The Holocene evolution of Lake St Lucia, Africa's largest estuary: Geological implications for contemporary management

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Abstract:	The Holocene evolution of Africa's largest estuary, Lake St Lucia on the east coast of South Africa, is examined and juxtaposed with previous and contemporary management practices aimed at preserving a brief snapshot of the system's overall evolutionary pathway. The estuary has been heavily altered over the course of the last century, mostly though mouth management activities aimed at maintaining a direct connection with the ocean. Based on seismic reflection, geomorphological, palaeontological and geochemical data, we investigate the system-wide and coeval evolution of the three different sub-basins (False Bay, North Lake and South Lake) that comprise the current estuarine lake system. The northern and southern sections of the system evolved independently of each other since the Last Glacial Maximum, with each area responding differently to early sea-level forcings. In North Lake, the lagoon evolved from fully estuarine (8300 cal. BP) to a restricted lagoon with occasional marine incursions, steadily decreasing tidal prism and the development of marginal spits by wind-driven lagoonal waves. The tidal inlet closed approximately 6200 cal. BP and fluvial conditions became more dominant as main back-barrier conditions became attuned to fluvial supply. Similar conditions prevailed in the adjacent False Bay basin, albeit with an earlier onset due to sheltering by prominent bedrock peninsulas. In contrast, South Lake evolved from a fully estuarine system (9500 cal. BP) with a persistent ocean connection, to a segmented system with a diminished tidal connection by 5500 cal. BP. The inlet sealed at this point and an isolated back barrier system developed. This prompted the system-wide impoundment of waters causing back-barrier flooding and in situ drowning of bayhead deltas and segmenting spits. By 2000 cal. BP, these areas had flooded sufficiently to connect over a bedrock high that had diverted the initial palaeo-valleys to the north and south. A new, single lagoon, representative of the modern-day system formed, with a new marine connection to the modern day Mfolozi River and contemporary estuary. Periodic desiccation of the lake sub-basins since this point has been apparent. Given the complex management plans implemented to stop excess sedimentation, hypersaline events, and the continuation of "normal" lake levels, this is at odds with the natural system's evolution to a pan or wetland-type state. This geological background should be key to informing management plans that work within the natural evolutionary trajectory of the system, as opposed to attempting to maintain an unattainable status quo.
Suggested Reviewers:	Edward Anthony anthony@cerege.fr Prof. Anthony has experience in working in large African estuaries and is well versed with the work here at St Lucia

	Scott Nichol scott.nichol@ga.gov.au Dr Nichol has worked on such system previously in Australia
	Fiona Mackay fmackay@ori.org.za Dr Mackay is a benthic habitat specialist who ahs worked on forams of South Africa, in addition to providing inputs to the St Lucia management plans
	Derek Stretch stretchd@ukzn.ac.za Prof. Stretch has been instrumental in modelling the estuary dynamics and has worked on a project trying to differentiate the ages of the estuary. He has been a major player in informing the management plans of the system.
	Helene Burningham h.burningham@ucl.ac.uk Prof. Burningham has been a very active researcher in the geomorphology of UK estuaries and management, she also recognizes how important geological control is on estuarine evolution (a fact missed by many!)
Opposed Reviewers:	

Dear Prof. Mitchell

Please find attached our submission entitled "The Holocene evolution of Lake St Lucia, Africa's largest estuary: geological implications for contemporary management". In our paper we examine the last 8000 years of evolution of the largest estuary in Africa, with the aim of outlining the geological background for management of the estuary. We highlight how the system has evolved as two separate basins with separate incised valleys and has since merged following closing of the inlets and backflooding. We provide the first age for the development of the modern estuary and highlight the evolutionary trajectory of the system. This is juxtaposed with the previous management plans and concerns of the estuary, that have seen major and likely unnecessary changes to the estuary configuration and water management plans. We urge for better dialogue between ecologists, managers and geologists in managing this world heritage site.

The paper follows from previous papers that have appeared in marine geology and ECSS, however we examine unreported seismic, foraminiferal, elevation and isotope data that provide an up to date and unreported evolutionary story of the system over the last 8000 years. We have not submitted this elsewhere and the work is wholly original.

We hope this meets the expectations of the journal and very much look forward to hearing from you.

Kind regards

Andy Green (on behalf of the authors)

Highlights

First system-wide appraisal of Holocene evolution of Lake St Lucia

Outline development of the modern estuary

Propose a geological trajectory for the system

Juxtapose system evolution with management plans

The Holocene evolution of Lake St Lucia, Africa's largest estuary: geological implications for contemporary management

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Abstract

The Holocene evolution of Africa's largest estuary, Lake St Lucia on the east coast of South Africa, is examined and juxtaposed with previous and contemporary management practices aimed at preserving a brief snapshot of the system's overall evolutionary pathway. The estuary has been heavily altered over the course of the last century, mostly though mouth management activities aimed at maintaining a direct connection with the ocean. Based on seismic reflection, geomorphological, palaeontological and geochemical data, we investigate the system-wide and coeval evolution of the three different sub-basins (False Bay, North Lake and South Lake) that comprise the current estuarine lake system. The northern and southern sections of the system evolved independently of each other since the Last Glacial Maximum, with each area responding differently to early sea-level forcings. In North Lake, the lagoon evolved from fully estuarine (8300 cal. BP) to a restricted lagoon with occasional marine incursions, steadily decreasing tidal prism and the development of marginal spits by wind-driven lagoonal waves. The tidal inlet closed approximately 6200 cal. BP and fluvial conditions became more dominant as main back-barrier conditions became attuned to fluvial supply. Similar conditions prevailed in the adjacent False Bay basin, albeit with an earlier onset due to sheltering by prominent bedrock peninsulas. In contrast, South Lake evolved from a fully estuarine system (9500 cal. BP) with a persistent ocean connection, to a segmented system with a diminished tidal connection by 5500 cal. BP. The inlet sealed at this point and an isolated back barrier system developed. This prompted the system-wide impoundment of waters causing back-barrier flooding and in situ drowning of bayhead deltas and segmenting spits. By 2000 cal. BP, these areas had flooded sufficiently to connect over a bedrock high that had diverted the initial palaeo-valleys to the north and south. A new, single lagoon, representative of the modern-day system formed, with a new marine connection to the modern day Mfolozi River and contemporary estuary. Periodic desiccation of the lake sub-basins since this point has been apparent. Given the complex management plans implemented to stop excess sedimentation, hypersaline events, and the continuation of "normal" lake levels, this is at odds with the natural system's evolution to a pan or wetland-type state. This geological background should be key to informing management plans that work within the natural evolutionary trajectory of the system, as opposed to attempting to maintain an unattainable status quo.

Keywords

lagoon evolution; back-barrier; foraminifers; Lake St Lucia, estuary management

1. Introduction

Barriers and associated back-barrier systems comprise ~ 15% of the global coastline (Stutz and Pilkey, 2011) and are amongst those environments most vulnerable to climate change and human influences (FitzGerald et al., 2018). Rising sea level, storm impacts on the barrier and the associated changes to inlets and tidal prisms are important considerations in the effective management of these systems. This is in addition to any human interferences such as dredging, mouth management and water regulations during droughts and floods (Cooper, 2003). A clear understanding of back-barrier dynamics, as linked to barrier/inlet functioning, is thus critically important for framing management decision making and intervention strategies (Cooper and Pilkey, 2004; Lazarus et al., 2015).

Examining the Holocene geological record of change in barrier/back-barrier systems and the linkages between inherited geological framework, sediment supply and dynamic forcing, can help in placing modern systems in geological context and in forecasting the short-term behaviour of modern systems under rates of sea-level rise that have not been experienced in the historical record. Likewise, the geological and morphological record provides a framework within which expected changes, vs changes related to management concerns, can be addressed (e.g. Brush, 1986; Anthony and Dobroniak, 2000; Pye and Allen, 2000; Pye and Blott, 2014). Management practice in estuaries, as in many other coastal systems, may often involve strategies to maximise diversity, restore habitats and preserve existing states that are often at odds with the geological and morphological trajectory of the system (e.g. Cooper and Jackson, 2021).

The coastal lagoons and estuarine lakes along the SE coast of Africa provide an excellent location for examining long-term geomorphic processes of interlinked-barrier and back-barrier environments. They originated as a series of branching fluvial systems, deflected by long-lived and stable Pleistocene-age barrier segments (Porat and Botha, 2008), which were then flooded during the rise and subsequent stabilisation of sea level during the Holocene (Wright et al., 2000; Benallack et al., 2016). Their Holocene back-barrier evolution is the result of the interaction between fluvial and marine forces, the dynamics of which are summarily recorded in the sedimentary deposits and infill of the system. Such records disclose detailed information on the timing and rate of change in reconstructing the long-term evolution of the coastal systems, including the barrier and associated marine connections, and can cast light on the overall coastal evolution and environmental history of the region (De Lecea et al., 2016). Contemporary systems in the region have reached different stages in their evolutionary pathway (e.g. in terms of sedimentary infilling some are relatively youthful (Cooper et al., 2012) while others are largely infilled (Benallack et al.,2016). This creates marked contemporary bio- and geo-diversity but also indicates their likely future evolutionary pathway, which should be important in steering management strategies.

This paper focuses on the Holocene evolution of Africa’s largest estuary, Lake St Lucia (Fig. 1) over the last ~ 8000 years. The system comprises several interlinked estuarine lake basins that have been subject to large-scale anthropogenic changes aligned with management strategies (Forbes et al., 2020). These include the separation of the major fluvial input, the Mfolozi River, from the estuary, the dredging of the St Lucia estuary mouth, canalisation of various fluvial conduits to the system (e.g the Mkhuze River), and forced breaching of the estuary mouth during droughts. These measures were introduced in an attempt to maintain a stable ecological and geomorphological state (or the appearance thereof) over short term management cycles at the decadal scale (Forbes et al., 2020). This paper aims to assess the Holocene evolution of Lake St Lucia to provide longer term geological context to the dynamic state of the system, and to better inform management strategies for Africa’s largest estuary. We show a unique back-barrier evolution that differs from other systems worldwide, and in turn requires tailored management strategies that align with the system’s evolutionary pathway over geological time scales.

2. Regional setting and background

Lake St Lucia, the largest estuarine system in Africa (Perissinotto et al., 2013), 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 back-barrier lagoon is separated from the ocean by a continuous, 100 – 140 m-high Pleistocene-Holocene barrier dune complex (Porat and Botha, 2008) and is fed by five rivers. The Mkhuze River in the north and the Mfolozi River in the south are the largest contributors to the supply of freshwater and sediment, and the upper ~ 10 m of sedimentary fill within the main lagoon basins consists predominantly of fluvially-derived fine silt and clays (Humphries et al., 2016).

The Mfolozi River was artificially separated from the main estuary in the early 1950’s, a practice which was maintained for the next 60 years (Forbes et al., 2020). This was implemented to allay concerns over excessive sediment delivered by the Mfolozi River to the mouth, causing it to remain closed for long periods of time. This was thought to be the result of canalisation of the river and the draining of adjacent wetlands for sugar cane cultivation.

The current fluvial discharge into Lake St Lucia is typically seasonal, flowing during the wet summer season, but typically reduced to seepage through bed sediments during winter. Persistent groundwater seepage occurs through shallow coastal plain aquifers, although this is estimated to contribute only a small component to the overall water balance of the system (Kelbe et al., 2013). The only contemporary link to the ocean is via a sinuous, 20 km-long channel known as the Narrows, though the estuary mouth is prone to prolonged periods of closure (Forbes et al., 2020). These closures are considered in a negative light by contemporary management and have been associated with hypersaline conditions during low lake levels that prompted mass invertebrate die-offs throughout the system (Pillay and Perissinotto, 2008; Nel et al., 2011). Since 2016, the connection to the Mfolozi River was re-stablished in the hopes that the increases in fresh water would establish a greater hydraulic head at the mouth and reinstitute a more regular open-closing cycle. This connection is maintained via a small channel along the barrier, bringing freshwater to the system (Forbes et al., 2020). Paradoxically, this resulted in a substantial accumulation of fine sediment in the mouth area, after which the mouth closed. The mouth was artificially breached in 2020 in an attempt to remove this excess sediment. When the mouth is open, tidal effects penetrate landward 14 km up the Narrows (Orme, 1975), but the waterbody system and lake basins are not tidal. With an average water depth of ~ 1.5 m, the different basins are subject to extreme changes in ecological state as a result of evaporation and variable river inflow as opposed to tidal effects.

The long-term geological history of the system has been reported on by Benallack et al. (2016) and Dladla et al. (2019). Gomes et al. (2017) further discuss some of the Holocene-age palaeo-environmental changes of the system using diatom assemblages. However, these observations pertain only to the northern sub-basins, or individual sub-basins, and thus do not constitute a full system appraisal. Future management strategies would benefit from a full system appraisal that would enable human interventions to be placed in proper perspective.

Estuaries are constantly evolving in response to sediment supply and sea-level change. The aim in this paper is to synthesise the Holocene evolution of the St Lucia system using both new and existing data. This will enable historical changes and human interventions to be placed in perspective and will provide a sound geological basis for the development of future management strategies.

2.2. Postglacial sea level history

The Late Pleistocene/Holocene sea level of the east coast of South Africa reflects a trend of stepped rise since the last glacial maximum (LGM) sea level of -125 m (Cooper et al., 2018). This paper is focussed on the last 10,000 years (Fig. 2) during which sea level reached the present and oscillated around it by a few metres. There are relatively few data for the period spanning 10000 to 7200 cal BP. However, Dladla et al. (2019) placed sea level at approximately -15 m ~ 9400 cal BP, based on the presence of tidal flat deposits at South Lake, and data from Maputo Bay, ~250 km to the north indicate a period of slow rise in sea level from 8500 cal BP (De Lecea et al., 2016). Sea level reached the current mean sea level (MSL) ~ 7000 cal BP (Cooper et al., 2018) (Fig. 2), and was followed by a pronounced highstand of +3.8 m between 6500 and 5500 cal BP. Sea level then fell to +1.6 m ~ 4950 cal BP around which it has oscillated between +1.5 and + 0.5 m until ~ 1000 cal BP (Cooper et al, 2018), before falling to present MSL.

3. Methods

3.1 Sediment coring and dating

Using a barge-mounted piston corer coupled to a percussion drill, three continuous sediment cores (NL-1, FB-1 and CB-2) were extracted from each of the main depocentres of the system (Fig. 1) in order to investigate the Holocene environmental change in each basin. Cores were sited to intersect the upper incised valley fills identified from the earlier intensive seismic-reflection surveys documented in Benallack et al. (2016) and Dladla et al. (2019). The maximum depth of core penetration varied between 13 and 16 m. Cores were sealed in the field and transported to the laboratory where they were split longitudinally and logged according to standard sedimentological procedures. These involved a visual examination of unit colour, consistency, macro-palaeontological content, grain size and shape, and sedimentary structures where evident (cf. Folk, 1980).

AMS radiocarbon dating was carried out on bulk organic carbon samples and, where possible, well-preserved whole shells (see Humphries et al., 2016). Analyses were carried out by Beta Analytic Incorporated, Florida, USA. Calendar calibrated ages were calculated using the Southern Hemisphere atmospheric curve SHCal13 (Hogg et al., 2013). Dating revealed basal ages for cores NL-1 (1543 cm), FB-1 (1591 cm) and CB-2 (1364 cm) of ~7600 cal. BP, ~8300 cal. BP and 9500 cal. BP, respectively. Age-models based on the radiocarbon chronology presented in Humphries et al. (2016) were applied in this study. Bayesian age-depth models for NL-1 and FB-1 were developed using Bacon 2.2 (Blaauw and Christen, 2011). A non-Bayesian ‘classical’ age-depth model (Blaauw, 2010) was developed for CB-2, due to marked changes in sediment accumulation rate in this core and resulting poor fit of the Bacon model.

3.2 Foraminiferal analysis

Cores were subsampled at 20 – 40 cm intervals for foraminiferal analysis, resulting in 67, 49, and 42 samples from NL-1, FB-1 and CB-2, respectively. Each sample was preserved in 70% ethanol and then washed over a nest of 500 µm and 63 µm sieves to remove silt, clay and shell fragments. The material from the 63 µm sieve was retained and sub-divided into eight aliquots using a wet splitter (Gehrels, 2002). An aliquot of each sample was air-dried and counted on a gridded picking tray using a stereomicroscope at 40x to 100x magnification. Additional aliquots were added where necessary to achieve the standard count size (100 specimens), whilst always analysing individual aliquots to completion. A count of 100 was considered sufficient (Southall et al., 2006) given the low species diversity at St Lucia. Identifications of foraminifera were confirmed via comparison with Debenay (2012), Horton and Edwards (2006), and Murray (1979).

Relative abundances of fossil foraminiferal assemblages for each site were plotted as percentages against depth and age using C2 software (Juggins, 2007). For each site the foraminiferal abundance was expressed as the number of individuals per 5 cm^3 of sediment. For the purpose of this study, small volumes of *Quinqueloculina Seminula*, *Quinqueloculina vulgaris* and *Quinqueloculine bidentata* were grouped to provide a solid database for statistical purposes. The palaeo-ecological environments represented by benthic foraminiferal assemblages were interpreted based on modern foraminiferal assemblages found in coastal environments along the southern African coastline (Cooper and McMillan, 1987; Wright et al., 1990; Murray, 2006; Ovechkina et al., 2010; Meric et al., 2014; Strachan et al., 2015, 2016, 2017).

3.3 Diatom analysis

Diatom results from cores NL-1 and FB-1 are presented in Gomes et al. (2017), and new sub-samples (20 – 40 cm intervals) from CB-2 were processed in this study using the same standard methods (Battarbee, 1986). A minimum of 300 valves were counted per sample in cases where diatom concentration allowed quantitative estimates. However, most samples analysed contained too few diatom valves for quantitative analysis and instead are used here as qualitative indicators of the paleoenvironment in addition to the more robust foraminiferal, sedimentological and seismic data.

3.4 Sulfur isotope chemistry

Total stable sulfur isotope composition ($\delta^{34}S$) of core CB-2 was determined at a downcore resolution of 20 – 30 cm. Samples were dried at 60 ^{0}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‰.

3.5 Terrain models

In 2016, the iSimangaliso Wetland Park commissioned a comprehensive LiDAR and bathymetric survey of the St Lucia system. Terrestrial Lidar was acquired from a fixed wing aircraft flying at an elevation of ~ 1050 m. A vertical accuracy of ~ 10 cm in the z domain was achieved, with an average density of 1.5 points per square meter. The data are presented as non-ground strikes. All data were related to multiple ground control points.

Single-beam bathymetry was collected on a 100 x 100 m grid across the entire system. The two data sets were then merged to produce a single digital elevation model with a resolution of 10 m in the horizontal, and 10 cm in the vertical. Due to ongoing management efforts, the data are restricted and as such only relative depths, as opposed to true depths referenced to MSL, are reported in this paper.

4. Results

4.1. Bathymetry and system geomorphology

The landward edges of the North and South Lake sub-basins are characterised by steep bedrock cliffs (Fig. 3a). South Lake forms the deepest sub-basin and is ~ 1 m deeper than the northern systems with an average seafloor elevation of -1.45 m below MSL. It is separated from the North Lake sub-basin by a shallow point at Fani's Island that marks a sediment spit that has extended from a steep set of Pleistocene-aged dunes to seaward, and which now abuts the cliffed western shoreline. This correlates with a bedrock high that marks a separating point between the southern incised valley sets and the northern incised valley sets (Fig. 3b). Several small, cuspate spits line the margins of South Lake, oriented NE-SW.

In contrast to the South Lake sub-basin, the North Lake is shallower with an average seafloor elevation of ~ -0.75 m below MSL. The basin is dominated by the broad and shallow bayhead delta of the Mkhuze River. Several long (≤ 4 km) and wide (≤ 500 m) spits are evident, however, these do not fully enclose smaller portions of the sub-basin (Fig. 3a). The bedrock surface is shallower where the two main peninsulas narrow at Hells Gate (Fig. 3b). To the east, a less well-defined Pleistocene dune occurs on the seaward shoreline of North Lake.

False Bay is dominated mostly by the bedrock cliffs that fringe the seaward side of the sub-basin and the bayhead deltas of the Mzinene, Nyalazi and Hluhluwe Rivers (Fig. 3a). The basin is shallow with a maximum seafloor depth of ~ 1.25 below MSL. Several incipient spits 100 m long and 50 m wide are associated with some of the cuspate shoreline protuberances defined by bedrock outcrop (Cooper et al., 2013). The northern portions of False Bay are mostly underlain by shallow bedrock (Fig. 3b).

4.2. Seismic stratigraphy of Holocene sediment and core context

4.2.1. False Bay

The upper 15 m of the False Bay stratigraphy is dominated by a series of incised valleys, the upper stratigraphy of which may be divided into four main units (1-4) (Fig. 4). The upper portions of these valley fills (Unit 1) comprise low to moderate amplitude drapes that onlap the bedrock surfaces of the valley walls and are often associated with gas blanking (Fig. 4). The lithofacies correspond to a homogenous silty clay succession deposited between ~8100 – 7000 cal. BP with the presence of *Spiroloculina* spp., *Triloculina* spp. and *Cassidelina subcapitata*.

The overlying unit (Unit 2) comprises a sigmoidal prograding, blanketing sediment body that onlaps the valley high points and downlaps the flat-lying upper surface of the underlying seismic facies. It comprises a similarly monotonous succession of silty clay characterised by the dominance of *Ammonia tepida*, accompanied by *Balticammina pseudomacrescens* and *Haplophragmoides wilberti*. This was deposited between ~7000 and 3800 cal. BP, with occasional silt lenses containing *Triloculina* spp., *Quinqueloculina* spp. and *Rosalina bradyi* deposited between ~5500 and 4000 cal. BP. Where prominent morphological constrictions in the system arise from the bedrock margins (Fig. 5a and b), Unit 2 may also occur as a ≤ 5 m-thick strongly sigmoid prograding moderate amplitude reflector package that onlaps and downlaps the bedrock surface (Fig. 5c). Where associated with fluvial entrance points, small (25 m-wide and 4 m-deep) channels and accompanying 3-4 m-thick lenses of prograding reflectors occur (Fig, 5d). These downlap the bedrock surface.

A third sediment package (Unit 3) is marked by a similar, sigmoid prograding sediment body that downlaps the upper surface of (Unit 2) (Fig. 4). This basal surface is marked by a sandy layer, over which an upward coarsening package of silt to fine sand occurs (~2700 – 1000 cal. BP). This unit is marked by increased abundances in *Haynesina depressula*, *A. tepida*. and *Nonion* sp.

The capping fill of False Bay is characterised by a mostly uniform, metre-thick sediment body that comprises flat-lying, low amplitude reflectors (Unit 4). The corresponding foraminiferally-barren silty clay represents the last 1000 years of deposition (Fig. 4).

4.2.2. North Lake

Like False Bay, several incised valleys are apparent in the North Lake stratigraphy. Three main units can be recognised in relation to the litho- and seismic stratigraphy (Fig. 6). The upper valley fill (Unit 1) comprises a series of onlapping drapes that correspond to a fining upward package of medium sand to silt. This was deposited between ~8300 – 7700 cal. BP and is dominated by the presence of *Spiroloculina* spp., which accounts for ~70% of the foraminifera present in this unit.

This is overlain by a second drape package (Unit 2), with occasional gassy washouts. Isolated bodies of high angle, oblique tangential prograding reflectors are apparent (Fig. 5c; 6). The boundary between Unit 1 and 2 is marked by the introduction of *Balticammina pseudomacrescens* and *Helenina anderseni*. The overlying package of clays (Unit 2) is dominated by *A. tepida,* with sporadic occurrences of *Triloculina* spp., *Triloculina rotunda*, *Hanzawaia grossepuncta* and *Cibicides refulgens* between ~6500 and 2500 cal. BP. Species diversity generally increases between ~4500and– 3500 cal. BP.

Where the isolated packages of higher angle reflectors occur, these do not reflect changes in the primary lithofacies, however, sharp peaks in *Triloculina* spp., *Balticammina pseudomacrescens* and *Nonion sp*. are noted (~ 2700 cal. BP). Where associated with fluvial entrance points, Unit 2 also forms lenses with prograding internal geometries, up to 5 m-thick, that rest directly on the bedrock surface (Fig. 5d). The upper 1 m of the North Lake succession comprises clays with occasional sand lenses (Unit 4) and is continuous with the capping seismic unit of False Bay (Fig. 4). Like False Bay, the upper fill material is devoid of foraminifera, and was deposited from 1000 cal. BP to present day.

4.2.3. South Lake

Multiple incised valleys are evident in the South Lake geophysical record (Fig. 7 and 8). The uppermost package here (Unit 1) is intersected by the core and comprises a draping set of alternating low to high amplitude reflectors. This package corresponds with a rhythmically interbedded very fine sand clay succession of 9500 cal. BP to ~ 8200 cal. BP (Fig. 7). From ~8900 to 8200 cal. BP, *Quinqueloculina* spp., *Triloculina* spp., *Spiroloculina* sp. and

Miliolinella spp are dominant. This period coincides with strong enrichment in sedimentary δ34S.

This succession is in turn overlain by Unit 2, a basal sand that fines upward into well-laminated silty clay. This corresponds to a small, 10 m-wide, 5 m-deep channel filled by draped, high amplitude reflectors (Fig. 7). This represents the period from ~8200 cal. BP, where *A. tepida* and *Cassidelina subcapitata* are dominant, accompanied by *Balticammina pseudomacrescens*, *Cribroelphidium articulatum* and *Haplophragmoides wilberti*. A corresponding decline in $\delta^{34}S$ after ~8200 cal. BP is evident, as well as an increase in abundance of brackish and fresh-brackish diatom species (Fig. 7; far right).

This succession terminates with a medium sand horizon, over which uniform silty clay was deposited (Unit 3). In the seismic record, this package corresponds to ≤ 3 m-thick, prograding, high amplitude reflector bodies (Fig. 7). These are often associated with elongate, cuspate bathymetric high points in the South lake system (Fig. 5b). Where proximal to fluvial sources, lenses of sigmoid prograding reflectors downlap bedrock (Fig. 5e). These deposits correspond to a foraminiferally barren zone deposited between ~5500 and 2000 cal. BP (Fig. 7). Diatoms were conversely well preserved at this time and are characterised by mixed assemblages.

The capping succession of Unit 4 is, like the other sub-basins, marked by alternating, low to moderate amplitude parallel reflectors (Fig. 7). This corresponds with a silty clay, with a relatively low foraminiferal diversity and in contrast to the other basins, not devoid of foraminifera and is instead dominated by the species *A. tepida*.

5. Discussion

Below we outline the Holocene evolution of the three separate basins and their evolutionary trajectory from separate incised valley systems to a contiguous whole. These long-term dynamics indicate the present configuration to have been achieved relatively recently (within the past 2000 years) through a process of basin drowning, enclosure by marine barriers and flooding that connected the formerly isolated basins. These dramatic changes highlight the need for a full understanding of the long term morphodynamics of the estuary to inform management decision-making in the contemporary system.

5.1. North Lake

In the North Lake basin, well preserved, intertidal to shallow inner-shelf benthic foraminifera were present from 8300 to 7700 cal. BP. The dominance of *Spiroloculina spp*., an inner-shelf marine taxon suggests a strong marine connection at that time. The seismic record shows the base of the core resting in a small channel within a draped accumulation of low-amplitude bedrock-onlapping reflectors. This seismic package has been interpreted as the central basin of a wave-dominated estuary (Benallack et al., 2016). The small channel is similar in size and scale to tidal channels found within the central basin of contemporary estuaries of the region (Cooper, 2001). In association with the micro-palaeontological assemblages, we consider this to represent a period with an open ocean connection in the north. Given the core location, and close approximation of palaeo-sea level to that of today's MSL, this indicates a tidal prism large enough to exchange seawater ~ 10 km inland. This is in keeping with the degree of flood tide incursion documented by Wright and Mason (1993) for the contemporary St Lucia estuary, and indicates a similar tidal prism to that of present.

From ~7700 to 1000 cal. BP, the abundance in inner-shelf species declines and species common to the intertidal and brackish lower marsh environments of the South African east coast (*Balticammina pseudomacrescens*, *Helenina anderseni* and *Miliammina* sp.; Strachan et al., 2017) appear. This reduction in marine influence points to a shallowing of the back-barrier and an overall reduction in back-barrier volume as the environment transformed to more marsh-like environment. The timing relates to a period when sea level fell from its late Holocene highstand (Fig. 3). The isolated packages of high angle prograding reflectors (in Unit 2-Fig. 6) are akin to spits that formed during wind-wave driven sediment redistribution (see Nutz et al., 2015), which also points to back-barrier aggradation at this time, likely accompanying the sealing of the northern ocean connection at Leven Point.

As the system gradually sealed off from the ocean, fluvial influences became more dominant. We interpret the 5 m-thick progradational sediment bodies of Unit 2 associated with fluvial entrance points as relict bayhead deltas (Fig. 5d). In North Lake, the Mkhuze River delta is preserved as an isolated feature stranded on the bedrock surface of the lake margin. Its preservation as a full set of sigmoidal reflectors (Fig. 5d) suggests minimal reworking and in-place drowning of the delta form. We consider their drowning the result of rapid freshwater flooding (from both river and groundwater sources) of the back-barrier, thus offsetting the delta to near its present position (Fig. 3). The northern-most oceanic connection had closed at ~ 6200 cal. BP (Benallack et al., 2016) which aided in this process by rapidly impounding the back-barrier waters.

Sporadic occurrences of inner-shelf marine species (*Triloculina* spp., *Triloculina rotunda, Hanzawaia grossepuncta* and *Cibicides refulgens;* Meric et al., 2014) suggest intermittent marine incursions between ~6500 and 2500 cal. BP and confirm the diatom-based observations of Gomes et al. (2017). They interpreted this period as characterised by a low-lying northern barrier with periodic marine inundations associated with overwash or breaching during occasional large storms. The peak of these incursions postdates the timing of the peak Holocene highstand of +3.5 m ~ 5100 cal. BP (Cooper et al., 2018).

From ~2700 to 1000 cal. BP the prevalence of intertidal-marine species, and subordinate lagoon species, suggests the formation of an isolated or distal brackish waterbody. An important finding is that this time interval is also characterized by occasional periods of hypersalinity or desiccation (Humphries et al., 2016). In common with the modern system, these intervals likely coincided with droughts and a lack of tidal inflow. The absence of foraminifera between ~1000 and 30 cal. BP is indicative of an isolated back-barrier basin dominated exclusively by freshwater recharge as opposed to tidal exchanges.

5.2. False Bay

The record from the more sheltered False Bay reflects a similar geomorphic evolution to North Lake. An early (~8100 – 7000 cal. BP) dominance of inner-shelf marine species (*Spiroloculina* spp., *Triloculina* spp. and *Cassidelina subcapitata*) indicates estuarine conditions with an open marine connection in North Lake. A general reduction in the efficacy of this connection to the ocean is reflected in the dominance of *A. tepida*, accompanied by several other brackish species (*Balticammina pseudomacrescens* and *Haplophragmoides wilberti*) that point to shallowing of the system ~7000 cal. BP. This interpretation is bolstered by the sigmoid prograding nature of Unit 2 in seismic section (Fig. 5c) which is indicative of spit development in the back barrier (e.g. Ashton et al., 2009), a process associated with shoreline emergence and promoted by bedrock constrictions of the shoreline that allow the capture of sediment transported in winddrive littoral cells. This is coeval with the lake-marginal beach ridges that began to develop ca 6240 cal. BP (Botha et al., 2018), and which has continued periodically until ca 600 cal. BP.

Foraminiferal assemblages show that the effects of the closure of the North Lake inlet ~ 6200 cal. BP were experienced first in the sheltered False Bay sub basin. The sheltering by the rocky peninsulas to the east, coupled with the proximity to fluvial sources drowned both spits and in situ as the impounded water levels rose rapidly.

As with the North Lake sub-basin, sporadic appearances of intertidal-marine species (*Triloculina* spp., *Quinqueloculina* spp. and *Rosalina bradyi*) between ~5500 and 4000 cal. BP highlight intermittent marine inputs. Their spread into False Bay from the North Lake basin may have been assisted by wind-driven currents (see Schoen et al., 2014). These conditions post-date the Holocene highstand, inlet closure and reflect marine storm impingement over the low-lying barrier at Leven Point.

From ~2700 cal. BP marine species are absent and marginal marine-brackish species, namely *Haplophragmoides wilberti* and *Cribroelphidium articulatum* emerge. Species tolerant to fluctuations in salinity (*A. tepida* and *Nonion* sp.), together with marginal-marine and intertidal-marine species (*Haynesina depressula*, and *Elphidium* spp.) are also common.

5.3. South Lake

The draped reflector pattern and corresponding interbedded clay-sand rhythmites points to the development of a sub-basin-wide system of tidal flats at ~ 9500 to 8200 cal. BP. Dladla et al. (2019) consider this to be indicative of a period of comparative sea-level stability. The sediment reflects a strong marine connection, evidenced by species commonly associated with intertidal and marine environments of the South African east coast (*Quinqueloculina* spp., *Triloculina* spp., *Spiroloculina* sp. and *Miliolinella* spp; Strachan et al., 2016). This is further supported by strong enrichments in sedimentary δ^{34}S. Meyer et al. (2001) described cores that intersected an estuarine succession at Mission Rocks, directly adjacent to the South Lake sub-basin. A coast parallel seismic profile from just inshore of the barrier also reveals multiple incised valleys (Fig. 8), with associated smaller channels in the upper stratigraphy that we have previously interpreted as tidal channels (Dladla et al., 2019). These rest within packages of prograding reflectors akin to flood tide deltas or spits in a similar arrangement to inlet-associated flood tide deltas reported by Simms et al. (2006) from Mustang Island, Texas. We thus infer an open ocean connection near Mission Rocks that connected the South Lake basin to the ocean.

Up to ~ 5500 cal. BP, intertidal- and marginal-marine species (viz. *A. tepida* and *Cassidelina subcapitata*) are dominant, accompanied by marginal marine-brackish species (*Balticammina pseudomacrescens*, *Cribroelphidium articulatum* and *Haplophragmoides wilberti*). The associated decline in marine species signals the transition from an estuarine-marginal marine environment to a more marine-restricted, brackish environment. This reduction in marine influence during this time is indicated by a marked decline in δ^{34}S after ~8200 cal. BP. This is supported qualitatively to some extent in the increasing abundances of brackish and fresh-brackish diatom species (Fig. 7; far right).

The seismic records also show that after 8200 cal. BP, smaller channels were present within the larger incised valley channel (Unit 2). This can be considered consistent with a reducing tidal prism (Walton and Adams, 1973). The corollary, barrier segmentation and inlet development, would produce increased tidal prisms and scour effects (Mallinson et al., 2018), which could account for the generation of smaller tidal channel incisions in the record. However, the continuous, Pleistocene-age high-elevation barrier sequence to seaward (Porat and Botha, 2008) tends to favour the former argument of closure of ocean connections and a reduction in the tidal influences in the northern sub-basins.

Sediment from the period ~5500 – 2000 cal. BP is barren of foraminifera. Diatoms, however, were well preserved at this time and are characterised by mixed assemblages. Together, this suggests the presence of an isolated back-barrier basin unconnected to the ocean. This is supported by $\delta^{34}S$-depleted (-9 to -25‰) sediments that indicate the dominance of sulfate reduction under anoxic conditions. The inferred closure of the southern ocean connection allowed for the in situ drowning of both bayhead deltas and spits (Fig. 5e and 7) of Unit 3 by rising lake levels. Some of these depositional features maintain some seafloor expression to the present (Fig. 5b).

Sediments from ~2000 cal. BP to present have relatively low species diversity and are dominated by the foraminiferal species *A. tepida*. The parallel, flat-lying reflectors that drape the spits and underlying stratigraphy along the system margins point to deposition in quiet water lagoonal conditions that characterise the modern system in all three basins.

5.4. Differential basin evolution

The differences in sub-basin configuration and environment during the Holocene reflect differential responses to sea-level, evolving geomorphology and lake level and are mediated by their relative positions within the system (Fig. 9). The North and False Bay basins on the one hand, appear to be quite distinct from the southern basin in terms of their Holocene stratigraphy until 2000 cal. BP. Their divergent evolution alludes to their having evolved as separate basins until a geomorphic threshold was crossed and the contemporary lagoon system was formed.

At the start of the Holocene, two separate incised valley systems connected the ocean to the St Lucia system in the north and south basins, respectively (Fig. 9a). The composite coastal barrier complex was punctuated by two inlets, one serving each tidal basin. The northern inlet closed ~ 6200 cal. BP (Fig. 9b) and the southern basin sealed its connection ~ 5500 cal. BP (Fig. 9c). Both appear to have breached periodically after closing up to about 2000 BP. By comparison with modern lagoons on the same coast, breaching may be related to marine storms (Bond et al., 2013; Green et al., 2013) and/or increased freshwater discharge (Cooper, 1990, Cooper et al., 1989).

Prior to ~ 5500 cal. BP, the southern basin had an open connection to the ocean, however its limited lagoon area and relatively high fluvial sediment supply were in direct contrast to the northern basins (Fig. 9a and b). The relative fluvial dominance in the southern portion of the system is consistent with a smaller tidal prism and consequently smaller degree of tidal exchange with the ocean along the lines of the modern river dominated estuaries described by Cooper (1990). This in turn reflects the basin’s smaller size. In the north, the presence of a variety of corals on the shores landward of the northern basin attests to multiple prior phases of a large open-water marine embayment (Cooper et al., 2013), a phenomenon not observed elsewhere in the system.

From 6200 cal. BP, sediment from multiple fluvial sources began to fill the northern basins, and brackish-water deposits are intercalated with sediment derived from brief marine incursions, interpreted as overwash events (Gomes et al., 2017). This preceded closure of the southern ocean connection by ~ 700 years. In the south basin, inlet sealing (Fig. 9c) was accompanied by a rapid reduction in sediment supply, as evidenced by the in-place drowning of the southern bayhead deltas and no further delta development. Notably, the reduced fluvial sediment supply, compared to the northern basin, also saw a reduction in input of muddy fluvial materials.

In the southern basin, marine incursions were significantly less frequent than in the north and we postulate that this may have been due to a higher and wider barrier. Upon closure of the inlet, the Mfolozi River began to discharge into the Ocean in its pre-1950's position. Indeed, periodic avulsion of the Mfolozi River, which continues to the present day (Grenfell et al., 2009), may have been a factor in abandonment and closure of the former inlet.

The closure of both ocean connections promoted the in-place drowning of the main bayhead deltas and spits of the north and south basins as the consequent impoundment of fluvial inputs caused water levels to rise (Fig. 9d). Water impoundment at 2000 cal. BP promoted overspilling of the topographic high point in the vicinity of Fanie's Island that had separated the two basins. Associated flooding of the basin margins enabled the combined water body to expand laterally, such that it achieved a surface water connection with the inlet of the adjacent Mfolozi River. By 2000 cal BP, all basins shared a similar uppermost stratigraphic package of foraminiferally barren sandy silt, apart from the southern basin (Fig. 9d). We consider the appearance of *A. Tepida* in the record a result of increased wind-driven transport between the basins as their fetch increased with connection (e.g. Schoen et al., 2014). This period marks the connection between all basins and the development of a contiguous back-barrier lagoonal waterbody fronted by a continuous barrier to seaward. This provides an age constraint for the formation of the Narrows and the contemporary connection to the ocean, which likely only formed within the last 2000 years once lake levels reached a point where waters were diverted southward to meet the Mfolozi River.

Lake St Lucia has transformed rapidly over the last 8000 years, producing geomorphological and hydrological changes that have fundamentally altered ecosystem functioning. The modern system is now dominated in its northern areas by fluvial inputs and progradation of bayhead deltas of the small rivers which enter the system (Fig. 9e). This is accompanied with the general segmentation of the system by wind-driven modification of the lagoon shorelines (Botha et al., 2018) and a trend towards gradual isolation of the basins into smaller sub-basins including shallow pan and wetland areas (Fig. 9e). Indeed, these basins have faced wholesale desiccation linked to El Niño cycles during this phase in their evolution (Humphries et al., 2016).

The contemporary Lake St Lucia thus represents an advanced stage of infill in its geological trajectory. Even with stable lake levels, the system is on a natural trajectory that will eventually result in its transformation into a series of swamps or wetlands in response to ongoing fluvial delta progradation and infilling of the limited available accommodation space. Such processes are seldom acknowledged in estuarine management policies, which instead focus on maintaining a set of goals linked to the present (transient) state of the estuary (e.g. sufficient water levels in the lakes, an opening and closing of the mouth as per the pre-intervention state, limiting hyper-saline conditions). These goals seek to maintain a condition from which the system is departing through natural processes of change. The current management strategy thus conflicts with the natural long-term evolution of the system. St Lucia is not alone in this respect; conservation in many coastal systems involves goals and strategies to maximise diversity, restore habitats and preserve existing states that are often at odds with the natural direction of environmental change (Grenier, 2000; Cooper and Jackson, 2021).

6. Conclusions

Distinct differences in fauna, sedimentology and seismic structure characterise the back barrier evolution of the two main depocentres of Africa's largest estuary. The modern St Lucia system has evolved from two separate incised valleys, formed in the Late Pleistocene. These exhibit different responses to local sediment supply conditions in the context of a shared sea level history. During transgression, tidal inlets were established in the north (at Leven Point), and in the south (near Mission Rocks). In the south, limited lagoon area and a high sediment supply contrasted with the north's more dominant marine influences. The inlets sealed ~ 6200 cal yr BP in the north and ~5500 cal yr BP in the south, after which, fluvial deposition in the form of bayhead deltas occurred, intermingled with wind wave-driven segmentation of the back barrier. Water impoundment behind a now contiguous barrier caused the overtopping of a bedrock high that had formerly separated the adjoining incised valley systems. The contemporary estuarine system became established only ca. 2000 cal yr BP, and is controlled now by hydrological and wind forcing that cause sub-basin segmentation into pans and isolated wetlands. The modern inlet consequently formed by back-barrier impoundment and overspilling that created a new morphodynamic pathway for the system.

In the case of St. Lucia, our studies have revealed a far more complex evolution than previously envisaged. The system comprises several sub-systems that evolved separately and rapidly, completely dependent on previous inlets that were spatially separated from the very recent (~

2000 year old) contemporary one. Their closure and sealing were natural phenomena which played an integral part of the normal evolutionary trajectory of the estuary as a whole. The present recurring hypersaline conditions and desiccation intervals appear to have occurred more commonly than in the geological past than considered by management plans of today. Likewise, the move of the system towards a wetland or pan-like state should be expected given the contemporary stability in sea levels and continued segmentation of the back barrier over the last ~6000 years. This study emphasizes how short-term perceptions, mostly negative, of aspects of the natural dynamics of Africa's largest estuary, may indeed be unfounded when juxtaposed with the natural trajectory on which the system is on. Importantly, we hope this study opens dialogue and debate between managers, biologists, ecologists and geologists working not just in St Lucia, but in other similar systems globally.

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Figure captions

Figure 1. Locality map of the study area. Core locations FB-1, NL-1 and CB-2 are provided together with the seismic reflection coverage. Note the previous course of the Mfolozi River (in red) prior to its separation from the shared St Lucia/Mflozi Estuary.

Figure 2. a) Lidar and single-beam bathymetry-derived elevation model of the St Lucia system. Note the strong division of the modern system into basins, separated by bedrock promontories and spits (e.g. Fani's Island). b) Sediment isopach map for the system detailing the underlying bedrock structure (modified from Benallack et al., 2016). The Fani's Island region that separates the northern basins from the southern, is underlain by a shallow bedrock high.

Figure 3. a) Holocene sea level history of the east coast of South Africa (from Cooper et al., 2018). b) System-wide changes to the system morphology in relation to sea-level trends (discussed further in the paper).

Figure 4. Seismic reflection data and interpretation, together with the core lithology of FB-1, age model (after Humphries et al., 2016) and major palaeontological assemblages for the False Bay sub-basin. Seismic line location shown in Fig. 1. Brackish to marine gradient signifies changes in salinity based on Strachan et al. (2015).

Figure 5. a) Digital elevation model detailing the False Bay and North Lake basins and the location of seismic sections c,d and e. Note the morphological constrictions of the bedrock margins in the False Bay area. b) Elevation of the South Lake/Fani's Island area and the

location of seismic profile e. Note the elongate cuspate bathymetric highs of South Lake. c) Seismic reflection profile collected over a spit in False Bay, note the sigmoid prograding package of high amplitude reflectors. d) Seismic reflection profile of the Mkhuze bayhead delta comprising steep, sigmoidal prograding reflectors. Note the easterly prograding spit to the left. f) Seismic reflection profile of a bayhead delta in South Lake, comprising a lens of sigmoidal reflectors that downlap bedrock.

Figure 6. Seismic reflection data and interpretation, together with the core lithology of NL-1, age model (after Humphries et al., 2016) and major palaeontological assemblages for the North Lake sub-basin. Seismic line location shown in Fig. 1. Brackish to marine gradient signifies changes in salinity based on Strachan et al. (2015).

Figure 7. Seismic reflection data and interpretation, together with the core lithology of CB-2, age model (after Humphries et al., 2016) and major palaeontological assemblages for the South Lake sub-basin. Seismic line location shown in Fig. 1. Brackish to marine gradient signifies changes in salinity based on Strachan et al. (2015).

Figure 8. Interpreted and uninterpreted coast-parallel seismic profile from just inshore of the barrier in South Lake. Note the smaller channel features (highlighted by arrows) formed within the larger valley network, and found in association with prograding reflector packages, interpreted as spits/flood tide deltas in the back barrier.

Figure 9. Evolutionary model of the St Lucia system. a) 9400 cal. BP., estuaries form in two separate incised valley systems, separated by bedrock high. b) 6200 cal. BP., the inlet that was established with the Indian Ocean seals to the north, fluvial back flooding occurs and bayhead

deltas are drowned. In the south, barrier growth restricts the oceanic connection, reducing tidal prism. c) 5500-2000 cal BP., bayhead deltas and spits are drowned in the south with the sealing of the inlet. Fluvial inputs now dominate the two basins, segmentation via wind wave reworking occurs and is super-imposed by climate driven desiccation cycles (Humphries et al., 2016). d) 2000 cal. BP., back barrier water levels impound sufficiently to laterally breach the bedrock high, waters expand in the back barrier and connect to the Mfolozi River, the pre-1950's inlet associated with the Narrows developed. Deposition of Unit 4. e) Today, segmentation occurs around the bedrock high, beginning a new phase of basin isolation. f)Tthe future? Given reduced oceanic connections, Africa's largest wetland and biodiversity hotspot evolves to a series of wetlands and pans associated with fluvial sources.

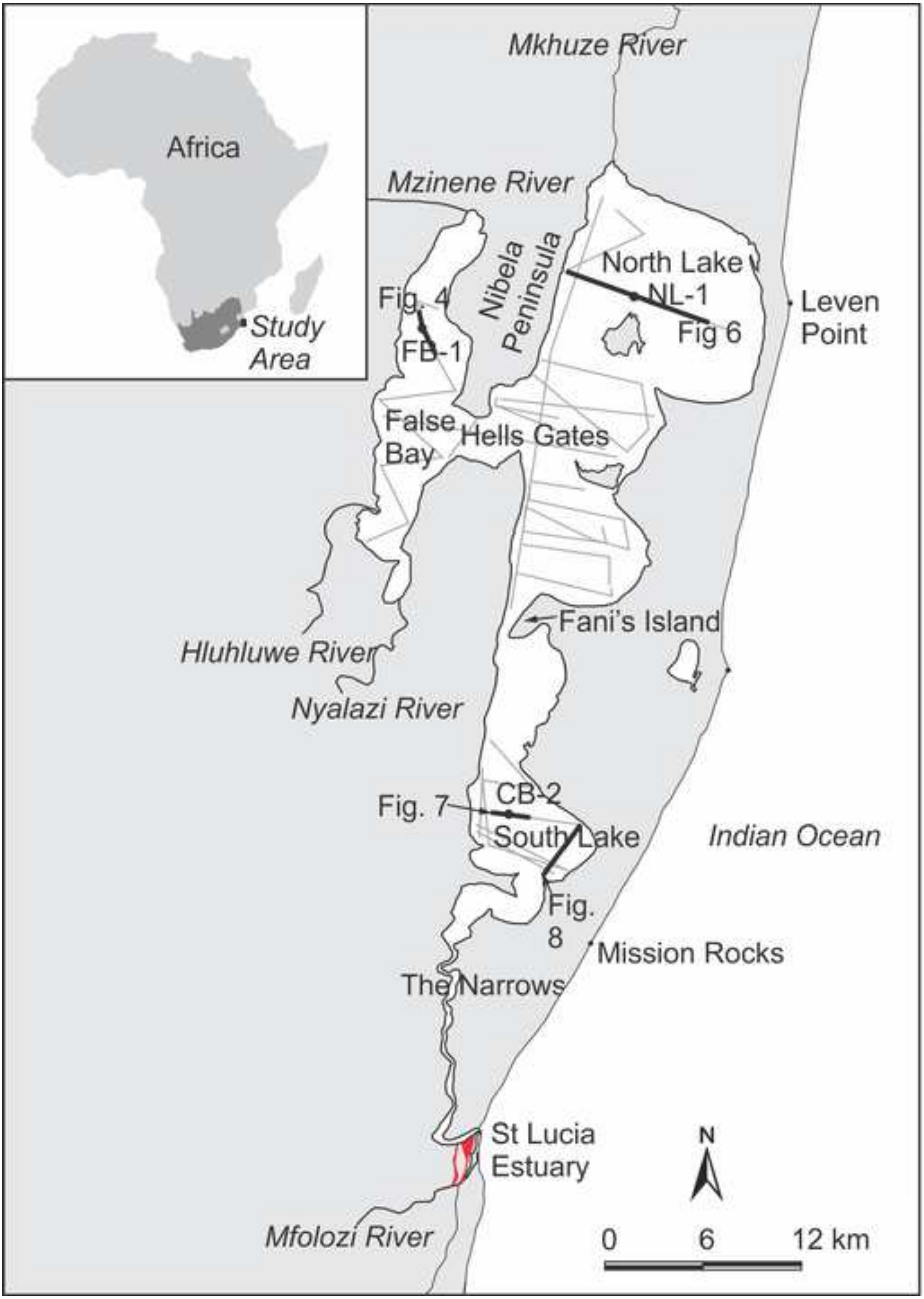
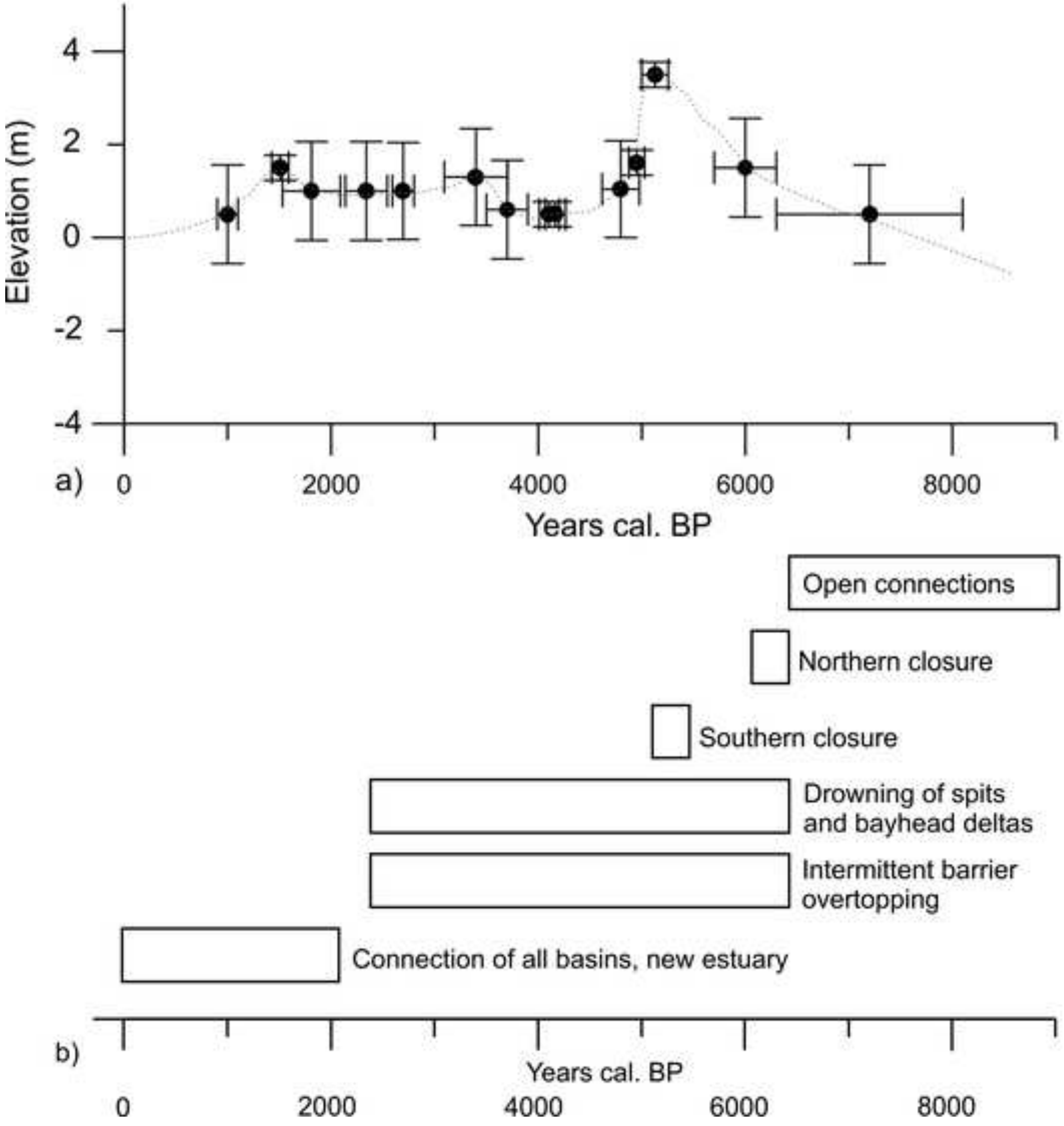

Africa
Study Area
Mkhuze River
Mzinene River
Nibela Peninsula
North Lake
NL-1
Fig 6
Leven Point
Fig. 4
FB-1
False Bay
Hells Gates
Fani's Island
Hluhluwe River
Nyalazi River
Fig. 7
CB-2
South Lake
Indian Ocean
Fig. 8
Mission Rocks
The Narrows
St Lucia Estuary
Mfolozi River
N
0
6
12 km

Figure 2


Elevation (m)
4
2
0
-2
-4
a)
0
2000
4000
6000
8000
Years cal. BP
Open connections
Northern closure
Southern closure
Drowning of spits and bayhead deltas
Intermittent barrier overtopping
Connection of all basins, new estuary
b)
Years cal. BP
0
2000
4000
6000
8000

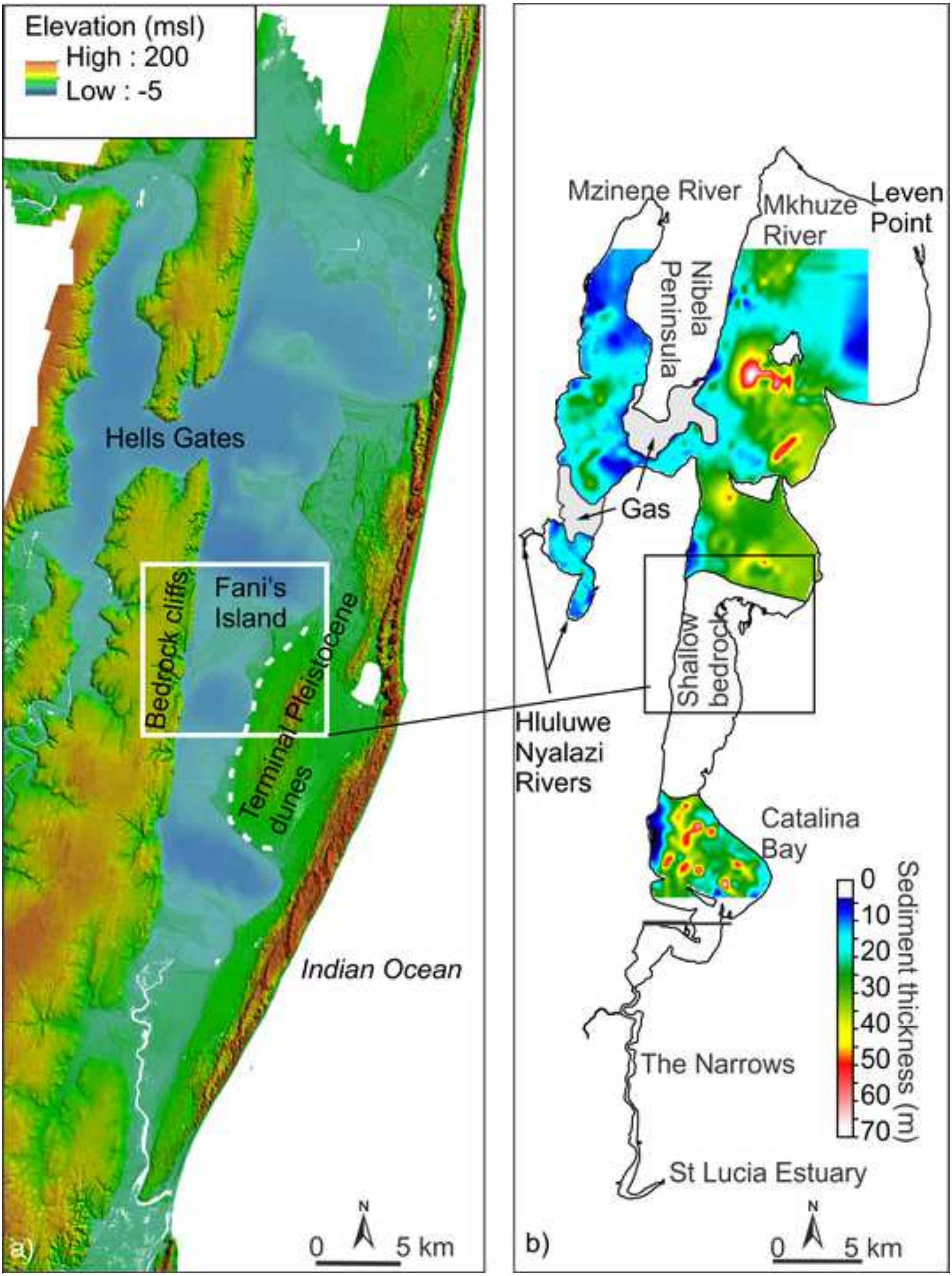
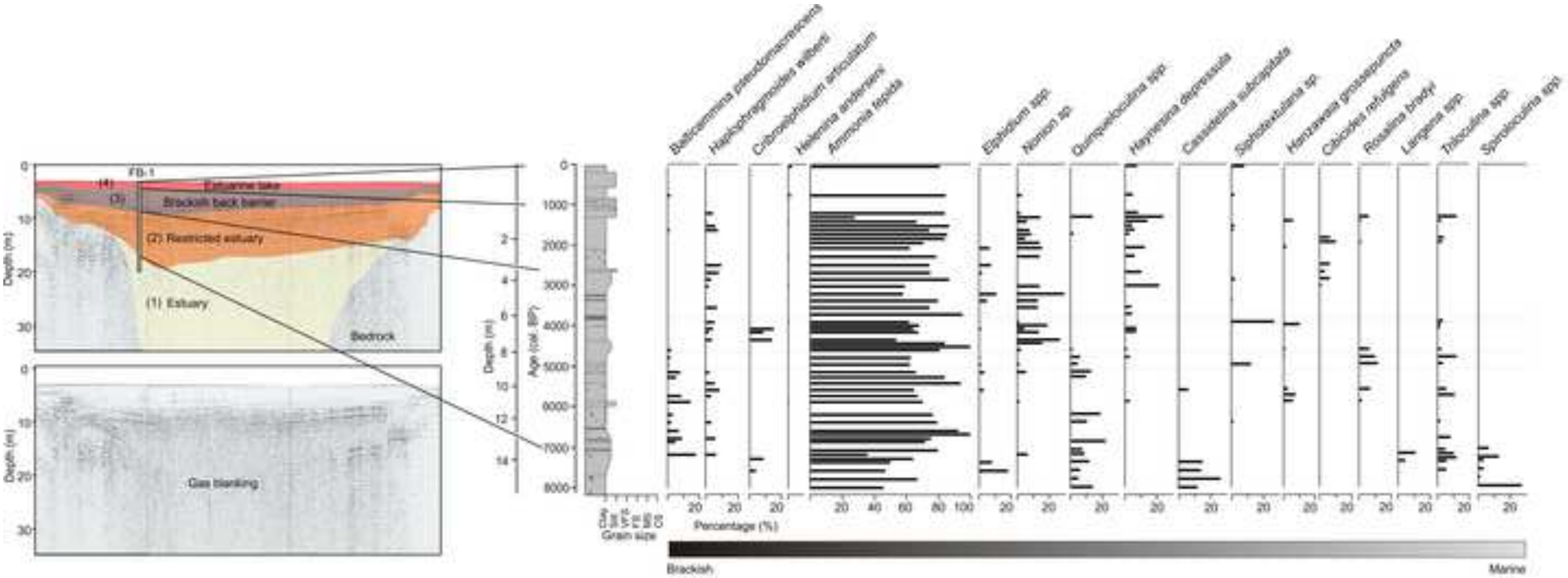

Elevation (msl)
High : 200
Low : -5
Hells Gates
Bedrock cliffs
Fani's Island
Terminal Pleistocene dunes
Indian Ocean
a)
N
0
5 km
Mzinene River
Mkhuze River
Leven Point
Nibela Peninsula
Gas
Shallow bedrock
Hluluwe Nyalazi Rivers
Catalina Bay
Sediment thickness (m)
0
10
20
30
40
50
60
70
The Narrows
St Lucia Estuary
b)
N
0
5 km

Figure 4


FB-1
(4) Estuarine lake
(3) Brackish back barrier
(2) Restricted estuary
(1) Estuary
Bedrock
Gas blanking
Depth (m)
0
10
20
30
Depth (m)
2
4
6
8
10
12
14
Age (cal. BP)
0
1000
2000
3000
4000
5000
6000
7000
8000
Clay
Silt
vfs
fs
ms
cs
Grain size
Balticammina pseudomacrescens
Haplophragmoides wilberti
Cribroelphidium articulatum
Helenina anderseni
Ammonia tepida
Elphidium spp.
Nonion sp.
Quinqueloculina spp.
Haynesina depressula
Cassidulina subcapitata
Siphotextularia sp.
Hanzawaia grossepunctata
Cibicides refulgens
Rosalina bradyi
Lagena spp.
Triloculina spp.
Spiroloculina spp.
20
40
60
80
100
Percentage (%)
Brackish
Marine

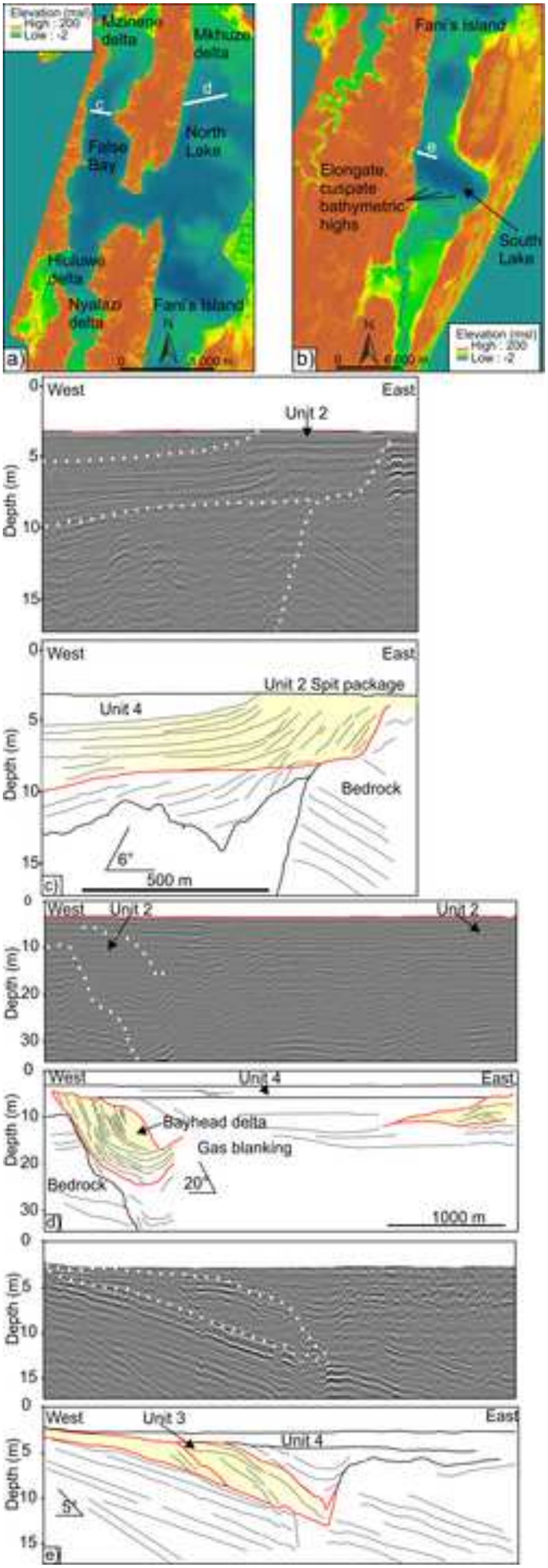
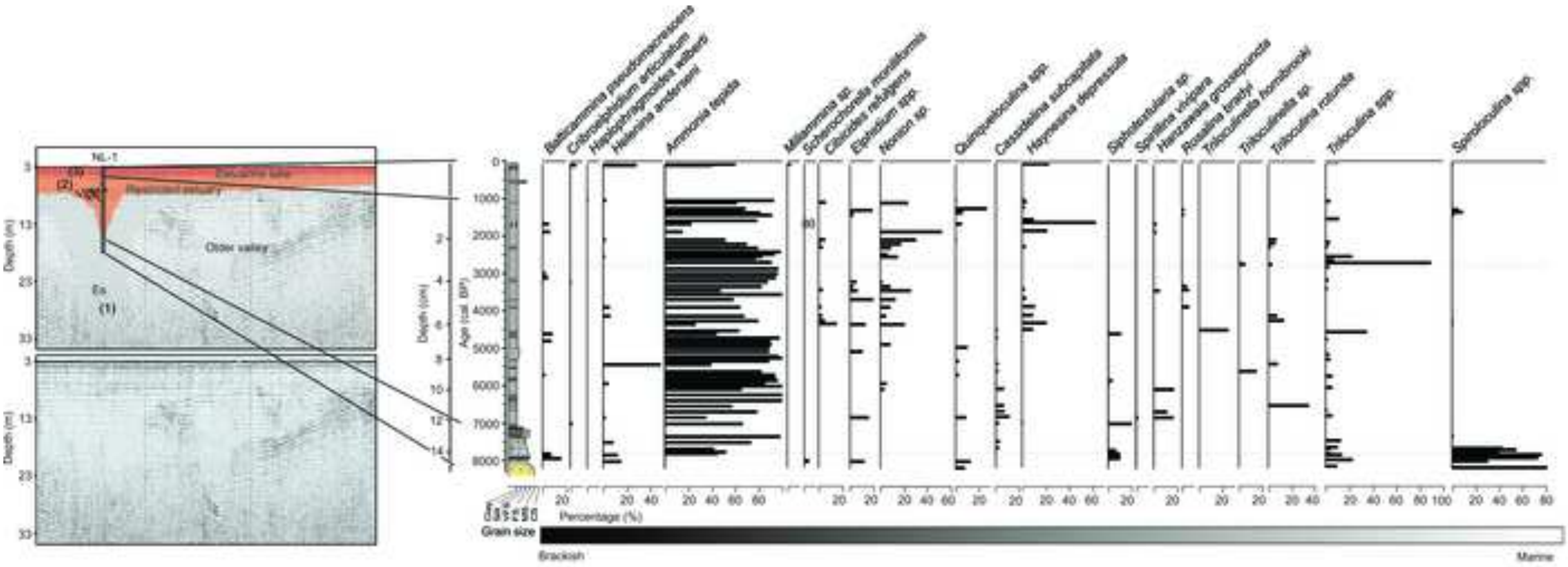
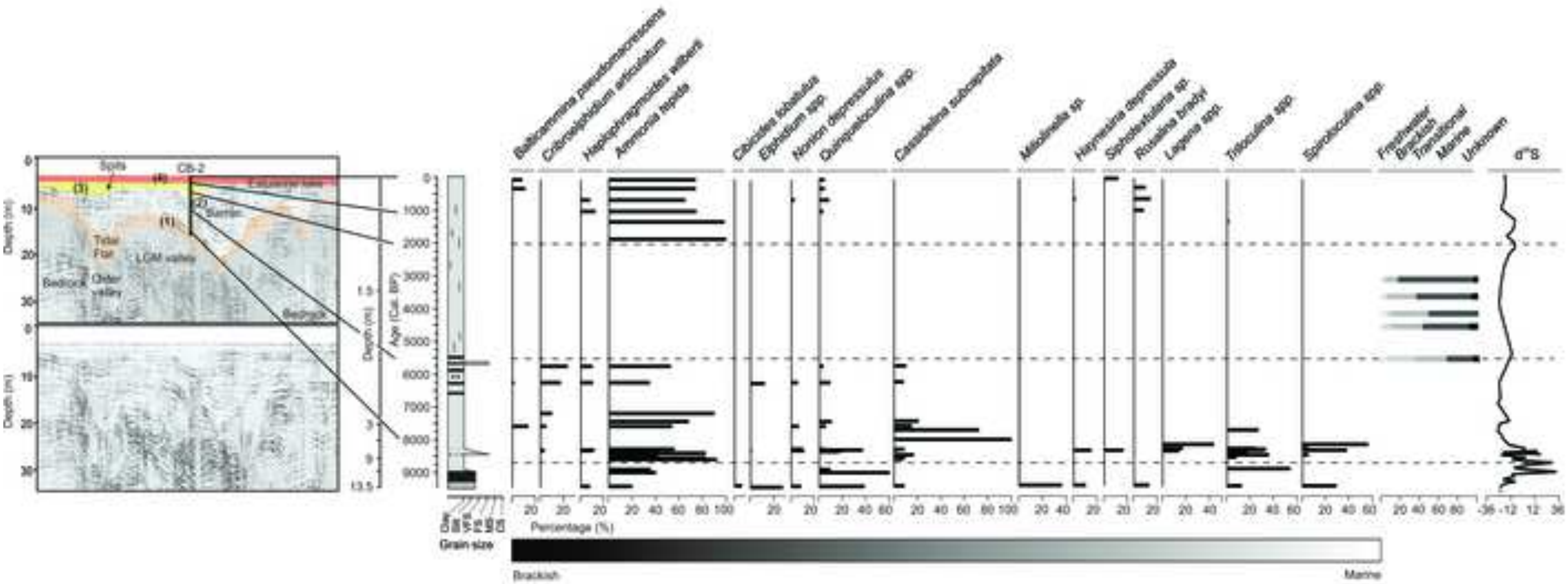

Elevation (msl)
High : 200
Low : -2
Mzinene delta
Mkhuze delta
c
d
False Bay
North Lake
Hluhluwe delta
Nyalazi delta
Fani's Island
N
0
1,000 m
a)
Fani's Island
e
Elongate, cuspate bathymetric highs
South Lake
N
0
6,000 m
Elevation (msl)
High : 200
Low : -2
b)
West
East
Unit 2
Depth (m)
0
5
10
15
West
East
Unit 2 Spit package
Unit 4
Bedrock
6°
500 m
c)
West
Unit 2
Unit 2
Depth (m)
0
10
20
30
West
Unit 4
East
Bayhead delta
Gas blanking
Bedrock
20°
1000 m
d)
West
Unit 3
Unit 4
East
5°
e)

Figure 6


NL-1
(3)
(2)
Estuarine lake
Restricted estuary
Older valley
Es
(1)
Depth (m)
3
13
23
33
Depth (cm)
Age (cal. BP)
0
1000
2000
3000
4000
5000
6000
7000
8000
2
4
6
8
10
12
14
Balticammina pseudomacrescens
Cribroelphidium articulatum
Haplophragmoides wilberti
Helenina andersoni
Ammonia tepida
Miliammina sp.
Schenckiella moniliformis
Cibicides refulgens
Elphidium spp.
Nonion sp.
Quinqueloculina spp.
Cassidulina subcapitata
Haynesina depressula
Siphotextularia sp.
Spirillina vivipara
Hanzawaia grossepuncta
Rosalina bradyi
Triloculinella hornibrooki
Triloculinella sp.
Triloculina rotunda
Triloculina spp.
Spiroloculina spp.
20
40
60
80
100
Percentage (%)
Grain size
Brackish
Marine


Spits
CB-2
(4)
(3)
(2)
(1)
Estuarine lake
Barrier
Tidal Flat
LGM valley
Bedrock
Older valley
Bedrock
Depth (m)
0
10
20
30
Depth (m)
1.5
3
9
13.5
Age (Cal. BP)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
Grain size
Balticammina pseudomacrescens
Cribroelphidium articulatum
Haplophragmoides wilberti
Ammonia tepida
Cibicides lobatulus
Elphidium spp.
Nonion depressulus
Quinqueloculina spp.
Cassidulina subcapitata
Miliolinella sp.
Haynesina depressula
Siphotextularia sp.
Rosalina bradyi
Lagena spp.
Triloculina spp.
Spiroloculina spp.
Freshwater
Brackish
Transitional
Marine
Unknown
d³⁴S
20
40
60
80
100
Percentage (%)
-36
-12
12
36
Brackish
Marine

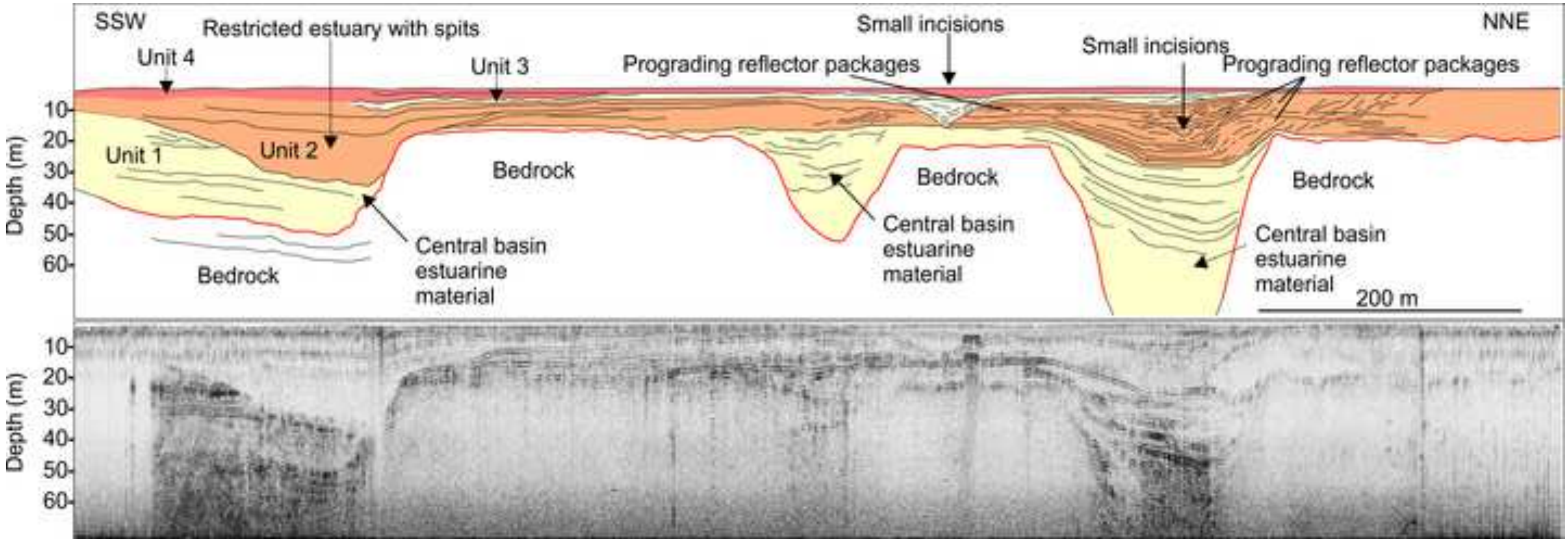
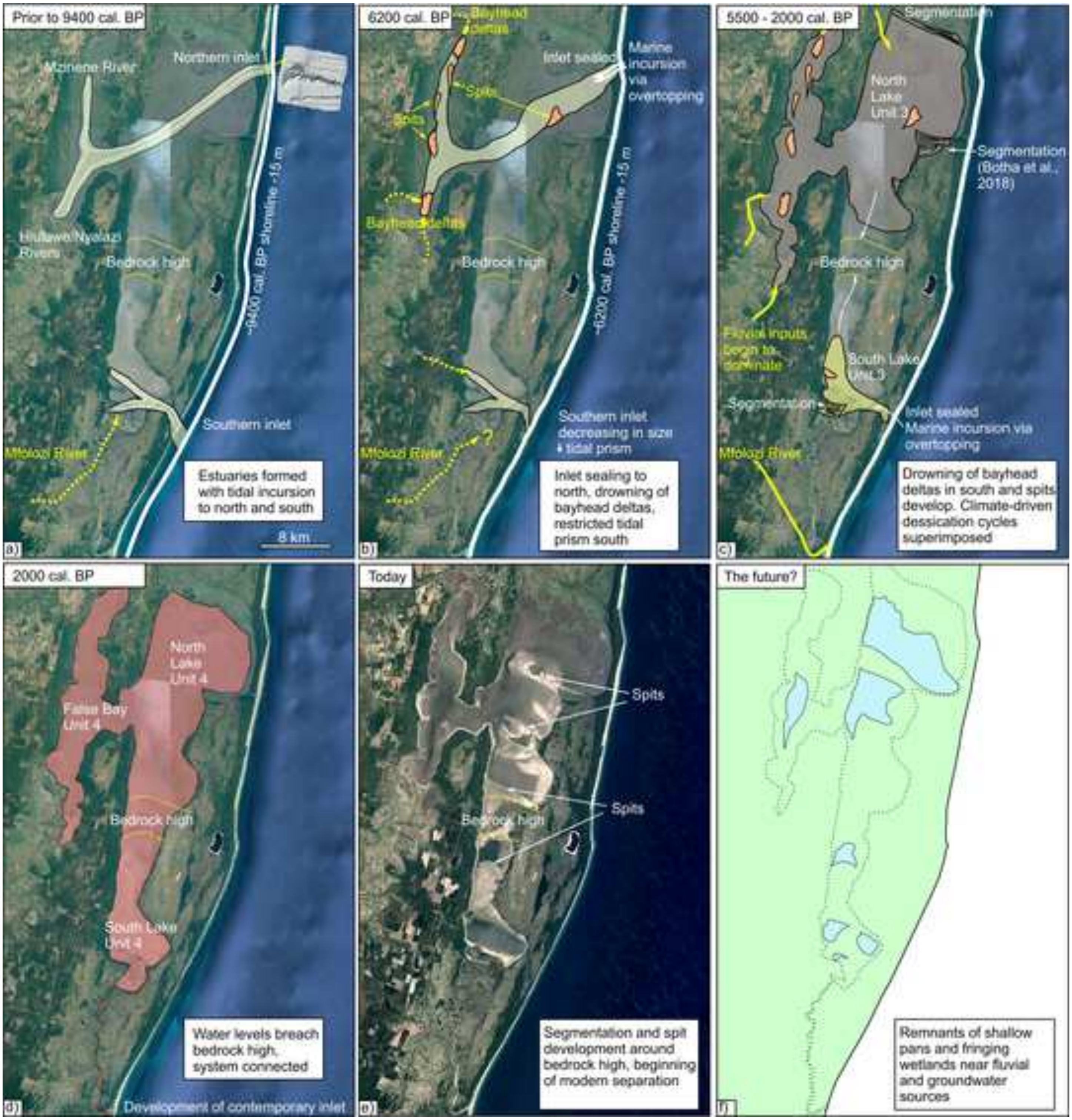

SSW
Restricted estuary with spits
Unit 4
Unit 3
Small incisions
Prograding reflector packages
Small incisions
Prograding reflector packages
NNE
Depth (m)
10
20
30
40
50
60
Unit 1
Unit 2
Bedrock
Bedrock
Bedrock
Central basin estuarine material
Central basin estuarine material
Central basin estuarine material
Bedrock
200 m
Depth (m)
10
20
30
40
50
60

Figure 9



Prior to 9400 cal. BP

Estuaries formed with tidal incursion to north and south

6200 cal. BP

Inlet sealing to north, drowning of bayhead deltas, restricted tidal prism south

5500 - 2000 cal. BP

Drowning of bayhead deltas in south and spits develop. Climate-driven dessication cycles superimposed

2000 cal. BP

Water levels breach bedrock high, system connected

Today

Segmentation and spit development around bedrock high, beginning of modern separation

The future?

Remnants of shallow pans and fringing wetlands near fluvial and groundwater sources

Declaration of interests

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: