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BEACH RIDGE SETS REFLECT THE LATE HOLOCENE EVOLUTION OF THE ST LUCIA ESTUARINE LAKE SYSTEM, SOUTH AFRICA

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ABSTRACT

Sets of sandy beach ridges and intervening swales define shoreline sections of the shallow St Lucia wetland system within the iSimangaliso Wetland Park, World Heritage Site in northern KwaZulu-Natal province, South Africa. The sets comprise 3–10 beach ridges, the most prominent being 80-150 m wide and rising 0.5-2 m above the adjacent swales. The highest beach ridge crests elevated 3.2–4.6 m above mean sea level are furthest from the present shoreline and the lowest ridges, rising about 0.5 m above the swales, occur closest to the present mean lake level shoreline. This investigation assesses the genesis of the sandy beach ridges on five strand plain remnants within the estuarine lake. The ridges were topographically surveyed and their ages estimated using optically stimulated luminescence (OSL) dating.

OSL dating reveals that the oldest beach ridge formed around 6,240 years ago, with a sequence of beach ridges having accumulated during the period ~4,000 to 1,500 years ago reflecting coeval accretion around the lake. The present mean lake level shoreline was only reached within the past ~600 years. Sedimentation changed from marine-dominated to lacustrine deposition in the estuary during the period of beach ridge accretion.

The dated beach ridges, supported by new radiocarbon dates of fixed biological indicators from Holocene intertidal zone settings on the coast, are used with published sea-level curves to set the context of periodic beach ridge accretion in the marine-linked estuarine lake. The dated ridges suggest that episodic regression of the estuarine lake shoreline occurred after a mid-Holocene sea-level highstand. The record of sea-level change is also reflected by the long-term natural shrinking and shallowing of the proto-St Lucia lagoon/estuarine lake in the context of reduced marine influences due to closure of former marine channels by progressive barrier dune accretion. The sequence of coeval beach ridges reflects a pulsed lowering of relative sea-level in the shallowing estuarine lake. Height differences between the coeval ridges at sites around the lake reflect local environmental controls including the range of wind fetch distances across shallow lake compartments, wave height and wind-induced seiche effects.

1. INTRODUCTION

The Maputaland coastal plain stretches north from St Lucia estuary into the Maputo Bay area of Mozambique, representing the southern extent of the southeast African coastal plain (Bruton, 1980). The morphology of the Maputaland coastal plain evolved over several million years of dune accretion and remobilisation linked to climate change and groundwater table level fluctuations (Grundling, 2004, Porat and Botha, 2008). The variably weathered dune sands, groundwater seepage-fed rivers and lakes, unique vegetation patterns and biodiversity are conserved within the iSimangaliso Wetland Park, a UNESCO World Heritage Site and RAMSAR Wetland of International Importance (Whitfield at al., 2013).

A unique aspect of the coastal lakes within the region is the sets of 3–10 shore-parallel, concentric or slightly oblique sand ridges raised above the margins of St Lucia lake (Orme, 1973, 1974; Hobday 1979; van Heerden, 1987; Wright, 2002). These low sand ridge and swale patterns form broad strand plains, composite spits or barrier berms isolating tributary streams or wetlands (Figs. 1, 3-7). The asymmetrical ridges have slightly steeper slopes on the lake shoreline side and are elevated 0.5 to ~4.6 m above the present mean lake level shoreline.

Similar beach ridge/swale patterns on strandplains have been described from numerous littoral marine or lacustrine settings where the temporal aspects of beach ridge accretion have been recorded. The strandplains comprising numerous, closely spaced beach ridges around the Great Lakes of Canada and USA reflect rapid development of beach ridge sets over timeframes of several decades. Ridges aggrade during lake-level highstands with increased sediment supply and prograde when water levels stabilize lakeward during the fluctuations (Thompson and Baedke, 1995; Johnstone et al., 2007). On the Mediterranean coast of Spain, Goy et al. (2003) describe beach ridges spanning the period from the early to late Holocene with high rates of ridge set accretion over decadal periodicities, related to a relative mean sea level that did not exceed +1.3 m. On the Atlantic coast of Spain, Zazo et al. (1994, 2008) dated grouped ‘sets’ of beach ridges, separated by wide swales that form coastal spits at river mouths where littoral drift associated with storms supplies sediment and spit progradation. Ridge accumulation since the early Holocene (cf. 6900 yr BP) was related to short-term sea-level rise associated with climate change, with accretionary beach ridge set units, comprising numerous beach ridge couplets formed over decadal timeframes, that accumulated during episodes with 1400–300 year cyclicity, separated by periods of swale development (Zazo et al., 2008). In the context of the low wind- and wave energy coastline of Rockingham Bay, north Queensland, Australia, Forsyth et al. (2010) attributed the formation of a sequence of 19 shore-parallel beach ridges rising up to 5.5m above mean sea level to tropical cyclones that can generate significant wave heights and storm surges. Despite the shoreward-younging succession, falling sea level was regarded as unlikely to have been a principal driver controlling the elevation of ridge crests across the beach ridge plain over the past 5000 years.

The St Lucia ridges conform to the definition of beach ridges (Hesp, 2004) that include swash aligned, swash and storm wave built deposits or ridges formed of sand, pebbles, cobbles and gravel at or above the normal spring high tide level. Beach ridge growth from a submerged longshore bar, spit or emergent points influenced by swash action during the high tide and the possible addition of an aeolian cap are genetic considerations for interpreting beach ridge formation as described by Evans (1942), Tanner (1995) and Hesp (2004).

This investigation into the distribution, morphology, sedimentology and age of the St Lucia estuarine lake beach ridges aims to elucidate their formation and assess their value in defining an environmental and chronological framework for the Holocene development of the estuarine lake. Like many estuaries along the microtidal South African coast which is a high energy, swell-dominated environment (Cooper, 2001) the St Lucia system shows temporal modification from the Last Interglacial, marine embayment (Wright et al., 2000; Wright, 2002) to a probable tide-dominated system during the early Holocene. The change in morphodynamics affecting the proto-St Lucia lagoon follows the modification of a tidal current and prism dominated system to river-dominated sedimentation (Cooper, 1994, 2001).

The key question to be addressed is to what extent the sequence of raised beach ridges represents estuarine shoreline accretion in response to relative sea-level change. Local environmental effects consider include wind fetch, wave action and seiche. The possible influence of climatically driven lake level fluctuation and flooding in response to catchment discharge, alternating with periods of lowered lake level or even desiccation during long droughts, are factors that must also be considered. Estuary and lake shorelines, combined with records of lake bed sedimentation and regional relative sea-level records, hold the potential for constructing a geochronological framework of Holocene environmental change in the system.

OSL dating was undertaken on the sequence of beach ridges in five sites around the estuarine lake shoreline (Fig. 1). The age distribution and relief of the beach ridge sets, supported by new dated sea-level index point, is compared with published Holocene relative sea-level curves for the eastern coast of South Africa (after Ramsay, 1995, 1996, Compton, 2001, 2006, Ramsay and Cooper, 2002, Botha et al., 2013). The depositional context is supported by St Lucia lake sedimentation records (Benallack et al., 2016, Humphries et al., 2016) and the geochronological framework of dune formation pulses against the coastal barrier and sand remobilization on the coastal plain (Porat and Botha, 2008). The interpretation can be evaluated against palaeo-environmental records from lacustrine settings in the adjacent Mfabeni fen (Baker et al., 2014) and nearby Lake Eteza (Neumann et al., 2010).

The long-term impacts of sea level on the progressively shallowing, compartmentalized lake and the local environmental influences on beach ridge construction within the young, dynamic system is a crucial consideration in the holistic environmental management of the sensitive shoreline environments in this protected ecosystem.

2. PHYSICAL ENVIRONMENT OF THE ST LUCIA ESTUARINE LAKE SYSTEM

The iSimangaliso Wetland Park includes the St Lucia wetland is the largest estuarine system on the African continent (Begg, 1978; Cowan, 1993). Situated on the southern Maputaland coastal plain, the St Lucia wetland complex currently spans a length of ~58 km from 27° 45’S to 28° 23’S. The lake is compartmentalized into the North Lake (including Tewate Bay) with False Bay in the west and South Lake that includes Makakatana Bay or Catalina Bay (Fig. 1). The main water body extends over 42 km from the paludal “northeastern shallows” or “Selley’s lakes” to South Lake. False Bay is ~16 km long by 2–4 km wide. The surface area and form of the shallow lakes changes according to water level and spits form constrictions along the shoreline that segment the wetland into several basins particularly during periods of low water level. The estuarine lake is subject to fluctuating water levels and salinities due to variable annual rainfall and inflow from the catchments feeding the lake (Kriel et al., 1966, Taylor, 2006, 2013), groundwater seepage that buffers the lake salinisation effect from evaporation during dry periods (Taylor et al., 2006) and marine inflow influenced by over 80 years of engineered management of the estuary mouth and link to the Mfolozi River.

Long-term lake level monitoring has revealed a fluctuation range from a maximum weekly average of 0.97 m to the minimum average level of –0.43m relative to the estuary mean level which is +0.25 m relative to mean sea level (msl) (Kriel, 1965; Taylor, 1982a). The Indian Ocean high microtidal or low mesotidal range is at most 2.1 m at equinox spring tide near the estuary mouth (Connell and Porter, 2013) although very limited tidal influence occurs towards the upper section of “The Narrows” channel some 14 km from the sea (Taylor, 1982a; Wright, 1995).

The estuarine lake system has some 347 km of shorelines and is fed by five main rivers, the Mkhuze, Hluhluwe, Mzinene, Nyalazi and Mpate River catchments covering 7575 km^2, which contribute erratic seasonal runoff (Stretch and Maro, 2013). With the exception of the Mpate River, the rivers supply a high load of suspended silt and clay which flocculates when fresh river water mixes with the saline lake water. The shallow system has a large surface area to volume ratio and is sensitive to rainfall gains and evaporation losses (Perissinotto et al., 2013) which displace the lake shoreline laterally over considerable distances within the shallow lake basin. The estuarine lake level can rise by 1 m during floods when the area reaches 417 km^2, shrinking to just 225 km^2 during droughts (Fortuin, 1992) and losing 80% of its surface area during extreme conditions influenced by a combination of estuary mouth closure and the engineered separation of the Mfolozi River.

Prevailing winds with speeds greater than 4 ms^{-1} are predominantly from the northeast and southwest (Schoen et al., 2014) and create circulation patterns characterized by shallow water downwind jets along the shoreline and deeper water counter-flows interlinked by circulatory gyres. Northerly to northeasterly winds dominate the December wind rose while in July there is a bidirectional split between southerly and northerly winds. The southwesterly to southerly winds occur less frequently than the northerly winds but are stronger (Cooper et al., 2012; Stretch et al., 2013). The north-south lake axis parallels the prevailing winds (see wind rose in

Fig. 1) which generate circulation and vigorous turbulence in the system. Wind-induced wave growth depends on the prevailing wind speed, fetch and duration that the wind blows.

Presently the water depth is a limiting factor for wave development as once wave height and wavelength become influenced by the bottom, wave growth becomes ‘depth limited’, particularly during periods of low water levels. Waves on the lake have a short wave length due to the shallow water and the wave amplitude is greatest where the fetch is longest, hence the greatest wave energy is at the northeasterly and southwesterly ends of the main water compartments. The eastern shorelines are less turbid due to the sandy aeolian sand substrate than the western shoreline which have siltstone substrate and are sites of confluences of the main fluvial inputs (Fig. 1). Strong winds can result in meteorological tides (seiches) or wind set-up currents when piling of water at the northern end of the lake during a southerly wind can cause water levels to rise 0.3–0.43 m (Begg, 1978) or 0.5 m in a few hours (Taylor, 1982b, 2006, Schoen et al., 2014). Constrictions in the segmented lake such as the narrow channel at Fani’s Island impart hydraulic control and have the effect of the lake basins behaving nearly independently (Schoen et al., 2014).

2.1 Geological evolution and sedimentation

The St Lucia lake basin is the product of short glacio-eustatic marine incursions during the Plio-Pleistocene with the long intervening periods characterized by fluvial channel incision in response to lowered base level during marine regression events that were accompanied by mobilization of dunes around the lake (Botha et al., 2013). Differential erosion of the low-lying Pleistocene dune landscape of the Eastern Shores relative to the Cretaceous and Neogene bedrock ridge topography of the western shores strongly influenced lake development. The unconsolidated, raised Holocene sand beach ridge strand plains are readily distinguished from the products of preceding marine incursions (Hobday, 1975; Ramsay, 1996, Cooper et al., 2013).

The late Neogene Uloa Formation littoral marine deposits unconformably overlie Upper Cretaceous marine siltstone above ~10 m msl on the cliffed Western Shores and False Bay shorelines of Nibela and Ndlozi peninsulas. On the Maputaland coast there is no evidence of the raised shoreline deposits from the prolonged MIS 11 sea-level highstand at +14 m msl (Roberts et al., 2012). The MIS 5e highstand that deposited sediment at +6.2 m above msl (Roberts et al., 2012) inundated the St Lucia basin to form a marine embayment and offshore barrier island, similar to the Bazaruto or Inhaca island archipelagos in Mozambique (Wright, 2002). The ancient barrier island extended south of Cape Vidal to First Rocks, forming a seaward dune barrier comprising several ages of Isipingo Formation aeolianite accreted against older Kosi Bay Formation aeolian sediments (Botha and Porat, 2007; Porat and Botha, 2008). The bioclastic conglomerate platform exposed along the western shore of False Bay (Hobday, 1975, Cooper et al., 2013) and barnacles within the lower Mzinene River valley (Ramsay and Cooper, 2002), provide evidence of the broad Last Interglacial open-water marine lagoon. The undulating coastal plain forming the Eastern Shores comprises terminal Pleistocene to early Holocene dunes (Wright et al., 2000; Wright, 2002; Botha et al., 2003, 2007; Porat and Botha, 2008). Remobilization of the dune landscape led to the development of complex patterns of northward-migrating parabolic dunes inland of the present composite coastal barrier from ~12 ka to ~7ka, corresponding to the period after which rising groundwater table encouraged peat deposition in the Maputaland interdune wetlands (Thamm et al., 1996; Grundling et al., 1998).

The record of Holocene sedimentation in St Lucia, the Mkhuze River and Mfolozi River/Lake Eteza estuarine system that were modified by the Holocene marine incursion and subsequently by fluvial erosional processes associated with marine regression events has been recorded by Turner and Plater (2004), Grenfell et al. (2010), Neumann et al. (2010); Benallack et al. (2016), Humphries et al. (2016) and Gomes et al. (2017). Sediment probes, core borehole drilling and seismic profiling have revealed the thickness of the proto-lake deposits and delineated bedrock valleys beneath the bed of the St Lucia waterbody. A channel system up to 40 m deep was mapped by Hill (1975), Van Heerden (1987) and Sydow and van Heerden (1988). Recent high resolution seismic profiling by Benallack et al (2016) mapped a more intricate network of narrow channels incised into bedrock mapped that have been correlated with the long-lived marine channel that linked the proto- North Lake with the sea near Leven Point (Fig. 2).

The age of raised beach ridge sets must be seen in relation to the shallowing of lake depth and relative sea-level change during the Holocene as indicated by the changes from the tide-dominated lagoonal environment to lacustrine sedimentation in a river-dominated system (Cooper, 1994, 2001) reflected by the dated channel infill sediment from boreholes described by Kriel et al. (1966), van Heerden (1975) and recently by Benallack et al. (2016), Humphries et al. (2016) and Gomes et al. (2017). The impact of Holocene sea-level change on the low-lying Maputaland coastal zone had a profound influence on the systems' marine linkage. St Lucia is cited by van Heerden (1987) and Orme (1990) as an example of an open lagoon created by the early Holocene transgression that has since been largely transformed into a wetland after 5,000 years of sedimentation, segmentation and reed-swamp encroachment. The beach ridge strand plain remnants represent the more expansive St Lucia proto-lagoon which Orme (1975, 1990) speculated at the mid-Holocene highstand occupied an area of 912 km^2 and together with 253 km^2 of the inundated lower Mfolozi River wetland covered a total area of 1165 km^2, extending 112 km parallel with the coastline. Lake St Lucia was up to 40 m deep (Fig. 2) but is today a shallow lagoon averaging 0.9 m deep covering 350 km^2 (Orme, 1990; Taylor et al., 2006) due to sediment infilling. The interdune Mfabeni fen wetland preserves peat deposits that have yielded a long-term palaeo-environmental change record in the Eastern Shores area (Thamm et al., 1996; Grundling et al., 1998, 2013; Finch and Hill, 2008; Baker et al., 2014, 2017).

Late Pleistocene Isipingo Formation aeolianite forming the upper part of the coastal barrier core (Porat and Botha, 2008) is exposed as coastal cliffs and rocky intertidal zone promontories where deposits representing late Holocene raised sea-levels have been dated. Episodic accretion of the forested coastal barrier dune, locally up to 159 m high, played a critical role in the isolation of coastal wetlands from the Indian Ocean shore. The western retention ridges of the Sibayi Formation barrier dune ridge are formed by successive accretion of ascending parabolic dunes at ~8,100, 6,600, 5,700–5,100 and 2,300 years BP (Porat and Botha, 2008).

3. MATERIALS AND METHODS

The distribution of the sand ridge sets studied is depicted in Fig. 1 and Figs 4-8. The Makakatana, Sengwane and Meme sites are situated around the southern, north-central and northeastern sections of the Eastern Shores. The ridges generally parallel the present lake shoreline but slight changes in concentricity of the curvature of successive ridges record a shrinking of the lake basins. The KwaMbonjane ridges isolate a tributary on the northern shores of False Bay and a beach ridge extending west from the Meme set, partially isolates the Mkhuze River delta at its confluence with the northeastern shallows. The site descriptions are supported by topographic ridge crest profiles surveyed using a dumpy level (Figs 4–8). Differential GPS elevation readings taken on a ridge crest along each of the traverse lines were used to correct the traverse elevations relative to mean sea level.

The ridge crests were sampled along the surveyed traverse line using an Eijkelkamp bucket auger. Samples for optically stimulated luminescence (OSL) dating (Duller, 2004) were taken from the mid or lower part of the ridges to avoid bioturbation effects or possible aeolian reworking of the ridge crests. The sample to be dated was retrieved from below a plastic tube-lined section of the auger hole using a narrower auger bit to avoid contamination from sediment falling into the base of the augered hole. Samples were retrieved from the auger bit under a black plastic sheet and contained in opaque black plastic sample bags. An additional sediment sample was collected from each sampling depth for moisture content and dose rate measurements.

The Sengwane ridges samples were processed and measured at the luminescence dating lab in Aberystwyth and at the Geological Survey of Israel (GSI). In each laboratory quartz was extracted using routine procedures (Rodnight et al., 2005; Faershtein et al., 2016). Equivalent dose (D_e) values were measured in both laboratories using the single aliquot regenerative (SAR) dose protocol (Murray and Wintle, 2000) with a range of pre-heats to determine a preheat plateau (Fig. 3). Dose recovery tests were carried out on representative samples from each site. Alpha and beta dose rates for all samples were calculated from the concentrations of radioactive elements K, U and Th in the sediments, measured at the GSI. U and Th were measured by inductively coupled plasma mass spectroscopy (ICP-MS) and the K content measured by ICP-atomic emission spectroscopy (ICP-AES). Gamma dose rates were measured *in-situ* in the sampled horizon using a portable Rotem P-11 gamma scintillator with a 2-in sodium iodide crystal, calibrated to measure cosmic rays (Porat and Halicz, 1996). Where this was not possible, the gamma dose was calculated from the concentrations of the radioactive elements and the cosmic dose was estimated from the current burial depth. Moisture contents were either measured on the sediment samples or estimated (Table 1).

The quartz extracted from the St Lucia beach ridge samples has a bright OSL signal dominated by the fast component (Fig. 3). Dose recovery results are all within 5% of unity (Table 1), indicating that the SAR protocol can adequately correct for sensitivity changes taking place in the quartz during the measurement cycles. Recycling ratios overall within 10% of unity support the suitability of the SAR protocol for measuring the D_e. Pre-heat plateaus over a range of temperatures imply that the measured OSL signal is thermally stable.

Two samples were collected from the modern beach, one at Makakatana (MAK-mod) and one at Sengwane (SNG-mod). These gave De values very close to zero, equivalent to an age of ~15 years, demonstrating that the sediments in this environment are well bleached at deposition.

4 RESULTS

4.1 Makakatana

In the South Lake, the Makakatana shoreline extends 500m across the southern part of Catalina Bay (Figs. 4 a-c). The undulating strand plain, about 1300,m, wide terminates against the confluence of ‘The Narrows’ channel with the southern margin of Catalina Bay.

The broad promontory comprises seven distinct, laterally continuous sand ridges separated by poorly drained swales with a clay substrate. A reed swamp separates the Plio-Pleistocene red dune sand ridge footslopes from the forested Mak5 sand ridge which rises to 3.19,m above msl, elevated 1.2,m above the adjacent landward swale. The composite ridge defines a concave embayment shoreline curve in the west and midway along the ridge, an angular inflection towards the south defines an older embayment. Towards the east this section of ridge Mak5 is split into two ridges separated by a shallow swale. Ridges Mak4, 3, 2 are of similar height, around 1.92–2.,1m msl, and rise 0.47–0.7,m above the swales which are at 1.35,m msl. The lowest ridge, Mak 1 reaches 1.47 m and is backed by a swale at 1.08,m msl. The Mak1 ridge and recent grassed foredunes close to the mean lake level shoreline are breached locally by incised channels that drain higher lying swales. Adjacent to the lake the inter-ridge swales are colonized by salt marsh vegetation whereas the elevated swales inland support grasslands and fresh water wetland environments.

4.2 Meme wetland

The palustrine northeastern margin of the North Lake is defined by a set of low sand ridges that isolate the Meme swamp in the Dotsheni area. This reed-swamp has been encroached upon from the northeast by the transgressive coastal barrier dune and is flanked in the west by a hummocky dune complex (Figs. 5a-d). The strandline ridges can be traced for over 10 km northwestwards to a point where a complex of split ridges extend 3 km westward across the confluence of the Mkhuze River with the main lake.

The highest ridge, Dot2, is 80 m wide and reaches an elevation of 3.24 m relative to the Meme swamp base level which lies at, or just below, mean sea level. It is separated by a 140 m-wide swale from the slightly lower Dot1 ridge which rises to 3.11 m and is fronted by a low ridge up to 1.2 m high. The local base level of the lake bed is slightly lower than other points in the lake system suggesting that this area is close to the possible location of the former marine connection channel near Leven Point (Figs. 1, 2).

4.3 Sengwane

The Sengwane peninsula extends west of the forested coastal barrier which is at its narrowest and youngest along this shoreline. The strand plain comprises six slightly obliquely arranged, forested or grass-covered sand ridges, separated by reed swamp or hygrophilous grassland swales. The ridges, Sng1-6, have been truncated by erosion of the north–south aligned Eastern Shores shoreline (Figs . 6a-d).

The prominent, forested Sng4 ridge is over 120 m wide with a narrow ridge, Sng4b, welded onto its southern margin. The main ridge abuts obliquely against the low NNE-SSW trending coastal plain dunes and flooded interdune areas that lie at the foot of the prograding transverse coastal barrier dune. The shorter, narrow ridges to the south of Sng4b, numbered Sng1–3, extend obliquely into a shallow wetland depression. Grass covered sand ridge Sng1 is a very low feature reaching 1m above the lake shore and ridge Sng3 is a short, discrete ridge about 0.5 m high. Sng1 lies oblique to the Sng2 and 3 ridges and probably separated the former embayment before being truncated by present shoreline erosion.

Ridge Sng5 lies parallel to the Sng4/4B ridge but the eastward extension has been truncated by the slightly oblique development of narrow ridge Sng6 and a series of slightly oblique younger shoreline ridges that define changes in the embayment curvature suggestive of a reducing diameter (Fig. 6b).

4.4 KwaMbonjane

A series of three low sand ridges extend across the 400 m-wide embayment where the KwaMbonjane tributary stream discharges into the northern shoreline of False Bay (Figs. 7ad). The youngest ridge (Nib1, +2.26 m msl) is separated by a narrow swale (+1m msl) from the most extensive ridge (Nib2, +3.18 m msl). The Nib1 ridge has a well-defined asymmetrical profile with lower gradient slopes on the lake side flank. A section through the composite ridge Nib2 is exposed in sand excavation pits (Figs. 7c, d). The profile comprises light grey sand with weakly developed textural lamellae that buries slightly more cohesive sand at a depth of ~2 m. The composite sand ridge rises to +4.61 m msl at the crest of Nib3 ridge inland.

4.5 Lake Bhangazi (south) sand barrier

The lake is fed by seepage from the coastal barrier dunes and overflow from the Mfabeni swamp (Figs. 1, 8). The southwestern shoreline is defined by a steep sand berm that rises to over 8 m msl and separates the lake from the Mfabeni reed swamps to the south with an overflow point at each end. The berm was augered and sample Bzi-1 dated to ascertain whether this feature was active during the same period as the main lake shorelines and to confirm the age relationship between berm accretion and progradation of the high coastal barrier dune.

4.6 Sediment characteristics

Apart from a thin granule to pebble gravel bed within the base of the high MAK5 ridge at Makakatana , all the beach ridge profiles analysed comprise predominantly medium- and fine-grained sand with a similar sand grain-size distribution through each ridge profile.

The Sengwane ridges are the coarsest textured with a mean grain-size in the medium-grained sand fraction (1.1–1.75 phi). The berm at Lake Bhangazi and the Meme ridges are slightly finer grained (1.75–2 phi) and the Makakatana and KwaMbonjane ridges cluster in the 2–3.2 phi range of fine-grained sand. A plot of mean grain-size against sorting for individual ridges at the Sengwane complex demonstrates that each ridge is unique with a characteristic narrow textural range. The Bhangazi berm sand is the most well-sorted whereas the Mak-5/5B and Nib2 sites are more poorly sorted than the others. Meme samples show the narrowest range of sorting of the St Lucia ridges. Plots of the standard deviation about the mean grain-size against skewness do not differentiate the beach ridge sands from the regional dune sand cover of Maputaland or the aeolian sand forming the beds of the other coastal lakes.

4.7 Chronology of sand ridges

The OSL ages are presented in Table 1 and on Figs. 4-8. The age range for samples from the beach ridges are from 6,240 to 600 years (before 2000 AD) and apart from individual exceptions, show overall agreement with the beach ridge sequence. Multiple ages from the same ridge indicate that in places the ridge accumulated slowly (e.g. Meme 2 (Dot2) ridge on Fig. 5d) while at Nib2 ridge (Fig. 7d) accumulation was more rapid. The anomalous age of the Nib3-1 sample, further inland and stratigraphically above the Nib2 ridge could point to localized aeolian remobilization of the Nib2 ridge crest. The apparent age reversal indicated by dates at Meme (Dot2-1/2-2) and KwaMbonjane (Nib2-1/2-2) is not regarded as diagnostic as the dates are within the error range.

Table 1. OSL ages derived from beach ridge crest profiles.

Sample	Depth (m)	Water (%)	Grain size (μm)	Field γ (μGy/a)	K (%)	U (ppm)	Th (ppm)	Ext. α (μGy/a)	Ext. β (μGy/a)	Total dose (μGy/a)	No. aliquots	Dose recovery	De (Gy)	Age (years)
Makakatana														
MAK-1	0.5	7.2	125-150	470	0.47	0.71	1.88	2	427	899±52	12/14		0.69±0.01	760±50
MAK-2	0.5	6.8	125-150	640	0.53	0.88	1.89	3	448	1131±68	13/13		1.48±0.05	1310±90
MAK-3	0.5	8.0	125-150	594	0.61	1.24	2.22	4	582	1180±64	13/13		1.55±0.06	1310±90
MAK-4	0.6	8.0	125-150	346	0.21	0.56	1.20	2	226	573±40	13/14		1.24±0.03	2160±160
MAK-5	1.4	2.5	150-177	747	0.09	1.63	4.31	37	368	1153 ± 78	20/21	0.99	3.55 ± 0.28	3080 ± 320
MAK-5b	0.5	2.5	125-177	841	0.11	0.23	5.81	55	501	1396 ± 88	18/21	1.05	3.36 ± 0.62	2410 ± 470
MAK - Mod	0		125-150								12/13		0.013±0.008	
Meme/Dotsheni														
DOT-1	0.7	0.6	150-177	364	0.37	0.39	0.79	8	325	698 ± 42	24/24	1.02	0.56 ± 0.06	800 ± 100
DOT-2-1	1.0	2.0	125-150	322	0.13	0.65	0.81	2	190	514±38	12/13		1.92±0.19	3740±460
DOT-2-2	2.0	1.9	125-150	368	0.2	0.86	1.36	3	277	648±42	13/13		2.13±0.11	3290±270
DOT-2-3	1.0	2.8	150-210	258	0.11	0.49	0.88	9	155	422 ± 33	21/24	1.02	1.42± 0.13	3360 ± 410
DOT-2-4	2.0	2.0	125-150	275	0.17	0.52	0.85	2	202	478±35	12/14		1.96±0.09	4100±360
Sengwane														
SNG-1	1.5	15	250-299	305	0.44	0.36	1.05	4	304	613±39	23/24		1.00±0.09	1630±180
SNG-2	1.5	15	212-249	286	0.37	0.45	1.11	6	281	555±35	22/24		3.29±0.28	5920±630
SNG-3	1.5	15	212-249	324*	0.41	0.35	0.76	4	286	614±27	19/24		3.60±0.23	5850±460
SNG-4a	1.5	15	212-249	289*	0.33	0.27	0.50	3	227	519±25	21/24		2.74±0.21	5280±470
SNG-4b	1.5	15	212-249	321*	0.32	0.33	1.2	5	241	586±25	21/24		3.54±0.23	6240±500
SNG-5	1.5	15	212-249	309*	0.37	0.30	0.73	4	257	571±26	23/24		2.14±0.15	3740±310
SNG-6	1.5	15	300-354	317*	0.36	0.36	0.82	3	249	569±25	21/23		1.27±0.19	2230±350
SNG-mod	0		300-354										0.008±0.021	
KwaMbonjane/ Nibela store														
NIB-1-1	0.5	0.6	125-150	588	0.61	0.64	1.87	3	549	1140±63	13/13		1.14±0.06	600±50
NIB-2-1	1.0	0.4	125-150	498	0.52	0.49	1.31	2	456	955±54	11/13		3.82±0.20	3990±310
NIB-2-2	2.2	16.5	125-150	892	0.83	1.96	6.56	7	823	1722±93	13/13		6.61±0.23	3840±250
NIB-3-1	1.0	0.6	150-177	680	0.52	1.09	3.67	29	589	1298 ± 72	18/21	1.02	2.91 ± 0.54	2240 ± 440
Bhangazi														

BZI-1	0.8	0.7	150-210	318	0.25	0.5	1.14	10	263	591 ± 89	20/24	1.02	1.06 ± 0.06	1800 ± 160

Notes:

Ages are in years before 2000 AD. Blue shaded D_e values were measured in Aberystwyth while the remaining D_e values were measured at the GSI. The D_e value given in the table is the unweighted mean of the individual determinations. Gamma was either measured in the field ("Field gamma") or calculated from the concentrations of the radioactive elements with an added cosmic dose of 174 μGy/ka (marked with an *). "No. aliquots" is the number used for age calculations from all those measured. Layer removed by etching is 10±2 μm for Sengwane and 20±2 μm for the remaining samples. Moisture contents for Sengwane samples were estimated at 15±5 %. The error on the measured moisture contents is 10% of the value. Errors on the K, U and Th contents are 5%, 8% and 10% of the values, respectively. Most samples had clear preheat plateaus and recycling ratios were mostly in the range of 0.9-1.1.

4.8 Holocene relative sea-level indicators

The occurrence of raised beach ridges around parts of the St Lucia estuarine lake that formerly had a more direct marine link prompts a comparison with published relative sea-level curves for the region. A composite relative sea-level curve for the KwaZulu-Natal coast was compiled by Ramsay (1995, 1996) and Ramsay and Cooper (2002). An envelope representing their interpreted relative sea-level range is presented in Figs 9 and 10a. New evidence presented here was derived from encrustations of calcareous tube building worms sampled from above the present tidal range at sites near St Lucia and Durban (Table 2).

The faunal structures are similar to those of the extant species *Pomatoleios kraussi* that forms coralline masses (Beckley, 1988). These fixed biological indicators of intertidal zone biota (Rovere et al., 2015) are commonly associated with the mid-littoral assemblages ranging from the Upper- to Lower Balanoid Zone and their distribution approximates the neap tide range (Beckley, 1988; Lewis et al., 2008). Their range varies under high energy conditions and can extend to depths below low tide level. In the absence of other Balanoid Zone species with which to refine their zonal occurrence on the raised intertidal platform, relative to that of the same species in the present intertidal zone, an error range of ±0.5m relative to mean sea level has been adopted (after Baker et al., 2001) to bracket the likely neap tidal index range of the tubeworms.

At the First Rocks promontory north of St Lucia estuary an intertidal zone pothole contains tubeworm structures accreted on the sidewalls that were DGPS surveyed at an elevation of +1.04 m relative to mean sea level. Radiocarbon dating yielded an age of 4320 ± 50 ^{14}C yr BP (Pta 9449) or 4977 – 4797 cal. years BP. Northwards near Mission Rocks, a tubeworm encrusted pothole at +1 m msl yielded an age of 2650±40 ^{14}C yr BP (Pta 9452) or 2800 – 2695 cal. yr BP. A massive tubeworm encrustation of a raised intertidal rockpool and pothole complex at Tiger Rocks near Durban was DGPS surveyed to establish the +1.1 to +1.5 m msl elevation range of the encrustations dated at 3370 ± 60 ^{14}C yr BP (Pta-9423) or 3705–3399 cal. yr BP. An tubeworm encrusted raised intertidal pothole at +1m msl near Umgababa south of Durban yielded an age of 2020±60 ^{14}C yr BP (Pta-9419) or 2090-1810 cal. BP (Bosman, 2012).

Latitude (DMdec)	**Longitude (DMdec)**	**Site**	**Sample material**	**Elevation & MSL index range**	**Lab. number**	**Radiocarbon age (years BP)**	**Calibrated radiocarbon age (cal yr BP)**
28 18.379	32 28.172	Oyst fill 2	Pothole fill; oyster shell	+1 ± 0.5m	Pta-9460	2440±45	2542–2340
28 19.132	32 27.706	Tube fill	Pothole tubeworm encrustation	+1.5 ± 0.5m	Pta-9449	4320±50	4977 – 4797
28 17.619	32 28.662	Pothole tube	Pothole tubeworm encrustation	+1 ± 0.5m	Pta-9452	2650±40	2800 – 2695
30 0.283	30 56.519	Tiger Rocks D104/RC10	Raised tidal pool tubeworm encrustation	+1.5 ± 0.5m	Pta-9423	3370±60	3705–3399
30 09.416	30 49.809	Umgababa, OS-5 (Bosman, 2012)	Pothole tubeworm encrustation	+1 ± 0.5m	Pta-9419	2020±60	2090-1810

Table 2 New relative sea-level indicator sites with elevation and interpreted environmental MSL index elevation range. Calibration of radiocarbon dates used OxCal 4.3 and the SHCal13 curve.

5. DISCUSSION

The discussion presented here addresses the genesis of sandy beach ridge in the context of evidence of glacio-eustatic sea-level regression during the mid- to late Holocene and local environmental influences. The dated beach ridge sets at five sites around the estuarine lake show generally coeval ridge formation with a progressive lowering of ridge elevations and progradation of the shoreline into a shrinking, shallowing waterbody.

The recent high resolution geophysical survey of the lake bed and borehole logs describing the record of channel infill sediments and changing depositional environments has been described by Benallack et al. (2016), Humphries et al. (2016) and Gomes et al. (2017). These lake bed sedimentation records span the same period as the beach ridge record of raised lake level. This corresponds to the period during which the marine channel became progressively infilled and the lagoon was modified to become a restricted estuarine lake environment dominated by fluvial inputs and lacustrine sedimentation.

The beach ridge and fixed biological indicator data presented here are used in conjunction with the published sea-level data for the region (Ramsay, 1996) to assess whether the sequence of raised beach ridges reflect a gradual or pulsed regression or oscillating sea-level during the late Holocene (Figs. 9, 10a). The influences of shoreline wave erosion and longshore current redistribution processes, spit formation and lake segmentation dynamics on swash zone beach ridge construction are also considered. Relief variation of coeval ridges at different points around the lake suggests that ridge construction was influenced by local environmental including fetch limited wave action and wind-induced seiche effects in the shallowing, increasingly segmented lake.

5.1 Beach ridge formation in the context of Holocene relative sea-level change

The context of a periodic regression in lake level, linked to a progressively restricted marine link, can be assessed by indexing the shoreline ridges against the Holocene sea-level change curve for this region (Figs 9, 10a). Khan et al. (2015) placed the passive southeast African continental margin within a “far-field” zone where uncertainties exist regarding the timing and amplitude of a predicted mid-Holocene highstand of ~2.5 – 3.5 m above present by 6 ka.

The evolution of the iSimangaliso coastal lakes and estuaries in response to glacio-eustatic marine transgression across the Pleistocene/Holocene boundary has been described by Hill (1975), Hobday (1975), van Heerden (1975), Ramsay (1995, 1996),Wright et al, (2000), Miller (2001), Ramsay and Cooper (2002), Benallack et al. (2016), Humphries et al. (2016), Gomes et al. (2017). After peaking in the mid-Holocene, a general regressive trend is reflected by the southern African late Holocene sea-level curves published by Jaritz (1977), Miller et al (1993, 1995), Ramsay (1995), Compton (2001, 2006), Ramsay and Cooper (2002). At Macassa Bay in southern Mozambique, Norström et al. (2012) identified a sea-level highstand c. 6600–6300 cal. BP contemporaneously with the Holocene climatic optimum that coincides with the Sng-4b ridge (Table 1, Fig. 10a).

The sea-level curve compiled by Ramsay (1996) is based on radiocarbon-dated shell, coral and calcareous cement derived from beachrock, estuarine and marine mollusc shell, calcareous algae, peat and driftwood. Depending on their sedimentary context, some of these biota or cements do not represent precise sea-level indicators that accurately constrainrelative sea-level elevation information. The curves published by Ramsay (1996) and the Cape West Coast/Namibia curve by Compton (2001) differ over some time intervals raising questions as to whether the mid- to late Holocene sea-level trend was a smooth/pulsed regression or characterized by short-term oscillations from the regressive trend. This could reflect the variable precision of sea-level indicators used and possible differences between the interpretation of marine and lagoonal/estuarine index materials sampled. Ramsay (1995, 1996) arbitrarily corrected the radiocarbon dates he published for the reservoir age of southeastern African coastal waters by subtracting 400 years. The relative sea-level envelope shown in Figs. 9 and 10a is based on Ramsay's (1995) original laboratory data for these samples that have been calibrated using the OxCal calculator and the SHcal13 curve.

The tubeworm encrustations used to indicate the neap tidal range of raised mean sea-level during the mid- to late Holocene (Table 2, Fig. 10a) provide a new perspective on the Holocene relative sea-level change during a period when the Ramsay sea-level curve indicates a lack of data, presumed to indicate a lower sea-level. Marine erosion features such as benches, pools and notches yield quite accurate sea-level determinations, especially where supported by marine organisms in growth position or fixed biological indicators e.g. serpulids, vermetid gastropods, barnacles (Pirazzoli, 1991; Baker et al., 2001; Rovere et al., 2015). Contributions from many researchers cited above have highlighted the evolution of the St Lucia lake basins under a tidal prism through a former open marine channel connection, buried by what is now a high forested barrier dune accretion ridge near Leven Point (Figs 1, 2). Estuaries along the subtropical KwaZulu-Natal coast are generally linked to large flood-prone catchments (Cooper, 2001) and estuarine saline flat or mangrove deposits that represent relatively well-constrained sea-level indicators are limited in this region. The St Lucia beach ridges are from a lower energy, estuarine and lagoonal environment data provide an additional basis for a comparative assessment of the sea-level curves derived from the high energy coastline.

The OSL ages of the beach ridges (Table 1 and Figs 9, 10a) suggest that the present active shorelines formed in response to average lake levels achieved since the formation of the lowest raised beach ridges some 600 to 800 years ago. The Mak-1, Nib-1-1 and Dot-1 ridges are backed by swales elevated around +1m msl. There is a correspondence of ridge crests at the +3 m msl level at different times at sites around the lake. The Nib-2-1 (3990±310 yrs.), Dot-2-3, 2-4 (4100±360 to 3360±410 yrs.) and Mak-5 ridge (3080±320 yrs.) are distinct from those of the lower, younger ridges. The high Nib-3-1 ridge crest (+4.6 m msl) yielded an anomalously young age of 2240±440 yrs., possibly due to reworking or deposition of an aeolian sand cap on the ~3990 yr beach ridge base. Swales at the ~1.3 m msl level separate the Mak-4 and Mak-5b ridges dated at 2160±160ka and 2410±47 ka, respectively (Table 1).

The evidence of an early to mid-Holocene sea-level highstand is broadly supportive of data from the southeast Australian coast (Sloss et al., 2007), the southern coast of Australia (Baker et al., 2001), the southeastern coast of Brazil (Ybert et al., 2003) and from the Rio del Plata between Argentina and Uruguay (Prieto et al., 2017). The combined record of raised beach ridges and fixed biological indicators (Table 2, Fig 10a) contradict the Ramsay (1995, 1996) interpretation by placing mean sea-level in the +1.0 m–1.5 m msl level during the late middle Holocene when the published records are interpreted as a drop in sea-level during the ~2000 year period preceding formation of a beachrock at +1.5m, dated at ~1916 cal yr BP (Pta-4972) (Figs 9, 10a). The youngest beach ridges dated at St Lucia coincide with indications that current sea-level was attained after 1175–651 cal. yr BP when beachrocks formed at Vilanculos, Mozambique (Siesser, 1974).

5.1.1 St Lucia lagoon shallowing during the Holocene

The temporal relationship between lake shallowing and progressive closure of the marine link is an important corollary that must be considered when interpreting the sequence of beach ridge construction events. Drilling of the lake bed described by Kriel et al. (1966) revealed composite channels incised into Cretaceous siltstone bedrock that are infilled by a complex sequence of marine and lagoonal sediments. The cores lack stratigraphic similarity apart from a coarser base. The very high-resolution seismic study of the lake bed by Benallack et al. (2016) delineated seven seismic sedimentary units that reveal two episodes of incised valley formation and channel infill deposits (Fig. 2). Up to 35 m of estuarine basin and valley fill deposits covered by tidal channel fill and aggrading back barrier lagoonal drape deposits are attributed to Holocene sedimentation. These laterally extensive deposits from 2-12 m thick, underlying the present lake bed, record lake shallowing from ~16 m to ~3 m during the period from 8295 cal. yr BP to ~2490 cal. yr BP (Benallack et al., 2016, Fig. 9; Humphries et al., 2016). Figs. 9 and 10a contextualize the period of beach ridge accretion relative to relative sea-level change and St Lucia lake bed channel sedimentation. The rate of sediment accretion shown in Fig 9 is based on the boreholes in False Bay (FB-1), the North Lake (NL-1) and South Lake (CB-2) (after Humphries et al., 2016) and unpublished data from a shallow core from the Jetty site on the northern edge of Catalina Bay. The channel sedimentation rate in North Lake and False Bay is near linear from around 8,000 cal. yr BP until about 2,000 cal. yr BP. In the South Lake sedimentation until ~8,000 cal yr BP was at a high rate with a lower rate of sediment accretion thereafter mimicked by the unpublished data from Catalina Bay Jetty core.

The representation of the dated beach ridges in Fig. 10a uses a parabola shape to bracket the beach ridge relief between the crest and swale elevations, centered on the OSL age but spanning the dating uncertainty. The plotted beach ridge crest/swale heights generally indicate reduced swash zone activity over time, possibly linked to the shallowing of the lagoon and shrinking lake compartments, although the rate is clearly not directly linked to the sedimentary depositional processes active in the lake channels and adjacent lake bed. Sand accretion on the beach ridges occurred during the period recorded in the lake bed deposits when lake sedimentation patterns changed from marine dominated to progressively restricted lagoon- /-lacustrine environments. Sea-level rise which triggered coastal barrier dune development also initiated accumulation of fluvial sediment on bayhead deltas that prograded into the lake from the Mkhuze and Mzinene Rivers promoting lake shallowing (Humphries et al., 2016).

Cholnoky (1965) found the diatom flora from 12 boreholes drilled to -10.5 m as being chiefly of marine origin and laid down in last 4000 years (Kriel et al., 1966). Gomes et al. (2016) identified marine benthic and epiphytic diatom species that reveal marine water influx with salt marsh and tidal flat habitats until ~4550 cal BP when a shift in biological community indicates development of a back barrier, brackish water body. Marine planktonics and enriched $\delta^{34}S$ with an isotopic composition similar to seawater, point to influx of marine organic matter through recurrent, large-scale barrier inundation events spanning the period from the mid-Holocene highstand to ~1200 cal. yr BP. (Gomes et al., 2016).

Intertidal tubeworm encrustations on the coast (Table 2) indicate relative mean sea-level at +1 m to +1.5 m msl during this period (Fig. 10a) indicating that a marine link and possible tidal influence, or beach barrier washover events could have been maintained well after this period until the final beach ridge construction event from 800 – 600 years ago (Mak-1, Dot-1, Nib1-1, Table 1). Although ridge crests reach elevations over 4.6 m msl, individual beach heights are more closely related to swash zone energy as influence by wave height and do not represent precise index points relative to the tidal range or mean sea level. The intervening swales with elevations ranging between +1 m and +1.5 m msl around different parts of the lake (Figs. 4–8) that indicate the most likely mean lake level over the period from 4,000 – 2,000 cal. yr BP. During this period the ridge/swale sequence at some sites approximates the elevated sea-level range represented by the dated tubeworm encrustations (Figs. 9, 10a).

5.2 The influence of wind fetch, wave height and lake seiche

The marked morphological differences between generally coeval ridges at different sites around the estuarine lake point to the role of secondary, local influences on beach ridge construction. The definition of estuarine beaches by Nordstrom (1992) focuses on beach ridges in such environments being shaped by waves and wave-induced currents influenced by wind speed, duration and fetch distance. Shallow, short fetch embayments generate low height / short-period waves and under high wind speeds, wind set-up can exceed tidal ranges (Nordstrom and Jackson, 2012). Beach ridges of clearly proven wave-built origin may serve as evidence of higher than present sea-levels (Otvos, 2000) but crest heights alone are not reliable RSL index elevations (Prieto et al., 2017). The only ridge with gravel is Mak-5b ridge where the basal ferricrete pebble gravel is likely a swash zone lag concentration of ferruginous rhizolith fragments eroded from the underlying clayey plinthite soil horizons that were exposed by shoreline erosion of the Makakatana wetland.

Uncertainty can be imposed by aeolian capping which is usually significant in comparison with the amplitude of relative sea-level changes since the mid-Holocene (Tamura, 2012). The St Lucia ridge sediment granulometry does not differentiate an interface between beach swash deposition and wind-blown sediment reworked off the beach. It appears that the aeolian sand provenance of the traction and saltated sediment transported by wind-generated longshore currents around the St Lucia shoreline has a stronger influence on the sand grain-size distribution than the beach or possible aeolian depositional processes over short transport distances across the sand ridges. The lack of coarse to very coarse-grained sand fraction is evident and indicates that the marine influx of sand contributed little to the available sediment redistributed by wave action on the beaches, which was mainly derived from eroded aeolian deposits forming the lake shores. Otvos (2000) showed that grain-size characteristics are not an effective criterion for distinguishing the aeolian/beach boundary in beach ridges. Utilization of sandy beach ridges as direct sea-level indicators presupposes a recognizable interface between the wave-built foreshore and the overlying aeolian cover sand within a given ridge.

Orme (1973) noted that the present shallow and gently shelving shorelines of Lake St Lucia result in significant lateral movement of the lake shoreline due to changes in tides, freshwater input and prevailing winds. The effects of wind set-up and seiche oscillations in the northeastern shallows of Selley’s lakes and Makakatana Bay results in dramatic lateral change in the position of the lake shoreline. In the context of the ~5,500 year period between the oldest and youngest ridges in the progressively lowering St Lucia ridge sequence it is clear that stabilization during sea-level stillstands is required for cross-shore processes that accrete swash beach ridges. The action of prevailing onshore winds and related transgressive swash zone wave action can lead to the construction of long, low beach ridges during long periods of relatively consistent lake level. The influence of other local environmental factors such as daily tidal range, diurnal wind speed changes and wave regimes on the rate of ridge growth, the width and height achieved, landward accretion and possibly back-barrier sedimentation in the swale, can usually only be surmised.

The variation in ridge relief indicates the variation in seiche and wind fetch on wave action at different points around the proto-St Lucia estuarine lake. From the sequence of beach ridges it is possible to infer the influence of fetch effects on wind seiche and wave energy on ridge construction. The highest ridges at KwaMbonjane and Meme have open water wind fetch lengths of about 23 km relative to the prevailing southerly winds (Figs. 1, 10a). The lower Sengwane ridges were somewhat sheltered from northeasterly winds by rising coastal barrier dunes and an open water wind fetch of less than 10km. At the southern end of the South Lake, the Makakatana ridges are exposed to wind fetch of ~13 km aligned with the northeasterly prevailing winds.

It is the broadly coeval beach ridge accretion events and sequential retreat of the lake shoreline over periods of thousands of years, represented around all quadrants of the compartmentalized lake, that favour the direct influence of relative sea-level change as the primary mechanism controlling beach ridge accretion. The temporal correspondence of dated beach ridges depicted in Fig. 10a point to long periods of shoreline stability influenced by regressing eustatic sea-level change operating in a deeper estuary that was also subjected to a progressively restricted marine connection. The beaches point to abundant sand supply through erosion of the aeolian sand substrate and transport by longshore current processes under the influence of a limited fetch wave regime around the shallow lagoon.

The difficulty in defining the mean estuarine lake level responsible for beach ridge accretion limits the use of these deposits as precise sea-level index points due to the influence of secondary variables including wind fetch and seiche effect across the lake, uncertain tidal prism influences and changing influence of lake depth on wave base and wave height over time.

5.3 Beach ridge development and lake segmentation

The beach ridge sets described here have played a role in the segmentation of the St Lucia system into six distinct sedimentary basins (Orme, 1975). The shoreline sand ridges bear similarities with the construction of cuspate spits with heights not exceeding 70-80 cm described by Zenkovitch (1959) as being found only in narrow bodies of water with widths of about half or less of their length. In narrow lagoons such as north-south elongated St Lucia, spits prograding off opposite shores constrict wave activity and the sediment load is reduced, causing deposition, extension and secondary modification of spit symmetry by other wind regimes. Cooper et al. (2012) described longshore sediment transport by wind-generated lagoonal waves and deposition at the downstream terminus of sediment transport cells that can develop into cuspate forms and spits on the lagoon shoreline or estuarine barriers, comprising low sand ridges, developed in the style described by Zenkovitch (1959) and Ashton et al (2009). In the St Lucia segmented lagoon the alignment of the long axis of the lakes with the northerly and southerly prevailing winds resulted in moderately high wave energy and nearshore circulation capable of moving appreciable sediment loads along the shore to form spits.

The Dot1 beach ridge at Meme (Figs. 1, 4) can be traced westward to the Mkhuze wetland confluence, where a 3 km extension resulted in temporary isolation of the lower Mkhuze swamp basin about 800 years ago until receding sea-level increased the river gradient, breaching the incipient shoreline and the back-barrier embayment. The embayed eastern shorelines of Catalina and Tewate Bays and the prominent Makakatana and Sengwane beach ridges that once extended further across the northern and southern lake shorelines have been truncated over the past 1000 years by longshore current erosion and falling base level in response to lowered sea-level. Despite the lack of erodible aeolian sand on the False Bay shore, the well-developed KwaMbonjane beach ridges closed a tributary stream channel. In this context the availability of fluvially transported, reworked aeolian sand from the catchment and the long fetch of False Bay probably provided adequate sediment for beach ridge construction. The Sengwane spit accreted vertically through swash action to form a beach ridge, anchoring the estuary shoreline around 6,240 years ago (Sng4b; Fig. 6c). This site, and the Meme ridges on the opposite lake shoreline, are located close to the ~40 m-deep channel that discharged near Leven Point (Fig. 2) during the marine regression after the MIS 5e highstand. The Sengwane ridges are the coarsest in the system so it is possible that the marine channel current could have increased the tidal sediment budget or led to accumulation of a flood tidal delta, similar to that which forms in the St Lucia estuary mouth during spring high tide (Wright, 1995).

5.4 Other possible influences on beach ridge construction.

Differing opinions regarding the genesis of the St Lucia sand ridges have been published. Hobday (1979) envisaged ridge formation during flood periods of raised lake level when onshore winds caused additional mounding of water (wind seiche effect) against the shore. Sydow and van Heerden (1988) described the beach ridge features as storm related cheniers, formed in response to increased cyclonic activity. Indeed, catchment discharge after Cyclone Domoina in 1984 resulted in a short-term rise of the lake level to 3.2-m (Wright, 1995).

The short-term stabilization of lake level during seasonal inundation or draw-down is unlikely to account for generally coeval accumulation of significant volumes of sand around the lake. Field evidence suggests that short-term inundation of the vegetated beach ridges by flooding events is associated with localized breaching of ridges by decanting flow from swales as the flood subsides. This periodic flooding mechanism does not account for the compelling chronological evidence of shrinking lake shorelines during the late Holocene.

The possible influence of short-term climatic forcing on the lake level can be assessed indirectly in relation to high-resolution, long-term records of palaeoclimatic change. From the alluvium-blocked valley south of St Lucia hosting Lake Eteza, Neumann et al. (2010) described humid climatic conditions during the middle Holocene (ca. 6800–3600 cal. yr BP) when the abundance of mangrove and swamp forest elements correspond with the sea- level highstand and SST peak. The high resolution Cold Air Cave speleothem isotopic record (Holmgren et al., 2003) shows the early Holocene warming trend and cooling after ~6 ka. This trend is also recorded in the peat deposits of the Mfabeni fen (Baker et al., 2014, 2017) where fluctuations between pervasive wet and warm to cool/dry conditions, with intermittent abrupt millennial scale cooling/dry events occurred at c.7.1, c.5.3, c. 1.4 ka (Fig. 10b).

6. CONCLUSIONS

The raised beach ridge sets along parts of the shoreline of the St Lucia estuarine lake have been surveyed and dated using OSL to determine their context relative to the composite relative sea-level curve for eastern South Africa. Beach ridges formation is coeval at different points around the lake and spans the period when lake sedimentation resulted in significant shallowing during the period from ~6200 to 2000 years BP. The lowest, youngest ridges formed during the past 2,000 years when the shallow lake depth would have influenced wave base, water turbidity and wind generated currents.

There is no compelling evidence to suggest that the generally regressive beach ridge sequence was driven by short-term palaeoclimatic change events. The OSL date framework does not suggest that the individual St Lucia beach ridges accreted over the short decadal timeframes that have been recorded for ridge/swale couplets and sets along the Mediterranean coast or the Great Lakes shorelines.

The highest ridges (Meme/Dotsheni and KwaMbonjane) lie at the northern end of lake segments with ~23 km open water fetch aligned with the southerly winds. The lower Sengwane and Makakatana ridges lie on the southern shoreline of embayment with ~10 km and 13 km fetch distances, respectively, aligned with the northerly winds. The ridges young towards the present lake shore, and the curvature of successive ridges suggests a shrinking of discrete lake basins and shallowing due to sedimentation during the Holocene, spanning a period when the lake was open to the sea and subject to a tidal prism and elevated relative sea-levels. During the mid-Holocene the highest beach ridges formed by wave action and beach sedimentation that was enhanced by the generally deeper lake during that period and short-term elevated water levels due to seiche effects over the long fetch of the North Lake, South Lake and False Bay basins which are aligned sub-parallel to the prevailing wind directions.

Although some of the older ridges are elevated close to the +2–4 m msl elevations of radiocarbon-dated beachrock and intertidal pothole fill deposits along the Maputaland coast, the sequence of beach ridges also spans the period when previous authors have indicated that relative sea-level was lower than present mean sea-level. The dated tubeworm fixed biological indicators of raised intertidal sea-level reported here suggest that mean sea-level was within the +1 to 1.5 m range above present sea-level during the period from ~ from 4,900 – 2,000 cal. years BP, coincident with the formation of many of the dated beach ridges. It will be necessary to undertake a higher density of ridge profile dates and date the intervening swale deposits to ascertain whether the successive beach ridge construction and abandonment events could be due to small scale sea-level oscillations superimposed on a progressive decline in relative sea-level, or whether the progressive closure of the marine channel exerted additional controls on ridge development. The elevations of beach ridge crests could be exaggerated by superposition of aeolian deposits on the beach swash sediments and therefore do not necessarily have a direct relationship with mean sea-level and the tidal prism during this period.

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Captions

Figure 1 Locality map showing the beach ridge sets relative to the main features of the St Lucia estuarine lake within iSimangaliso Wetland Park in northern KwaZulu-Natal Province, South Africa.

Figure 2 Map showing the position of bedrock channels beneath St Lucia recorded by seismic profiling. The former marine channel link through North Lake near Leven point is buried by the coastal barrier dune (after Sydow and van Heerden, 1988). The more recent study by Benallack et al., (2016) traced additional infilled channels (dark grey) and described sediment core from boreholes NL-1 and FB-1.

Figure 3 OSL results for sample SNG-4a.

a. Natural OSL signal of an aliquot measured in a Riso TL/OSL reader using blue diodes for stimulation. Note the bright signal and that it decays to background levels within 2 s (inset).

b. Dose response curve for the same aliquot (De=2.61±0.07 Gy). Recycling point merges with the dose point at 5 Gy giving a recycling ratio of 1.00, indicating that the SAR protocol adequately corrects for sensitivity changes. Recuperation is 1% of the natural signal, indicating minimal thermal transfer.

c. De measured over a range of preheat temperatures (160-300ºC). The plateau in the De values shows that the signal is thermally stable over that temperature range.

d. The same data as in c. plotted as a radial plot (N=21). Note tight distribution of aliquots, giving a De of 2.74±0.21 Gy with an over dispersion of 5.6%.

Figures 4 a-c. (a) Oblique aerial view towards the west from Brodies Crossing over the

Makakatana strand plain showing the beach ridge and swale sequence. (b) Plan showing beach ridges marking the change in embayment shoreline profile over the past ~3,000 years. (c) Surveyed section showing the relief relationships between sand ridges and swales.

Figures 5 a-d. (a) Plan view of the beach ridge set that separate Meme swamp from the Selley’s Lakes in the northeastern shallows of North Lake. (b) Aerial view towards the northeast over Meme swamp and the beach ridges. (c) View east showing the vegetated oldest ridge. (d) Survey transect through the beach ridges/swales that isolated Meme swamp. The dated 2-1, 2-2 and 2-3, 2-4 profiles are about 50m apart on the Meme 2 ridge.

Figures 6 a-c. (a) Oblique aerial view over the Sengwane beach ridges towards the coastal barrier dunes in the east. (b) Plan showing the early SNG 4B/SNG 3 ridges against which the SNG 4, 5 and 6 beach ridges accreted as the North Lake embayment shrank, presumably due to progressive restriction of the marine channel as the barrier dune accreted. (c) OSL dates from ridges SNG 1-6. (d) Topographic survey showing the relative elevations of the ridge crests across the Sengwane strand plain.

Figure 7 a-d. (a) Plan showing the arrangement of beach ridges across the confluence of the KwaMbonjane stream channel with False Bay. (b) View west over the beach ridge set and swales. (c) Profile through the NIB2 sand pit profile showing the soft plinthic mottling in grey sand and the buried lower surface, (d) Surveyed transect through the beach ridge set showing the positions of OSL dated sediments.

Figure 8 View northeast over Lake Bhangazi (south) showing the forested linear berm that accreted around 1800 years ago, separating the lake from Mfabeni fen to the south. The high barrier dune to the east was mobile at 2300 years BP (Porat and Botha, 2008).

Fig. 9 Dated channel infill deposits relative to the Ramsay relative sea-level curve and tubeworm encrustation envelope representing raised intertidal elevations (see Table 2, Fig. 10a). The Catalina Bay sedimentation curve is based on unpublished sediment core and dated shell data from S. Haldorsen and B. Stabell. The False Bay, North Lake and South Lake lines are derived from Benallack et al., (2016).

Fig. 10a Graphical representation of the relief of OSL dated beach ridges relative to the radiocarbon dated, relative sea-level curve and tidal range envelope based on calibrated ages (after Ramsay, 1995) and the tidal range envelope radiocarbon dated tube worm encrustations representing raised intertidal zones.

Fig 10b Environmental change trends indicated by variation in Mfabeni wetland bulk organic matter $\delta^{13}C$ (after Baker et al., 2014).

Table 1 OSL ages derived from beach ridge crest profiles.

Table 2 New relative sea-level indicator sites with elevation and interpreted environmental MSL index elevation range. Calibration of radiocarbon dates used OxCal 4.3 and the SHCal13 curve.

Figure 1:


Mkhuze swamp
KwaNibela store
Mkhuze R.
Meme beach ridges
KwaMbonjane beach ridges
Mzinene R.
Selley's Lakes
Leven Point
Nibela
Bird Island
Lister's point
FALSE BAY
NORTH LAKE
Sengwane beach ridges
Picnic Point
Hell's Gates
Ndlozi
Lane Island
TEWATE BAY
Hluhluwe R.
Fani's island
Nyalazi R.
Lake Bhangazi barrier
Cape Vidal
Dead Tree Bay
Western Shores
Eastern Shores
Sibomvini
Mfabeni
SOUTH LAKE
Makakatana beach ridges
Catalina Bay
Brodies Crossing
Scale
0
5km
wind rose
Mpate R.
incised shoreline
THE NARROWS
St Lucia estuary mouth
Mfolozi R.
iSimangaliso
KWAZULU NATAL
SOUTH AFRICA
Durban
N

Figure 2:

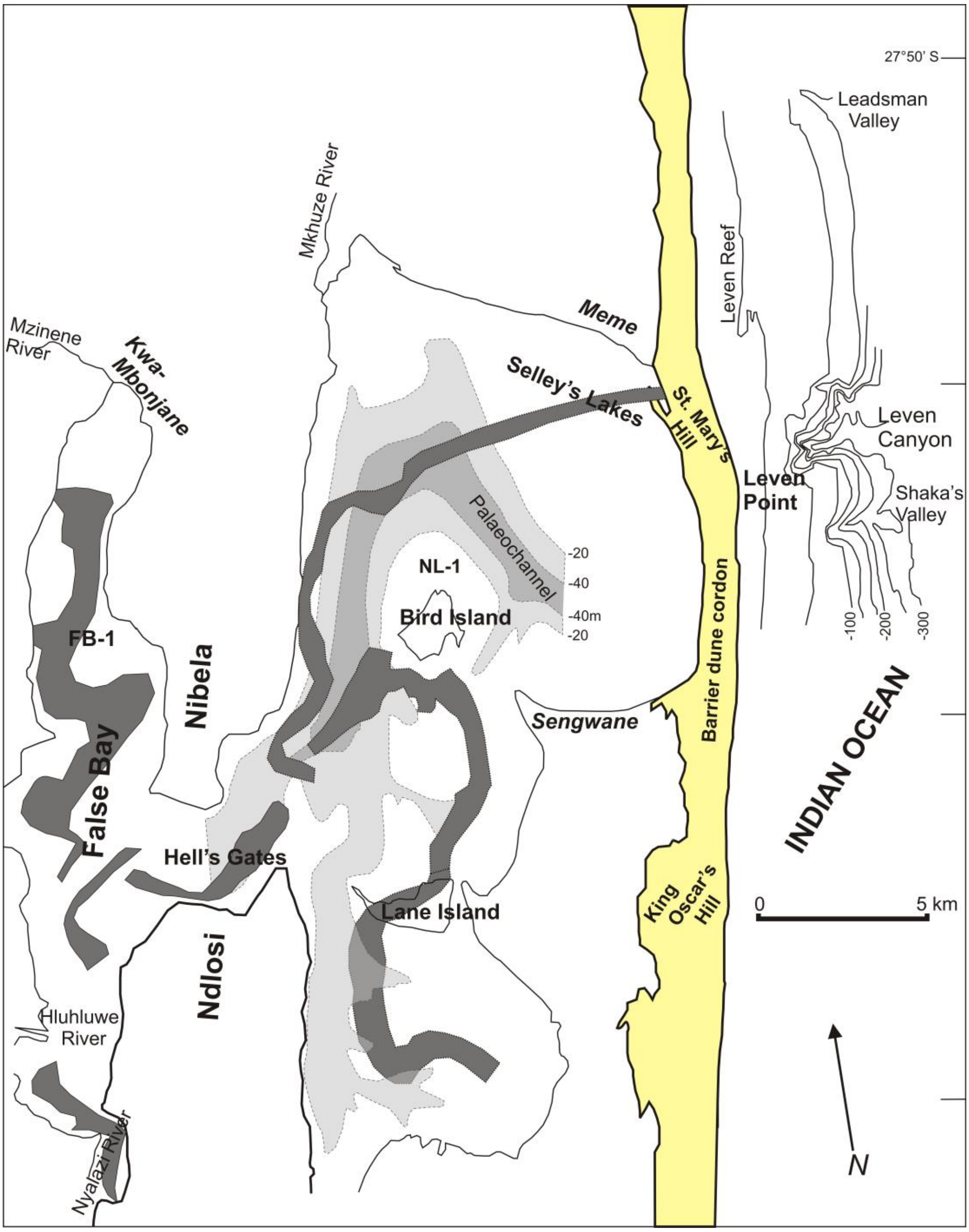

27°50' S
Leadsman Valley
Mkhuze River
Leven Reef
Meme
Mzinene River
Kwa-Mbonjane
Selley's Lakes
St. Mary's Hill
Leven Canyon
Leven Point
Shaka's Valley
Palaeochannel
-20
-40
-40m
-20
NL-1
Bird Island
FB-1
-100
-200
-300
Barrier dune cordon
Nibela
INDIAN OCEAN
Sengwane
False Bay
Hell's Gates
King Oscar's Hill
0
5 km
Lane Island
Ndlosi
Hluhluwe River
Nyalazi River
N

Figure 3:

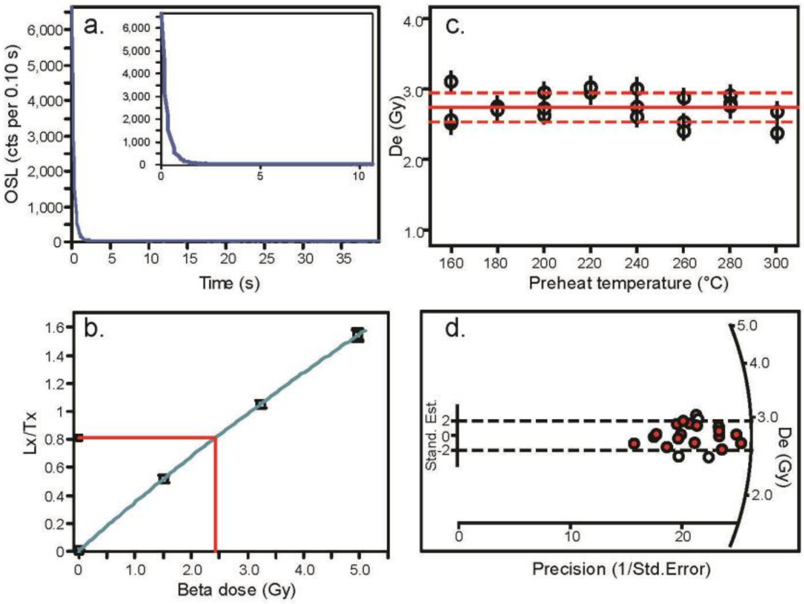
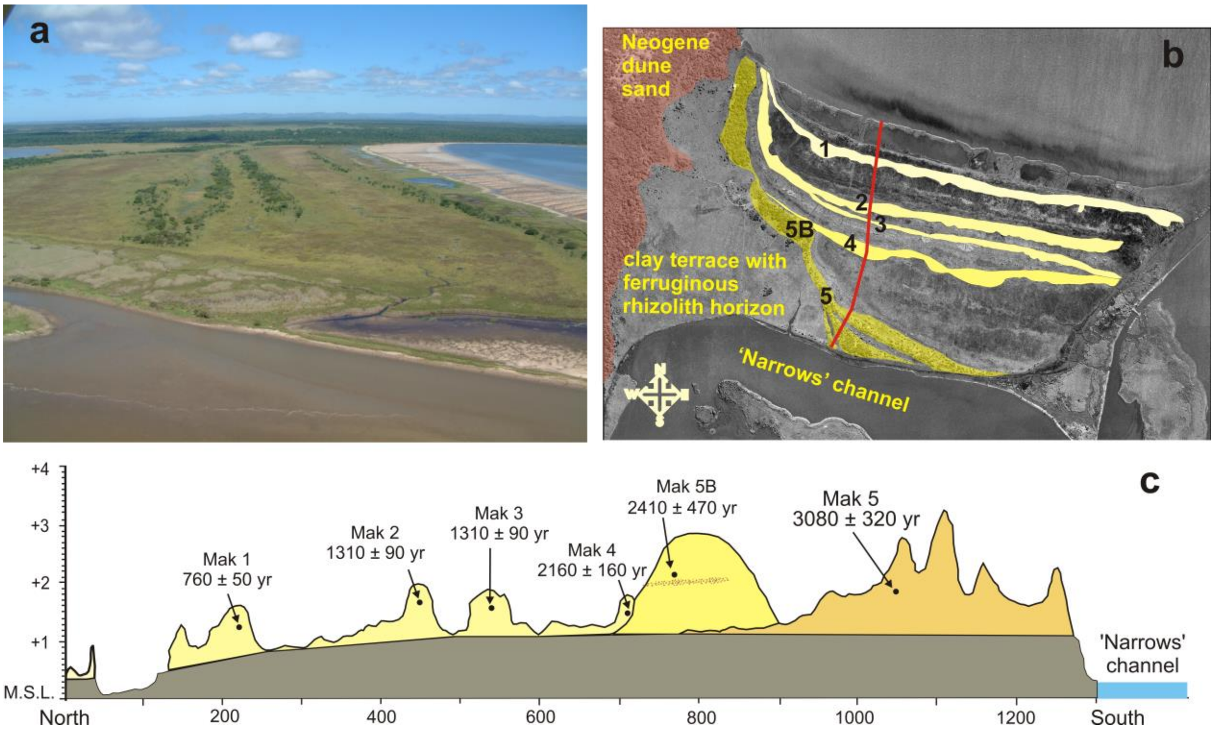


Figure 4:



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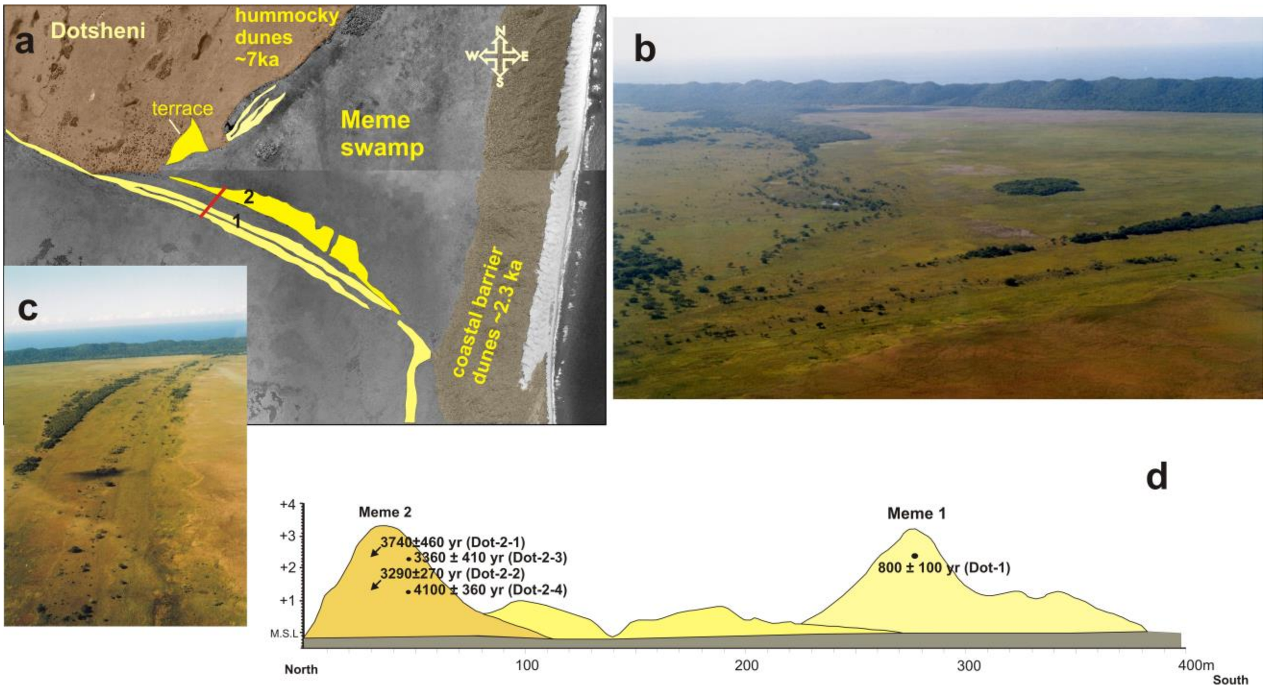

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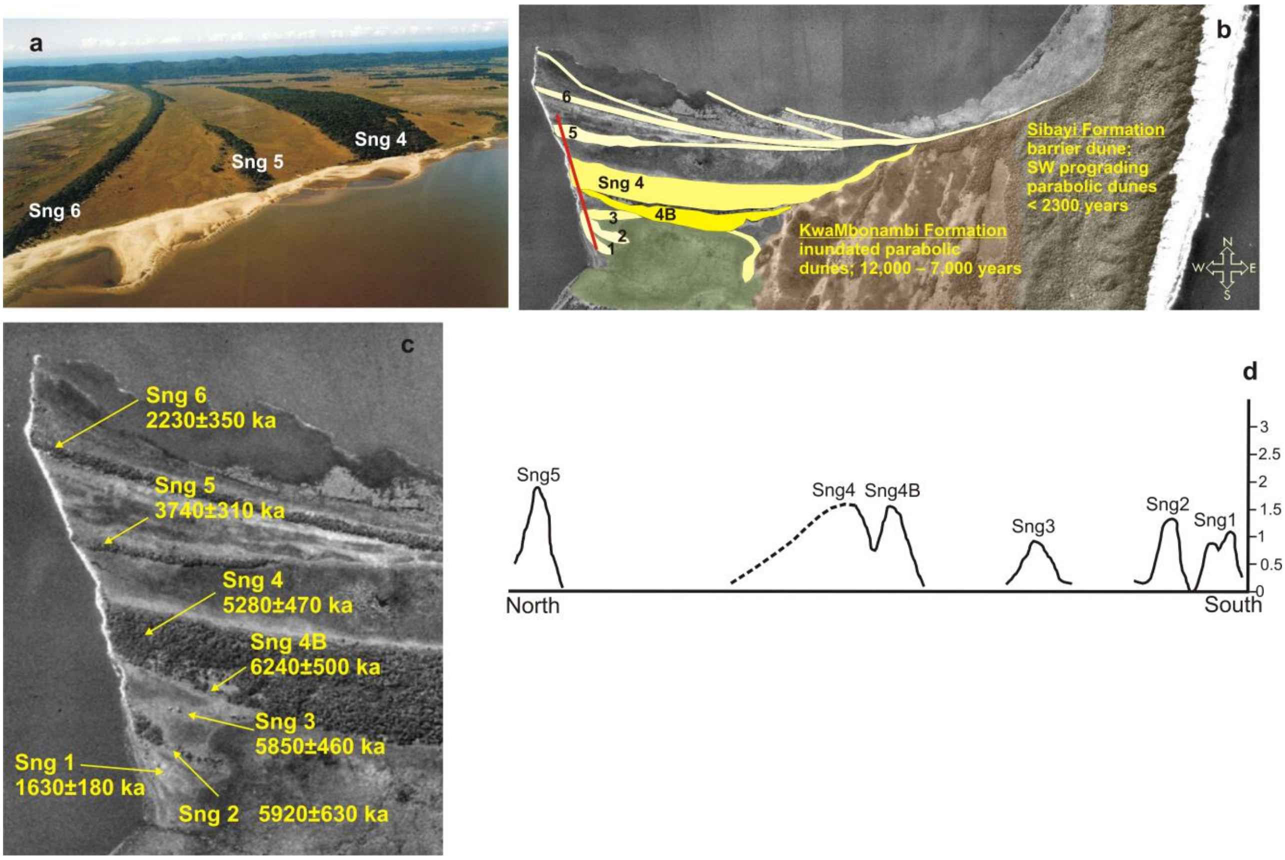

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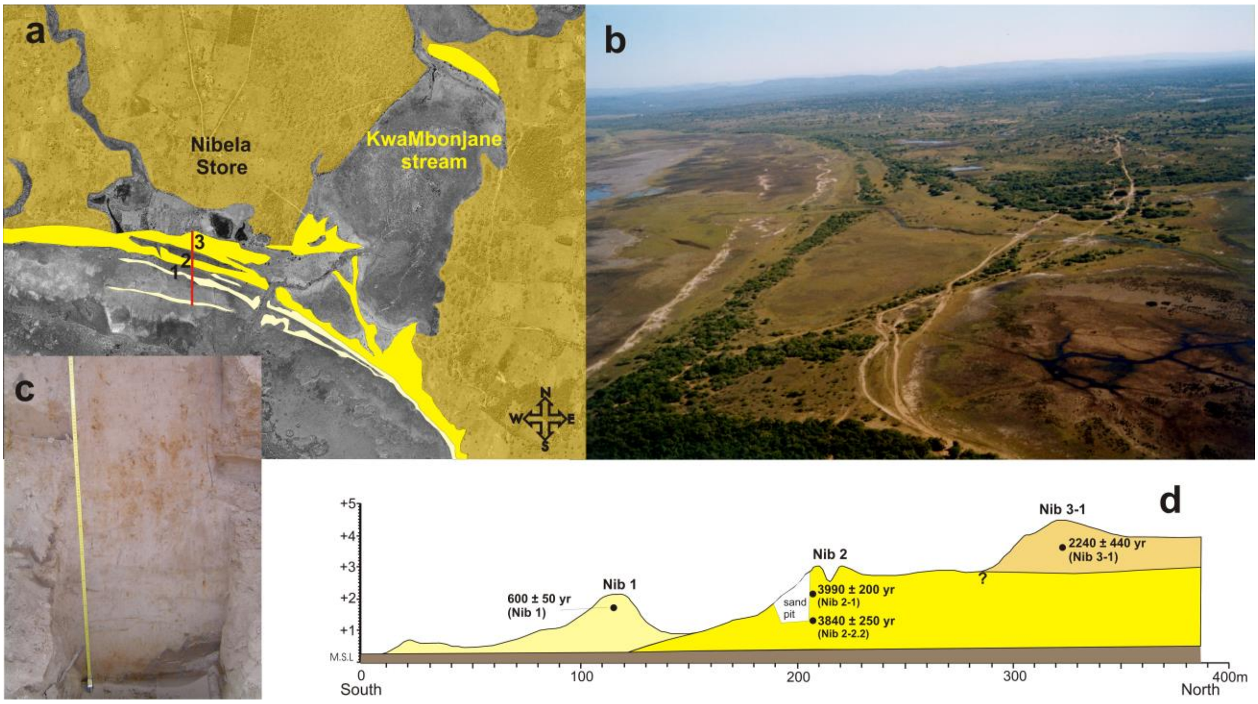

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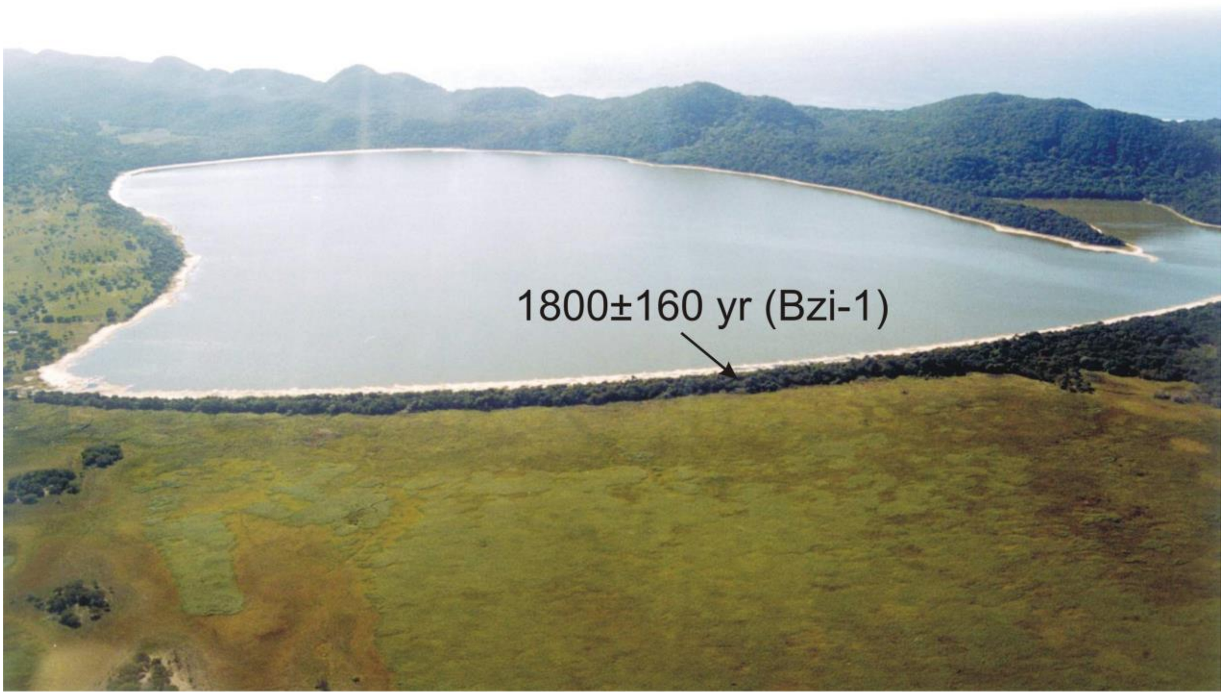

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Figure 9:

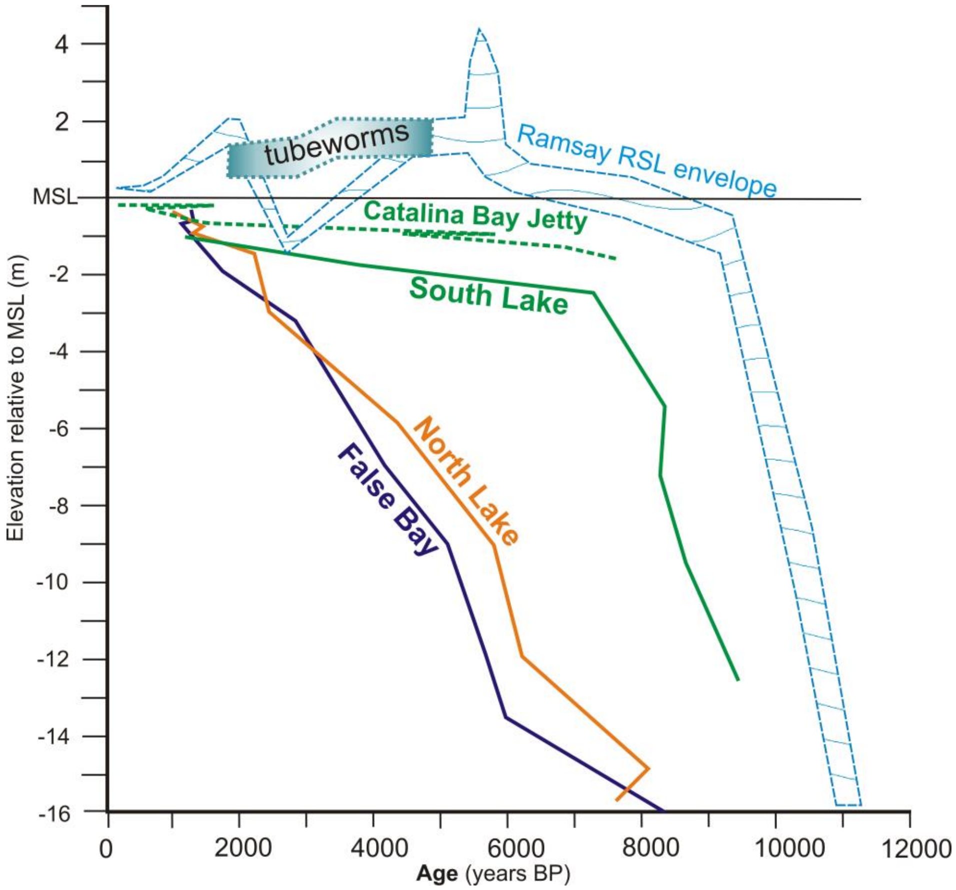
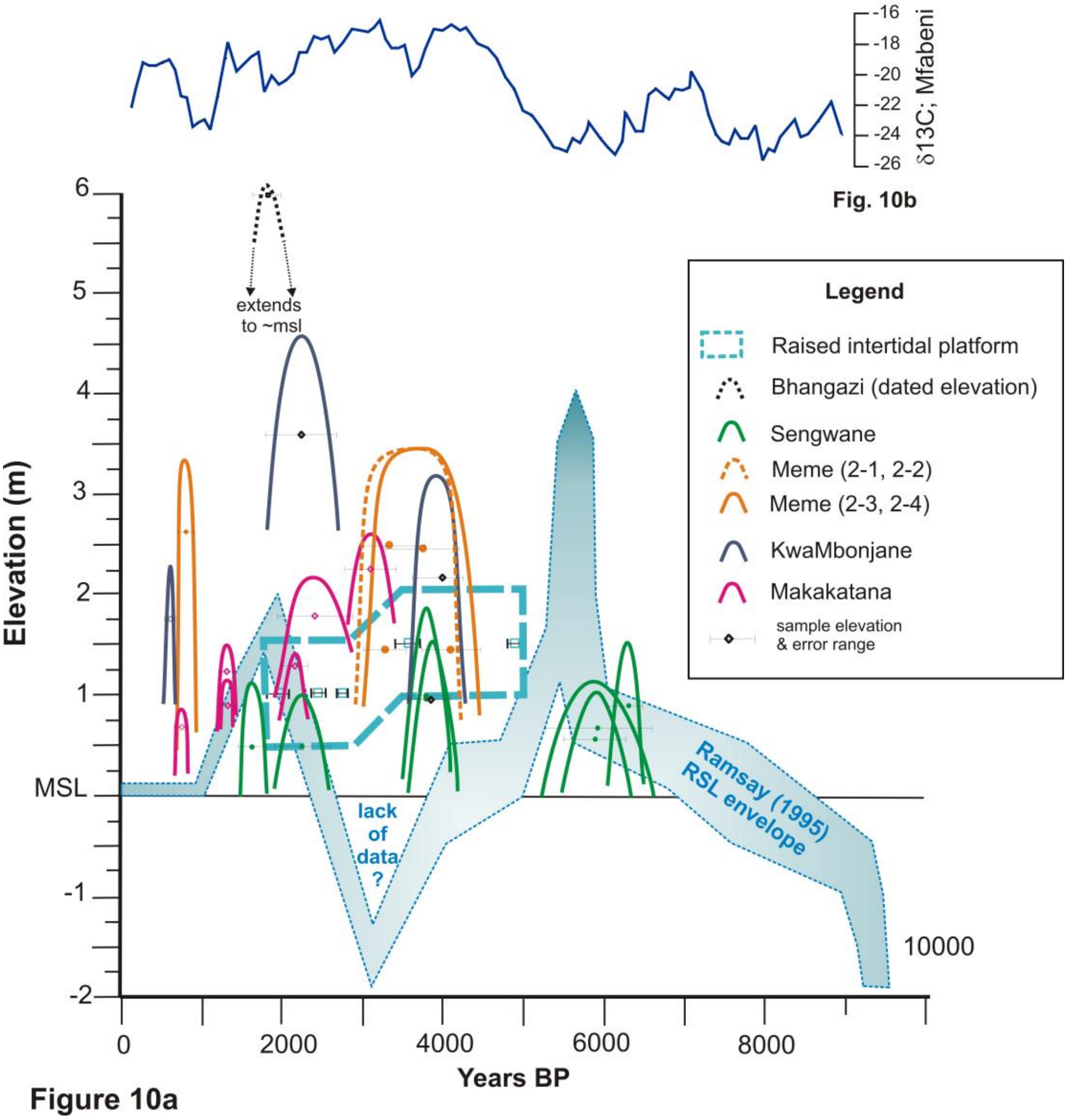


Figure 10:


-16
-18
-20
-22
-24
-26
δ13C; Mfabeni
Fig. 10b
Elevation (m)
6
5
4
3
2
1
MSL
-1
-2
extends to ~msl
lack of data ?
Ramsay (1995) RSL envelope
10000
0
2000
4000
6000
8000
Years BP
Figure 10a
Legend
Raised intertidal platform
Bhangazi (dated elevation)
Sengwane
Meme (2-1, 2-2)
Meme (2-3, 2-4)
KwaMbonjane
Makakatana
sample elevation & error range