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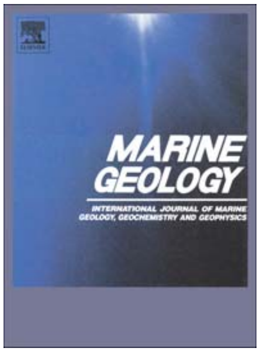

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The stratigraphic evolution of a large back-barrier lagoon system with a non-migrating barrier

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Abstract

Lake St Lucia, the largest estuarine system in Africa, is enclosed by a 120 m-high compound Quaternary barrier-dune system in northern KwaZulu-Natal, South Africa. It comprises several discrete sedimentary basins within a single shallow back-barrier water body. This paper reports the first very-high-resolution seismic study of the system. Seven seismic units (A-G) are identified and interpreted based on their geometry, acoustic properties and a sediment coring programme. The units are bounded by regionally developed sequence boundaries and lower order unconformity surfaces corresponding to bay and tidal ravinement and hiatus surfaces. The lowermost subaerial unconformity formed during regression related to late-Pliocene hinterland uplift. Initial infilling of this surface in the proximal areas reflects estuarine sedimentation in a mixed wave- and tide-dominated system during the subsequent lowstand and early transgressive systems tracts, overlain by prograding highstand deltaic deposits that developed as sea-levels began to stabilise. Distally, this cycle of sedimentation is initially reflected by the infilling of a similar estuarine system that gradually transitioned to a back-barrier lagoon. Superimposed stillstands drove imbalances in the rate of sediment supply and accommodation space, and this, coupled with the development of an early barrier complex, caused lagoon aggradation and shallowing. A second similar cycle is repeated for the recent postglacial sea-level cycle. There appears to be no preservation of the intervening Pleistocene cycles of erosion and deposition. The system is capped by estuarine-lacustrine deposits. The onset of lower energy estuarine-lake conditions began ~ 6235 cal BP in North Lake and started earlier in the proximal False Bay owing to sheltering by the antecedent barrier of a rocky peninsula. This study reveals a markedly different evolutionary history in adjacent basins of the same back-barrier system during two full sea-level cycles. These are attributed to a long established, non-migrating barrier, and to the influence of antecedent conditions on the system response to transgression. Unlike the US Atlantic margin, where migrating barriers truncate the infilling sequences, the main stratigraphic unconformities within each fill sequence correspond to tidal and bay ravinement surfaces.

Key words

Incised valleys, back-barrier evolution, estuarine infilling, antecedent conditions, Lake St Lucia

1. Introduction

Lake St Lucia in South Africa is the largest estuarine lake in Africa and is regarded as the most important estuarine system on the continent (Fig. 1). The system is sheltered from direct ocean influence by a high compound dune barrier that has existed since at least the mid-

Pleistocene (Porat and Botha 2008) and thus contains a sedimentary record of Quaternary lagoon evolution under the influence of changing sea level and environmental conditions. The high and stable barrier position offers a comparison with evolving barrier-lagoon systems elsewhere: the latter are influenced by barrier island migration. The separation of the lake basins by a large sheltering peninsula has also produced a comparatively different evolutionary history between proximal (bayhead dominated) and distal areas (inlet dominated) within the same back-barrier, an undescribed phenomena from other large lagoonal systems around the world.

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

2. Regional setting

Lake St Lucia is situated in Maputaland on the southern tip of the southeast African coastal plain (Fig. 1). Covering an area of ~ 350 km^2, the system comprises three main lake compartments, viz. False Bay, North Lake and South Lake, which are separated from the ocean by a Pleistocene-Holocene barrier dune complex. The Mfolozi River in the south and the Mkhuze River in the north are the largest fluvial inputs to the lake (Hutchison, 1976). The lake’s only contemporary oceanic link is via the Narrows, a 21 km-long channel (Wright, 1995) that opens into the Indian Ocean adjacent to the Mfolozi River outlet (Fig. 1).

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

3. Methods

Geophysical and sedimentological surveys of Lake St Lucia involved the collection of approximately 300 line kilometres of single-channel, high resolution Boomer seismic reflection data. Geophysical data collection was carried out in conjunction with the extraction of two continuous 16 m-long cores from strategic sites within the lake (Fig. 1).

3.1 Seismic reflection data

This study focuses on 80 line kilometres of the seismic reflection data set (Fig. 1) concentrated in the northern portions of False Bay and the North Lake sub-basins (Fig. 1.) High resolution, single-channel seismic data were collected using a Design Projects Boomer and a 20 element hydrophone array, at a power level of 175 J throughout the study area. These data were recorded using the HypackTM hydrographic software package and positioning was achieved using a DGPS of ~1 m accuracy.

The raw seismic data were processed using in-house designed processing software. Band pass filtering and time-varied gains were applied to all data. Constant sound velocities in water (1500 ms-1) and sediment (1650 ms-1) were used to extrapolate the time-depth conversions. Post-processing, the vertical resolution of the Boomer system is between 0.3 to 0.5 m. All data were interpreted according to standard seismic stratigraphic principles (Mitchum, 1977)

3.2 Core data

Cores NL-1 and FB-1 sample the upper sedimentary deposits and were collected using a barge-mounted piston corer. The cores were sited where incised valleys were deepest (cf. Van Heerden, 1987) and thus the greatest length of undisturbed sediment could be recovered. Unfortunately, these areas are prone to the greatest amounts of gas trapping (cf. Weschenfelder et al., 2016) and the seismic records in some places are obscured. The total length of each core was ~16 m and targeted the upper incised valley fills and the entire low-energy, estuarine-lacustrine succession. The cores were subsampled at 20 cm intervals for particle size analysis, performed on a Malvern Mastersizer 2000 (measuring range: 0.02-2000 µm).

In an attempt to provide a geochronological framework for the upper sedimentary packages, bulk sediment and intact shell samples were selected for ^{14}C dating using accelerator mass spectrometry (AMS). Calendar calibrated ages were calculated using the Southern Hemisphere atmospheric curve SHCal13 (Hogg et al., 2013).

4. Results

4.1 Seismic stratigraphy

Seven seismic units, A-G, were resolved beneath the lake bed within each area, identified on the basis of seismic impedance, reflection termination patterns, internal reflection configuration and bounding acoustic reflectors (Figs 3-7; Table 1). Sub-units were recognised within each seismic unit and were assigned numbers e.g., A1, A2 and A3 of unit A. Each sub-unit is separated by an acoustic reflector (e.g., reflector-ai overlying sub-unit A1). Two master reflectors, reflector SB1 and reflector SB2 are recognized underlying the successions of each area.

4.1.1 Unit A

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

4.1.2 Unit B

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

Sub-unit B1 overlies reflector SB1 and is characterized by moderate to high amplitude, chaotic, discontinuous aggrading to prograding reflectors that onlap and downlap onto the underlying surface and may be truncated by an overlying master reflector (Fig. 4). B1 attains an average thickness of 5-7m which varies laterally. Deposits of B1 vary in lateral extent, and may be restricted in occurrence to only the deeply incised valley thalwegs of reflector SB1 in the distal North Lake, whilst rarely attaining a thickness of more than 12 m throughout.

Sub-unit B2 comprises low to moderate amplitude steeply dipping, prograding oblique-parallel reflectors which onlap valley flanks and downlap reflector SB1 or reflector-bi, forming a valley flank attached unit which may be attached to either one or both valley flanks (Fig. 7), and in some cases may be absent (Fig. 6). Deposits of B2 occur only within the distal V-shaped incised valleys of reflector SB1.

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

Sub-unit B4 is the uppermost facies of unit B, and overlies reflector-biii. The moderate amplitude, sub-parallel continuous internal reflectors of B4 exhibit a low angle (3-5°) dip toward the valley thalweg, downlapping the underlying surface, and are erosionally truncated by reflector SB2 (Fig. 4). The thickness of this unit is indeterminate as it is erosionally bound at its lower and upper surface.

4.1.3 Unit C

Unit C, which is divisible into three sub-units, C1 to C3, constitutes the uppermost unit deposited above reflector SB1, and is restricted to North Lake. The reflectors of unit C are commonly weakly developed, exhibiting dominantly low to isolated moderate amplitudes.

The basal reflectors are partially definable, but pass upwards into chaotic, unstructured semi-opaque packages.

Sub-unit C1 directly overlies reflector SB1 and forms the capping fill for the distal V-shaped valleys incised into reflector SB1. The low-amplitude, draping reflectors of this facies fill these depressions, along with many other minor depressions, onlapping the valley flanks in reflector SB1. This facies reaches up to 20 m thickness within valley margins, whilst spreading laterally and thinning out to 10 m after overspilling its confining interfluves (Fig. 6). The transition from sub-unit C1 to C3 is represented by reflector-ci, although C1 may be truncated locally by reflector SB2.

Sub-unit C2 is spatially restricted to the Hells Gate area, and comprises convex prograding moderate amplitude reflectors that downlap the underlying reflector-biii (Fig. 7). These reflectors prograde laterally from north-west to south-east and are confined to the antecedent depression within reflector-biii. The upper surface of C2 is incised by reflector SB2. This lens-like accumulation of sediment thickens to 18 m, pinching out laterally.

Sub-unit C3 is the thickest of the unit C sub-units and caps the succession, overlying either C1 (Fig. 6) or unit A (separated by reflector SB1) as shown in figure 7. This unit represents a vertical continuation from sub-unit C1, but is significantly less organized, with the low-amplitude reflectors appearing chaotic and structureless. C3 occurs over a significant lateral distance and unconfined by valley interfluves (Figs. 6 and 7). It averages a thickness of 25 m.

4.1.4 Unit D

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

Distally, sub-unit D1 is the lowermost of the four Unit D sub-units, and comprises a depression bound, 10-17 m thick drape fill succession represented by low to moderate amplitude reflectors that onlap the gently undulating valleys of reflector SB2 (Figs. 6 and 7). These reflectors grade vertically into the predominantly acoustically opaque, structure-less sub-unit D2, a transition represented by reflector-di. Sub-unit D2 dominates the unit D succession in North Lake, and much like sub-unit C3, occurs over a significant lateral extent, attaining thicknesses of up to 20 m, whilst thinning to 8 m in places, again visible in all three North Lake seismic lines (Figs. 6 and 7).

In the proximal False Bay area, sub-units D3 and D4 predominate. Sub-unit D3 occurs as a series of moderate to high-amplitude, prograding convex sigmoid reflectors that onlap valley flanks and downlap the underlying erosional boundary reflector SB1 (Figs. 3 and 4). The reflectors of D3 prograde towards the valley thalweg in all cases and may be present on either one (Fig. 3) or both valley sides (Fig. 4).

Sub-unit D4 comprises low to moderate amplitude, sub-parallel to sigmoid-oblique reflectors developed as a thick drape package within the incisions of reflector SB2 that onlap either reflector-di, where D3 is developed (Figs. 3 and 4), or reflector SB2 (Figs. 3 and 5). Sub-unit D4 attains a maximum thickness of 13 m.

4.1.5 Unit E

Unit E occurs in the more proximal False Bay area and exhibits three distinct sub-units (E1 to E3) that comprise generally aggrading (Figs. 4 and 5) to prograding (Fig. 3), low to moderate-amplitude, sub-parallel to oblique wavy reflectors that onlap, downlap and locally toplap their bounding surfaces (Figs. 3-5). These facies may extend laterally as thin ‘fingers’, eventually pinching out or terminating against erosional boundaries (Figs. 4 and 5).

Sub-unit E1 is the lowermost of the three sub-units and directly overlies reflector SB2 (Figs. 3 and 4) or reflector-dii. Internal reflectors comprise moderate amplitude, sub-parallel and wavy packages and occur as a drape succession that onlaps onto reflector SB2, often filling minor, low relief depressions (Fig. 4).

Sub-unit E2 is separated from the underlying E1 by reflector-ei, onto which the internal reflectors of this facies downlap and onlap (Figs. 3 and 5). The upper reflectors of this package may in places be erosionally truncated by reflector-eiii (Fig. 3). They are characteristically low to moderate amplitude, sigmoid prograding (Figs. 3-5).

Sub-unit E3 is the thinnest and least developed of the three observed sub-units that comprise unit E. The low amplitude, sigmoid-oblique prograding reflectors onlap and downlap (Fig. 4) the underlying reflector-eii. E3 is overlain by reflector-eiii, which truncates the prograding reflectors of this package in places (Fig. 4).

4.1.6 Unit F

Unit F comprises two sub-units, F1 and F2 that drape (F1, Figs. 3, 4 and 7) or prograde (F2, Fig. 6) into the depressions of reflector-dii distally or reflector-eiii. This underlying surface displays an erosive topography similar in nature but on a smaller scale to those of reflectors SB1 and SB2. The reflectors of F1 are low-amplitude, typically onlapping the minor depressions of reflector-dii (Figs. 4 and 7), whilst the reflectors of E2 are of moderate-amplitude and are commonly oblique to oblique tangential, downlapping onto reflector-dii (Fig. 6) On average, unit E displays a thickness of 5-8 m, but where depression bound may thicken to 14 m.

4.1.7 Unit G

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

4.2 Core Lithologies

The position of cores FB-1 and NL-1 in the context of the seismic sections are shown in figures 4 and 6 respectively. The 16 m-long FB-1 (Fig. 9) comprises predominantly stiff, and in restricted sections, fluid-rich clayey sediment that is interspersed with thin beds of coarser sediment. The core is mostly homogenous clay, with occasional spikes in grain size (Fig. 9c). These layers are typically poorly sorted (Fig. 9d).

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

5. Discussion

5.1 Regionally Developed Sequence Boundaries

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

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

The most recent recorded sea-level lowstand occurred ~18 000 yr BP during the LGM (Fig. 2). Reflector SB2 constitutes the uppermost and thus youngest subaerial unconformity and is thus associated with the LGM age lowstand. This surface is recognized by Green (2009), Green (2011b) and Green et al. (2013) as the most common erosion surface on the southeast South African continental shelf.

5.2 Acoustic basement

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

5.3 Unit B

Unit B is separated from the underlying unit A by SB1 (Figs. 3-7), and is divided into 4 distinct sub-units (B1 to B4) that constitute the onlapping or downlapping fills of the observed incised-valleys in SB1.

Sub-unit B1

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

Sub-unit B2

The flank attached, progradational nature of sub-unit B2 reflectors (Fig. 7) is suggestive of deposition at the valley margins by backfilling of the newly formed incised valley under transgressive conditions. Within an incised valley, the early phases of transgression are characterized by the landward migration of a zone of fluvial aggradation and tidal influence as base-level rises (Dalrymple et al., 1992; Allen and Posamentier, 1994; Zaitlin et al., 1994). Nordfjord et al. (2006) document the development of salt marsh and tidal flats sediments along the margins of incised valleys on the New Jersey Continental shelf during similar conditions, which are represented by valley flank attached reflectors similar to those of sub-unit B2. The deposits of sub-unit B2 are ascribed to deposition in a similar setting, and are consequently allocated to the early phases of transgression, during which valley confined estuarine deposition backfilled the incised valleys of SB1.

Sub-unit B3

The low to moderate amplitude, sub-parallel continuous reflectors of unit B3 typically onlap the SB1 valley flanks, and display striking similarity to features observed by Thomas and

Anderson (1994) and Menier et al. (2006), which were interpreted as fine grained central basin deposits in a wave-dominated estuary. These sediments are deposited during the early transgressive stages of base-level rise as fluvial sediment supply is commonly outstripped by the rate of creation of accommodation space, and a drowned-valley estuary is generated at the seaward end of the incised valley (Dalrymple et al., 1992; Oertel et al., 1992; Zaitlin et al., 1994).

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

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

Sub-unit B4

The restricted occurrence of sub-unit B4 (Fig. 4), combined with an absence of groundtruthing data, inhibits a rigorous evaluation of the unit. The inclined, aggrading to gently prograding strata, however, are suggestive of a gradual advance in sediment migration toward the valley thalweg. The erosional lower contact is consistent with deposition by the forward advance of sediment within a channelized conduit, gradually incising down into the underlying unit B3. Nichol et al. (1994) document modern fluvial channel and bay-head delta facies incised into aggraded central basin deposits at the head of the estuary in Lake Calcasieu along the Louisiana coast. This progradational sediment body is attributed to the onset of highstand conditions. These conditions can also prevail if there is sufficient stability in sea-level to promote normal regression of the bayhead delta shoreline. Either case may be applicable here.

5.4. Unit C

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

Sub-unit C1

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

Sub-unit C2

The convex, progradational nature of the sub-unit C2 reflectors, and their location within a channel-like depression (Fig. 7), suggests that this sub-unit may also be considered as a fluvial or tidal channel-hosted bedform. Weber et al. (2004) document similar style sub-units, and similarly attribute them to such an environment. The large scale of the unit’s clinoform structures suggests their deposition by tidal currents associated with a rise in sea-level and an increase in tidal regime consistent with an increasing tidal prism and deeper back-barrier conditions.

Sub-unit C3

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

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

5.5 Unit D

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

Sub-units D1 and D2

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

Core NL-1 (Fig. 9a) intersected unit D2 (Fig. 6). The basal facies of the core is dominated by sandy sediment displaying occasional mud draping, indicative of deposition within a tidal environment in an initially shallow back-barrier setting. Gradual broadening and deepening of the system as sea level rose is reflected by a gradual decrease in grain size and an increase in the finer sediment fraction (Fig. 9). The intercalation of clayey sands and silts with thin quartz rich sand beds is consistent with storm surge episodes depositing coarser sandy sediments within the back-barrier lagoon (e.g., Davis and Flemming, 1995).

Sub-unit D3

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

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

Sub-unit D4

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

5.6 Unit E

Sub-unit E1

This sub-unit displays an architecture similar to that described above for sub-unit D4. The moderate amplitude, sub-parallel wavy reflectors occur as a drape succession that terminate or onlap onto SB2 (Fig. 4), often filling minor, low relief depressions. A difference in reflector geometry with regard the underlying sub-unit D4 is the continuous, unconfined nature of sub-unit E1 reflectors that are observed as overtopping their valley margins. This suggests that sub-unit E1 represents the earliest departure from valley confinement as relative sea-level rose beyond the limit of SB2 valley relief, promoting the lateral development of accommodation space and a subsequent adjustment from confined, low-energy depositional conditions to a more laterally extensive zone of deposition. These packages are interpreted as settling packages formed within a tranquil back-barrier lagoonal type setting. Groundtruthing of similar seismic packages in the estuaries of KwaZulu-Natal revealed the presence of stiff clays (Orme, 1973), interpreted by the authors as lagoonal. Sub-unit E1 is likely to have developed as a lagoon within the zone of low-energy landward of the Nibela Peninsula and the early development of the contemporary dune barrier complex (cf. Porat and Botha, 2008).

Sub-unit E2 and E3

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

5.7 Unit F

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

Sub-unit F1

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

Sub-unit F2

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

5.8 Unit G

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

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

5.9 Bounding surfaces

The rugged, low to moderate relief reflector-bi and the more proximal portion of reflector-di separate fluvial deposits from the overlying central basin deposits in unit B and D respectively. Surface –biii separates the overlying prograding bayhead delta deposits from the underlying central basin deposits. Zaitlin et al. (1994) recognize this surface as the bay ravinement surface, recognised as forming during the landward transition of fluvial bayhead delta deposits during the early transgressive systems tract and during the seaward advance of the bayhead delta during the highstand systems tract. Foyle and Oertel (1997) describe a similar surface underlying the middle to upper central basin deposits within the Quaternary Virginia estuary-shelf system. The reflectors of the estuarine drape packages B3 and D4 (proximally) may onlap or downlap these surfaces, which is to be expected (cf. Foyle and Oertel, 1997).

Reflectors -ei,-eii and -eiii all exhibit erosional characteristics, displaying minor incisions and truncating reflectors of underlying units. Units E2 and E3, underlain by reflectors -ei and -eii respectively, have been identified as migrating tidal bedforms, attributable to the formation of tidal inlets related to barrier constriction. Additionally, Unit F, which is underlain by reflector-dii (distally) and reflector-eiii, has been identified as the final stage of lagoonal occupation prior to subsequent enclosure and the development of the modern day estuarine lake setting. On this basis, the surfaces underlying units E2, E3 and F are identified as tidal ravinement surfaces formed under the influence of migrating tidal inlets and channels. These surfaces exhibit similar seismic expressions to those tidal ravinements identified by Menier et al. (2006) and Nordfjord et al. (2006) in their respective study areas.

Reflector -ci and the distal portions of reflector -di represent a low amplitude transition from predominantly deep lagoonal sedimentation to reworked, shallow lagoonal sediments throughout North Lake. They mark the final stages of lagoonal suspension settling intercalated with tidally deposited sediments as tidal currents migrated throughout the gradually shallowing back-barrier system. This warrants the application of the term 'intra-lagoonal transition surfaces' for the purpose of this study.

5.10. Evolutionary model

An evolutionary model detailing coeval changes to the proximal (False Bay) and distal (North Lake) areas (Fig. 10a-h) is presented here. This model also includes the effect of the early establishment and stability of the barrier on the evolution of the back-barrier areas, an effect not recognised in other systems around the world, where barrier migration is an important process.

Both areas are marked by two episodes of incised valley formation (SB1 and SB2) that formed during sea-level lowstand. The oldest phase of valley incision is linked to the late Pliocene uplift (Fig. 10a). The initial infill of Pliocene valleys of the distal North Lake reflects lowstand to transgressive infilling of the inner to middle segment of a mixed wave- and tide dominated incised valley (Fig. 10b). The estuarine central basin deposits were deposited as sea-levels rose to ~30 m depth. This is coeval with the development of a coastal barrier on the seaward side of North Lake as well as the onset of estuarine conditions within the incised valleys of the more proximal False Bay (Fig. 10c).

The development of the coastal barrier complex served to impound the waters, drowning the North Lake interfluves as the back-barrier transitioned from an estuary to a deep back-barrier lagoon (Fig. 10c). Sedimentation is dominated by the migration of tidal channels which eroded the underlying sediments to form a tidal ravinement surface; overlain by prograding subtidal bedforms. Coeval sedimentation in False Bay reflects a similar cycle of lowstand to transgressive infilling of a mixed wave- and tide dominated estuary (Fig. 10c).

As the coastal barrier complex grew, the constriction of the tidal inlet of North Lake occurred, promoting the lateral infilling of the lagoon. This suggests a slowing of sea-level rise or a stillstand. As the lagoon transitioned from deep to shallow, the influence of wind-generated waves gradually began to rework new and older lagoonal sediments, producing chaotic, structureless packages (Fig. 10d). A differential preservation of coeval facies in False Bay occurred due to the progradation of the highstand bayhead delta with the slowing of sea-level rise. This prograding unit eroded the underlying sediments, producing a bay ravinement surface (Fig. 10d).

The entire lowstand-transgressive-highstand succession of False Bay and North Lake was truncated by the LGM age set of valleys. Rapid postglacial transgression triggered the onset of another cycle of lagoonal sedimentation in the distal North Lake, driven by further accretion onto the coastal barrier (Fig. 10f). This broad system was fed by a network of tidal inlets, including that at Leven Point.

Proximally, the fluvial channels incised into False Bay were slowly filled as direct marine influence was staved off by the influence of the Nibela Peninsula. Estuarine conditions prevailed within the valley margins, promoting the formation of a second cycle of mixed wave- and tide dominated sedimentation. Continued lateral growth of False Bay and the onset of fully lagoonal conditions throughout much of Lake St Lucia occurred (Fig. 10f). The initially deepen lagoon covered a significant surface area, forming the basis for what is now the modern day lake system.

With the now well-established barrier system coupled with a slowing of sea-level rise, tidal flow was constricted within the now broadened lagoon. A second cycle of lateral infilling, aggradation and lagoonal shallowing followed (Fig. 10g). This is reflected by the presence by prograding tidal bedforms in False Bay and possibly North Lake, although the effect of wind-wave reworking in the larger of the two areas would likely have reconstituted these.

The shallow lagoonal sediments of North Lake and False Bay were truncated by a final tidal ravinement surface during renewed sea-level rise (Fig. 10g). Large prograding bedforms, particularly in North Lake, indicate increased tidal prisms and deeper back-barrier conditions. A slowing of sea-level rise towards the contemporary highstand conditions, together with the final accretion of the seaward coastal barrier, eventually impounded the waterbody (Fig. 10h). This occurred between 7123 and 6235 cal BP in North Lake, with earlier low-energy conditions at ~ 8355 cal BP in False Bay. The time difference is likely due to the shelter afforded by the Nibela Peninsula.

5.11 Back-barrier infilling and inlet response

Due to the early establishment of the seaward barrier in a stable position, and its persistence throughout most of the system's evolution, the antecedent conditions have ensured that the back-barrier has remained sheltered from oceanic ravinement processes. Unlike the US Atlantic margin, where migrating barriers truncate the infilling sequences (e.g., Belknap and

Kraft, 1985; Mallinson et al. 2010a), the main stratigraphic unconformities within each fill sequence correspond to tidal and bay ravinement surfaces. This effect is further exacerbated in the proximal areas, where the added effect of the pre-existing Nibela Peninsula has caused additional sheltering, and the preferential development of lagoon and central estuarine basin-like conditions as opposed to the coeval higher-energy estuarine conditions experienced in the distally seaward areas. The overall response of the back-barrier system is to have evolved a relatively thick sequence comprising mainly post-glacial Holocene infill; when compared to other systems with thicker fills corresponding to several eustatic cycles (e.g., Mallinson et al., 2010a). Truncation by oceanic ravinement is likely to account for the thinner Holocene and Pleistocene sediments in the US Atlantic examples.

In contrast to the migrating inlet models of Culver et al. (2006) and Mallinson et al. (2010b), the main inlets of St Lucia appear to have occupied fixed positions (as noted in the simple channel system extending towards Leven Point in figure 8) over long periods of time (> 1 ka), which abruptly sealed and likely never re-opened. The US Atlantic systems are conversely characterised by migrating inlets that open and close frequently, a result of the strong drift aligned beach systems and larger tidal prisms that characterise the area. In the study area, longshore transport is limited by the log-spiral coastal configurations (Cooper, 2001) and coupled with a relatively low fluvial sediment supply, a stable inlet position can be maintained. This can remain open due to the relatively large tidal prism that would exist for a broad and shallow lagoonal setting such as St Lucia.

The inlets of most of the large US Atlantic systems also appear to be persistent; the longevity of the inlets in these barrier systems (e.g., Halsey, 1979), particularly along the Mississippi delta plain, where modern inlets tend to be aligned with relict inlets (Kulp et al., 2007) is well documented. These modern inlets are understood to have migrated approximately 3 km in a landward direction during the past 100 years with little lateral migration, constrained within older inlet channels (Kulp et al., 2007). Similarly the Ocracoke Inlet in the Outer Banks Barrier Islands, North Carolina, is located within a former river valley that drained the Pamlico Sound basin during the Last Glacial Maximum, the inheritance of this geomorphological framework considered to account for both the inlet stability and longevity (Mallinson et al., 2010b). There does not appear to be a similar style of antecedent inheritance in the St Lucia system. The high degree of post-glacial sediment supply to the barrier, and consequently lowered supply to the back-barrier, has caused the system to choke the inlets and seal them semi-permanently. This has similarly caused a thick sequence of back-barrier material to accumulate, the majority of which is a single transgressive package of late Pleitocene/Holocene age.

6. Conclusions

We show the effects of differential back-barrier response to sea-level rise and sediment supply based on the inheritance of antecedent conditions (a rocky peninsula). The model presented shows that even over small distances, coeval responses to the same event can be quite different. Sheltering from open ocean conditions during transgression can produce remarkably different sedimentation styles in the same incised valley system. These can further influence the later styles of sedimentation by imparting changes to the depth of each separate sub-basin in the back-barrier (shallow as opposed to deep lagoonal). Furthermore, the early development and persistence of a non-migrating barrier system can produce a unique set of conditions whereby oceanic ravinement processes in this middle to outer segment of the valley are curtailed. The result is thick and heterogeneous transgressive infilling, usually representative of a single transgressive cycle. These types of systems thus have a high potential for unravelling the climatic and deglacial sea-level history of areas where fixed, long-lived barriers are found.

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Figure captions

Figure 1. Locality map of the study area, encompassing the two main areas of focus; the North Lake and False Bay areas of Lake St Lucia. The core locations are denoted FB-1 (False Bay), NL-1 (North Lake). The seismic coverage is provided with heavy black lines corresponding to subsequent figures.

Figure 2. Late Pleistocene sea-level curve for the east coast of South Africa. Note the rapid transgression during deglaciation in the latest Pleistocene/ early Holocene (After Ramsay and Cooper, 2002).

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

Figure 4. W-E seismic profile from False Bay displaying interpreted (top) and raw (bottom) data, with enlarged raw data detailing the stratigraphic relationships of Units B, D and E. All seismic stratigraphic units from the False Bay area are evident in this section. Units A and B are truncated by a series of incisions within reflectors SB1 and SB2 respectively. Note the strongly prograding reflectors of subunit D3. Bold line on inset indicates position of seismic line.

Figure 5. NNW-SSE seismic profile from False Bay displaying interpreted (top) and raw (bottom) data, with enlarged raw data detailing the characteristics of Units, B, D and E. Note the pronounced gas blanking throughout most of the line. Bold line on inset indicates position of seismic line.

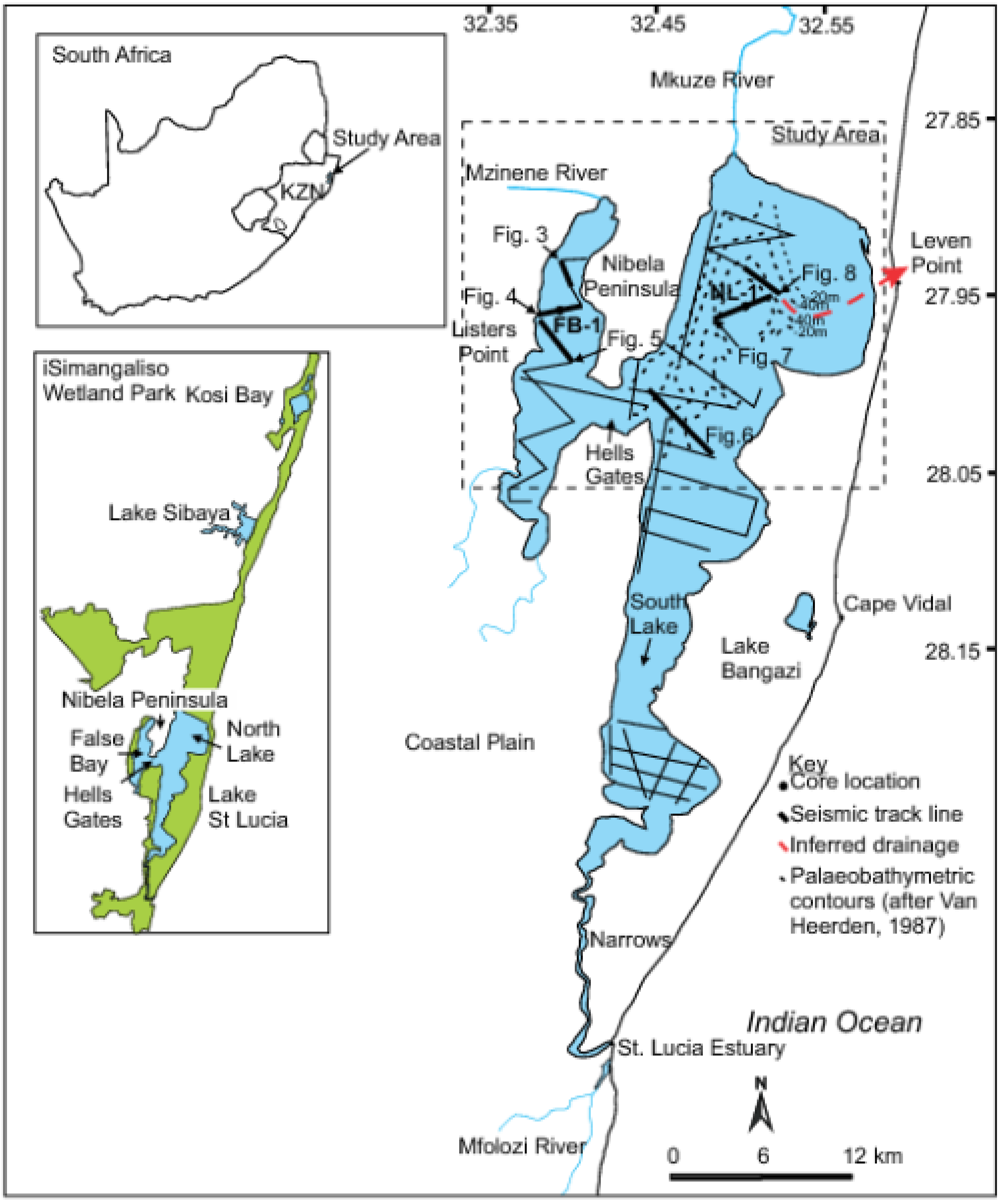
Figure 6. E-W seismic profile from North Lake displaying interpreted (top) and raw (bottom) data, with enlarged raw data. All seismic stratigraphic units are observable in this line. Note the deep V-shaped valleys. Bold line on inset indicates position of seismic line.

Figure 7. SW-NE seismic profile from North Lake displaying interpreted (top) and raw (bottom) data, with enlarged raw data. Valley fills are prominent here, capped notably by the strongly prograding subunit C2. Note the laterally persistent occurrence of unit D2. Bold line on inset indicates position of seismic line.

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

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

Figure 10. A schematic evolutionary model of the North Lake and False Bay areas of Lake St Lucia.



South Africa
Study Area
KZN
iSimangaliso
Wetland Park
Kosi Bay
Lake Sibaya
Nibela Peninsula
False Bay
North Lake
Hells Gates
Lake St Lucia
32.35
32.45
32.55
Mkuze River
Study Area
27.85
Mzinene River
Fig. 3
Nibela Peninsula
Fig. 4
Listers Point
FB-1
Fig. 5
NL-1
Fig. 8
Fig. 7
Fig. 6
Leven Point
27.95
Hells Gates
28.05
South Lake
Cape Vidal
Lake Bangazi
28.15
Coastal Plain
Key
Core location
Seismic track line
Inferred drainage
Palaeobathymetric contours (after Van Heerden, 1987)
Narrows
Indian Ocean
St. Lucia Estuary
N
Mfolozi River
0
6
12 km

Figure 1

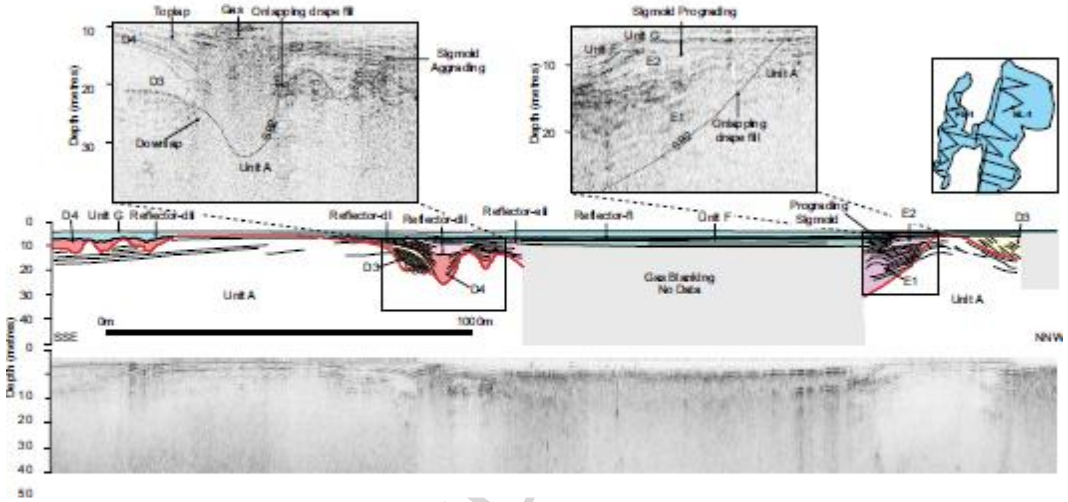
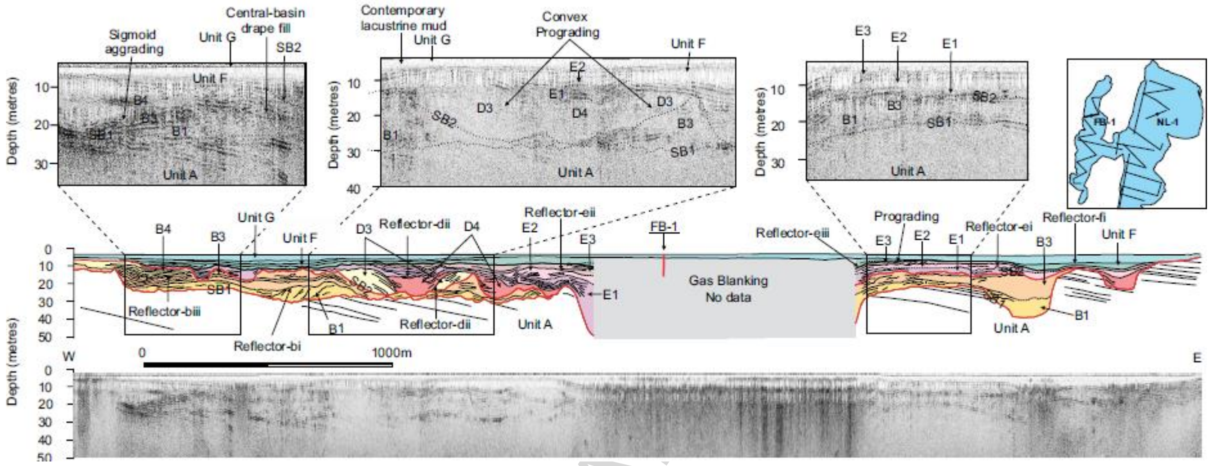


Figure 3


Sigmoid aggrading
Unit G
Central-basin drape fill
SB2
Unit F
B4
B3
SB1
B1
Unit A
Depth (metres)
Contemporary lacustrine mud
Convex Prograding
E2
E1
D3
D4
SB2
B1
B3
SB1
E3
Reflector-dii
Reflector-eii
FB-1
Reflector-eiii
Prograding
Reflector-ei
Reflector-fi
Reflector-biii
Reflector-bi
Gas Blanking
No data
NL-1
W
E
0
1000m
Figure 4

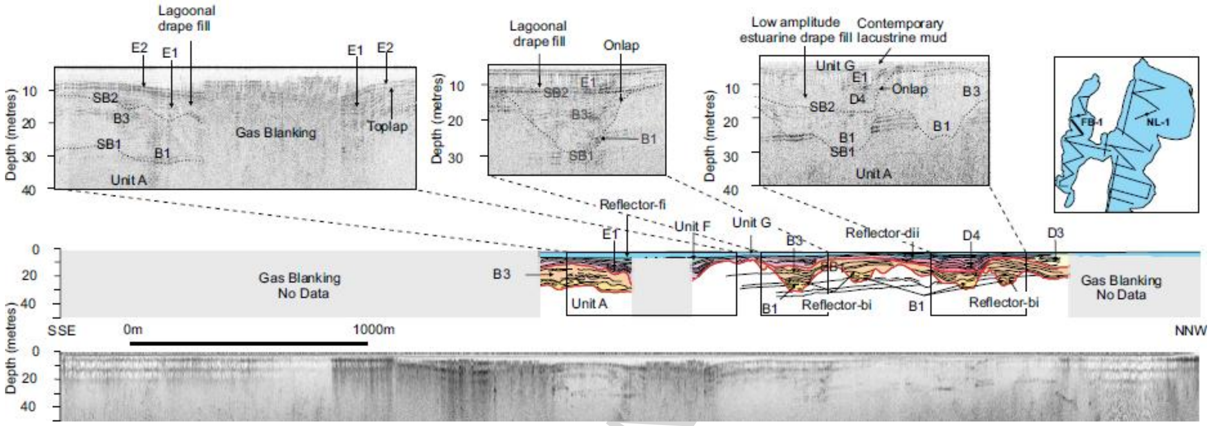

Lagoonal drape fill
E2
E1
E1
E2
SB2
B3
SB1
B1
Unit A
Gas Blanking
Toplap
Depth (metres)
Lagoonal drape fill
Onlap
SB2
E1
B3
B1
SB1
Low amplitude estuarine drape fill
Contemporary lacustrine mud
Unit G
E1
D4
Onlap
B3
SB2
B1
SB1
Unit A
FB-1
NL-1
Reflector-fi
Unit F
Unit G
B3
Reflector-dii
D4
D3
Gas Blanking No Data
Reflector-bi
SSE
0m
1000m
NNW

Figure 5

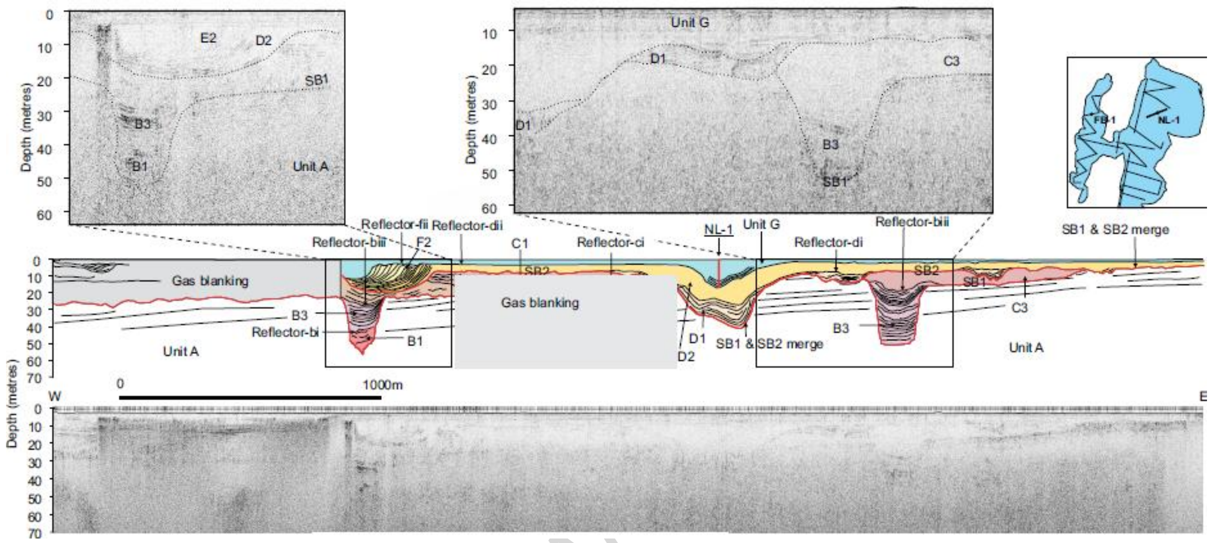
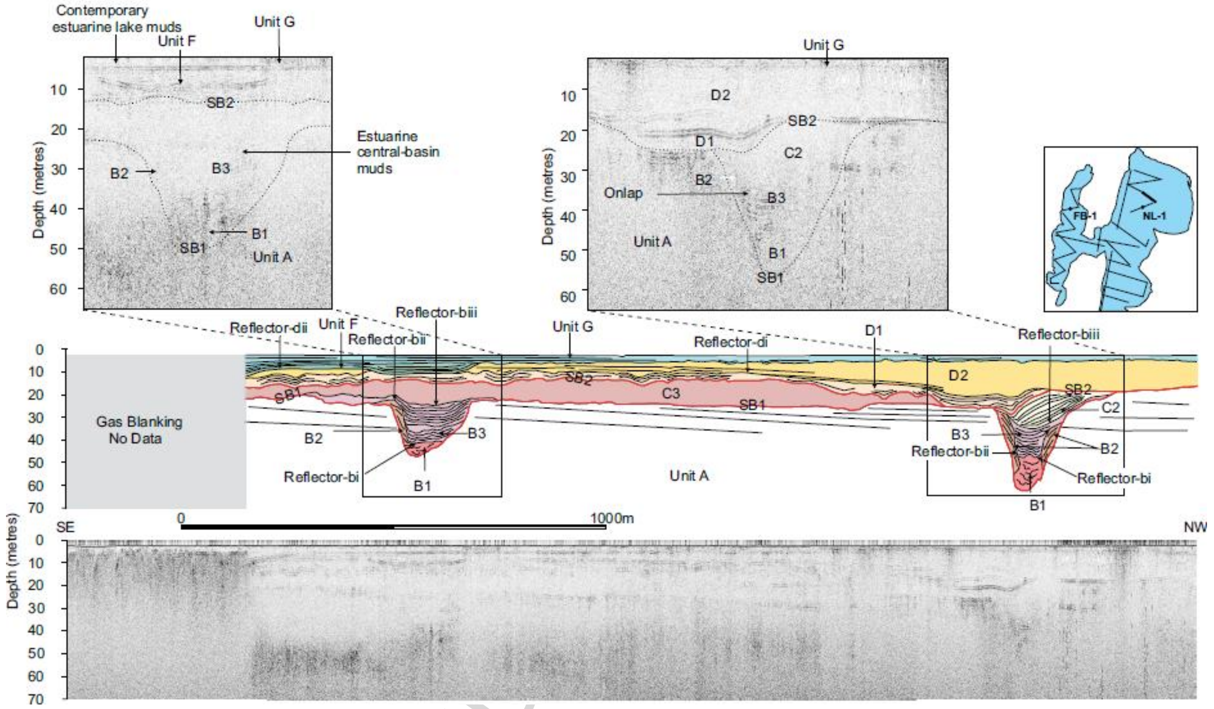
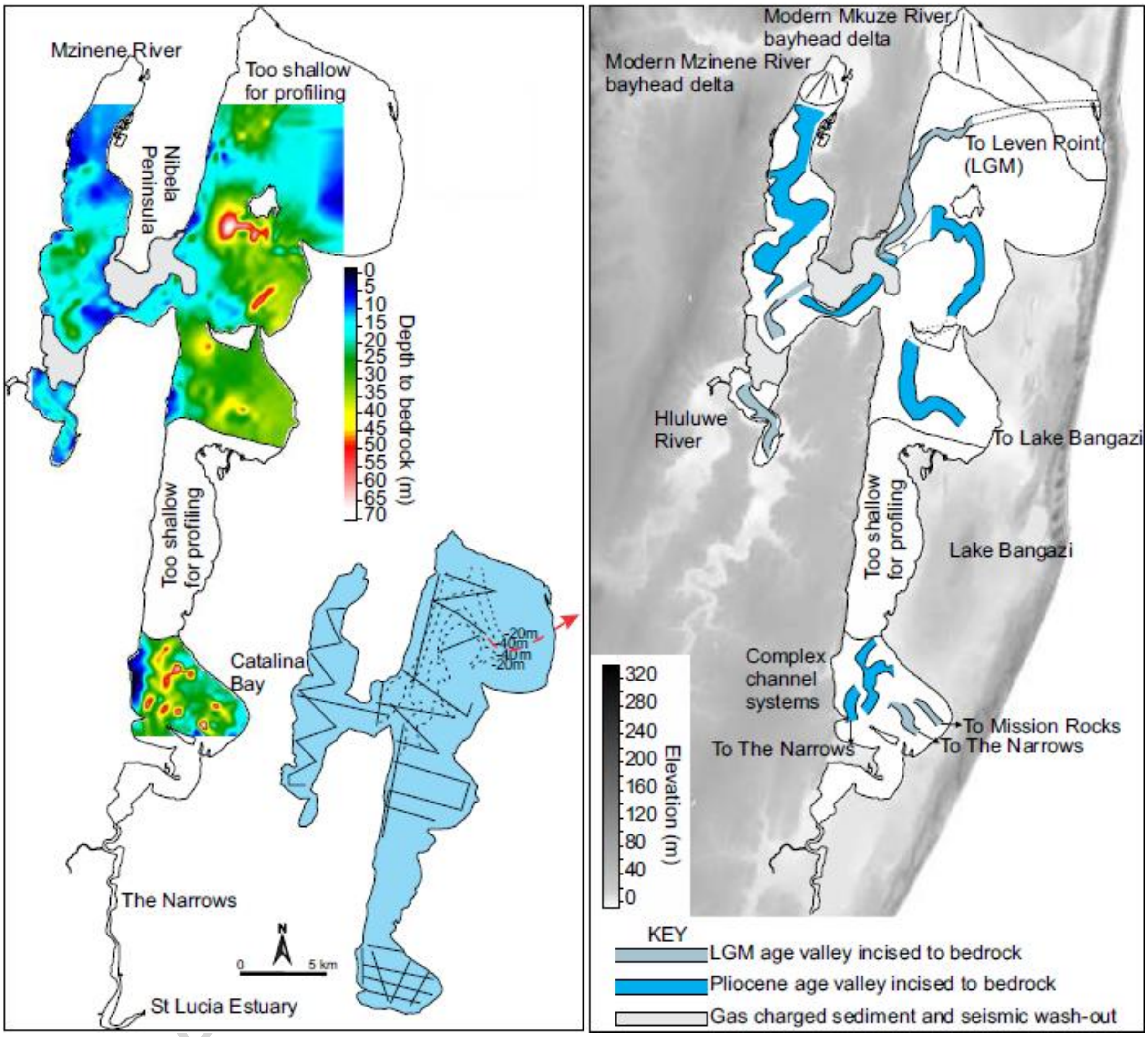

Depth (metres)
E2
D2
SB1
B3
B1
Unit A
Unit G
D1
C3
B3
SB1
FB-1
NL-1
Reflector-fii Reflector-dii
Reflector-biii
F2
C1
Reflector-ci
NL-1
Unit G
Reflector-di
Reflector-biii
SB1 & SB2 merge
Gas blanking
SB2
Gas blanking
B3
Reflector-bi
B1
Unit A
D1
D2
SB1 & SB2 merge
B3
C3
Unit A
1000m
W
E

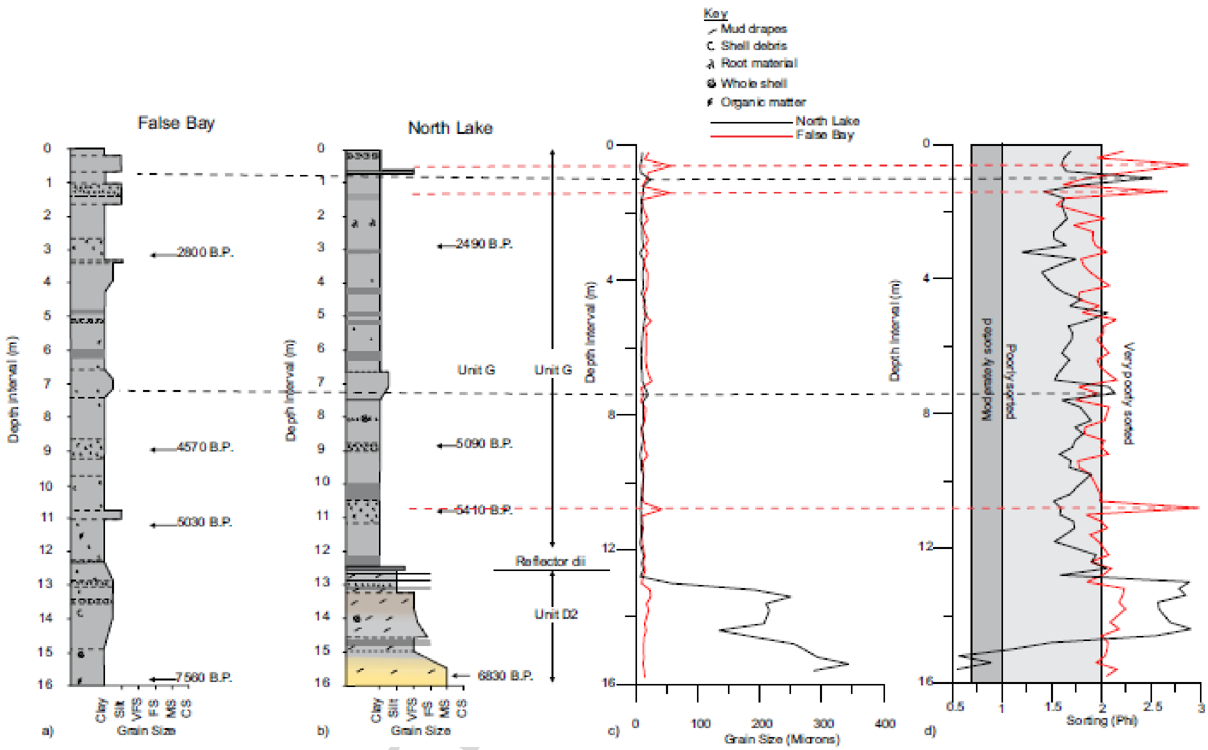
Figure 6


Contemporary estuarine lake muds
Unit F
Unit G
SB2
B2
B3
Estuarine central-basin muds
B1
SB1
Unit A
Depth (metres)
D2
D1
SB2
C2
Onlap
Unit A
FB-1
NL-1
Reflector-dii
Reflector-bii
Reflector-biii
Reflector-di
Gas Blanking No Data
SB1
C3
Reflector-bi
SE
NW
1000m
Figure 7



Mzinene River
Too shallow for profiling
Nibela Peninsula
Depth to bedrock (m)
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
Too shallow for profiling
Catalina Bay
The Narrows
St Lucia Estuary
N
0
5 km
Modern Mkuze River bayhead delta
Modern Mzinene River bayhead delta
To Leven Point (LGM)
Hluluwe River
To Lake Bangazi
Too shallow for profiling
Lake Bangazi
Complex channel systems
To The Narrows
To Mission Rocks
To The Narrows
320
280
240
200
160
120
80
40
0
Elevation (m)
KEY
LGM age valley incised to bedrock
Pliocene age valley incised to bedrock
Gas charged sediment and seismic wash-out

Figure 8



Key
Mud drapes
Shell debris
Root material
Whole shell
Organic matter
North Lake
False Bay
False Bay
North Lake
2800 B.P.
4570 B.P.
5030 B.P.
7560 B.P.
2490 B.P.
5090 B.P.
5410 B.P.
6830 B.P.
Unit G
Unit G
Reflector dii
Unit D2
Depth interval (m)
Clay Silt VFS FS MS CS
Grain Size
Grain Size (Microns)
Moderately sorted
Poorly sorted
Very poorly sorted
Sorting (Phi)
a)
b)
c)
d)

Figure 9

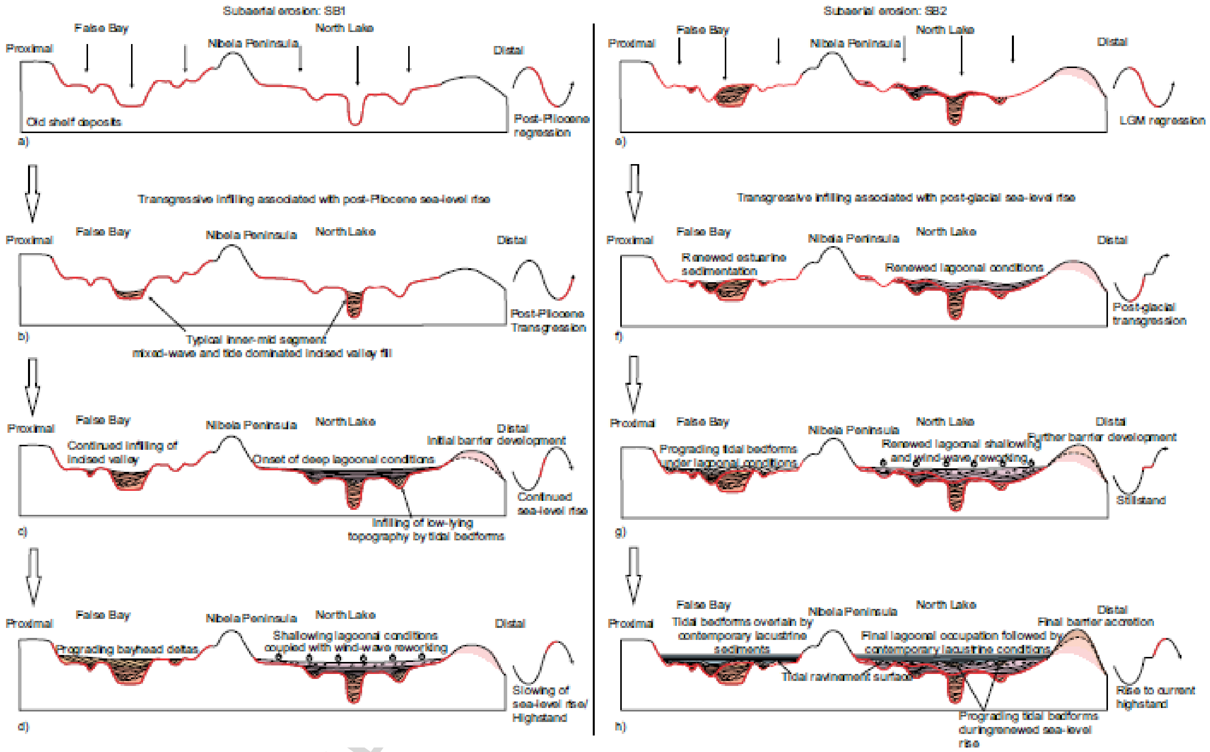

Subaerial erosion: SB1
False Bay
North Lake
Proximal
Nibela Peninsula
Distal
Old shelf deposits
Post-Pliocene regression
a)
Transgressive infilling associated with post-Pliocene sea-level rise
Post-Pliocene Transgression
b)
Typical inner-mid segment mixed-wave and tide dominated incised valley fill
Continued infilling of incised valley
Onset of deep lagoonal conditions
Initial barrier development
Continued sea-level rise
c)
Infilling of low-lying topography by tidal bedforms
Prograding bayhead deltas
Shallowing lagoonal conditions coupled with wind-wave reworking
Slowing of sea-level rise/ Highstand
d)
Subaerial erosion: SB2
LGM regression
e)
Transgressive infilling associated with post-glacial sea-level rise
Renewed estuarine sedimentation
Renewed lagoonal conditions
Post-glacial transgression
f)
Prograding tidal bedforms under lagoonal conditions
Renewed lagoonal shallowing and wind-wave reworking
Further barrier development
Stillstand
g)
Tidal bedforms overlain by contemporary lacustrine sediments
Final lagoonal occupation followed by contemporary lacustrine conditions
Final barrier accretion
Tidal ravinement surface
Rise to current highstand
Prograding tidal bedforms during renewed sea-level rise
h)

Figure 10

Table 1. Simplified stratigraphic framework for False Bay and North Lake, describing seismic units, the age of each unit, and the interpreted depositional environments.

Underlying horizon	Seismic unit/ surface	Sub-unit	Modern description	Thickness	Characteristics	Distal/proximal	Interpreted depositional Environment	Systems tract	Age
Reflector-fi	G		Capping fill	2-8m	Acoustically semi-transparent reflectors, laterally extensive	Both	Lacustrine fill	Contemp. highstand	Late Holocene
Reflector-fi		F2	Prograding tidal bedforms		Moderate-amplitude oblique to oblique tangential, downlapping the TRS	Distal	Prograding tidal channel sediments	Stillstand	Holocene
Reflector-dii/-eii	F	F1	Laterally extensive drape package	<10m	Sub-parallel to oblique tangential low amplitude continuous reflectors	Distal	Back-barrier lagoonal drape fill	TST	Holocene
Reflector-eii		E3	Laterally extensive prograding package	Variable: 2m-5m	Sigmoid-oblique prograding reflectors onlap and downlap the underlying reflector	Distal	Prograding back-barrier tidal channel sediments	TST/stillstand	Holocene
Reflector-ei		E2	Prograding tidal bedforms	5-8 m	Moderate-amplitude oblique to oblique tangential, downlapping the TRS	Both	Prograding back-barrier tidal channel sediments	TST/Stillstand	Holocene
Reflector-dii	E	E1	Depression bound drape package	5-8m	Low-amplitude, typically onlapping the minor depressions of the TRS	Both	Back-barrier lagoonal drape fill	TST	Holocene
Reflector-di		D4	Channel drape package	≤13m	Low to moderate amplitude, sub-parallel to sigmoid-oblique reflectors drape valley walls	Proximal	Estuarine central-basin deposits	Early-mid TST	Late Pleistocene-Holocene
Reflector SB2		D3	Side attached prograding wedge	<14m	High-amplitude, prograding convex sigmoid reflectors that onlap valley flanks,	Proximal	Valley flank attached fluvial point bars	Early-mid TST	Late Pleistocene

					downlap SB1				
Reflector-di		D2	Chaotic structureless capping fill	Variable: 8-20m	Predominantly acoustically opaque, structureless reflectors, disorganized	Distal	Shallow aggrading lagoonal	TST/stillstand	Late Pleistocene/ Holocene
Reflector SB2	D	D1	Moderately developed drape package	Variable: 10-17m	Low to moderate amplitude reflectors that onlap the gently undulating valleys of SB2	Distal	Deep backbarrier lagoonal	TST	Late Pleistocene/ Holocene
	Reflector SB2		Extensive erosional reflector		Erosional truncation of B and C, rugged incised valleys		Both	Subaerial unconformity	
Reflector-ci		C3	Chaotic, structureless capping fill	25m	Low-amplitude reflectors appearing chaotic and structureless	Not recognised proximally	Shallow aggrading lagoonal	TST/stillstand	Pleistocene
Reflector-biii		C2	Prograding tidal dune	≤18m	Convex prograding moderate amplitude reflectors,	Not recognised proximally	Lagoonal tidal channel	TST	Pleistocene
Reflector-biii	C	C1	Well-developed drape package	10-20m	Low-amplitude, draping reflectors	Not recognised proximally	Deep back-barrier lagoonal	TST	Pleistocene
		B4	Isolated prograding package		Moderate amplitude, sub-parallel reflectors, low angle (3-5°) degree dip toward the valley thalweg		Prograding Bayhead delta	HST	Pleistocene
Reflector-bi/bii		B3	Thick drape package	≤45m	Low amplitude oblique parallel to wavy sigmoid reflectors, onlap valley flanks	Both	Estuarine central-basin deposits	Early-TST to TST	Pleistocene
Reflector SB1/ reflector-bi		B2	Valley flank attached wedge	5-10m	Moderate amplitude steeply dipping, prograding oblique-parallel reflectors which onlap valley flanks	Both	Tidal flats	Early TST	Pleistocene
Reflector SB1	B	B1	Isolated channel sediments	≤12m	Chaotic, discontinuous high amplitude Reflectors	Both	Fluvial lag deposits	Late LST	Late Pliocene -Pleistocene

	Reflector SB1		Extensive erosional reflector		Erosional truncation of A, deeply incised undulating surface		Both	Subaerial unconf.	
	A	n/a	Mid-upper slope prograding acoustic basement.	<50m	Continuous sub-parallel to parallel, moderate to high amplitude reflectors dipping at approximately 2-3°in a seaward direction	Both	Shallow marine		Maastrichtian

Highlights

- Describe the seismic and lithostratigraphy of Lake St Lucia
- Compare the coeval evolution of the distal and proximal system
- Show how the long term stability of a barrier influences backbarrier deposition
- We relate the stratigraphic preservation to a lack of oceanic ravinement