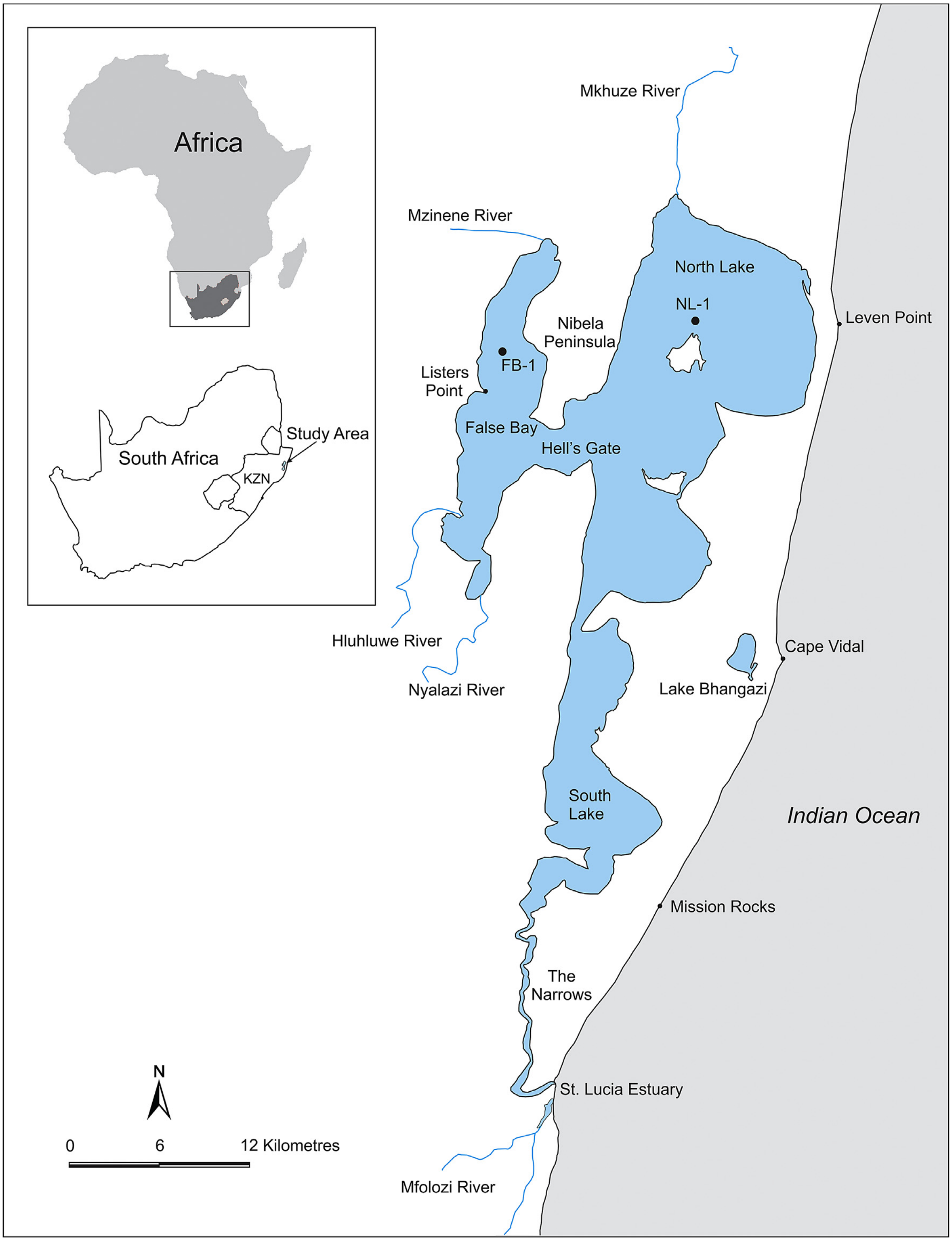

Fig. 1. Map of Lake St Lucia on the east coast of KwaZulu-Natal (KZN), South Africa, showing the location of coring sites NL-1 (15.62 m) and FB-1 (15.91 m).

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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 study 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.

2. Regional environment

Lake St Lucia is situated on the sub-tropical east coast of South Africa (28°00′26″ S, 32°28′51″ E) and comprises three interconnected basins, viz. False Bay, North Lake and South Lake (Fig. 1). The lake compartments are separated from the ocean by a 100–140 m high Pleistocene-Holocene barrier dune complex, with the only contemporary link to the ocean via an ~21 km long sinuous channel known as the Narrows. Tidal effects penetrate 14 km up the Narrows when the inlet is open (Orme, 1975), but the lake itself is not tidal. With an average water depth of ~1 m, the lake basins are susceptible to extreme changes in ecological state as a result of evaporation and variable river inflow. The system is therefore subject to extreme fluctuations in lake level and physicochemical conditions, frequently shifting between freshwater and hypersaline states. The highly dynamic nature of the system exerts strong influence on estuarine biological communities and ecosystem productivity (Cyrus et al., 2010; Nche-Fambo et al., 2015).

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 the supply of freshwater and sediment. The rivers are seasonal, flowing during the wet summer. Thunderstorms and mid-latitude cyclones are the dominant weather patterns. Rainfall varies from 1200 mm yr^{-1} at the St Lucia estuary mouth to 625 mm yr^{-1} at Listers Point, although the region is characterised by high inter-annual variability (Mason and Jury, 1997). The coast is wave-dominated. Maximum significant wave heights of 9 m and 8.5 m were experienced during Tropical Storm Imboa (1984) (Guastella and Rossouw, 2009) and a severe Cut-Off-Low (CoL) in March 2007 (Salzmann and Green, 2012), respectively. The tidal range is upper mesotidal, with a spring maximum tidal range of 1.8 m (SAN, 2016).

The present St Lucia system owes its origin to mid-Holocene flooding of river valleys incised into Cretaceous bedrock during the Last Glacial Maximum (LGM) regression, ~18–20 kyr BP (Wright et al., 2000). Seismic data reveal a complex network of buried palaeochannels that represent the lower reaches of coastal rivers that were last scoured during the LGM (Benallack et al., 2016). During the regression, sand from the exposed continental shelf accumulated along the present coastline forming the early coastal dune barrier (Wright et al., 2000). An outlet at Leven Point (Fig. 1) was maintained through much of the Late Pleistocene/Holocene transgression (Green, 2009), but ultimately sealed between ~7100 and 6200 cal. BP (Benallack et al., 2016) in response to littoral and aeolian sediment accumulation. This transformed the system from an open lagoon to an estuarine lake, characterized by shallowing, segmentation and reed swamp encroachment. Today, the coastal barrier is narrowest (~1 km wide) at Leven Point and extends ~100 m above sea level.

3. Methods

3.1. Coring

In 2014, two continuous sediment cores (NL-1, 15.62 m and FB-1, 15.91 m) were extracted from the northern basins of Lake St Lucia (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 intensive seismic-reflection survey (Benallack et al., 2016). Cores were extracted where incised valleys were deepest to maximise the recovery of undisturbed sediment. Cores were transported to the laboratory where they were split longitudinally and logged according to standard sedimentological procedures.

3.2. Radiocarbon dating

Bulk organic sediment and intact shell samples were selected for radiocarbon dating using accelerator mass spectrometry (AMS) to provide a chronology for the sedimentary packages. Analyses were carried out by Beta Analytic Incorporated, Florida, USA. Calendar calibrated ages were calculated using the Southern Hemisphere atmospheric curve SHCal.13 (Hogg et al., 2013). Bayesian age-depth models for NL-1 and FB-1 were developed using Bacon 2.2 (Blaauw and Christen, 2011; Supplementary information).

3.3. Diatom analysis

The upper 25 cm of each core was sampled at 1 cm intervals, with samples from the remainder of each sequence taken at 40 cm intervals. This resulted in a total of 75 and 74 samples from NL-1 and FB-1, respectively. 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 h intervals to remove clay particulates. Microscope slides were mounted using Pleurax and examined under a light microscope at a magnification of up to ×1000. 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 groupings within the data (Grimm, 1987, 1993).

3.4. Sulfur isotope chemistry

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‰.

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4. Results

4.1. Core chronology and lithology

The core extracted from North Lake, NL-1, intersected the last ~7600 cal. BP of sedimentary infill and is largely stratigraphically consistent (Table 1). 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. The calibrated radiocarbon ages generally display a linear relationship with depth, although the rate of sediment accumulation decreases markedly from ~2000 cal. BP to the present. The upper 12 m of the sequence comprises mostly clay dominated sediments, underlain by a basal sandy unit comprising medium to fine sand and a number of bivalve shells (Fig. 2). The FB-1 core consists predominantly of fine silt and clay (Fig. 3), with a basal radiocarbon date of ~8300 cal. BP (Table 1). Radiocarbon dating revealed a largely stratigraphically consistent record, with the exception of a single inverted age at 65 cm.

4.2. Diatom stratigraphy

4.2.1. North Lake

Based on CONISS, three zones were identified (Fig. 2) for the NL-1 record, namely NL-A (1089–689 cm; ~6500–4500 cal. BP), NL-B (649–549 cm; ~4500–4000 cal. BP) and NL-C (509–89 cm; ~4000–1300 cal. 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. BP) and LF4, from 49 cm to the surface (~1200 cal. BP – present). These periods are either devoid of fossils or are composed of frustule fragments.

4.2.1.1. Zone NL-A (6500–4550 cal. 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. BP (LP3). Marine species decline towards the low preservation zone of LP3, accompanied by rapid rises in transitional taxa, particularly *Nitzschia compressa* (Fig. 2). 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. BP, reaching a maximum of ~33%. The epipelic marine, *Petroneis marina,* occurs persistently during this stage, with greatest abundance (8.1%) at 4500 cal. BP.

4.2.1.2. 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*. Increases in the marine littoral species *Hyalodiscus radiatus* are coupled with a decline of *D. crabro* (Fig. 2). *Coscinodiscus wittianus* and the littoral zone species, *Epithemia adnata,* are prevalent during the early stages until 4400 cal. BP. Low fossil preservation occurs at ~4300 cal. BP. The eutrophic, (tyco-)planktonics *Melosira varians* and *Cyclotella meneghiniana* have notable occurrences between 4500 and 4400 cal. BP (Fig. 2).

4.2.1.3. 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 to 3750 cal. BP and again at 1450 cal. BP. The fresh-brackish taxon, *Terpsinoe musica* reaches maximum abundance at 3850 cal. BP and between 2700 and 2550 cal. BP, accompanied by the planktonic *Stephanodiscus hantzschii* which peaks at 2550 cal. BP (Fig. 2). *N. compressa,* although prevalent throughout this period, rises near the close of the zone, increasing to 31% by 1300 cal. BP.

4.2.2. False Bay

The FB-1 core was divided into three zones according to CONISS (Fig. 3), viz FB-A (1109–789 cm; 6000–4550 cal. BP), FB-B (709 -549 cm; 4550–3500 cal. BP) and FB-C (509–23 cm; 3500–530 cal. 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. BP) and LP3, from 22 cm to the surface (~500 cal. BP – present).

Table 1
Radiocarbon ages and calibration information.

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-386292	1591	Sediment	7560	30	8295-8402 (82.1%)

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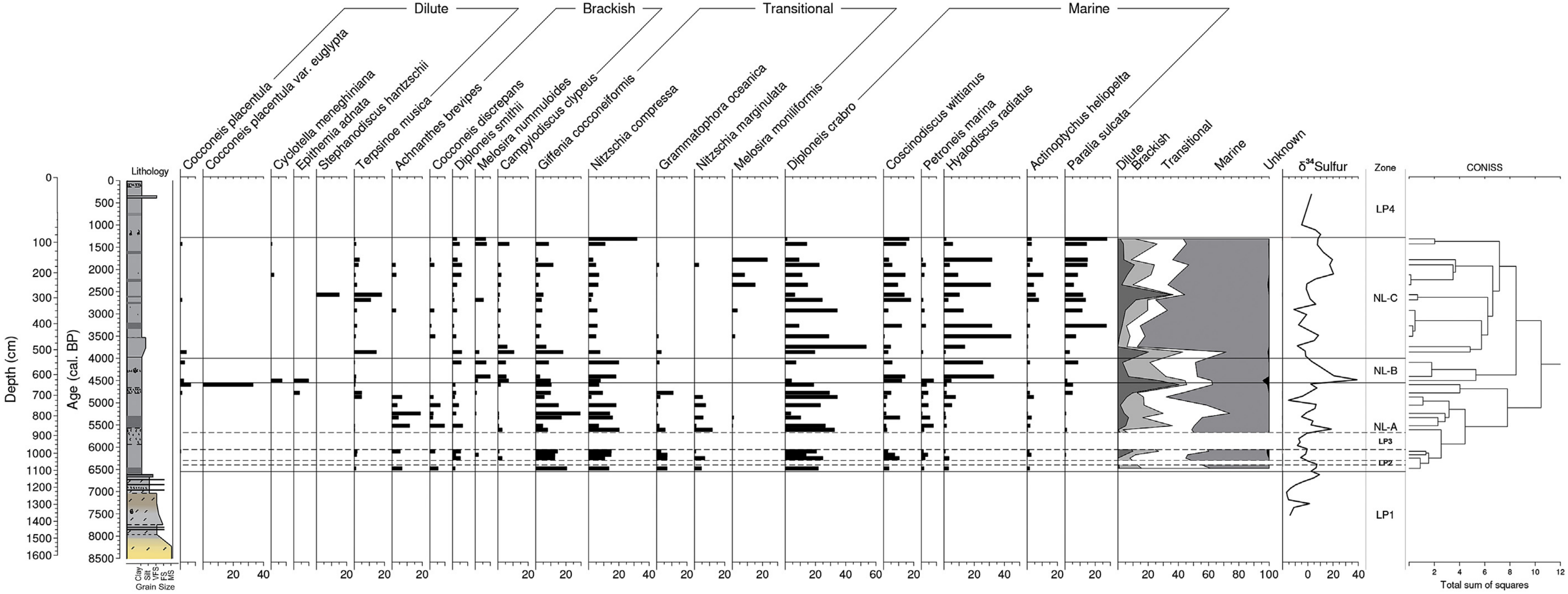

Fig. 2. Variation in lithology, δ^{34}S and relative distribution of selected diatom species from core NL-1 against depth (cm) and age (cal. BP). Depths indicated are distorted to fit the age scale. Diatom species are grouped according to their salinity preferences. Full diatom counts are provided in Supplementary information.

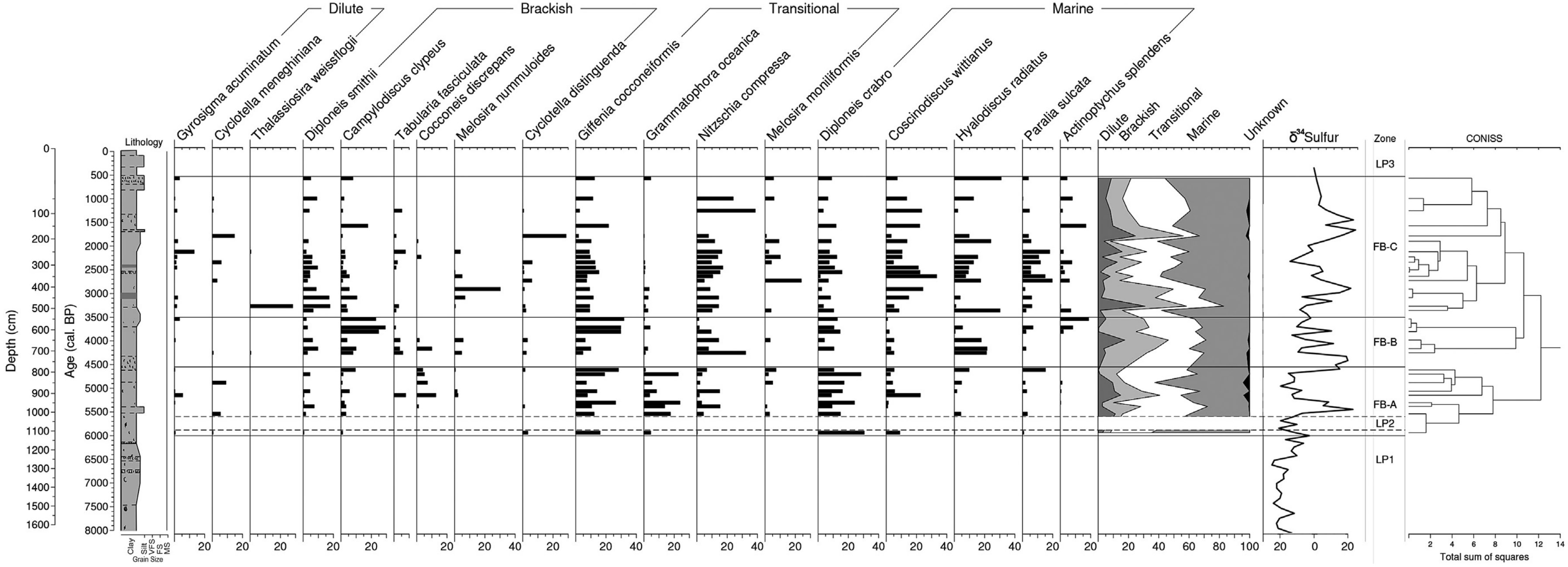

Fig. 3. Variation in lithology, $\delta^{34}S$ and relative distribution of selected diatom species from core FB-1 against depth (cm) and age (cal. BP). Depths indicated are distorted to fit the age scale. Diatom species are grouped according to their salinity preferences. Full diatom counts are provided in Supplementary information.

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4.2.2.1. 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. 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. BP with greatest (4.4%) representation at 5150 cal. BP. Dilute taxa, *C. meneghiniana*, the benthic, eutrophic *Gyrosigma acuminatum* and epiphytic *Cocconeis placentula* make notable appearances throughout the zone, particularly from 5300 to 4900 cal. BP. These species are accompanied by the brackish, epiphyte *Cocconeis discrepans* which peaks at 5150 cal. 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.

4.2.2.2. Zone FB-B (4550 - 3500 cal. BP). Following on from 4600 cal. 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 to 3500 cal. BP. Brackish taxa are well represented *with C. discrepans* and *Diploneis smithii* comprising nearly 20% of the overall community at 4150 cal. BP. A brief resurgence in the dilute, epiphytes *Diploneis elliptica*, *Epithemia adnata* and *Mastogloia densei* is observed at 4000 cal. BP. The marine, planktonic *Actinoptychus splendens* progressively increases in representation from 3800 cal. BP until the termination of the zone.

4.2.2.3. 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. BP. The brackish, benthic *Melosira nummuloides* and *C. wittianus* peak simultaneously between ~3100 and 2900 cal. BP. At ~2750 cal. BP, the marine-brackish *Melosira moniliformis* as well as *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. BP, with *C. meneghiniana* reaching a maximum of 15% at 1900 cal. BP. Fossil preservation declines at 1350 cal. BP and between 650 and 600 cal. BP. Prior to a brief period of low preservation at ~1350 cal. BP, *N. compressa* and *C. wittianus* reached a maximum of 38% and 23%, respectively.

4.2.3. 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. 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. BP in addition to experiencing extended episodes of low preservation of the diatom frustules particularly prior to ~6000 cal. 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*.

4.3. Sulfur isotope chemistry

Sediment δ^{34}S values are highly variable, ranging between −16.6 and +38.6‰ in NL-1 (Fig. 2), and between −24.7 and +24.7‰ in FB-1 (Fig. 3). 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 δ^{34}S enrichments in both the NL-1 and FB-1 records are evident. These enrichments occur at ~5500, 4500 and 1800–1400 cal. BP, and show δ^{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.

5. Discussion

5.1. Hydrological reconstruction

The cores extracted from the North Lake and False Bay basins document the most recent cycle of sedimentary infilling 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 (Fig. 1; Benallack et al., 2016). Poor diatom preservation, numerous fragmented frustules, and reworked shells distributed throughout the sand matrix in lower part of the core, provide evidence for an environment that was subject to tidal current reworking. Similar biostratigraphical observations have been made in other shallow coastal environments subjected to strong tidal currents and sea level fluctuations (Zong, 1997; Bak, 2015). A shift from marine sand to silt-dominated sedimentation at ~6200 cal. 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 (Fig. 4a). The transition to low-energy conditions appears to have occurred earlier (prior to 8300 cal. BP) in False Bay, an observation that is explained by its relatively sheltered landward position (Benallack et al., 2016).

The diatom assemblages from North Lake and False Bay reveal a system which was structured by the influx of marine waters (Fig. 4). From the initiation of the records until ~4550 cal. BP, marine water intrusion and occurrence of marsh and tidal flat habitats is indicated. The appearance of several diatom taxa restricted to brackish and fresh waters coincident with marine species suggests mixing between fluvial and marine sources under a relatively low energy environment. This is supported by the draped, low amplitude seismic reflectors associated with this interval, representative of low energy sedimentation (cf. Benallack et al., 2016). The zones of low preservation observed in both core records may be attributed to high energy events associated with barrier inundation (e.g. Matias et al., 2008) or wind generated turbulence. This is supported by δ^{34}S sedimentary data which suggest the periodic input of marine derived organic material. The dominance of benthic species in both basins suggests a relatively shallow water environment persisted prior to 4550 cal. BP.

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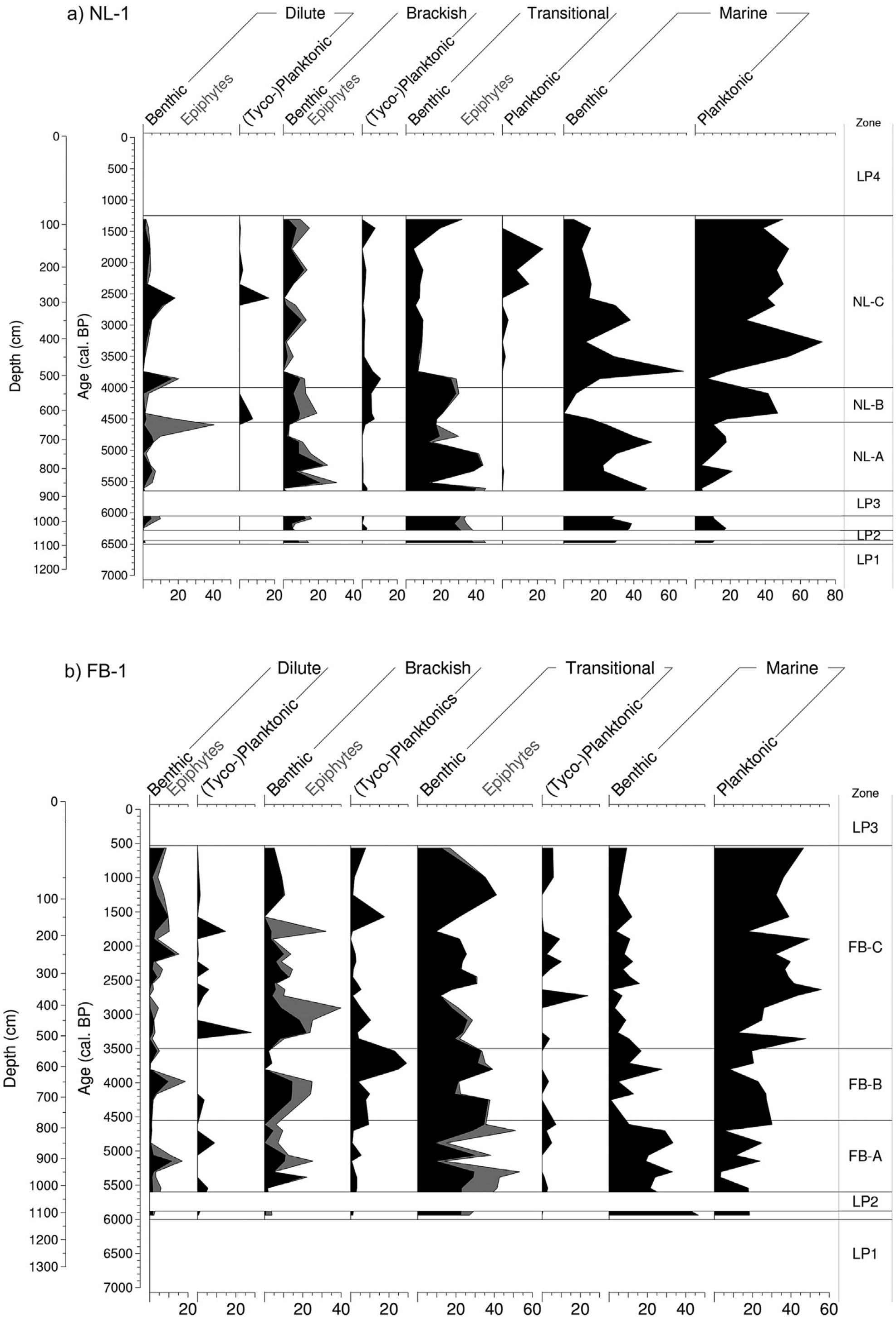

Fig. 4. Summary classification of diatom species found in core a) NL-1 and b) FB-1 based on salinity preferences and habitat.

A shift in the biological community at ~4550 cal. BP signals the transition 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 to 3500 cal. BP (Fig. 4). This transition is evident in both NL-1 and FB-1, and points to the establishment of a back-barrier waterbody associated with the impoundment of water behind an increasingly emergent barrier at Leven Point. In NL-1, this coincides with a distinctive increase in freshwater assemblages ~4700-4500 cal. BP, associated with the impoundment of riverine inflows. The input of nutrient-enriched, freshwater supported a habitat favourable for a brackish community. Marine influences begin to decline from ~3500 cal. BP. This was likely driven by further accretion and stabilisation of the barrier at Leven Point, which limited the frequency of wash over and inundation events. The marine group are dominated by planktonics, which are easily transported and point to intermittent seawater intrusions into the system rather than complete barrier inundation or transgression. This is further

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supported by periodic enrichments in $\delta^{34}S$, which likely reflect the input of marine derived sulfate. Warm water marine species typify the assemblages, consistent with the nature of the Agulhas current, although cool water taxa, particularly *P. sulcata*, show peaks in distribution from 3250 cal. BP onwards in North Lake and between 2650 and 2100 cal. BP in False Bay. The likely origin of these cold water species may be the Cape St. Lucia upwelling cell (Roberts and Nieuwenhuys, 2016), suggesting a period of greater activity in upwelling along the coast at this time. Both basins reveal the presence of mixed diatom communities, suggesting an environment characterised by high salinity variability, with appreciable water exchanges occurring between the basins. Discrepancies between records, particularly in the abundance of marine species, are attributed to the proximity of the two sites to Leven Point, with overwash and intermittent seawater intrusion exerting greater influence at NL-1. Low fossil preservation at the top of both cores may point to periods of desiccation (Humphries et al., 2016) or frustule fragmentation caused by wind-induced turbulence or deflation, as the gradual shallowing of the basins proceeded. Issues related to the poor preservation of diatoms in shallow lake environments have been noted by several other authors (e.g. Dong et al., 2008; Bennion et al., 2010). 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.

5.2. 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 (NL-1).

5.3. 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. BP. Infilling of the basin was initiated when deglacial sea-level rise slowed and stabilised around present day levels (Fig. 5). 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. BP (Ramsay, 1995, Fig. 5).

5.4. Mid-Holocene highstand

Our sedimentary records indicate a change to low energy conditions consistent with barrier growth and inlet closure at ~6200 cal BP (Benallack et al., 2016). 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., 1995; 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. BP (Ramsay, 1995). Co-incident 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).

5.5. 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. BP (Fig. 5). 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 gradual declining water levels and shrinking of area of St Lucia in response to declining sea-levels (Botha et al., 2013). Periodic marine incursions associated with storm surges and overwash, remained prevalent until at least ~1200 cal. 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. 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 filled 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.

This study highlights the effect isolated back-barrier basins can have on litho- and biostratigraphic successions of coastal water-bodies. The long-term persistence of a fronting barrier (Benallack et al., 2016), apart from the intermittent connection via barrier inundation at Leven Point, makes this system particularly effective as an archive of geomorphological changes. The sheltering effects of a long-lived barrier have buffered the system from protracted erosion by oceanic ravinement during rising sea levels (Benallack et al., 2016). Major changes in the system are, to a far greater extent, driven by extreme climatic fluctuations over the last 2000 years, especially desiccation cycles linked to El Niño events (Humphries et al., 2016), or by local system modifications, e.g. segmentation. False Bay in particular displays a sensitivity to back-barrier geomorphic change that appears to be missing from other similar studies from the US East Coast (Mallinson et al., 2010), Brazil (Dos Santos-Fischer et al., 2016), and the southern coast of South Africa (Cawthra et al., 2014). The additional shelter afforded by the rocky headlands of Nibela Peninsula predisposes this area to a particular sensitivity towards reconfigurations of the lake margin by segmentation, evaporation and increased volumes of fluvial

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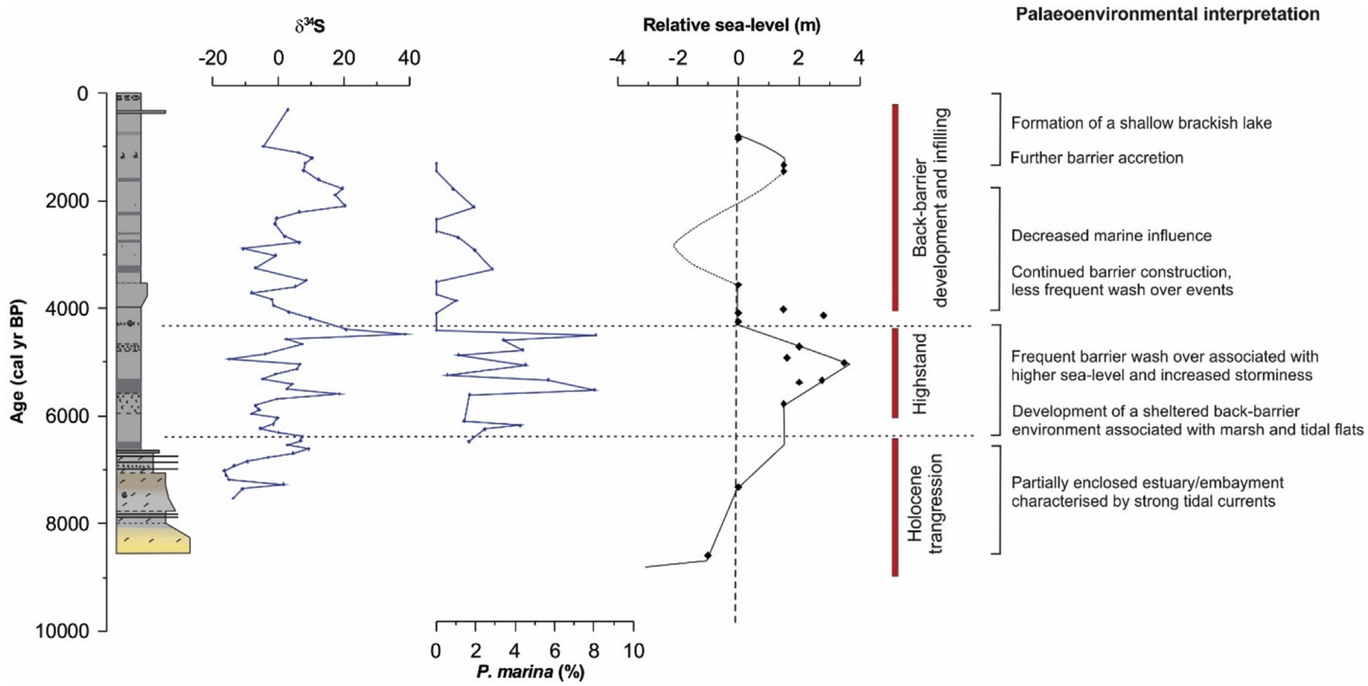

Fig. 5. Palaeoenvironmental evolution of Lake St Lucia based on sedimentological, geochemical and diatom indicators from core NL-1. Sea level curve from Ramsay (1995), data have been calibrated using ShCal13.

sediment supply. Differential responses to the main geomorphic drivers are thus observable between each isolated basin and provide a clear, distal-proximal evolutionary pathway. Discrimination between sediment-supply driven changes (extra sheltered bayhead deltas areas), climate cycles (the entire area) and sea level (the more proximal areas nearest the palaeo-inlets) can thus be made. These are distributed unevenly over several isolated back-barrier basins.

6. Conclusions

The evolution of Lake St Lucia has been strongly influenced by changes in relative sea-level and geomorphic processes over the mid-to late Holocene. Systematic changes in 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 with St Lucia over the last ~6000 years. Caution should be exercised in interpreting climatic records obtained from similar systems where geomorphic overprinting either completely or partially masks evidence of independent climate change.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.ecss.2017.03.030.

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