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Abstract

Richards Bay is part of a back-barrier lagoon fronted by high coastal dunes on the NE, Indian Ocean coast of South Africa. In the early 1970s, a berm was constructed, dividing the original Mhlathuze Estuary into two separate systems; the Richards Bay Harbour and the new Mhlathuze Estuary. This study investigates the stratigraphic evolution of the incised valley system and bayhead delta in the Richards Bay Harbour segment. Seven seismic units (Units 1–7) were imaged. A single regionally developed sequence boundary (SB) along with two tidal ravinement surfaces (tRS1 and tRS2) were identified. Surface SB is associated with the LGM lowstand which developed when sea levels were ~130 m below present, until ~18 000 year BP. Cretaceous age siltstones (Unit 1) form the basement. Transgressive material overlying SB (Unit 2) reflects the filling of an incised valley located in the middle segment of a wave-dominated back-barrier system. It is overlain by a bayhead delta (Unit 3), the geometry and seismic signature of which indicate alternating periods of aggradation/progradation and backstepping. The behaviour is attributed to episodic jumps in sea level, and is tentatively (on the basis of elevations in relation to the regional sea-level curve) linked to periods of rapidly rising sea level (8.2 ka event and Meltwater Pulse (MWP)-1d). These intervals of rapidly rising sea level, combined with relatively low gradient settings facilitated backstepping of the delta. Fills (Unit 4) occur within minor incisions along the delta top. These are interpreted as distributary channels that fed sediment to the seaward edge of the bayhead delta system. Elongated mounds on the seafloor (Unit 5) are interpreted as spoil from contemporary port dredging. Slump deposits (Unit 6) along the delta front are attributed to a combination of oversteepening of the delta by dredging, as well as deposition of modern sediments brought into the system by tidal currents. The system is capped by fine-grained, tidally redistributed and deposited sediments (Unit 7) which were possibly sourced from older organic material of an indeterminate source. This site is especially sensitive to episodic rates of sea level change due to the relatively small Glacial Isostatic Adjustments (GIA) during the postglacial transgression and the flat antecedent gradients of both the subaerial unconformity and the overlying tidal ravinement.

1. Introduction

Bayhead deltas are defined as fluvially-dominated deltas that prograde into a semi-enclosed body of marine water (Nichol et al., 1997). On a transgressive coastline bayhead deltas form where the rate of sediment input from a fluvial source surpasses the rate of sea-level rise (Aschoff et al., 2018). As such, bayhead deltas are an integral component of most classic wave-dominated lagoon/embayment systems (Dalrymple et al., 1992). They provide a link between the fluvial and central basin depositional environments of many incised valley systems (Simms and Rodriguez, 2015). However, they are not restricted to incised valley systems (Bhattacharya and Giosan, 2003) and also form in fjords, structural basins, interdistributary bays, and other backbarrier environments (see Simms et al., 2018).

In most cases, fluvial systems associated with bayhead deltas provide the majority of the sediment and freshwater input to the upper portions of these systems (Smith et al., 2013). They are also an important part of the rock record, providing vital information for sequence stratigraphic models, and play host to important hydrocarbon reservoirs worldwide (Simms et al., 2018). Many ports and coastal cities are also partly constructed on bayhead deltas, underlining the importance of these shallow and flat-lying areas for land reclamation.

Here we document the stratigraphic evolution of a bayhead delta and incised valley system on which one of the busiest ports in Africa, Richards Bay Harbour, is situated. The purpose of this study is to: (1) provide a detailed and complete stratigraphic framework of the underlying incised valley network of the palaeo-Mhlatuze Estuary, now the site of Richards Bay Harbour; (2) describe the stratigraphic evolution of the backbarrier system and its bayhead delta and (3) determine the process and controls on bayhead delta backstepping in the local context of sea-level change.

2. Regional setting

2.1. Physiography

The Richards Bay Harbour is situated on the subtropical northeast coast of South Africa (approximately 28°47'55.15" S, 32°03'26.71" E) and lies adjacent to the Mhlathuze Estuary (Fig. 1). Before the harbour was developed, the two systems comprised a single large lagoonal system (Weerts and Cyrus, 2002) connected to the Indian Ocean via a narrow inlet roughly in the location of the modern harbour entrance (Jerling, 2003) (Fig. 1).

The original estuary system had five rivers flowing into it, the Mhlathuze, Bhizolo, Mzingazi, Mtantatweni and Manzinyama rivers (Jerling, 2003), of which the west-east-trending Mhlathuze River was dominant. The construction of a berm that divided the estuary into two systems, commenced in 1972 and allowed the two embayments to now function independently, with two separate inlets (Fig. 1) situated 4 km from each other (Weerts and Cyrus, 2002). The Mhlathuze River was re-directed to flow into the new Mhlathuze Estuary and not into the harbour (Jerling, 2003), though a small channel still occurs where the palaeo-Mhlatuze River had previously entered. Large portions of the former back-barrier have now been reclaimed and converted into various docks and industrial spaces (Fig. 1).

To the north of the harbour lies Lake Mzingazi, which enters the system via the Mzingazi Canal (Weerts et al., 2014). Apart from the tidal inlets, the system is separated from the Indian Ocean by a peninsula comprising a coastal dune-ridge with an elevation of approximately 20-30 m to its west and 5 m in the east (Maud and Orr, 1975).

2.2. Hydrodynamic regime

Semi-diurnal tides dominate the northern KwaZulu-Natal coastal plain. The neap tidal range in the Richards Bay area is 0.52 m, whereas the mean spring range is approximately 1.80 m (Schoonees et al., 2006). The KwaZulu-Natal coast is thus described as microtidal (Davies, 1964) or lower mesotidal (Hayes, 1979; cf. Flemming 2005).

The open coast is dominated by high energy waves (Salzmann and Green, 2012). The average significant wave height offshore Richards Bay is 1.5 m (Moes and Rossouw, 2008) and there are only small seasonal changes in wave height and direction (Rossouw, 1984). For approximately 40% of the time, southeast prevailing high-amplitude swells are dominant in the area (Begg, 1978; Rossouw, 1984). However, when northeasterly winds prevail, low-amplitude and short period waves develop for a further 40% of the time (Van Heerden and Swart, 1986). Offshore the harbour, the middle to outer shelf is dominated by the Agulhas Current, a swiftly-flowing western boundary current that can reach speeds of up to 2 m s-1 (Lutjeharms, 2006) and which removes most of the sediment that accumulates along the shelf edge since the early Holocene (Flemming, 1981).

Schoonees et al. (2006) outline both the swell and wind-wave climate of the harbour interior. Significant wave heights in the centre of the main channel (Fig. 1) were modelled and values of 0.7 m and 1.1 m obtained for return periods of 1 and 100 years respectively. Wave penetration decreases substantially to landward in the backbarrier (Schoonees et al., 2006).

2.3. Fluvial sediment load

Before the development of the Richards Bay Harbour, the Mhlathuze River delivered a sediment load of approximately 20 500 m^3 pear year to the unaltered estuary (Anon, 1972, cited in Weerts, 2002). Subsequent to the harbour development, this increased to approximately 237 000 m^3 per annum in the now separated Mhlatuze estuary to the south (Huizinga and Van Niekerk, 2000, cited in Weerts, 2002). Sediment delivery to the current harbour is limited to almost entirely marine materials (Begg, 1978), with very little fluvial sediment entering the system (Cloete and Oliff, 1976; Mehlhorn et al., in 2021).

3. Methods

3.1. Seismic reflection data

This study focuses on a series of incised valleys and sedimentation related to the palaeo-Mhlatuze River entrance to the Richards Bay backbarrier system. 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. Data were collected along coastal strike with a line spacing of 25-50 m. Several tie lines were collected down-dip with a line spacing of ≤200 m totalling approximately 180 line kilometres (Fig .1). These data were recorded using the

Hypack^{TM} hydrographic software package and positioning was achieved using a Real Time Kinematic DGPS of ~ decimetre accuracy. The raw seismic data were processed using the Hypack SBP utility. Bandpass 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 0.5 and 0.7 m. All data were interpreted according to standard seismic stratigraphic principles (Mitchum and Vail, 1977).

3.2. Bathymetry

Multibeam bathymetry data were collected using a Norbit iWBMS narrow beam multibeam echosounder with an integrated Applanix Wavemaster II inertial navigation unit. Sound velocity in water was measured using an AML Base X system, and tides were corrected in real time using the RTK GPS position. All data were processed in Hypack and the final product exported as 0.5 x 0.5 m grid.

3.3. Coring and sediment sampling

Several gravity cores were collected to sample some of the key seismic surfaces and facies observed in the seismic records. The cores were collected using a Uwitec large-gauge gravity corer with an 86 mm diameter barrel. The cores were split, described, photographed, and sampled for AMS C^{14} dating. Samples of organic sediment were sent for radiocarbon analysis from two cores, RBH-18-23 and RBH-18-18. All samples were calibrated using the marine20.14c model (Heaton et al., 2020), with a reservoir effect of 716 +-26 years (Maboya et al. 2018).

4. Results

4.1. Bathymetry

The study area encompasses a shallow, low-gradient intertidal-subtidal bayhead delta of sediment adjacent to the entry point of the palaeo-Mhlatuze River into the Richards Bay Harbour. The platform is fringed landward by mangroves and is modified along its southeastern and northeastern margins by regular seafloor dredging (Fig. 2). A clear, planar morphology is evident, with the platform widening seaward (Fig. 2). Platform elevations range from +1 m MSL along the mangrove fringes in the northwest of the study area, to -24 m where the bayhead delta drops off steeply and where dredging is common in the main shipping channels. A series of shallow channels incise the surface of the platform. They are up to 100 m-wide and ≤2 m deep. These extend from the current channel that enters the port, to the southeastern terminus of the platform (Fig. 2), decreasing in relief until they are barely perceptible in the gridded bathymetry.

4.2. Seismic stratigraphy

Seven seismic units (Unit 1 – 7) were imaged beneath Richards Bay Harbour (Figs. 3-10). Of these, Units 2 and 7 are subdivided into a number of sub-units (e.g. Unit 2a, b and c) (Fig. 3 and 4). Acoustic reflectors separate these units from each other (e.g. Reflector-1/3 separates Unit 1 and Unit 3). Unit 1 is separated from the overlying units by Surface SB. Unit 2 occurs between Surface SB and tRS1. Units 3, 4 and 6 occur above Reflector-1/3 and crop out on the seabed. Unit 5 occurs between tRS1 and tRS2 or between tRS1 and the seabed, and Unit 7a occurs between tRS1 and tRS2 or between tRS1 and the seabed. Unit 7b exclusively occurs between tRS2 and the seabed. The elevations of the main seismic surfaces are presented in figure 11.

Unit 1

Unit 1 is the oldest unit resolved in the study area. This unit is characterised by continuous, parallel, seaward dipping and prograding reflectors of moderate amplitude. These reflectors are truncated by high amplitude erosional surfaces SB and tRS1 or tRS2 (Figs. 3-10) or may crop out on the seabed (Figs. 4 and 7b). In places, this unit also directly underlies Unit 3, where the lateral extent of Surface SB is unknown (Figs. 8-10). The maximum thickness of this unit cannot be determined but is at least 58 m.

Unit 2

Unit 2 occurs as fills within incisions of Surface SB. This unit is subdivided into three sub-units (2a, b and c) which are present to varying degrees throughout the study area.

Unit 2a

Unit 2a occurs throughout the study area, forming the majority of the valley fills (Figs. 3-10). It mainly manifests itself as aggrading/draping reflectors of low to moderate amplitude (e.g. Fig. 3-7 and 9a). These either onlap Surface SB (Figs. 3-7 and 9a) or Reflector-2a/c (Figs. 3, 5-7a). In some incisions, these reflectors are randomly oriented, showing no particular configuration (e.g. Figs. 7b and 10), while in others they are sigmoidal to oblique-parallel. They downlap Surface SB and onlap Reflector- 2a/b (Figs. 8 and 9b). In all instances, reflectors of Unit 2a are truncated by the overlying tRS1. The average thickness of this unit cannot be determined as its basal surface is mainly beyond the penetration depth of the Boomer but appears to reach maximum thicknesses of more than 30 m.

Unit 2b

Unit 2b occurs sporadically in the study area, comprising low amplitude, concave down to oblique-parallel, valley-flank attached reflectors which form mounds (Figs. 7a, 8 and 9). These reflectors onlap and downlap Surface SB. Where present, this unit is mainly attached to only one valley-flank and is separated from Unit 2a by Reflector-2a/b. This unit attains a maximum thickness of 2.5 m.

Unit 2c

Unit 2c occurs as lenses of prograding, sigmoid to oblique-parallel reflectors of low to moderate amplitude (Figs. 3, 5-7a and 10). These onlap Surface SB and downlap Reflector-2a/c. In all cases, this unit is truncated by tRS1 and is mainly attached to incised valley-flanks. This unit is 4 to 8 m thick and lies approximately 24 m below sea level.

Unit 3

With a maximum thickness of 22 m, Unit 3 consists of continuous, high to moderate amplitude, aggrading and prograding reflectors (Figs. 8-10). The unit is overall planar, with very flat topsets confined to the distal margins. Clinoforms of this unit aggrade and also backstep, with successive rollovers initiated further landwards and at shallower elevations. They all prograde into and over the underlying incised valley fill of Unit 2 (Figs. 8-10). Along the delta bottomsets, the reflectors are sub-parallel, exhibiting dip angles of 6 to 11^{o} and either abut against Unit 6 (Figs. 8, 9b and 10b) or intercalate with Unit 7 (Figs. 9a and 10a). The rollover of Unit 3's clinoforms are associated with three distinct elevations at ~ -12.5 m, ~ -11 m and ~ -7.5 m (Fig. 11f).

Unit 4

Unit 4 forms fills within small, isolated incisions (Fig, 8, 9b and 10b). These incisions are exclusively found within the upper portions of Unit 3 and reach depths of 7-15 m (Fig. 11). This unit comprises low to moderate amplitude, aggrading to concave up reflectors.

Unit 5

Unit 5 forms as isolated mounds with chaotic, high amplitude reflectors showing no particular configuration (Figs. 3-6). These mounds are found within or crop out of Unit 7 and lie directly on tRS1. These form small peaks on the seafloor, surrounded by contemporary furrows formed by active dredging (Fig. 3b)

Unit 6

Unit 6 forms adjacent to Unit 3 and comprises moderate to high amplitude, randomly oriented to sigmoid parallel reflectors (Figs. 8, 9b and 10b). These may either onlap Reflector-2/6 (e.g. Fig. 8) or Reflector-3/6 (e.g. Figs. 9b and 10b). This unit reaches maximum thicknesses of approximately 10 m.

Unit 7

Capping most incised valleys is Unit 7, which can be divided into two sub-units (7a and b). This unit may either be laterally extensive or may pinch out landward or seaward.

Unit 7a

Unit 7a occurs throughout the study area and consists of aggrading and prograding, moderate to low amplitude reflectors (Figs. 3-10). The reflectors are mostly parallel and, drape the depressions formed by the underlying tRS1 surface (e.g. Fig. 5). They may also be sigmoidal, discontinuous, randomly oriented or show no particular internal configuration (Fig 3-10). Where sigmoidal, they downlap tRS1 and in places, onlap Reflector-6/7 (Fig 9b and 10b). This unit underlies tRS2 (Figs. 3-5 and 9a) and may be up to 5.5 m thick.

Unit 7b

Where present, Unit 7b lies directly above Unit 7a (Figs. 3-5 and 9a). This unit comprises very low to low amplitude reflectors with no apparent configuration. The unit pinches out landward and/or seaward and attains a maximum thickness of approximately 2 m.

Stratigraphic surfaces

Three major stratigraphic surfaces characterise the study area (SB, tRS1 and tRS2). Their orientation, depth and attributes are shown in Fig. 11. Throughout the study area, reflectors of Unit 1 are erosionally truncated by the high amplitude, continuous, rugged, undulating Surface SB. Numerous incisions of various widths and depths characterise this surface. The incisions in Surface SB either trend N-S or W-E and reach depths greater than 40 m (Fig. 11a).

Surface tRS1 occurs throughout the study area. This erosional surface is characterised by the presence of numerous minor incisions and may either be limited to the major incised valley network (Figs. 8-10) or may extend laterally beyond the incised valleys where it merges with SB on the incision interfluves (Figs. 3-7). Where Units 3 and 6 are present, tRS1 abuts gently against either of them (Figs. 8-10). Surface tRS1 reaches depths of ~ 29 m (Fig. 11b). The combined tRS1 and SB surfaces (over which unit 3 progrades) are generally flat (Figure 11c), with an average gradient of ~ 0.1°. Local gradients of this combined surface increase where there has been excavation by subsequent erosion during formation of tRS2 to remove tRS1. This usually occurs where pronounced valleys are present in SB.

As mentioned, surface tRS2 is erosional, consisting of numerous minor incisions and small scarps. This surface is not continuous across the system (Figs. 3-5 and 9a). Surface tRS2 extends to a depth of ~24 m (Fig. 11d). The small channels that house Unit 4 reach depths of 15 m relative to mean sea level (Fig. 11e).

Faults

A number of prominent normal faults are recognised in the study area. They are visible in the NNE-SSW (e.g. Figs. 6 and 7a) and WNW-ESE (Fig. 3) trending seismic lines as well as the N-S trending seismic line (Fig. 9b). Most of these faults occur within Unit 1 (Figs. 3, 6, 7a and 9b), with a single fault observed within the incised valley fill itself (Unit 2a) in Fig. 7a. In some instances, the faults influence the seabed morphology, displacing the seafloor by approximately 2 m (e.g. Fig. 3a and b).

4.3. Core lithology

The cores grouped in the landward-most part of the study site (RBH-18-23 and 24) are dominated by rhythmically interbedded silts and clays, with occasional sandy laminae and regular organic-rich horizons (Fig. 12). Occasional, high-angle plan cross-bedded sandy laminae occur. Towards the core tops, burrows are apparent. Core RBH-18-25 collected from the more distal parts of the platform-top channel is more organic-rich, with few laminations present and a lack of rhythmic interbedding (Fig. 12). Occasional shell debris occurs, marking very crude, flat-lying beds. Mottling and burrowing are common in the upper portions of the core where the sand content increases to medium sands with larger, grit-sized (2-4 mm) shell fragments. These cores intersect only Unit 7b. The landward expression of Unit 7b appears (Fig. 12a) sedimentologically different to the more seaward variant, as described below.

In the main dredge depression, cores RBH-18-18, RBH-18-11, RBH-18-12 and RBH-18-14 show similar alternating dark black and light brown silty laminations (Fig. 12b). RBH-18-14 has a brown, clay-rich basal section with very faint black laminae. Flat-lying sand lenses up to 1 cm-thick occur sporadically. Above the stratigraphically highest lens (~ 1.3 m downcore) the core comprises uniform brown clay which is sharply overlain by rhythmic interbeds of black and brown clays. These grade into dark black clays with stratigraphic height. The core intersects both Unit 7a and b (Fig. 4), with tRS2 reconciled to the uppermost sand lens at 92 cm downcore (Fig. 12b).

The deepest parts of RBH-18-12 intersect a basal set of dark black clay laminae which are sharply overlain by a faintly laminated brown clay with gently inclined sandy layers (Fig. 12b). This grades vertically into a dark brown and light brown interbedded clay unit. The core intersects tRS2 which is marked by a cm-thick sandy layer. Unit 7b can be reconciled with the lower, faintly laminated brown clay, and Unit 7a the overlying darker materials. RBH-18-11 consists almost entirely of the dark black laminae that marks the upper horizons of the other cores and appears to have terminated at tRS2 (Fig. 12b). RBH-18-18 comprises a similar dark black upper laminated package that terminates sharply on a lower stiff grey clay. The entire core represents Unit 7b.

The dates on RBH-18-23 are stratigraphically inconsistent. Organic sediment from a core depth of 70-71 cm dated to 1845 ± 30 BP. This is overlain at 33-34 cm by organic sediment dated at 3745 ± 30 BP (Fig. 12B). A single organic sediment date from RBH-18-18 at a core depth of 42-43 cm returned an age of 6060 ±165 cal BP.

5. Discussion

5.1. Seismic stratigraphic interpretation

5.1.1. Acoustic basement and LGM lowstand (Unit 1 and Surface SB)

Unit 1 forms the acoustic basement to the study area. This unit is intersected by numerous boreholes in the region (Maud and Orr, 1975) and represents the Cretaceous age siltstones that have been widely recognised along the shelf and underlying the coastal water bodies of the east coast of South Africa (Green and Garlick, 2011; Green et al., 2013; Benallack et al., 2016; Dladla et al., 2019). A series of incised valleys, represented by Surface SB, are cut into the Cretaceous siltstones. This unconformity surface can be traced onto the shelf and for several hundred kilometres along the east coast. Cores from incised valleys of similar stratigraphic positions on the Durban shelf (Pretorius et al., 2016) and in Lake St Lucia (Dladla et al., 2019) reveal the infilling materials to be Holocene in age. We thus associate this surface with the LGM lowstand, when sea levels occupied a position of the shelf break at ~130 m below present, ~18 000 year BP (Ramsay and Cooper, 2002; Cooper et al., 2018).

5.1.2. Post-LGM incised valley fills (Unit 2)

The incised valley network is dominated by the thick and homogenous fills of Unit 2a. Though these may occasionally show no particular reflector configuration, they are mainly aggrading in nature, forming onlapping drapes with the valley walls. This architecture closely resembles the central basin fills recognised in incised valleys to the south (e.g. Green et al., 2013) and to the north (e.g. Benallack et al., 2016; Dladla et al., 2019) of the study area, suggesting that Unit 2 is mainly characterised by central basin deposits (Unit 2a), intercalated with other deposits (e.g. Unit 2b). The thick nature of the central basin fill is in keeping with the location of the incised valley in the middle segment of a wave-dominated back-barrier system (e.g. Zaitlin et al., 1994).

The valley flank deposits of Unit 2b show strong similarity to the prograding point bars that other authors have recognised from incised valley fills (e.g. Weber et al., 2004; Chaumillon et al., 2008; Dladla et al., 2019). The high-angle, inclined reflectors and their location usually on the gentler bank of the valley support this interpretation.

Unit 2c forms as flank attached or isolated prograding packages with sigmoid to oblique-parallel reflectors. Simms et al. (2010) reported a similar, prograding, valley-flank attached package in the Baffin Bay incised valley. Here, they suggest that a package with this type of appearance can either be interpreted as buried prograding subtidal spits or lobes of a bayhead delta. They propose that the attached nature of the unit to valley flanks favours a buried spit interpretation over bayhead delta lobes. We similarly interpret Unit 2c as representing buried subtidal spits. In Lake St. Lucia, Dladla et al. (2019) recognise units of similar seismic architecture and describe these as wind-driven prograding sand spits. Such deposits are suggested to have formed due to the transport and reworking of sediment by wind-induced bottom currents (e.g. Nutz et al., 2015). These are commonly recognised in other large coastal water bodies of the area (Wright et al., 2000). The spits (Unit 2c) were later truncated by modern tidal processes (tRS1).

Surface tRS1 is characterised by numerous minor incisions, the morphology and scale of which are similar to those of contemporary tidal creeks and channels of the modern back-barrier system. tRS1 has a similar seismic expression to tidal ravinement surfaces documented elswhere (Menier et al., 2006; Nordfjord et al., 2006; Benallack et al., 2016; Dladla et al., 2019; Engelbrecht et al., 2020). Such surfaces form due to migrating tidal inlets or channels during sea-level rise (Catuneanu et al., 2009; Green et al., 2015).

5.1.3. Bayhead delta (Units 3 and 4)

The aggrading-prograding and backstepping seismic reflection architecture of Unit 3 closely resembles that of bayhead deltas subject to episodic jumps in sea level. Such features have previously been recognised worldwide (e.g. Allen and Posamentier, 1993; Nichol et al., 1997; Rodriguez et al., 2010; Smith et al., 2013; Benallack et al., 2016; Aschoff et al., 2018). Episodic landward shifts of many of these features have been directly linked to rapid sea level rise during the early Holocene period (Rodriguez et al., 2010; Kendall et al., 2008; Törnqvist et al., 2004).

Unit 4 occurs as fills within minor incisions along the delta top (Fig. 11e). We interpret these as tidal channels on the bayhead delta surface (distributaries) that fed sediment to the seaward edge of the system. A similar series of small, shallow channels incise the surface of the modern platform and are visible in the bathymetry (Fig. 2). The overall seismic architecture of Unit 3 and 4 is in combination similar to the bayhead deltas described from Florianopolis Bay of southern Brazil (Meireles et al., 2016). The fact that clinoforms are restricted to the seaward margin, points to vertical aggradation of the delta surface since its inception when sea level reached ca. -20 m.

The distinct elevations in delta clinoform rollover at ~ -12.5 m, ~ -11 m and ~ -7.5 m (Fig. 11f) are discussed below in section 5.3.2. Each of these can be considered approximate upper intertidal palaeo-shoreline positions and thus markers of palaeo-sea level. Their degree of accuracy can be related to palaeo-tidal influences, with larger tides extending the error of interpretation. In most instances, and in the absence of data, the palaeo-tidal ranges are related to the modern heights of these datums (Hijima et al., 2015). In the case of our study and the palaeo-shorelines above, the underlying incised valley stratigraphy, in combination with the wave-dominated shape of the delta, illustrates a former wave-dominated setting for an open bayhead delta (Simms et al., 2018). When related to the upper micro-tidal framework currently experienced in the area, these provide good sea level indicators with an approximate error of half the tidal amplitude (cf. Hijima et al., 2015). Given the contemporary spring tide amplitude of 1.8 m, this error equates to <0.9 m.

Despite the evidence for neotectonism presented later in section 5.2, the modelled glacial isostatic adjustment (GIA) for the last deglaciation in the study area reveals local sea levels to be within 1 m of the global predicted values (Milne and Mitrovica, 2008). This points to a relatively good fit between palaeo-sea level inferences based on the stratigraphy and global episodes of sea-level variation.

5.1.4. Anthropogenic features (Unit 5)

Figure 2 and 3 show several elongate mounded features of seafloor that crop out as semi-cohesive sediment piles of Unit 5, surrounded by fainter reflectors of Unit 7. These are clearly remnants of the dredging process, where small ridges remain between furrows that have been scoured. The erosional furrows represent the excavation of the seabed and formation of the tRS2 surface (discussed in section 5.1.6).

5.1.5. Slump deposits (Unit 6)

With randomly oriented reflectors, Unit 6 occurs in front of the bayhead delta and intercalates with valley fill material. Based on its position and chaotic seismic architecture, we interpret this unit as slump deposits, formed on the steepest part of the delta (distal delta front; cf. Aschoff et al., 2018). This could be the result of the oversteepening of the delta by dredging along its margins. However, we also recognise a strong association between the slumping (Unit 6) and the feeder channels (Unit 4), as all the seismic lines with feeder channels are characterised by the presence of slumping in front of the delta. We therefore suggest that the slumping may be due to the steepness of the delta front (Aschoff et al., 2018).

5.1.6. Fine-grained tidally deposited sediment (Unit 7)

Unit 7 caps the incised valley stratigraphy and is subdivided into two sub-units (Unit 7a and b). This unit is mostly characterised by low to moderate amplitude reflectors, which drape underlying units or may lack any internal reflector configuration, suggesting low energy depositional environments prevailed at the time of formation. Core data reveal that the uppermost portions of the stratigraphy are characterised by laminated silts and clays. tRS2 is revealed to be a sandy layer that separates a lower brown from upper dark black laminated clay. The building of the harbour and construction of a second mouth increased the tidal range in the area, leading to larger areas being exposed to tidal influences (Huizinga and van Niekerk (2000). Surface tRS2 likely represents remobilisation and winnowing of the seabed, possibly due to a combination of modern tidal reworking and dredging of the area.

The stratigraphical inconsistency of the dates of Unit 7b can be ascribed to reworking and redeposition of older-aged carbon that has been transported into the system as organic sediment. Their mixed age suggests that this unit is likely of recent origin, and that the seabed materials have been reworked from a sediment source of older organic material.

5.2. Neotectonics

Numerous faults were recorded in the seismic records. Neotectonism is identified as being pervasive across South Africa (Andreoli et al., 1996) and faults are found along the coastal regions and on the ocean floor. Late Pleistocene to Holocene faults are exposed from Port Durnford (Jackson and Hobday, 1980) northwards along the northern KwaZulu-Natal coastal plain (Kruger and Meyer, 1988) all the way to south Mozambique (cf. Andreoli et al., 1996). The faults reported in this study area are consistent with these other indicators of neotectonics.

5.3. Coastal evolution

We summarise the early geological evolution of the palaeo-Mhlatuze River and estuarine complex as follows (Fig. 13):

The stratigraphy is underlain by Cretaceous age siltstones (Unit 1; forming the acoustic basement), into which a single episode of incision occurred (SB), formed by the Mhlathuze River. This was associated with the Last Glacial Maximum when sea level fell ~130 m below present (Fig.13a). This produced a very flat antecedent slope along the valley interfluves.

The subsequent initial transgressive material overlying SB (Unit 2) reflects the filling of an incised valley located in the middle segment of a wave-dominated system (Fig. 13b). During a period of sea level stability, a bayhead delta (Unit 3) prograded into the underlying incised valley system, over a flat tidal ravinement surface (tRS1). This completely filled the remaining accommodation space of the valley (Fig. 13b and c).

5.3.1. Backstepping of the bayhead delta

Factors such as sediment supply, climatic changes, sea level variations, gradient, etc., govern the development and architecture of a sedimentary system (Feng et al., 2019). As such, the progradation and eventual backstepping of bayhead deltas can be attributed to a number of these processes. The position of multiple delta offset breaks can be used to describe changing palaeo-shoreline trajectories and overall coastal changes over time (Helland-Hansen and Gjelberg, 1994; Aschoff et al., 2018; Engelbrecht et al., 2020).

Factor 1. Sediment supply and local accommodation?

Apart from sea-level rise, Muto and Steel. (1992) and Feng et al. (2019) suggest that the main driving factors of the autogenic evolution of deltas are the availability of accommodation as well as sediment supply. A system's response to rapidly rising sea levels is dependent on the sediment supply/accommodation creation ratio (Rodriguez et al., 2008). In general, a system with a low sediment supply/accommodation creation ratio should respond instantaneously to increases in sea level, whereas one that has a high sediment supply/accommodation ratio should have very little to no response to rising sea levels (Cooper, 1993; Rodriguez et al., 2010).

Several lines of evidence suggest that the Mhlatuze lagoon had low sediment supply during the mid- to late Holocene since sea level reached the present. In contrast to most large estuaries in the region where sedimentation infilled the estuarine valleys with fluvial sediment (Cooper, 1993, 2002), the pre-engineered Mhlatuze lagoon was not completely infilled but had a tripartite division with tidal inlet and deltas, central basin and bayhead delta. This was associated with a large tidal prism that maintained the tidal inlet and is characteristic of gradually infilling estuarine basins.

In our study area, other authors have noted a decrease in sediment supply since the separation of the Mhlatuze River from the modern harbour (Cloete and Oliff, 1976), however this post-dates the bayhead delta development reported above by several thousand years. No data currently exist concerning sediment supply to the system, though seismic profiling directly offshore the Richards Bay area, revealed an up to 4 m-thick depocenter containing ~ 11.78 × 106 m^3 of Holocene-age sediment (Martin and Flemming, 1985). Assuming no significant erosion, this equates to an average rate of sedimentation of 1000 m^3 of sediment per year since the Holocene began 11 650 cal BP. This is significantly less than the 20 500 m^3 per year measured prior to the harbour construction, and given the shelf exposure to the strong Agulhas

Current in the area, likely reflects significant alongshore and off-shelf dispersal. Nonetheless, on geomorphological evidence, we consider the Mhlatuze system to exhibit a low sediment supply/accommodation ratio based on the shallow bedrock and thinly-developed sediment fill, so backstepping may have indeed been exacerbated by a low local sediment supply.

Factor 2. Meltwater pulses: the “other” driving force behind backstepping bayhead deltas?

Rapid increases in the rate of sea-level rise as a result of sudden pro- or subglacial meltwater, are referred to as meltwater pulses (Blanchon, 2011). Meltwater pulses, associated with the collapse of ice sheets, are prominent in the deglaciation phase of the last glacial period (e.g. Fairbanks, 1989). The study of these pulses is important as it provides a link between climatic, glacial and oceanic systems (Tian et al., 2020). During the deglaciation period from 16.5 and 8.2 ka BP, global warming triggered the extensive melting of ice sheets, resulting in a eustatic sea-level rise of ~130 m (Lambeck et al., 2014). Given the local GIA, which is relatively minor in the context of the far field location of Richards Bay, the behaviour of the bayhead delta is thus most probably a strong reflection of adjustments to sea level related to melt water pulses.

The first rollover that approximates palaeo-sea level occurs at -12.5 m, an elevation that places a constraint on the timing for delta development to an age of > 8.3 ka, based on the local sea level curve of Cooper et al. (2018). The aggrading landward planar reflectors of the delta indicate a slow rise in sea level, corroborated by the data of De Lecea et al. (2017) who observed a period of slowly rising sea level between 8.8 ka BP and 8.5 ka BP. We consider this period the point where the delta first formed, followed by a sharp rise in sea level to cause the first stage of backstepping in the clinoform rollovers from -12.5 to -11 m. Given the lack of sea level data for this time in South Africa, we tentatively ascribe this to the 8.2 ka event described by Liu et al. (2004). This hypothesis however remains to be tested by further coring and radiocarbon dating.

A further jump in sea level has been ascribed to MWP-1d (Liu et al., 2004). Though not widely recognised, this meltwater pulse is considered to have occurred between ~ 8.0 and 7.0 ka BP (Liu et al., 2004). Here, sea levels are thought to have risen by 6 m (Blanchon and Shaw, 1995). The final retreat of the delta may possibly have been related to this event. The rollover depth at -7.5 m implies that the delta stabilised at ~ 8 ka (Cooper et al., 2018), which matches well with these slightly younger ages reported for the most recent episodic jump in sea level

(Blanchon and Shaw, 1995). Kirkpatrick et al. (2019) similarly link backstepping delta geometries from the inner shelf of southern Namibia to these two episodes (8.2 ka event and MWP-1d). We again emphasize that these are hypotheses, however the seismic and stratigraphic data from the study area provide an alluring argument for the influence of meltwater pulses as drivers of stratigraphic change in this bayhead delta.

Factor 3. Antecedent topography

Low topographic gradients, when coupled with abruptly rising sea levels, may be crucial in the overall preservation of coastal systems (Sanders and Kumar, 1975) and the eventual backstepping of the shoreline as a whole (Törnqvist et al., 2004). Rodriguez et al. (2010) suggest that estuaries fringed by low lying gradients are more sensitive to low amplitude and sudden sea-level rises, as is evident for the northern Gulf of Mexico estuaries. Locally, a flat topographic surface and stepped rise in sea level has most likely aided in the preservation and backstepping of the deltaic body offshore on the wave dominated Thukela Shelf (Engelbrecht et al., 2020). Studies show that the inundation of flat-lying areas most likely exacerbates the backstepping of bayhead delta systems (Rodriguez et al., 2005), as the system is especially sensitive to any sea level variations in this case. The combined subaerial unconformity and tRS1 surfaces over which the deltas have prograded and been preserved on are exceptionally flat (between 0.1 and 0.02° on average-Fig. 11c). In tandem with stepped sea-level rise, this flat antecedent gradient has exaggerated the translation of the shoreline. We therefore suggest that the backstepping nature of the bayhead delta here is also partly a result of an autogenic response to rapid sea level changing its shoreline trajectory over the gentle antecedent topography. This likely dampened the bayline erosion along the edge of the bayhead delta and as such we consider this area a particularly good site for further sea-level reconstructions using palaeo-bayhead delta stratigraphy.

Considering the above arguments, we link the backstepping of the bayhead delta to rapid sea level rise during the early Holocene, initiated by the 8.2 ka event (Fig 13.d). Minor incisions, in the form of distributary channels, occurred above the bayhead delta and introduced further sediment into the system (Fig 13d). A second phase of backstepping occurred after another relatively stable period of sea level at ~ 8 ka BP. This backstepping is possibly related to MWP-1d.

5.3.2. Anthropogenic influences

In the early 1970s, a berm was constructed, dividing the original Mhlathuze Estuary into two separate systems; the Richards Bay Harbour and the new Mhlathuze Estuary (Fig. 13e). Here, the Mhlathuze River was redirected to flow into the new Mhlathuze Estuary. The low rates of sediment supply since have allowed the delta morphology to remain mostly unchanged apart from the modifications of the steeply dipping margins by dredging and gravity collapse. Dredging of the harbour has periodically occurred, pooling organic rich materials (Unit 7) around isolated mounds of undredged sediment (Unit 5) and produced a steepened delta front that has resulted in slumping (Unit 6) (Fig. 13e).

The tRS2 surface represents modern anthropogenic influence. The remobilisation and winnowing of the seabottom is currently due to a combination of modern tidal reworking and dredging of the area (Fig 13f).

The changes in system configuration from the pre-harbour to post development states can be linked to a reduction in water volumes and tidal prism respectively.

6. Conclusion

The backstepping of bayhead deltas into underlying incised valleys is a global phenomenon. The prograding and eventual backstepping of these bayhead deltas may be attributed to a number of different factors. These include: (1) the amount of sediment brought into the system by rivers, (2) the rate at which this sediment comes into the system, (3) the rate of accommodation creation, (4) rapidly rising sea levels, (5) the gradient of the palaeo-landscape surface, etc. For the Richards Bay Harbour bayhead delta, pulses of rapidly rising sea levels in combination with a relatively low gradient setting were key factors that played a role in the backstepping of the delta. The landward shift of the bayhead delta is proposed to have been linked to both the 8.2 ka event and to MWP-1d. Given the (1) relatively small GIA during the postglacial transgression and (2) the flat antecedent gradients of both the subaerial unconformity and the overlying tidal ravinement, this site is especially sensitive to episodic rates of sea level change. As such, it poses a key target for investigating these phenomena in the far field.

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Data availability

The data used for the research described in this article are proprietary and were released to us. They can be made available on request to Anchor Energy (Pty)Ltd.

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Figure Captions

Fig. 1. Locality map of the study area, outlining the Richards Bay Harbour situated on the northeast coast of South Africa. Note the pre- and post-harbour development geomorphology of the system (top right).

Fig. 2. Multibeam bathymetry of the study area with core locations. Note the clear apron-like morphology that is between +1 to -10 m in elevation. The platform is modified along its southeastern and northeastern margins by seafloor dredging (clear irregular lines in the

bathymetry). Note the presence of small channels ≤2 m deep in the northeastern portions of the study area (lower right inset A to B). These are near imperceptible at the scale presented in the bathymetry and at the gridding resolution of the shallow water areas.

Fig. 3. WNW-ESE seismic profile displaying interpreted (top) and raw (bottom) seismic data. Unit 2a dominates the incised valley fill. Units 2b, 3, 4 and 6 are absent from this seismic line. Enlarged seismic data (insets a and c) show the three major surfaces (SB, tRS1 and tRS2). A prograding bedform (Unit 2c) is truncated by tRS1 (Fig. 3c). The seafloor is displaced by faulting. Note the minor incisions formed by tRS2. Inset b shows the modern-day seabed corresponding to inset a (dashed line), with pinnacles of intact or more cohesive material surrounded by dredge scars. These correspond to Unit 5. The fault scarp at the seabed is labelled f. Note the position of core RBH-18-18.

Fig. 4. WNW-ESE seismic profile displaying interpreted (top) and raw (bottom) seismic data. Units 2b, 2c, 3, 4 and 6 are absent from this seismic line. Unit 2a dominates the fills. Enlarged seismic data clearly show the LGM-age incisions (SB), tRS1 and tRS2. Note the position of core RBH-18-14.

Fig. 5. NNE-SSW seismic profile displaying interpreted (top) and raw (bottom) seismic data. Only Units 1, 2a, 2c, 5, and 7 are present on this seismic line. All major surfaces are also noted. The enlarged seismic data show the prograding tidal bedform attached to tRS1. Note the numerous minor incisions formed by tRS1.

Fig. 6. NNE-SSW seismic profile displaying interpreted (top) and raw (bottom) seismic data. Only Units 1, 2a, 2c, 5 and 7a are present on this seismic line. Note the absence of tRS2. Enlarged seismic data clearly show the prominent faulting that characterises the area.

Fig. 7. (a) Shows a NNE-SSW seismic profile displaying interpreted (top) and raw (bottom) seismic data. Units 3, 4, 5, 6, 7b, as well as surface tRS2 are absent from this seismic line. Possible faulting of Unit 1 is observed. a(i) Shows the prograding bedform attached to tRS1. a(ii) Shows faulting within the incision itself. Draping fills dominate the incised valley. (b) Shows a WNW-ESE seismic profile displaying interpreted (top) and raw (bottom) seismic data. Only Unit 1, 2a and 7a are present on this seismic line. The incised valley fill may have randomly oriented or aggrading draping reflectors. Note the randomly oriented reflectors of Unit 7a. Surface tRS2 is absent from this line.

Fig. 8. WNW-ESE seismic profile displaying interpreted (top) and raw (bottom) seismic data. A single incised valley, dominated by sigmoid to oblique-parallel reflectors of Unit 2a, is present. Units 2c, 5 and 7b are absent from this seismic line. Enlarged seismic data (Fig. 8a) displays a feeder channel within Unit 3. Note the backstepping bayhead delta (Unit 3) as well as the slumping (Unit 6) occurring in front of it (Fig. 8b).

Fig. 9. (a) Shows a WNW-ESE seismic profile displaying interpreted (top) and raw (bottom) seismic data. A single incision formed by the LGM-age Surface SB is displayed. Unit 2a dominates the fills, with aggrading reflectors. Only Units 1, 2a, 2b, 3 and 7 are present on this seismic line. Note the presence of the prograding and backstepping bayhead delta. Both tRS1 and tRS2 are present. (b) Shows N-S seismic profile displaying interpreted (top) and raw (bottom) seismic data. An LGM-age incision is shown, dominated by Unit 2a. Units 2c, 5 and 7b, as well as surface tRS2, are absent from this seismic line. The enlargement clearly shows the prograding and backstepping bayhead delta, with slumping occurring in front of it. Also, note the presence of the feeder channel within the bayhead delta as well as the possible faulting of Unit 1.

Fig. 10. (a) Shows a WNW-ESE seismic profile displaying interpreted (top) and raw (bottom) seismic data. The incision is dominated by thick Unit 2a fills, which are aggrading in nature. Units 2b, 4,5 and 6 are absent from this line. The three major surfaces are present. The bayhead delta progrades into the underlying LGM-age incision. (b) Shows a WNW-ESE seismic profile displaying interpreted (top) and raw (bottom) seismic data. Only Units 1, 2a, 2c, 3, 4, 6 and 7a are present on this seismic. On the enlargement, note the prograding and backstepping bayhead delta (Unit 3) as well as the slumping (Unit 6) that occurs in front of it.

Fig. 11. Sun-shaded relief surface of (a) the SB unconformity, (b) tRS1, (c) gradient of the combined SB and tRS1 surfaces reflecting the antecedent gradient beneath Unit 3 (d) tRS2 and (e) feeder channels of Unit 4. (f) Shows the three positions of the clinoform rollover of Unit 3.

Fig. 12. (a) WNW-ESE seismic profile displaying interpreted (left) and raw (right) seismic data. Note the position cores RBH18-23; 24 and 25. (b) Shows seven cores from the study area. RBH18-18; 23; 24 and 25 only intersect Unit 7a. RBH18-11; 12 and 14 intersect both Unit 7a and 7b. Note the position of tRS2 on the uppermost sand lens at 92 cm downcore on core RBH18-11 and 14.

Fig. 13. The schematic evolution model of the Richards Bay Harbour estuarine stratigraphy. (a) LGM-age incision into Cretaceous siltstones. (b) Post-LGM transgressive infilling of incised valleys, tidal scouring (forming tRS1) and Prograding bayhead delta formation. (c) Continued prograding of delta into underlying incised valleys. (d) Rapid sea-level rise events resulting in backstepping of the bayhead delta. Increased sediment brought into the system by feeder channels. (e) Dividing of the system into the harbour and the Mhlathuze Estuary. Dredging of harbour, formation of dredge mounds and slumping on the delta front. Deposition of organic sediment from an inland source (Unit 7a). (f) Tidal scouring (tRS2) and continued deposition of organic material (Unit 7b).