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Outer- to inner-shelf response to stepped sea-level rise: Insights from incised valleys and submerged shorelines

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Abstract

Shorelines respond to rising sea-level through processes such as erosion, landward migration and in-situ drowning (i.e. overstepping). Submerged and preserved shorelines on the continental shelf play a key role in examining coastal response to rising sea levels as they provide important information on how modern shorelines may evolve in time and space within the context of changing climate and post-glacial sea-level rise. This study identifies and assesses the response of a continental shelf to stepped rises in sea level with particular focus on the stepwise evolution of incised valleys and shorelines from the shelf-edge to the inner shelf. Multibeam bathymetry data from the mid-outer allow for the analysis of seafloor morphology, including the Protea Banks Reef (a palaeo-shoreline complex), and the adjacent incised, sediment starved continental shelf. Six seismic units and intervening surfaces are identified using interpretations from sub-bottom profiles, these include the incised acoustic basement, variable incised valley fill successions, aeolianite ridges and post-transgressive shoreface and associated sediments that withstood wave ravinement processes. The incised valleys of the outer-shelf are manifested as distinctive seafloor depressions, filled at their bases by fluvial deposits overlain, in the unfilled valley, by deposits derived from cascading subaqueous dunes which comprise the upper-most post-transgressive sediments. A core intersecting the dune material yields a maximum age of deposition of 12751191 - 1263 cal. yr B.P,BP (68% range), synchronous with a period of higher than present sea-levels in the region suggesting reworking and redistribution of coastal sediment as shelf sediment post-transgression. During the stepped rises in sea level, the shoreface has disconnected from the contemporary shoreline and is preserved by means of topographic barriers formed by antecedent topography as relict shoreface deposits. We provide a new perspective of shoreline response to stepped rises in sea level by integrating the seismic architecture of incised valley fills and shorelines across the continental shelf thus allowing for the assessment of variation in rates of relative sea-level rise since the last glacial maximum.

Keywords

ShorelinePalaeo-shorelines, Preservation potential, Shoreface, Incised-valley, Overstepping

Highlights

- Unfilled incised-valleys during transgression because of a lack of sediment and/or an increase in accommodation space associated with a rapid increase in sea level.
- Confinement points created by aeolianite barriers on the outer-shelf prevent sediment stripping by the Agulhas current, suggesting antecedent controls on the preservation of shoreline deposits.
- Preservation of shoreline barriers by overstepping is related to the ensuing meltwater pulses 1A and 1B.

- During the stepped rises in sea level, the shoreface has disconnected from the contemporary shoreline.
- A reduction of sediment supply for back-barrier/beach and shoreface exchange during subsequent shoreline construction could lead to increased rates of shoreline retreat and potentially overstepping of low-lying coastal areas.

Introduction

Barriers and associated shorelines respond to sea-level rise by three archetypal processes. These include an erosional response, landward migration in step with sea-level rise, or overstepping of the shoreline and in-situ drowning of the shoreline deposits (Cattaneo and Steel, 2003; Cooper et al., 2018a). In the context of globally rising sea-levels and associated risks from erosion and coastal inundation (e.g. Saito 2001; Thanh et al. 2004; Gibbons and Nicholls 2006; Blum and Roberts 2009), significant planning to mitigate the future economic, environmental and social impacts of such “coastal squeeze” (Mellet et al., 2018) needs to be made. The understanding of shoreline behaviour under past and future conditions of sea-level change can be assisted by investigations of Holocene shoreline deposits on the continental shelf.

Submerged and preserved shorelines of the seafloor play a key role in examining coastal response to rising sea levels. Their preservation in relation to antecedent gradient (Green et al., 2018), rates of sea-level rise (Locker et al., 1996; Green et al., 2014) and sediment supply (Mellet et al., 2012) relay important information on how modern shorelines may evolve in time and space in the context of changing climate and post glacial sea-level rise.

The postglacial evolution of submerged shorelines has received much recent attention (Gardner et al., 2007; Storms et al., 2008; Maselli et al., 2011; Green et al., 2012, 2013a; Mellett et al., 2012; Salzmann et al., 2013; Pretorius et al., 2016) and has been shown to be intimately linked to stepped rises in sea level throughout the Late Pleistocene to Holocene. Shoreline-associated and co-occurring shoreface and incised valley deposits also provide valuable information on the evolution of coastal systems during and after transgression. This study thus aims to identify and assess the response ofIn particular, shelf-hosted incised valley systems may hold important clues to the relative balance between postglacial rises in sea level and available sediment. In this regard, Cooper et al. (2012) proposed a tripartite classification scheme for incised valleys.

"Keep-up" incised valleys maintain infilling in pace with rising sea level, as such their fills are mostly uniform sands. As Cooper et al. (2012) state "Such 'keep-up' estuaries are comparatively rare and occur only where conditions of high sediment supply kept pace with the very high rates of sea-level rise in the early to mid-Holocene". "Catch-up" incised valleys form when sea-level rises initially outpace sediment inputs, with a deep system forming, then later, during stable or slower rising sea levels, the system fills with marine or fluvial materials. The last example is the "give-up" system. Here, sea level increases as a rate significantly greater than can be balanced by sediment supply and the system is effectively drowned. There is insufficient sediment to produce an incised valley fill, or the classic "sediment sandwich" of Ashley and Sheridan (1994). Give-up systems thus point to situations where sea-level rise has been dramatic, or there has been a significant reduction in sediment form either marine or fluvial sources.

Using a series of newly discovered submerged shorelines and multiple give-up, or underfilled incised valleys exposed on the seafloor, we examine the shelf morphology and stratigraphy of a portion of current-swept shelf from the South African margin. By virtue of the high levels of preservation of these geomorphic forms on the shelf, we aim to identify and assess the

response of such a shelf to stepped rises in sea level. In particular, we focus on the stepwise evolution of incised valleys and shorelines from the shelf-edge to the inner shelf; and consider the general evolution of the associated shoreface in this regard.

2. Regional Setting

The southern KwaZulu-Natal continental shelf is narrow (~8 km) and steep (~0.6˚)6°) when compared to global averages (75 km and 0.1˚,1° , respectively) (Shepard, 1963). The shelf break occurs at ~100 m water depth and marks the transition from the continental shelf to the upper-continental slope (Fig. 1) (Green et al., 2013a).

The KwaZulu-Natal coastline is wave-dominated throughout the year, with a significant wave height of 1.8 m (Moes and Rossouw, 2008). The coastline is upper microtidal with a spring tidal range of 1.8 m (Moes and Rossouw, 2008). The continental shelf is swept by the poleward flowing Agulhas current which accounts for the overall sediment starved nature of the shelf (Fig. 1) (Martin and Flemming, 1988; Green and McKay, 2016).

The acoustic basement of most of KwaZulu-Natal comprises seaward prograding Cretaceous-aged siltstones which can be traced north to the central and northern KwaZulu-Natal continental shelf (Green and Garlick, 2011; Cawthra et al., 2012; Green et al., 2013a; Salzmann et al., 2013). The shelf has been incised by a network of valleys during past lowstand events (Green et al., 2013b) the most recent of which was the Last Glacial Maximum (LGM) of ~18 000 yr BP when sea-level was ~120 m below present (Fig. 11) (Cooper et al., 2018b). The contemporary coast contains the estuaries of the Mzumbe and MzimkuluUmzimkulu rivers, whose seaward extensions can be traced offshore as incised valleys.

Overlying the Cretaceous siltstones is Protea Banks, comprising a set of positive seabed features with ridges whose crests occur at depths of >30 m in the southern portion of the study area (Fig. 1). theThe surface morphology includes linear ridges and parabolic plan forms. These features correspond to areas north of the study area, where several shore-parallel ridge features composed of aeolianite and beach rock material that represent former shoreline occupations (Green et al., 2014) occur and are considered to be late Pleistocene-Holocene in age (Martin and Flemming, 1987). The overall topography of the seafloor is rugged and uneven with a gentle seaward dipping gradient of 0.2° . The shelf break is linear and occurs at ~100 m water depth.

A discontinuous sediment wedge drapes the shelf and its surface features, with Cretaceous siltstones sub-cropping a winnowed gravel pavement on the outer-shelf edge (Flemming, 1980).

3. Materials and Methods

Bathymetric data were collected using a WASSP WMB 3250 multibeam sonar system. Accurate positioning (<30 cm RMS horizontal) was achieved using a Hemisphere VS330 Real Time Kinematic (RTK) and heading system, with the RTK base correction. Motion correction was applied by a xSens MTi-G motion reference unit mounted at the WMB 3250 transducer.

Sound velocity profiles were collected with a Valeport MiniSVP. The bathymetric data were corrected with RTK tides with an averaging of 300 seconds. The multibeam data were then post-processed employing a three-step procedure including: 1) Processing of navigation data for movement and physical properties of the water column such as roll, pitch, heave, tide, draft and sound velocity; 2) Operator based processing, manual removal of artefact data points; 3) Application of CUBE™ filter and TIN (Triangular Irregular Networks) using HypackTM software. TheseThe data were manually inspected, and point removal was carried out. The final bathymetric colour image map was produced using Golden Software Surfer 12 withthen exported as a data resolution of 102 x 102 m grid.

High-resolution seismic profiles were collected using a 200J sub-bottom profilerApplied Acoustics boomer, coupled to an 18-element hydrophone array. The data were collected and processed using HypackTM software that included the application of time-varied gains, band-pass filtering (300–1200 Hz), swell filtering, and manual seabed tracking. Streamer layback and antenna offset corrections were applied to the digitized data set, and constant sound velocities in water (1500 m/s) and sediment (1600 m/s) were used to extrapolate all time-depth conversions. The vertical resolution of these data is ~5070 cm. (Brown, 2011). Ultra high-resolution seismic profiles were collected using a PARASOUND parametric echosounder aboard the RV Meteor, during cruise M123. The low frequency output (3.5 kHz) was selected due to signal attenuation of the higher-frequency spectra. The data were de-spiked and match-filtered, and the envelope data exported in SEGY format for visualization in HypackTM. These data resolve to ~10 cm in the vertical domain. (Brown, 2011). A four metre-long core (GeoB20622-2) was acquired, from location 30°45.301'S; 30°35.520'E at a depth of ~80 m below mean sea level, aboard the Meteor RV M123 cruise. An initial report on the main sediment features can be found in order to examinethe cruise report published by Zabel (2016). The sediment core allowed for the examination of the sub-surface stratigraphy of the study area and to conduct ground-truthing of the seismic results. The core was collected using a 100-mm-diameter, five metre-long marine vibro-corer from a water depth of 90 m (Fig. 1). The cores were split into archive and working halves, scanned immediately after opening using a smartcube© camera image scanner capturing high resolution digital photographs, and logged according to standard Indian Ocean Drilling Project (IODP)GeoB sedimentological procedures. The core was sub-sampled for AMS C_{14} dating, microfossils and grain size analyses. The AMS C_{14} dates were calibrated using OXCAL software (Ramsey, 2001) and the marine13.14c calibration model (Reimer et al. 2013). The marine ΔR is assumed to be 121 ± 16 ^{14}C yr (Maboya et al. 2017). Despite there being 4 m worth of core material, only one intact bivalve was discovered. Datable materials (such as life-position articulated bivalves) accumulating in wave-dominated and current-swept shelves are notoriously difficult to find due to the extent of reworking of the substrate. Furthermore, the high energies preclude the accumulation of organic-muds, most of the sediments are considered palimpsest (Flemming, 1980).

Grain size analyses at 5cm intervals downcore were performed at the Center for Marine Environmental Sciences (MARUM) in Bremen, Germany, using standard laser diffraction analysis.a Coulter LS-13320 machine. The samples were pre-treated prior to analysis removing organic and carbonate fractions. The grain size analysis measured grain size contents in 117 classes which ranged from 0.04 to 2000 μm as a volume percent (vol%). GRADISTAT software (Blott and Pye, 2001) after the Folk and Ward (1957) method were used to calculate the first moment statistics.

4. Results

4.1. Seismic stratigraphy

Six units and intervening surfaces were identified using interpretations from ~67 line-km ultra-high resolution PARASOUNDthe sub-bottom profiles and 104 line-km 200 J, 600 Hz high resolution sub-bottom profiles (Fig. 1).. A summary of the seismic facies and intervening surfaces is indicated byprovided in Table 1.

Unit 1

This unit is uncommon and was evident only in two shore perpendicular section extending off the southern headland of the Umzimkulu River (Figs. 2 and 3). Unit 1 is acoustically opaque.

The upper limit of Unit 1 is marked by a very high amplitude, undulating reflector (Surface 1) (Fig. 2).

Unit 2

Unit 2 downlaps Unit 1 forming an unconformity, Surface 1 (Fig. 2). This unit is subdivided into two sub-units based on varying dip angle:

Unit 2.1.

Unit 2.1 comprises seaward dipping (12.5°), moderate to low amplitude, prograding reflectors. This unit crops out at the sea floor from the inner-shelf to mid-shelf and is planed off and incised by Surface 2 (Fig. 3). Unit 2.1 is unconformably overlain by Unit 2.2 at its most seaward extent in the mid-shelf (Figs. 2 and 3).

Unit 2.2.

Similar toLike Unit 2.1.,, Unit 2.2 comprises moderate to low amplitude, seaward prograding reflectors that dip at a steeper angle (~20°) (Fig. 3). This unit crops out on the seafloor from the mid-shelf to the shelf edge (Figs. 3 and 4). Unit 2.2 is similarly truncated and incised across the entire shelf by Surface 2.

Unit 3

Unit 3 comprises moderate to high amplitude, prograding seismic reflectors (Fig. 5a). This unit is isolated in occurrencedoes not frequently occur and when it does, it occurs in association with Unit 6.1. It directly onlaps the acoustic basement within topographic depressions occurring from the mid-shelf to outer-shelf and is planed off by a moderate to high amplitude seismic reflector/surface, Surface 3.

Unit 4

Unit 4 can be subdivided into three sub-units. Unit 4.1 comprises moderate amplitude, prograding reflectors that onlap Surface 2 (Figs. 2c, 3b, 4a and 4c). Unit 4.1 occurs at the base of incisions in Surface 2 and is capped by Surface 4. Unit 4.2 comprises either steep, larger-scale, moderate amplitude, prograding seismic reflectors; moderate amplitude, seismic reflectors onlapping Surface 2 (Figs. 2c, 3b, 4a and 4c); or poorly-developed, moderate amplitude, discontinuous and chaotic seismic reflectors (Fig. 2b). Unit 4.3 is not always present in the study area (FigsFig. 4a). Where it does occur, Unit 4.3 is separated from Unit 4.2 by a gently dipping, high amplitude erosional seismic reflector (Surface 5) and onlaps units 2 and 4.2 (Figs. 2c, 3b, 4a and 4c). Unit 4.3 is composed of horizontal, subparallel to chaotic, discontinuous seismic reflectors (Figs. 2c, 3b, 4a and 4c). In cases where the incisions of Surface 2 are less wide and deep, Unit 4 appears massive with a poorly developed internal structure (ege.g. Figs. 2b and 6b7b). Unit 4 is truncated by a high amplitude, flat lying erosional reflector, Surface 6, which merges with Surfaces 2, 3 and 5 to form a composite erosional surface 2/3/5/6 (Fig. 4c).

Unit 5

This rugged unit crops out on the sea floor and is acoustically opaque, with no internal seismic configuration (Figs. 2a, 3a, 5b, 5c and 7a). It is most abundant in the southern portion of the study area and crops out in the mid-shelf to outer-shelf region at depths of 40 m and greater.

Unit 5 is strongly associated with Unit 6.2 as it is often onlapped by Unit 6.2 (Figs. 2c, 3a, 2c, 5b, 5c and 7a). Where Unit 5 sub-crops, it is capped by a very high amplitude seismic reflector, Surface 67, that in some localities crops out as part of the sea floor (Fig. 7a).

Unit 6

Unit 6 can be subdivided into three sub-facies based on their seismic character and distribution on the shelf. Unit 6.1. consists of moderate to low amplitude, continuous, semi-parallel seismic

reflectors and onlaps the combined surface of 2/4 (Figs. 3b, 4c, 5a, 6a and 7b). From the ultra-high resolution seismic data, the reflectors are arranged in a semi-parallel configuration (Figs. 3b, 4c, 5a, 6a and 7b). This unit is most often situated in the in-shore portion of the shelf (Figs. 2, 3b, 4, 5a, 6 and 7). Unit 6.2. rests within depressions of Surface 5 and comprises moderate amplitude onlapping, occasionally chaotic, discontinuous seismic reflectors (Fig. 2a, 3a, 4a, 5b and 5c). This unit has a semi-opaque and occasionally shingled internal character and is capped by Surface 78 (Fig. 7a). Figure 5b shows the weak development of seaward-oblique prograding foresets in subunitUnit 6.2. Unit 6.3. is present mainly in the mid-shelf region (Figs. 2c, 3a, 4a, 4b, 5a, 5b and 7a). It is characterized by moderate amplitude, finely mottled reflector packages with larger scale bedding planes. This unit has an average thickness of ~4 m but can reach up to ~7 m thick within the topographical troughs formed by Unit 5 (Fig. 7a).

Table 1. A summary of seismic stratigraphic units, separating stratal surfaces and, interpreted depositional environments and stratigraphic ages.

Unit/
Sub-unit
Overlying
Surface
Seismic Description Interpretation of Depositional
Environment
U1 Acoustically opaque Granite-gneiss complexe of the Namaqua-
Natal Metamorphic Province (Cornell et
al., 2006)
S1 High amplitude, undulating Sequence Boundary (SB)
SU2.1 Seaward dipping (~12.5˚), low
amplitude, prograding
Siltstone
S2 Maximum Flooding Surface (MFS)
(Green and Garlick, 2011)
SU2.2 Seaward dipping (~20˚), low
amplitude, prograding
Siltstone (Green and Garlick, 2011)
S3 High amplitude, truncates and
incises Unit 2
Sequence Boundary (SB1) (Green and
Garlick, 2011)
3 Isolated, onlapping high
amplitude, prograding
Relict shallow near-shore facies (Green,
2011)
S4 Moderate to high amplitude Sequence Boundary?
SU4.1 Onlaps S2, moderate amplitude,
prograding
Fluvial lag

S5 Low to modereate amplitude Transgressive surface (Ts) (Nummendal
and Swift, 1987)
SU4.2 Onalps S2, steep, moderate

amplitude, prograding
Central basin-fill (Zaitlin et al., 1994;
Green et al., 2013b; Allen and
Posamentier, 1994)
S6 High amplitude, uneven Tidal ravinement surface (TRs)
SU4.3 Horizontal, sub-parallel to
chaotic discontinuous,
retrograding
Sandy estuarine barrier (Cooper, 2001;
Nordfjord et al., 2006; Green et al.,
2013b)
S6 Very high amplitude, rugged Wave ravinement surface (WRS)
5 Acoustically opaque, crops out
on sea-floor
Aeolianite barriers (Green and Garlick,
2011)
S6 Same as above -
SU6.1 Moderate to low amplitude,
continuous, semi-parallel
Contemporary shoreface (Martin and
Flemming, 1986)
SU6.2 Onlapping, moderate amplitude,
occasionally chaotic,
discontinuous, semi-opaque,
shingled, weakly seaward
oblique prograding
Palaeo-shoreface (Martin and Flemming,
1986)
S7 Weakly visible, low amplitude FS?
SU6.3 Moderate amplitude, finely
mottled, larger scale bedding
planes
Pebble-floored coarse sand with
bioclastics. Shelf dunes, highstand
sediment (Flemming, 1980; Green, 2009)

4.2. Seafloor morphology

Multibeam bathymetry of the mid-outer shelf provides additional information on the seafloor morphology including the Protea Banks Reef portion and incised continental shelf. The outer shelf comprises a series of alternating linear, shore parallel, arcuate and ridge features occurring at 60 m and 100 m depth. These ridge features have ~5-10 m relief above the sea floor (Figs. 8b and 8c), and in some areas exist as multiple parallel ridges over a distance spanning 200-300 m (Fig. 8b). These ridges correspond to seismic Unit 5. The shelf seaward of the ridges comprises undulating seafloor defined by NE-SW striking linear features. These linear features have gentle relief and mimic the contour of the present day shoreline. They represent the foresets of seismic Unit 2.2 cropping out on the seafloor and extending to the continental shelf break (Figs. 3, 4 and 8). The shelf is marked by sinuous to linear seafloor depressions with negative relief of ~20 m and widths ranging between 400 – 800 m (Figs. 8d and 8e). The seafloor depressions trend perpendicular to both the ridges and the modern-day shoreline. These depressions are dominantly asymmetrical U-shaped with gently, across-channel, sloping floors. The walls and floors of the depressions correspond with seismic Surface 2 and Unit 6.3, respectively (Figs. 4a and 9). Seaward of the ridge features, the depressions terminate in funnel-like depressions at ~65 m depth (Figs. 8d and 9). The depth structure surface of Surface 2 indicates a clear continuation of incision of the

MzimkuluUmzimkulu river and associated tributaries over the continental shelf towards the shelf break (Fig. 9). Underlying part of Protea Banks is a basement high in the southern portion of the study area. Basement depressions at stratigraphic depths of 65 m link up with less pronounced, coast-perpendicular channels which terminate on the outer-shelf at low-lying sites topped with arcuate spit features, and merge with underfilled valleys and seafloor depressions (Fig. 8b and c; 9).

4.3. Lithostratigraphy and chronostratigraphy

The basal facies of Core GeoB20622-2the sediment core comprises an approximately 2.5 m thick succession consisting of poorly sorted, very coarse sand with shell fragments and pebble clasts at the base (Fig. 10). The grain sizes fine upward from very coarse sand to coarse sand with occasional gritty sub-rounded quartz (Fig. 10). The lower facies correlates with seismic Unit 6.3 (Fig. 4a and Table 2).

The lower facies is truncated by a horizontally-orientated quartz pebble layer and overlain by a 1.4 m thick unit of medium to coarse sand with alternating bands of muddy sand (Fig. 10a). All the pebbles are homogenous in size with respect to their a- b- and c- axis (Figs. 10b - d). The a- axes average ~7.5 cm with the b- and c- axes ~5.5 cm and ~3 cm respectively. The b-axis is defined as the maximum horizontal width of the clast (Krumbein, 1939). The angle and orientation of the b-axis of pebbles can provide information on the depositional environment.

All the pebbles rest with their b-axes perpendicular to the seafloor (Fig. 10a). The upper unit is devoid of pebbles. The overall sediment composition of theUnit 6.3 is majority quartz with lesser amounts of feldspar, lithic fragments and bioclastic fragments. (comprising bivalve shell debris, bryozoa and coral). The upper Unit corresponds with seismic Unit 6.3 (Fig. 4a and Table 2). An intact gastropod shell, from the facies boundary that these pebbles mark, yields a ^{14}C age of 1275 ± 301191 - 1263 cal. yr BP. (68% range).

Table 2 Summary of core sediment facies and faunal descriptions relative to seismic stratigraphy

Core Facies	Thickness	Sediment description	Fauna	Seismic Unit
Lower facies	2.5 m	Poorly sorted, very coarse quartz-rich sand, shell fragments and pebbles at base. Upward fining.	Sublittoral marine taxa (i.e. echinoderm and brachiopod)	Unit 6.3
Boundary		Quartz pebbles		Internal master bedding plane (Allen, 1982)
Upper Facies	1.5 m	Majority quartz with lesser feldspar and lithic, and bioclastic fragments. Devoid of pebbles.	Rounded calcareous bioclasts	Unit 6.3

4.4. Biostratigraphy

Core GeoB20622-2The core generally comprises fragmented and abraded marine sublittoral fauna. The lower facies of the core (at ~361-362 cm depth down core) hosts fragmented marine taxa (i.e. echinoderms and gastropods), while the upper facies (at ~138-139 cm depth down core) hosts rounded bioclasts of calcareous nature (*Frenzel, P, pers. Comm.*). These faunae correspondThis lithofacies corresponds to unitUnit 6.3 (Table 2).

5. Discussion

5.1. Seismic Stratigraphy

Seismic Unit 1 forms the acoustic basement of the study area and is considered to correspond to the crystalline basement that crops out along the adjacent shoreline. These crystalline rocks are overlain by Seismic Unit 2, the seismic architecture of which has been recognised throughout the region as belonging to seaward-dipping Cretaceous age siltstones (Green and Garlick, 2011). The capping erosional surface, Surface 2 is considered to represent the most recent subaerial unconformity (e.g. Green, 2009; Pretorius et al., 2016) that formed as sea-level fell to the LGM at ~ 125 m depth (Green and Uken, 2005; Cooper et al., 2018b). Surface 2 reveals that the palaeo-MzimkuluUmzimkulu river incised the basement rocks during regression associated with the Last Glacial maximum (Fig. 9). The drainage network bypassed a basement high of Unit 2 in the southern region, indicating a geomorphological control on the passage of incised valleys across the continental shelf.

Seismic Unit 3 is a localised unit found in shallow depressions within Unit 2 at -60 m and at -150 m, respectively. Seismic Unit 3 is comparable to remnant prograding coastal deposits documented on the mid-shelf and at the shelf edge of the eastern Tyrrhenian Sea margin (Trincardi and Field, 1991). Green (2011) considered similar deposits to the north of the study area to represent shallow nearshore facies of indeterminable age. Their preservation appears to be controlled by their location on interfluves and in shallow topographic depressions which provided shelter from the erosional processes associated with the overlying wave ravinement surface. Trincardi and Field (1991) proposed that the sheer volume of the Tyrrhenian Sea deposits was the main factor contributing to their successful preservation. Their patchy distribution in the study area suggests that they may have been only locally developed.

Unit 4 represents a succession of incised valley fill deposits. The basal portions of chaotic, discontinuous reflectors (Unit 4.1) represent coarse fluvial channel lags and, when prograding in a shore-parallel orientation, point bar deposits (cf. Weber et al., 2004; Green and Garlick, 2011; Green et al., 2013b). The capping reflector, Surface 45, delineates the initial flooding of the fluvial system during the ensuing postglacial transgression and is interpreted as the transgressive surface (TS) (see Nummedal and Swift, 1987).

The mid portions of the valley fills (Unit 4.2) overlie this surface. The sub-parallel, and, in some cases, horizontal onlapping configurations have been recognized by many authors as indicative of the central basin fill of a developing wave-dominated (e.g. Zaitlin et al., 1994; Green et al., 2013b) or mixed wave-tide dominated (Allen and Posamentier, 1994) estuary.

Unit 4.2 is capped by an inclined, channel shaped, high amplitude reflector interpreted as the tidal ravinement surface. (S6). The tidal ravinement surface is best preserved on the inner-shelf portion whereas a horizontal, flatter high amplitude reflector tops Unit 4.2 on the outer-shelf segment, if present at all.

The upper fill (Unit 4.3) is variable along dip. Horizontal sub-parallel chaotic discontinuous reflectors indicate a retrogradational character and this unit likely represents small scale sandy estuarine barriers such as those seen offshore Durban (Nordfjord et al., 2006; Green et al., 2013b) and on the modern coast (Cooper, 2001). This sub-unit represents the transgressive systems tract of the incised valley fill succession.

Unit 5 is a rugged, acoustically opaque unit that crops out on the sea-floor. This unit is interpreted as cemented aeolianite ridges and barriers of relict shorelines. These occur at various localities on the southeast African shelf (Martin and Flemming, 1987; Green et al., 2014; Pretorius et al., 2016). These deposits) and record the depths of past stillstands during which significant shoreline deposits accumulated. They record shorelines from depths of -60 m and greater (Fig. 11) (Pretorius et al., 2016; Green et al., 2018). Unit 5 and sub-unitUnit 4.3

are capped by the postglacial wave ravinement surface (S7) (see Pretorius et al., 2016).

Seismic Unit 6 represents the post-transgressive shoreface and associated sediments that survived wave ravinement processes on the continental shelf. The contemporary shoreface wedge (Sub-unitUnit 6.1) appears as a thin package in the inner-shelf (Martin and Flemming, 1986), whereas the offshore sub-unitUnit 6.2 represents palaeo-shoreface deposits that have been decoupled from the contemporary wedge during shoreface translation (Pretorius et al., 2016). Unit 5 deposits act as obstacles that feed back into the shore translation process and inhibit the movement of the complete shoreface as it migrates landward, hence leaving remnants (Unit 6.2) behind. Unit 6.2 deposits are preserved when they are situated in depressions in Unit 5 and are sheltered to a degree from the mid- to outer-shelf current sweeping (Flemming 1980) by the Agulhas Current.

Unit 6.3 occurs as thin deposits from the mid-shelf to outer-shelf and as a fill in the underfilled incised valleys of the outer shelf. These fills comprise late Holocene age pebble-floored coarse sand and bioclastic successions. The bioclastic components of the core are wholly composed of marine sub-littoral shell fragments and rounded calcareous clasts. Flemming (1980) observed large to very large dunes forming in coarse sand and fine gravels across this shelf region along the east coast of South Africa. Green (2009) observed similar bedforms off the northern KwaZulu-Natal coast and attributed them to current-reworking of shelf sands and gravels comprising modern highstand sediments.

The date obtained from the upper portion of the outermost underfilled incised valley indicates a maximum age of deposition of 12751191 - 1263 cal. yr B.P,BP (68% range), which wasplaces sea level within a periodmetre or two of higher thanthat of the present sea-levels in the regionday (Fig. 11) (Cooper et al., 2018b). The unit therefore accumulated on the shelf under conditions similar to present. The horizontally-orientated quartz pebble layers indicate stratification under current influence associated with the bases of migrating contemporary shelf subaqueous dune fields (Martin and Flemming, 19922000). These are overlain by the main dune body of sub-littoral sourced sands and shell debris which have cascaded into the incised valleys and filled them.

The continental shelf, in its entirety, comprises a basement high coinciding with the ~60 m isobath and resulted in less accommodation space, allowing for dunes to accrete and concentrate on this portion of the continental shelf. Basement depressions along the -60 m isobath show a widening of channel systems likely associated with slowstand events. These depressions may represent low-lying back-barrier estuarine systems that were overstepped during transgression.

5.5.4. Facies architecture and distribution of incised valley fills across the shelf

The extent and distribution of the incised valley facies varies systematically across the shelf.

In the proximal inner-shelf segment, the fluvial Sub-unitUnit 4.1 makes upcomprises a large portion of the incised valley-fill (Fig. 12a). Central basin deposits (sub-unitUnit 4.2) are preserved and capped by tidal ravinement surfaces and then overlain by sandy barrier and estuarine tidal inlet facies.

In the mid-shelf region, the incised valley fill succession is comparable to that of the inner-shelf, although, with increasingly less volumes of fluvial material and an increase in volume of the central basin fill (Fig. 12b). The barrier facies is separated from the central basin deposits by a tidal ravinement surface and is capped by the wave ravinement surface.

The valleys of the outer-shelf retain a distinctive seafloor depression (Figs. 8d, 8e, 10 and 12c) and are filled at their bases by fluvial materials above which, in the unfilled valley, they are overlain by materials derived from cascading dunes (Fig. 12c). Payenberg et al. (2006), show a direct equivalent from Hervey Bay, Australia, where incised valleys on the shelf are filled with undifferentiated sandy material deposited into an exposed valley by migrating sub-aqueous dune fields on the contemporary shelf.

The absence of the central basin and barrier facies of the transgressive systems tract in the outer shelf valleys is striking (Fig. 12c). This relative underfilling of the valley during transgression suggests decoupling from the sea level/sediment supply balance associated with transgressive filling of estuaries (see Cooper et al., 2012). Such a scenario can occur either when sea-level rise is rapid (causing an increase in accommodation space) or when either fluvial or marine sediment supply is significantly reduced. The presence of fluvial deposits in the valley fill suggests that there was sufficient fluvial supply to the system prior to transgression. The valley was unfilled during transgression because of a lack of sediment and/or an increase in accommodation space associated with a rapid increase in sea level.

5.3. Outer-shelf Morphology (shoreline at 100 m below MSL)Mean Sea Level)

The series of aeolianite barriers of Unit 5 (Fig. 2a, 3a, 5b, 5c and 7a), are separated by small topographic lows (Fig. 8b) and mark a ~ -100 m palaeo-shoreline. The topographic lows have similar scales and orientations to the modern inlets of barrier-lagoon systems of SE Africa (cf. Cooper, 2001) and are consequently interpreted as remnants of barrier-inlet features of the palaeo-shoreline. The -100 m palaeo-shoreline is intersected and underlain by valleys exposed to the seafloor (Unit 4) (Fig. 9). Those valleys terminate in funnel shaped depressions at -100 m. The terminating morphology is identical to the morphology of river-dominated, microtidal estuaries of southern Africa (cf. Cooper, 1993,1994, 2001) (Fig. 8). Though large dune fields, intersected by small estuaries, are not evident on the adjacent contemporary coast, they are common on sediment-rich coasts to both north (Jackson et al., 2014) and south (Cooper et al., 2013) of the study area. This suggests that past hydrodynamic conditions were like those of today, however, a larger potential for barrier growth existed when sea levels were near -100 m.

Here, the open shelf, then palaeo-coastal plain, promoted greater wind-fetches, in addition to greater degree of accommodation whereby larger dunes could be built. In comparison, as sea level has risen to the modern-day shoreline, the coast has since transformed into a series of granitic headland-bound embayments and pocket beaches that, due to their steep and irregular natures, lack sufficient accommodation to allow for large dune building to occur.

The series of arcuate and cuspate ridges, together with the seaward prograded smaller ridges are surface continuations of Seismic Unit 5. Green et al. (2013a; 2014) were the first to describe such features from the seafloor and considered these to be features of a back barrier lagoonal shoreline produced by segmentation processes of a coastal waterbody (cf. Ashton et al., 2009). These ridges co-occur with seafloor depressions and the seaward termination point of the main Unit 5 barriers, estuaries and inlets. We thus consider them to have formed simultaneously with the seaward growth, through normal regression, of the -100 m palaeo-shoreline. The -100 m shoreline corresponds in elevation to sea levels associated with the Bølling Allerød period when sea level was at ~-100 m (Peltier and Fairbanks, 2006; Green et al., 2014). Recent work suggests that the LGM involved two periods of sea-level stability separated by rapid sea-level change (Yokoyama et al., 2018). As discussed by Salzmann et al. (2013), this general period of sea-level stability was long enough to promote the development of planform equilibrium shorelines with localised areas of normal regression, forming arcuate back barrier spits and large dune fields in equilibrium with prevailing energy conditions and sediment supply (cf. Ashton et al., 2009).

The association of underfilled, incised valleys with this shoreline is notable. As discussed above, these valleys on the outer shelf provide evidence for rapidly rising sea levels that left the outer segments completely drowned in situ. Likewise, we envision the preservation of the associated shorelines to be a result of sea-level rise that led to the rapid up-profile progression of wave ravinement across the continental shelf, leaving less time for the breakdown of shorelines in response to wave action and preserving shoreline deposits by overstepping (*sensu* Swift, 1968). We link this to Melt Water Pulse (MWP) 1-A, which followed the LGM stillstand and was associated with a ~16 m (26–53 mm/yr) rise in sea level between 14.6 and 13.8 ka BP. This has been linked to other -100 m shorelines both locally (Salzmann et al., 2013; Green et al., 2014) and globally (Peltier and Fairbanks, 2006; Liu and Milliman, 2004; Fairbanks, 1989).

5.4. Mid- to Outer-shelf (100 m to 60 m below MSL)

The outer to mid shelf areas (-60 to -100 m) are marked by the cropping-out foresets of Unit 2, with no sediment cover or shoreline features (Figs. 2, 3, 5 and 7). Following MWP-1A at 13.6 ka cal. B.P. (Peltier and Fairbanks, 2006), the rate of sea-level rise decreased significantly allowing wave ravinement processes to become more effective in eroding and reworking any existing deposits on the continental shelf (Fig. 12). Coupled with the contemporary erosion by the Agulhas current, and the lack of shelter by aeolianite pinnacles or depressions in the LGM subaerial unconformity, this has led to the complete sediment denudation of these areas by erosion. Other examples of similarly sediment scarce, current swept shelves around the world include the south-eastern shelf of the United States (Harris et al., 2013) and the North Adriatic epicontinental shelf (Trincardi et al., 1994).

5.5. Mid-shelf (shoreline at 60 m below MSL)

The mid-shelf is marked by a second generation of preserved shoreline complexes at -60 m (Figs. 2, 3, 5 and 7), overlying the LGM-aged incised valleys. Like the -100 m shoreline, remnant submerged shoreline complexes at this depth are prominent along the entire SE African coast (Salzmann et al., 2013; Green et al., 2014; Pretorius et al., 2016; De Lecea et al., 2017).

The set of shoals with U-shaped planforms in the shallowest upper portion of the aeolianite field are interpreted as preserved parabolic dune fields (Fig. 8a). Parabolic dunes occur where there are high rates of sediment supply, enough accommodation space to allow for accretion (Oestmo et al., 2014) and strong, unidirectional winds driving sediment transport (Landsberg, 1956). These features indicate southwesterly unidirectional dune migration, as is the case for the majority of parabolic dunes to the north of the study area (Jackson et al., 2014). The gentle relief of the palaeo-coastal plain (as evidenced in the subaerial unconformity) and the lack of confining headlands accounts for the size of this dune field compared to the absence of any dune fields in the contemporary coastal setting. The degree to which these aeolianites are preserved points to rapid supra- and intertidal lithification of the dunes, commonly seen in subtropical settings (Cooper and Green, 2016). Cooper et al. (2018b) consider prolonged sea-level stability as a major contributor to the aeolian sediments having longer residence times in the vadose zone, thus favouring the rapid lithification of dune bases. During the Younger Dryas Period (~12.8 cal Ka to 11.3 cal Ka), the associated slowstand allowed enough time for the construction and lithification of a prominent shelf-wide shoreline complex (Fig. 11) (Pretorius et al., 2016).

At 11.3 cal Ka, the rate of sea-level rise (13–15 mm/yr) (Liu and Milliman, 2004; Peltier and Fairbanks, 2006; Cooper et al. 2018) is considered to have accelerated substantially (Green et al., 2014) in response to Melt-Water Pulse 1B (MWP-1B) (Fig. 11). This rapid rise in sea level lead to the swift overstepping and submergence of the -60 m shoreline now left relict on the shelf. The aeolianite barriers (Unit 5) and shoreline deposits were partially eroded and deposited (Unit 6.2) within the hollows between confinement points created by the aeolianite barriers (Unit 5) (Fig. 7).

5.5.6. Post-transgressive sediment on the shelf

The morphological response of the shoreface to rapid sea-level rise takes longer than that of adjacent barriers (Swift, et al., 1985; Cooper et al., 2018a), hence the shoreface retreat lags behind the actual barrier migration (e.g. German Frisian barrier islands, Flemming and Davis, 1994; Fire Island, NY, Sanders and Kumar, 1975). During rapid sea-level rise, barriers separate from the shoreface leaving it submerged, while the surf- and barrier-zones migrate rapidly (Cooper et al., 2018a). The barrier then forms a subsequent shoreface by means of eroding the underlying strata at its new stabilization point (Cooper et al., 2018a). The original shoreface may remain drowned and stranded on the continental shelf or may continue to slowly migrate landwards to ‘catch-up’ with the surfzone and beach system when the sub-sequent shoreline stabilises (ege.g. Beets and van der Spek, 2000; Hijma and Cohen, 2010).

Cooper et al. (2018a) point out that reasons for this observed spatially variable relationship between shoreface and barrier behaviour have not been investigated but may likely include variability in geological controls and dynamic factors. We consider the mid-outer shelf pockets of unconsolidated sediment on the seafloor, resting above the wave ravinement and always in association with shoreline pinnacles to ebbe a good example of this. The -60 m and -100 m barrier shorelines acted as antecedent controls on the up-profile migration of shoreface sediment, thereby restricting and reducing the volume of material available for the barrier/beach to exchange with landward migration of reworked shoreface sediment during overstepping. This leadled to less sediment available for shoreface construction as the shoreline migrated landward, thus leaving stranded segments of shoreface deposits on the outer shelf.

Following the assumptions of Davis and Clifton (1987), Pretorius et al. (2016) showed that on the Durban shelf, rates of shoreface translation were manifestmanifested as changing gradients in the ravinement profile. A steeper ravinement was linked with MWP-1B, whereas the flatter inner-shelf ravinement was generated by slower rates of sea-level rise consequent with a considerable slowstand period (Cooper et al., 2018b). A similar scenario is invoked here. The inner-shelf shows limited preservation of shorelines with a lower gradient ravinement surface attributed to consequent slower rates of sea-level rise where the shoreface has managed to catch up the rising sea level.

Seaward of the -100 m shoreline outer-shelf, there are few morphological barriers to cross-shelf sediment transport deeper. Considering that sediments are usually deposited down profile during transgressive erosion (Pretorius et al., 2017), the transgression from the -100 m elevation likely shed eroded sediments off-shelf due to the steep and narrow nature of the region. The finer sediment would also later be entrained southward by the Agulhas current as bedload leaving winnowed shelf deposits where present.

6. Conclusion

The development of large aeolian dunes on the low-gradient palaeo-coastal plain of the continental shelf of Protea Banks indicates an open coastal plain palaeo-setting with an absence of geological controlled coastal compartments in contrast to the contemporary coast line. The large, unimpeded accommodation space allowed for large dune fields and open water bodies to develop.

The two sets of shorelines formed after the LGM and arewere related to stability of the shoreline during the Bølling Allerød and Younger Dryas periods. We hypothesize that their preservation, by overstepping, iswas related to the ensuing meltwater pulses 1A and 1B. The Holocene fill architecture of the co-occurring incised valley-fills show variation from the inner-shelf to the outer-shelf. The outer-shelf incised valleys are conspicuously under-filled, the fills comprise fluvial deposits truncated by wave ravinement and capped by contemporary shelf/dune sand deposits. The infill pattern is related to rapid overstepping of the shoreline due to MWP-1A. The inner shelf valleys conversely reflect a period of relatively slow sea-level rise which kept pace with sediment supply.

We show that during the stepped rises in sea level, the shoreface has disconnected from the contemporary shoreline. The role of antecedent topography is considered, together with the rapid rises in sea level, to produce the dislocation and preservation of relict shoreface sediment on the continental shelf. Given future predictions in sea-level rise, and the local onshore bedrock controls, a reduction of sediment supply for back-barrier/beach and shoreface exchange during subsequent shoreline construction could lead to increased rates of shoreline retreat and potentially overstepping of low-lying coastal areas.

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Figure Captions

Fig. 1 Locality map illustrating the extent of the bathymetric and seismic data collected. The study area is situated seaward of the Umzimkulu River mouth and focuses on the large seafloor shoal of the Protea Banks. Grey lines indicate boomer seismic profiles and blue lines indicate PARASOUND profiles. The red circle indicates the location of corescore GeoB20622-2.

Fig. 2 Interpreted shore-perpendicular seismic profile showing underlying Cretaceous strata and capping high amplitude reflector (Surface 2) and prominent ridges of Unit 5 at -60 m. Expanded areas show: a) Rugged Unit 5, capped by erosional Surface 3. b) An incision filled by Unit 4 showing chaotic, discontinuous reflectors. c) A complete incised valley-fill succession comprising Sub-units 4.1, 4.2 and 4.3, capped by an erosional reflector and overlain by Unit 6.3. S1 - Surface 1 (Sequence Boundary), S2 – Surface 2 (Maximum Flooding Surface) and S3 – (Sequence Boundary).

Fig. 3 Interpreted shore-perpendicular seismic profile. Note the lack of sediment cover above the acoustic basement. Expanded areas show: a) Acoustically opaque Unit 5 onlapped both landward and seaward by Sub-unitUnit 6.2, capped by a thin drape of Sub-unitUnit 6.3. b) A complete incised valley-fill succession comprising Sub-units 4.1, 4.2 and 4.3, capped by an erosional reflector and overlain by Unit 6.3

Fig. 4 Interpreted shore-perpendicular seismic profile showing incised valley systems on the inner-shelf, together with a ridge of Unit 5 at a depth of 100 m on the outer-shelf. Expanded areas show: a) an incised valley fill succession comprising Sub-unitUnit 4.1, truncated by an erosional surface and overlain by sub-parallel to chaotic reflectors of Sub-unitUnit 6.2. Core location is indicated by the red line which intersects Sub-unitUnit 6.3 only. b) a PARASOUND shore-parallel interpreted section showing an alternative view to Fig. 4a3a with marked core location (red line) and a bathymetric depression associated with an underfilled incised valley and core location (red dot). c) A complete incised valley-fill succession comprising Sub-units 4.1, 4.2 and 4.3, capped by an erosional reflector and overlain by Unit 6.3. Note that Unit 4.3 is truncated by Surface 4, which merges with Surfaces 2 and 3 to form a composite erosional surface 2/3/4

Fig 5 Interpreted shore-perpendicular PARASOUND profile showing the detailed internal configuration of the upper seismic units. The expanded areas show: a) Unit 3 resting within a depression created by Unit 2 and capped by an erosion surface. Unit 6.1 shows sub-parallel to chaotic reflectors draping the underlying erosional surface. Unit 6.3 drapes over Unit 6.1 with continuous, semi-parallel reflectors. b) Unit 5, onlapped by sub-units 6.2 and 6.3. Note the seaward-oblique prograding foresets in Sub-unitUnit 6.2. c) Unit 5 superimposed onto Cretaceous deposits, capped by an erosional surface and onlapped by Sub-unitUnit 6.2

Fig 6 Interpreted shore-parallel boomer seismic profile showing the inner-shelf sediment. The expanded areas show: a) Cretaceous basement truncated by an erosional reflector and overlain by the sub-parallel, horizontal reflector package of Sub-unitUnit 6.1. b) Incised valleys filled by the homogenous, discontinuous and chaotic seismic Unit 4. Sub-unitUnit 6.1 drapes Unit 4.

Fig 7 Interpreted shore-perpendicular boomer seismic profile showing planation surface truncating Cretaceous strata, superimposed in the outer-shelf region by ridge features. The expanded areas show: a) Unit 6.2 resting within depressions of Surface 5. Sub-unitUnit 6.3 onlaps both Sub-unitUnit 6.2 and Unit 5. b) Cropping out foresets of Unit 2.1 draped by a thin veneer of Sub-unitUnit 6.1 in the inner-shelf region.

Fig 8 Bathymetry of the study area showing the main morphological features of the continental shelf. The insets show: a) Parabolic ridges at ~60 m depth. b) Shore-parallel ridge features. c) A pronounced ridge feature with depressions on the seaward and landward side. Not the ‘break’ within the feature. d) Plan and cross-sectional view of wide, U-shaped depressions on seafloor. e) Plan and cross-sectional view of a sinuous sea-floor depression.

Fig 9 Depth structure map of the LGM subaerial unconformity (Surface 2), depicting the trend of the drainage network from the pre-LGM regression, in relation to the Umzimkulu river and antecedent topographical highs and lows. Note the correlation with the small ridges of Unit 5 at the shelf edge, together with sinuous seafloor depressions. Vessel lines are superimposed on Surface 2 as black lines.

Fig 10 IllustrationGraphic log of the sampled core corresponding to Sub-unit 6.3GeoB20622-

2. The core is dominated by very coarse to coarse, quartz sand interspersed with bioclastic material. The lower section of the core shows a crude upward fining trend in grain-size and is capped with flat-lying quartz pebble layers. The upper most pebble horizon yields an age of 1275 ± 30 Cal. yrs B.P.1191 - 1263 cal yr BP (68% range). The entire core comprises layers of Unit 6.3 separated by an internal master bedding plane (IMBP) indicated by the dashed line. Inset a) shows a high-resolution photograph of the pebble horizons in-situ. b) and c) Show rounded oblate quartz pebble obtained from the core. d) Shows a rounded, oblate beachrock pebble. Note the similarity in size of the pebbles.

Fig 11 Relative sea- level curve for the east coast of South Africa from the 12 20 000 Cal yr B.P. to present day (after Cooper et al., 20182018b). Grey shading marks periods of sea- level events pertaining to this study. After Cooper et al. (2018).

Fig 12 Interpreted shore perpendicular seismic profiles of incised valley fills from different zones of the shelf. a) The inner-shelf comprising fluvial, central basin and estuarine barrier deposits capped by shelf sand. b) Mid-shelf comprising a higher ratio of central basin deposits to fluvial deposits, topped by estuarine barrier and shelf sand deposits. c) Outer-shelf

comprising fluvial sediment overlain by shelf/subaqueous dune sediment. The locations of these valleys are indicated on Figure 1.

Table 1. Summary of seismic stratigraphic units, separating stratal surfaces and interpreted

depositional environments.

Table 2. Summary of core sediment facies and faunal descriptions relative to seismic stratigraphy.