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Understanding Late Quaternary change at the land-ocean interface: a synthesis of the evolution of the Wilderness coastline, South Africa

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Abstract
Coastal barrier systems have been widely used to understand the responses of coastal margins to fluctuating Pleistocene sea levels. What has become apparent, particularly with the development of robust chronological frameworks, is that gaps in terrestrial barrier sedimentary records are not uncommon and that they most likely reflect phases of barrier construction on the now submerged continental shelf. Thus, understanding the land-ocean interface through time is critical to fully appreciate the Quaternary archives contained within the barriers and their associated back-barrier deposits. This study uses offshore and lake floor (back-barrier) seismic profiling from the South African south coast at Wilderness to link the sub-aerially exposed barrier stratigraphy to the currently submerged geological and sedimentological record. A total of eight separate submerged aeolian units are identified at water depths of up to 130 m below mean sea level. Their approximate ages are constrained with reference to the eustatic sea-level record and the deepest units are consistent with the estimated magnitude of sea-level lowering during the Last Glacial Maximum (LGM) on the South African coastline. As previously assumed, Aeolian sedimentation tracked the shoreline onto the continental shelf during the Late Pleistocene. During sealevel regressions, both the incision of fluvial channels and the deposition of back-barrier systems occurred across the continental shelf. During late low stand/early transgression periods, landward shoreface migration occurred, pre-existing channel incisions were infilled and pre-existing barriers were truncated. Rapid transgression, however, allowed the preservation of some back-barrier deposits, possibly aided by protection from antecedent topography. As sea level neared the present-day elevation, erosion of the mid-shelf sediments resulted in the development of a Holocene sediment wedge, which was augmented by Holocene fluvial sediment supply. The Holocene sand wedge is preserved in the backbarrier lakes and was deposited during the Holocene highstand inundation. Overlying middle to late Holocene terrestrial muds reflect the deposition of river-borne mud onto the shelf. These results clearly demonstrate that within transgressive-regressive sea-level cycles, accommodation space for barriers is controlled by antecedent drainage systems and gradients on the adjacent inner continental shelf.

1. Introduction
The South African Wilderness Embayment is characterised by large-scale shore-parallel barriers or dune cordons which reach a maximum elevation of 200 m above Mean Sea Level (AMSL). These are separated by a series of interconnected back-barrier/interdune lakes (Bateman et al., 2011). Globally, the significance of coastal barrier systems is recognised in terms of their roles as terrestrial palaeoenvironmental archives (e.g. Billeaud et al., 2009), recorders of the geomorphic evolution of coastal margins (e.g. Cowell and Thom, 1994; Tomazelli and Dillenburg, 2000, 2007; Brooke, 2001) and their significance for our understanding of coastal geomorphological responses to Pleistocene sea-level change (e.g. Murray- Wallace et al., 1999; Dillenburg et al., 2000; Frechen et al., 2002;

Sloss et al., 2006; Hearty and O'Leary, 2008; Andreucci et al., 2009; Bateman et al., 2011). In the South African context they are also the key to understanding many significant Middle and Late Stone Age archaeological sites and the associated palaeoenvironments our ancestors occupied (e.g. Jacobs et al., 2003; Marean et al., 2007; Roberts et al., 2008).

Barrier systems are characteristic of wave dominated coastlines and typically comprise several depositional facies, the extent and arrangement of which, at any one time, are controlled by sediment supply, geological setting (hard rock geological and continental shelf configuration) and wave energy (Colman and Mixon, 1988; Dominguez et al., 1992; Riggs and Cleary, 1995). The links between the evolution of dune barriers (largely aeolian facies) and back-barrier development has been considered using chronologies of aeolian facies and marginal marine deposition (Murray-Wallace et al., 2001; Bateman et al., 2004; Carr et al., 2007; Murray-Wallace et al., 2010; Bateman et al., 2011). In some instances this has led to large chronological datasets from which phases of coastal dune accumulation and marine inundation have been identified. What has become apparent from such work is that in the absence of tectonic uplift gaps in the terrestrial barrier dune record probably reflect phases of barrier dune construction on currently submerged parts of the coastal plain (Bateman et al., 2011). It has also been shown that the morphology of the continental shelf as well as the route of rivers across this surface (both currently exposed and submerged) has a significant control on the timing, position and style of barrier construction (Dingle and Rogers, 1972; Bateman et al., 2004, 2011). Understanding the land-ocean interface is thus critical to appreciate fully the Quaternary sedimentary archives contained within the barriers and their associated backbarrier deposits. In this study, for the first time in a southern African context, the integrated links between accommodation space, sediment supply and coastal plain/barrier evolution are described. Deposits of the Wilderness Embayment (both terrestrial and currently submerged), offer an excellent opportunity to consider in detail the land-ocean interface, its response to Quaternary sea level forcing and the role of cumulative evolution or landscape inheritance in shaping the contemporary coastlines (e.g. Cowell and Thom, 1994). A fuller understanding of sedimentation history within the lakes/back-barrier lagoons is also relevant to ongoing work seeking to use these archives of palaeoenvironmental and palaeoecological change (Reinwarth et al., 2013).

2. Regional setting

The southern coastal plain of South Africa extends from the Bot River (34^{0}140S; 19^{0}200E) to Port Elizabeth (33_580S; 23_830E) (Fig. 1). We define the coastal plain as the emerged low-gradient zone flanking the shoreline. The adjacent submerged component currently constitutes the continental shelf, defined to shelf/slope break. Southern South Africa is located on an intra-plate continental margin which rifted during the Cretaceous (Watkeys, 2006) but is considered passive and tectonically stable within the Quaternary. Planation events enlarged this coastal plain during the Cenozoic (Partridge, 1998; Marker and Holmes, 2005; Erlanger et al., 2012), creating prominent erosional surfaces. The continuity of the southern Cape coast from Port Elizabeth in the east to Cape Agulhas in the west is broken by a series of zeta (half-moon) bays (Fig. 1). These are linked to deformation associated with Gondwana break-up (Toerien, 1979; H€albich, 1983; Malan and Viljoen, 1993; Watkeys, 2006) and the formation of several halfgrabens (e.g. Algoa Bay). The bedrock lithology of pre-Cenozoic strata along the south coast is highly variable, creating variation in geomorphic expression (Roberts et al., 2013). The south coast broadly comprises Neogene and Quaternary marine, aeolian and lacustrine deposits (Dingle et al., 1983; Partridge and Maud, 1987) with the former related to sea-level fluctuations within these time periods (Dingle et al., 1983; Malan, 1990). The origins and age of geologically recent coastal sediment accumulations, including episodes of coastal dune building, the accumulation of sand sheets and their association with sea-level fluctuations have been investigated in some detail during the last decade (Illenberger, 1996; Bateman et al., 2004; Marker and Holmes, 2005; Carr et al., 2007; Holmes et al., 2007; Bateman et al., 2008; Roberts et al., 2008; Carr et al., 2010; Marker and Holmes, 2010; Bateman et al., 2011).

The south coast is a wave-dominated coastline and the tidal range around much of the coastline is generally low and is classed as micro-tidal (<2 m spring tidal range) to meso-tidal (Davies, 1980). The major wave direction on the southern African coastline is from the southwest (Davies, 1980; Heydorn and Tinley, 1980) and the associated long fetch means that the coastline is dominated by swell waves (Whitfield, 1983). The Wilderness Embayment (Fig. 1) is a prominent physiographic feature within the coastal plain of the southern Cape, South Africa. It, along with Nature's Valley to the east, are unusual embayments in that the cliff lines are eroded in less resistant strata, rather than half-grabens. Eastward, longshore drift on the south coast provides a major source of sediment, ultimately derived from river discharge, and this has promoted the construction of a nearshore sediment wedge (Birch, 1980). Studies within the Wilderness Embayment have largely focussed on the system of shore-parallel barriers (dunes) which record long-term coastal aeolian activity, largely driven by glacial-interglacial sea-level change (e.g. Bateman et al., 2011). Within the Wilderness Embayment, Bateman et al. (2011) further proposed that localised variability in continental shelf bathymetry has resulted in complexity within the onshore sedimentary Aeolian record.

3. Previous studies

3.1. The Wilderness Embayment

The large, approximately shore-parallel ridges of the Wilderness Embayment are also referred to as cordon dunes (sensu Illenberger, 1996). These aeolian deposits comprise unconsolidated sand to heavily lithified aeolianite and they are separated by several back barrier lakes. While lithification of the aeolian sediments has rendered them relatively resistant to erosion, the barriers have been breached in places by rivers (e.g. the middle barrier by the Swartvlei River). Four shore-parallel barriers were originally identified by Martin (1962), termed (from landward to seaward) I, II, III and IV. Illenberger (1996) condensed these to three units by combining the most seaward barriers (III and IV) and referring to them as the seaward, middle and landward barriers, which is followed here (Fig. 1). The seaward and middle barriers are the most prominent features. The landward barrier often lacks clear geomorphic expression and its distribution is seemingly constrained by hard rock geology in some locations (Fig. 1). The modern seaward barrier is being eroded by the sea, forming seacliffs in excess of 180 m. Palaeo-seacliffs and wave cut platforms are observed on the seaward side of the middle barrier (Illenberger, 1996). The present chronological framework suggests that the each of the Wilderness barriers have been constructed over at least two glacial-interglacial cycles and possible as far back as Marine Isotope Stage (MIS) 11 (Illenberger, 1996; Bateman et al., 2011). Notable phases of construction have been constrained to between 241 and 221 ka, 159e143 ka, 130e120 ka, 92e87 ka and post 6 ka. These appear to be associated with regressive phases subsequent to sea-level highstands (Bateman et al., 2011). Tectonic stability within the embayment has meant that glacio-eustatically formed

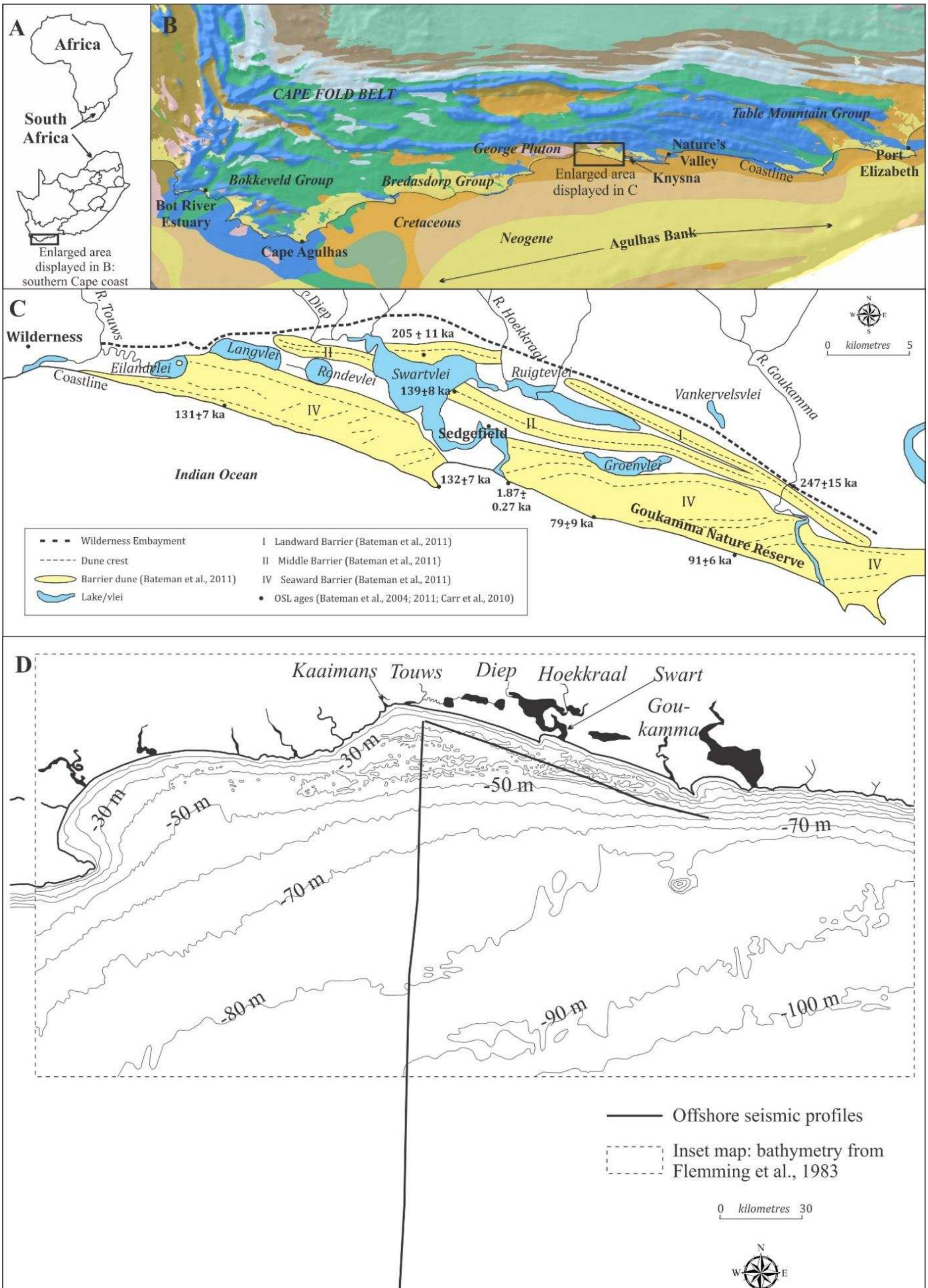

Fig. 1. A. Locality of the study area. B. The sub-aerially exposed regional geology in the vicinity of the study area is dominated by the Namibian age George Pluton (pink), the eastewest trending Cape Fold Belt (Palaeozoic Table Mountain and Bokkeveld Groups) (blue and green, respectively) and Cenozoic Bredasdorp Group deposits (yellow). The continental shelf bedrock is composed of Mesozoic deposits on the inshore and Neogene Agulhas Bank offshore. C. The study area in detail reveals the Wilderness Embayment to be characterised by Quaternary palaeodune ridges and coastal barrier lakes. Exemplar ages for the barriers are also shown. Numerous rivers drain the area. These are displayed with the prefix 'R.' D. Bathymetry of the continental shelf in the study area, derived from Birch et al. (1978) and Flemming et al. (1983). The locations of the two offshore seismic profiles acquired for this study are shown. The stippled zone represents the data acquired by Flemming et al. (1983).

shorelines occupied similar positions on multiple occasions. As such, the landscape record is incomplete and there is clear evidence for flooding and reworking of sediments from within the embayment, most notably during MIS 5e (Carr et al., 2010; Bateman et al., 2011).

A notable feature of the Wilderness embayment is the series of salt- and fresh-water lakes (Afrikaans: vleis) fed by a number of river systems entering the embayment (Fig. 1). The lakes preserve evidence for past fluctuations in marine influence inundation (Martin, 1968) and more general palaeoenvironmental conditions (Irving,1998; Reinwarth et al., 2013). It is currently unclear whether they persisted when sea-levels were lower or whether they were drained and replaced by river systems at such times. In the case of the latter, it is unclear the exact course such rivers would have taken, where they passed through relict barriers and how they extended onto the emergent coastal plain. Birch et al. (1978) suggested that sediment entering the ocean could have been deposited into offshore interdunal depressions, but it remains unclear how rivers, lakes and the marine embayment interacted with the barriers over the long-term. It has been suggested that individual rivers provided only localised sediment contributions to the barriers (Dunajko and Bateman, 2010).

Swartvlei is composed of two types of sediment: pure quartzose sand at the lake margins and organic-rich mud drapes the lakefloor (Birch et al., 1978). Birch et al. (1978) interpreted the incision of the cemented dune ridges of the middle and seaward barriers to reflect fluvial incisions with the sea-level regression following the Last Interglacial. This sedimentation model suggested that coarse lag material was deposited on the floors of interdune valleys (now vleis) during the retreat of sea level towards the Last Glacial Maximum (LGM). The subsequent Holocene transgression was interpreted to be responsible for the accumulation of finer grained sediment into the valleys and lastly pelagic sedimentation resulted in the deposition of the fines in the lake. Birch et al. (1978) proposed the presence of two seismic units in Swartvlei. 'Unit A' underlies a reflector interpreted to be remnant of the retreat towards the LGM and 'Unit B' overlies 'Unit A' and is interpreted to have been deposited since the Holocene transgression. This unit, according to Birch et al. (1978), is composed of both aeolian and pelagic sediment. Unit C is acoustically transparent and is interpreted to represent the most recent facies of Unit B. It is composed of finely laminated, organic muds.

3.2. Models for the preservation of Quaternary deposits on the continental shelf

Previous work on the relatively wide continental shelf in this area also hints at the presence of a submerged landscape with evidence of former barriers (Birch et al., 1978; Bateman et al., 2011). The first geophysical surveys conducted offshore of Wilderness mapped dune ridges on the inner shelf (Birch, 1975). Bathymetric characteristics include offshore shoals, which were interpreted to represent submerged cemented dune ridges, and a depression offshore of Groenvlei which was thought to likely represent an offshore lake (Fig. 1). Birch et al. (1978) observed no bathymetric evidence for the offshore extension of the Swart, Goukamma, or Touws Rivers but suggested that this reflected subsequent sedimentary infilling of the incised channels. A seismic investigation on the inner continental shelf revealed a nearshore sedimentary wedge reaching 20e30 m in thickness. Birch et al. (1978) proposed that the offshore dune ridges were deposited on minor transgressive pulses on the overall retreat in sea level towards the LGM. Bateman et al. (2011) presented palaeo-coastline reconstructions based on coarse resolution satellite data and indicated that approximately 5500 km2 of additional land was exposed during the LGM resulting in the coastline being over 100 km further south. The work also showed how spatial variations in offshore topography potentially had a profound effect on sediment delivery and construction of the onshore barriers. In the eastern section of the embayment, the coastline seemingly remained close to the present for much of MIS 5, resulting in the accretion of aeolian sediment throughout MIS 5e, 5c and 5a (Bateman et al., 2011). The coastline on the western side of the embayment, however, was further south after the MIS 5e highstand. Bateman et al. (2011) suggest that the high offshore gradient on the adjacent shelf associated with the Swart River palaeovalley limited lateral shoreline migration due to eustatic sea-level changes, meaning that sediment supply to the littoral zone was maintained for longer time periods.

On the South African East Coast, recent studies carried out by Green (2008) and Cawthra et al. (2012b) described potentially analogous processes for the existing shelf configuration. The east coast shelf deposits generally young in an offshore direction (Cawthra et al., 2012b; Bosman, 2013). Furthermore, Green (2008) reported incised palaeovalleys off the KwaZulu-Natal coast which were inferred to date to MIS 2, while in situ beach deposits have also been reported at depths of c. 125 m off Sodwana Bay (Green and Uken, 2005). Cawthra et al. (2012b) presented evidence for dune-building during the Marine Isotope Stage (MIS) 4 glacial period based on a 60 ka submerged aeolianite 30 m below Mean Sea Level (BMSL). Although the formation of aeolianite (as preserved in modern terrestrial environments) is largely recognised to be associated with interglacial sea-level highstands (Bateman et al., 2004; Armitage et al., 2006; Gardner et al., 2006; Roberts et al., 2008), there is increasing evidence for significant deposition of dune cordons on continental shelves during glacial periods as shelf carbonates become reworked into dunes (Brooke, 2001; Fornos et al., 2009; Brooke et al., 2010; Nichol and Brooke, 2011; Brooke et al., 2014).

4. Materials and methods

4.1. Site selection

This research examines the morphology of the largest lake within the Wilderness system, Swartvlei, located in the centre of the Wilderness Embayment (Fig. 1). It is presumed that fluctuating Quaternary sea levels not only resulted in barrier formation, but modified the lakes in terms of base levels, palaeodrainage off the coastal plain, and sediment accumulation, retention and removal (Martin, 1962; Birch et al., 1978). This site is used to investigate these processes in more detail with a view to mapping incised palaeo-drainage lines, submerged aeolianite ridges and sediment accumulations. A grid of coast-perpendicular and coast-parallel oriented pinger seismic lines were collected in Swartvlei (Fig. 2).

Given the important influence and largely unknown nature of the currently submerged part of the coastal plain, the geophysical dataset was extended offshore. Data from this survey were designed to correlate the Quaternary seafloor stratigraphy to the depocentre of sediments within the coastal embayment and to compare the stratigraphy within the Wilderness Embayment to the adjacent continental shelf. The offshore dataset is spatially limited because it was acquired to build on the earlier work of Birch et al. (1978). The previous work only considered the inner continental shelf and this survey was intended to acquire two regional transects, one extending to the shelf break. The offshore dataset was the first collected since the work of Birch et al. (1978). Following this preliminary study of the shelf, it is anticipated that an offshore model could be developed with the acquisition of oblique,

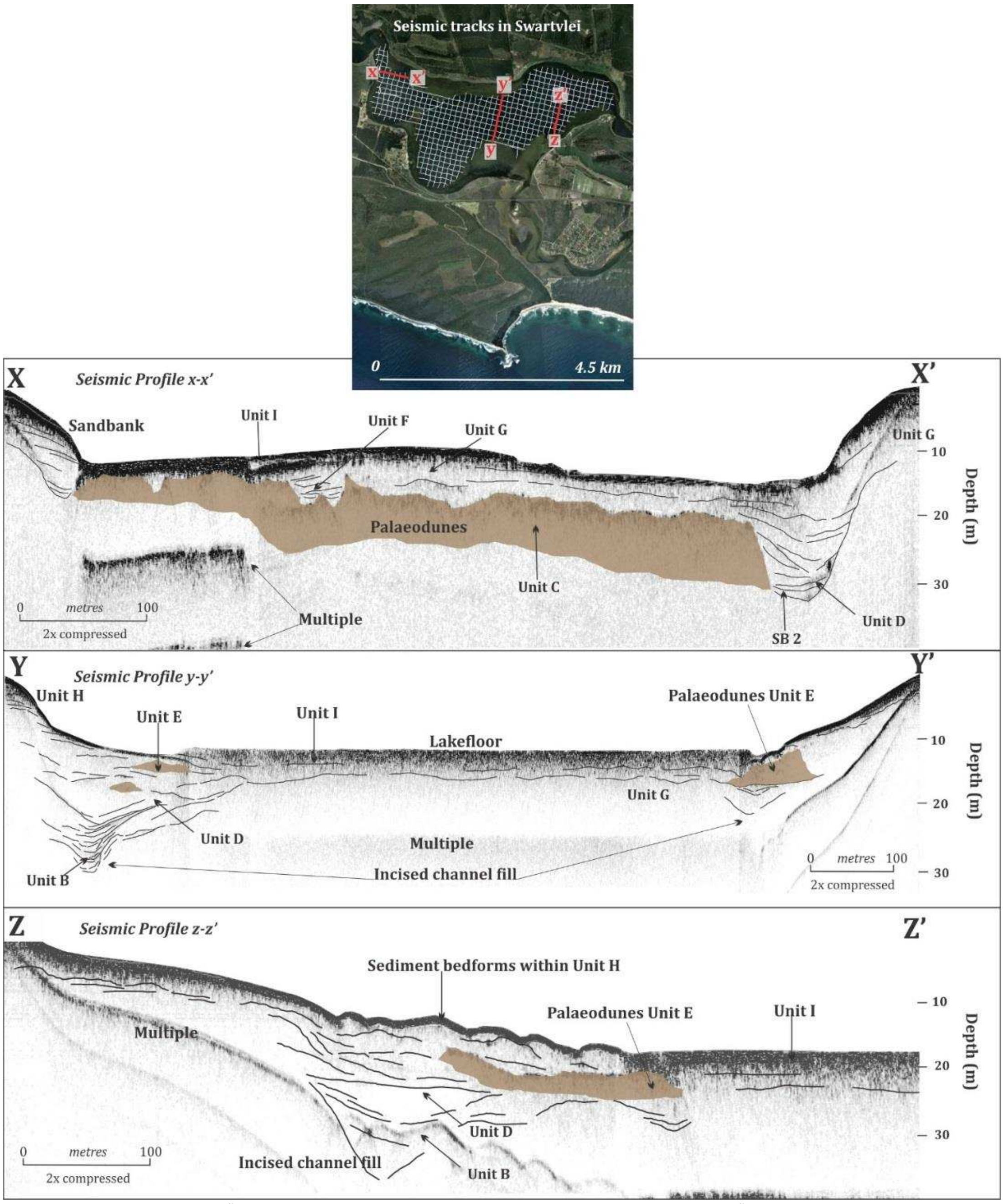

Fig. 2. Navigational transects of the seismic profiles are overlain on a Google Earth plot for context. Three Swartvlei seismic profiles are presented as cross sections XeX', YeY', ZeZ', showing the relationship between incised channels on the lakefloor and the spatial distribution of aeolianite in the lake basin. Seismic units and bounding surfaces are annotated.

intersecting, seismic profiles, to confirm the orientation and character of the features presented in this work.

4.2. Geophysical surveys

The Swartvlei data collection field survey was undertaken in September 2011 under low wind and calm lake conditions. Swartvlei was surveyed with 127 profiles of single-channel high resolution seismic reflection data totalling 125 line kilometres of coverage (Fig. 2). A pinger seismic profiler was selected based on anticipated depth of penetration (a function of water depth) and the sedimentological substrate identified by the previous survey of Birch et al. (1978). The seismic lines were arranged on both coast-parallel and coast-perpendicular orientations in evenly spaced (100 m) grids. Two offshore profiles (Fig. 1D) were collected in February 2012 from the continental shelf adjacent to Swartvlei along coast-parallel and coast-normal oriented transects. The latter extended to 110 m BMSL. The geodetic parameters applied to all data were produced in the World Geodetic System (WGS) 1984 ellipsoid with the Universal Transverse Mercator (UTM) projection of zone 34 south. The central meridian of the projection is 21_ east. The seismic surveys were positioned using a CSI Wireless differential GPS, providing sub-metre accuracy at a position update rate of 5 Hz. The seismic profiling system consisted of a Geo-Acoustics Model 5430A transmitter, an Octopus 760 seismic processor and an over the side mounted array of four Massa transducers. Pulse length cycles were selected to improve efficiency of the transducers and to reduce "ringing". The pinger system was triggered every 125 ms with a sweep period of 200 ms using a sampling rate of 24 kHz. The seismic profiler was hull-mounted on showing the relationship between incised channels on survey vessel to reduce cavitation effects associated with towing and interference from propellers.

4.3. Data analysis

Processing of the reflection seismic data involved the application of time-varied gain, a bandpass filter (optimised at 900e3000 Hz), swell filter and seabed tracking. Constant sound velocities through water and sediment were set at 1500 and 1650 m s_1 respectively to constrain time depth conversions. Sequence stratigraphic interpretations are based on the principles and standardised terminology of Catuneanu et al. (2009). Four systems tracts are recognised in each complete sequence (as per Coe and Church, 2003; Catuneanu et al., 2009): the falling stage systems tract, the low stand systems tract, the transgressive systems tract and the highstand systems tract. Within these classification schemes, a systems tract refers to the subdivisions of sequences that consist of discrete depositional units differing in geometry from other systems tracts and which have distinct boundaries (Coe and Church, 2003).

5. Results

5.1. Seafloor and Swartvlei morphology

Both seismic datasets indicate that the Termination I marine transgression (commencing at ~18 ka from a depth of 130 m BMSL (Clark et al., 2009) eroded most geological evidence of previous sub-aerial exposure of the seafloor during the LGM (26.5-18 ka). The planed offshore shelf is, however, punctuated by coast-parallel trending ridges (Fig. 4). These ridges reach a maximum elevation of up to 20 m above the surrounding seafloor and are preserved at depths of 33, 42, 77, 93, 97, 103, 108 and 115 m BMSL. Within Swartvlei, basin depo-centres are punctuated by the occasional occurrence of geological outcrops and linear depressions. The latter follow the general trend of dominant rivers entering Swartvlei. These are referred to as palaeochannels in this study. Other sedimentary bedforms (Fig. 2 profile Z-Z') reaching a maximum amplitude of 3.4 m and maximum wavelength 6 m, are asymmetrical, slanted towards the landward margin of the lake.

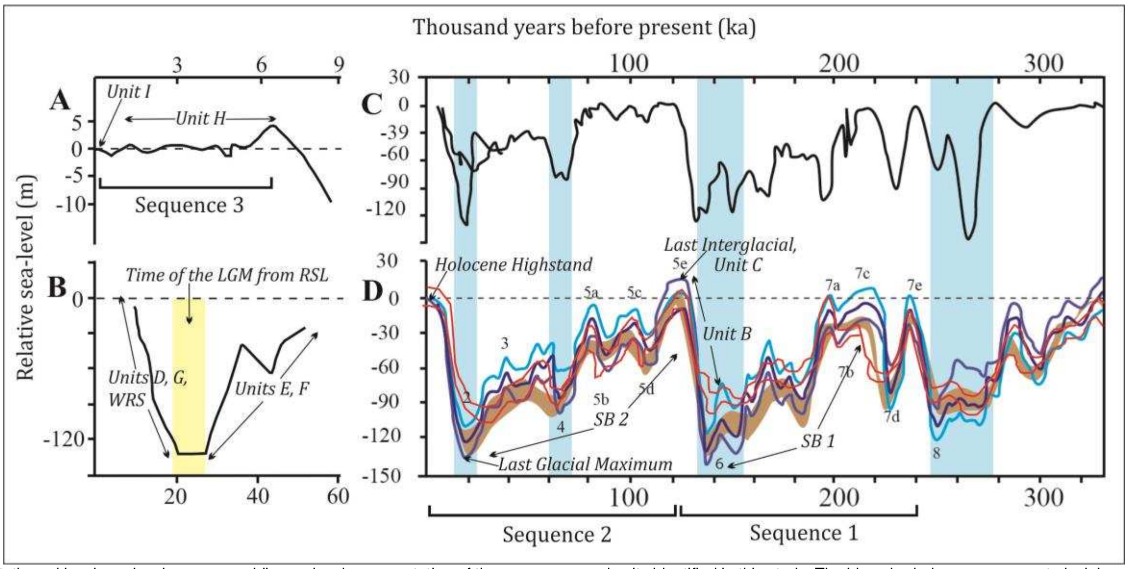

Fig. 3. Global eustatic and local sea-level curves providing a visual representation of the sequences and units identified in this study. The blue shaded areas represent glacial periods. A. Holocene sea-level of Compton (2001) for the last 9 ka. B. Compiled relative sea-level (RSL) data of Clark et al. (2009) spanning 60 ka. C. Sea-level records from southern Africa (Ramsay and Cooper, 2002; Compton and Wiltshire, 2009; Carr et al., 2010). D. Glacio-eustatic sea-level curves of Waelbroeck et al. (2002) in blue, Bintanja et al. (2005) in brown, Rohling et al. (2009) in red. C and D modified from Compton (2011).

5.2. Seismic stratigraphy

From a seismic stratigraphic viewpoint, the Wilderness Embayment and adjacent nearshore continental shelf area of interest are treated seamlessly. These environments, although now separated by modern sea level, form a composite geomorphic feature equally influenced by Late Quaternary sea-level fluctuations. Interpretation of selected representative profiles from Swartvlei and two offshore transects revealed ten seismic units (A-I) in the region (Table 1, Figs. 2 and 3) forming three sequences. The discrete seismic units are bounded by two regional sequence boundaries (SB 1&2) and one wave ravinement surface (WRS). Though numerous reflectors were observed, these are not interpreted to represent prominent bounding surfaces because they were not laterally continuous and were therefore applied only in the geometric classification of clinoforms where applicable.

Unit A (Fig. 4) is interpreted to represent basal Neogene deposits. As displayed in Fig.1, it is the lowermost seismic facies in the area and forms the acoustic basement. Unit A is not observed on all profiles, and no notable seismic features have been recorded within it. The uppermost boundary (SB 1) can be traced as a prominent erosional surface capping Unit A.

Units B and D (Figs. 2, 4 and 5) are interpreted to form sediments of incised channel fill of different ages. This seismic facies is composed of high amplitude reflectors that commonly dip toward the point of maximum incision of the incised valley, weakly layered parallel- to sub-parallel reflectors, and wavy reflectors that infill the incised valleys and on-lap adjacent valley flanks. In the case of Unit B, these sediments infill channels on the shelf at depths of 53, 44 and 38 m BMSL (Fig. 5 labelled aef). In Swartvlei the Unit B sediments occur at 15-20 m below the lakefloor. These are overlain by subsequent infill sequences of Unit D at shallower depths of 5-10m below the lakefloor. Unit B is separated from the underlying Unit A by a prominent horizon interpreted to represent Sequence Boundary 1 (Table 1). Unit D, however, is bounded by SB 2.

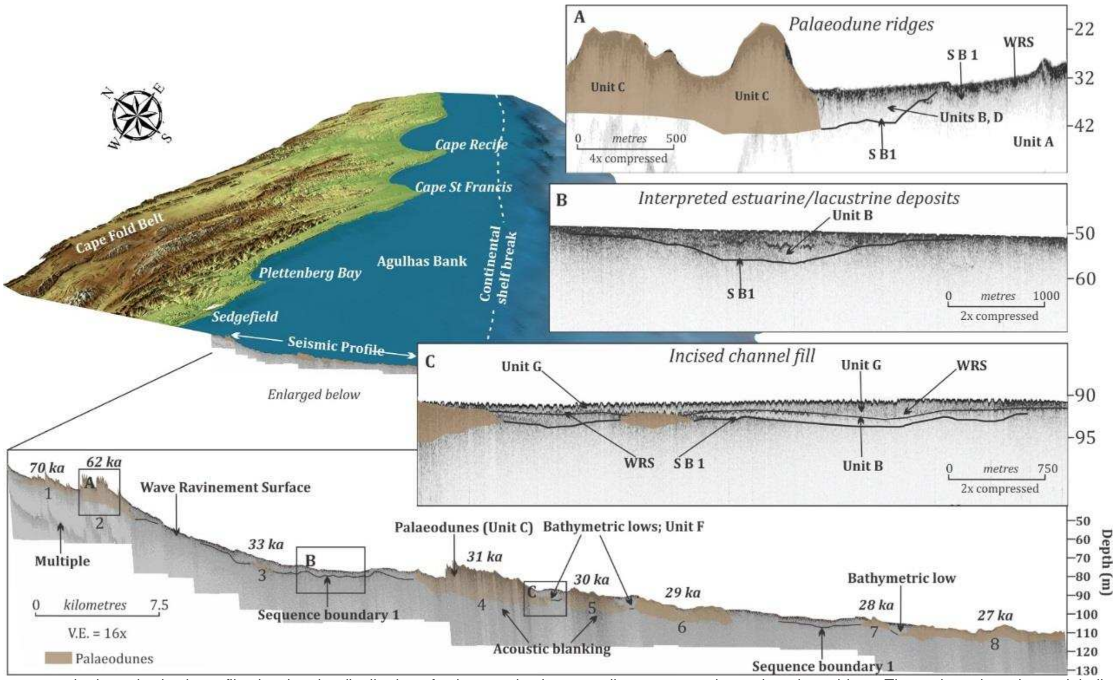

Fig. 4. Coast-normal oriented seismic profile showing the distribution of submerged palaeocoastlines preserved as palaeodune ridges. These dune deposits are labelled 1e8 and estimated ages are based on the depth of the coastal dunes and relative to expectations from eustatic sea-level records ofWaelbroeck et al. (2002), Bintanja et al. (2005), Clark et al. (2009) and Rohling et al. (2009). A, B and C are insets labelled on the seismic profile, showing seismic units in detail.

Units C and E (Figs. 2, 4 and 5) share similar seismic characteristics but are apparently temporally divided, forming components of two discrete sequences. Units C and E rest conformably and unconformably on the surfaces of Units A and B respectively. These units generally form rugged/relatively high relief outcrops, reaching a maximum vertical thickness of 20mon the continental shelf. Unit C is stacked in places where subcrops are separated by less reflective material of seismic Unit D. In places, high acoustic impedance of Units C and E hinder interpretation of the underlying seismic facies. Based on regional stratigraphy within and surrounding the Wilderness embayment, and the previously dredged offshore samples described by Birch et al. (1978), these units C and E are inferred to represent multiple phases of aeolianite ridge deposition.

Deposits of Unit F (Figs. 4 and 5) are closely associated with Unit E and tend to either accumulate against the landward flanks of the ridges or are draped between stacked components of Unit E. Unit F is acoustically semi-transparent, containing intermittent reflectors which are stacked aggradationally. Unit F is a thin, laterally discontinuous deposit lacking discernible internal structure. This unit crops out in low-lying depressions where relief of the ridges is more subdued. Based on the described stratigraphic relationship and reflection characteristics, Unit F is interpreted to be composed of semi-consolidated interdune or back-barrier sediments.

Offshore, Unit G overlies a distinct WRS and is best preserved in the nearshore, pinching out towards the mideshelf (Fig. 4). In Swartvlei, Unit G is generally overlain by Unit H and rests unconformably on the underlying Units B, C, E and F (Fig. 2). Unit G is separated from the overlying Unit H (Fig. 2) by a prominent reflector within this sediment wedge. In places, clinoforms within Unit G are truncated against the medium-gradient bathymetric slope of the Swartvlei margins where Unit G crops out. Large-scale structures (amplitudes reaching up to 3.4 m) are preserved in the southeast section of the mapped area (Fig. 2 profile Z-Z'). Unit H is defined by divergent reflectors indicative of progradation and this unit volumetrically dominates the sediments of the Swartvlei sandbanks. Unit H was not observed offshore.

Unit I (Fig. 2) is characterised by high acoustic impedance, though along some seismic lines internal sedimentary layering is discernible. Signal wash-out impinging onto the underlying packages is common. Unit I volumetrically dominates the lakefloor of Swartvlei and is stratigraphically the highest unit, representing the youngest deposit. The uppermost boundary of Unit I generally forms the present floor in the low-relief basins and sediment sampling confirmed the composition of Unit I to be silty mud. There is no equivalent of Unit I offshore. Unit I correlates to 'Unit C' of Birch et al. (1978).

Three primary reflecting horizons can be identified seismically within the surficial, latest Pleistocene to Holocene stratigraphic successions of the shelf and extending landward into the Wilderness Embayment (Figs. 2-4). These are the basal SB 1 horizon, a second stratigraphically higher SB 2 and a transgressive surface interpreted as a WRS. Sequence boundaries are generally interpreted to reflect sub-aerial unconformities e the most significant type of stratigraphic hiatus in the rock record (Catuneanu et al., 2009). SB 1 is interpreted to represent the commencement of Sequence 1 and SB 2 marks the start of the deposition of Sequence 2. Both surfaces are prominent sections in the seismic record and have probably been extensively modified by the Quaternary regressions on the continental shelf. WRS truncates all older horizons, channel fill strata and forms the base of the mobile sand sheet described by Martin and Flemming (1986). Based on seismic stratigraphic observations this is interpreted to be the transgressive ravinement of the Holocene transgression. Typically wave action in the surf zone erodes the bedrock substrate and acts as a winnowing agent, resulting in the formation of surficial coarse lag deposits (Posamentier, 2002; Nordfjord et al., 2009) (i.e. gravels and coarse sand). These surfaces have also been described off the South African east coast (Hay, 1984; Green, 2009; Cawthra et al., 2012a).

6. Seismic facies interpretations

6.1. Inferred temporal control on sequences as defined by the seismic architecture

From the lake floor and seafloor seismic stratigraphy an evolutionary model of this system is constructed by correlation to the

Table 1 : Seismic units and interpreted ages of the Swartvlei and Wilderness shelf deposits. Abbreviations are as follows: TST - Transgressive systems tract, HST - Highstand systems tract, FRST - Forced regressive systems tract, FSST - Falling stage systems tract, LST - Low stand systems tract, SB - Sequence boundary, WRS - Wave ravinement surface.

Seismic unit	Stratal characteristics of clinoforms	Seismic facies interpretation	Interpreted environment of deposition	Systems tract	Thickness	Interpreted age	Sequence
I	Not observable	Basin infill	Low energy back-barrier basin infill	Stillstand	≤ 9 m	Recent	3
H	Acoustically transparent; low-amplitude divergent reflectors	Basin infill, progradation	Back-barrier margin deposits (sandbanks) accreted since the fall from the Holocene Highstand	FSST	≥ 5 m	Holocene Highstand to Recent	3
G	Acoustically transparent, prograding wedge	Holocene sediment accumulation in response to rising sea-level	Transgressive deposit/sediment wedge offshore; sedimentary back edge margin in Swartvlei	LST-HST	≤ 12 m	Late Holocene	2
F	Structureless	Infill between outcrops of unit E	Interdune deposits/back barrier fill	Stillstand/HST	≥ 6 m	MIS 4-pre Holocene Highstand	2
E	Chaotic reflectors; rough texture	Aeolianite	Mobile sands on an active palaeoshoreline	Stillstand/HST	≥ 20 m	MIS 4-pre Holocene Highstand	2
WRS	Bounding horizon	Wave Ravinement surface	Regional marine flooding event across the rapidly drowning continental shelf	Transgressive surface	N/A	Early to late Holocene	2
D	Parallel and sub-parallel reflectors infilling structural depressions	Laterally discontinuous incised channel fill; onlapping clinoforms	Incised channel infill sequences (likely marine, estuarine, lacustrine facies)	TST	≥ 8 m	MIS 4-pre Holocene Highstand	2
SB 2	Erosional truncation of underlying surface	Prominent reflector which extends across the Wilderness Embayment	Subaerial exposure and erosion of the substrate	FSST	N/A	MIS 5e-4	Commencement of 2
C	Chaotic reflectors; rough texture	Aeolianite	Mobile sands on an active palaeoshoreline	Stillstand/HST	≥ 10 m	Last Interglacial (MIS 5e)	1
B	Parallel and sub-parallel reflectors infilling structural depressions	Laterally discontinuous incised channel fill; onlapping clinoforms	Incised channel infill sequences (likely marine, estuarine, lacustrine facies)	TST	≥ 15 m	MIS 6 (offshore) – 5e (Swartvlei)	1
SB 1	Erosional truncation of underlying surface	Prominent reflector which extends across the seafloor	Subaerial exposure and erosion of the substrate	FSST	N/A	MIS 7-6	Commencement of 1
A	Acoustically impenetrable	Bedrock	N/A	N/A	N/A	Cretaceous/ Neogene	N/A

well documented stratigraphic successions that post-date MIS 11 (Bateman et al., 2004, 2011; Carr et al., 2010). Initial deposition of sediments onto the section of coastal plain that would eventually become the 'Wilderness Embayment' may therefore have occurred prior to or during MIS 11. Associated with the deposition of the basal sediments of the oldest landward barrier (thought to be MIS 11 in age; Illenberger, 1996) was initial carving and subsequent infilling by the Swart River (Fig. 6), which is presumably no younger than the regressive phase of MIS 12. The deep incision observed adjacent to the landward barrier (Fig. 2) suggests a glacial phase with low base level.

The seismic record (Table 1, Fig. 2) suggests that Sequence 1 spans MIS 7 e 5e and it is characterised by incised channel fill sequences and aeolianite. SB 1 is interpreted to represent the commencement of Sequence 1 as sea-level regressed from MIS 7-6. We propose that Sequence 2 commenced during the Last Interglacial and terminated with the onset of the Holocene highstand (MIS 5e e 1). SB 2 marks the start of the deposition of Sequence 2 and represents the sub-aerial exposure of the shelf from MIS 5e-2. Sequence 2 contains evidence for incision of rivers, sedimentary infill sequences, aeolianite deposition and interdune deposits on the shelf. The youngest strata in this area form Sequence 3 and span the period from the Holocene highstand to the present. Sequence 3 represents the construction of sandbanks and low energy backbarrier basin infill sediments in Swartvlei (Fig. 3).

6.2. Distribution of submerged aeolianite

Onshore, the seismic record in Swartvlei indicates that the distribution of aeolianite below the lakefloor is concentrated at the margins of the vleis, in close association with palaeochannels. Eroded fragments of aeolianite are also preserved in the centre of Swartvlei (within the modern basin). Their location and orientation is consistent with them being former extensions of the three subaerial barriers within the embayment along strike (Fig. 2). Furthermore, the seismic profile collected perpendicular to the coast (Fig. 4) intercepted eight units of aeolianite on the continental shelf. Two of these units (1&2) were also imaged along a coast-parallel seismic profile (Fig. 5).

Previous studies on the south coast suggest that onshore barrier construction at Wilderness had largely terminated by ~75 ka and earlier (~90 ka) in the western part of the embayment (Bateman et al., 2011). This corresponds with a sea-level regression of c. 50 m below modern sea-level. Bathymetric data suggest that the shoreline would have retreated at least 15 km seaward at such times, cutting off the seaward barrier from its sediment supply (Bateman et al., 2011). However, barriers clearly continued to accrete on the offshore plain (now the inner continental shelf). It is probable that at least some of the offshore ridges visible on the offshore profile formed during still-stands within MIS 4 e 2, and similar features have been mapped and dated on the South African East Coast (Cawthra et al., 2012b). Based on correlation with the sub-aerial deposits (Bateman et al., 2011), geomorphic expression and seismic stratigraphic relationships, the ages are inferred to reflect the regression of sea-level from MIS 4 towards the LGM (c. 26 ka).

There are numerous potential responses of barrier systems to sea-level rise (Carter, 2002). Rising sea-levels may erode the drowning coastline by wave erosion, coastal landforms may be shifted landward, remaining in step with sea-level rise (translation and rollover), and rapid overstepping may occur when the entire shoreline is submerged and stranded. In the case of the Termination

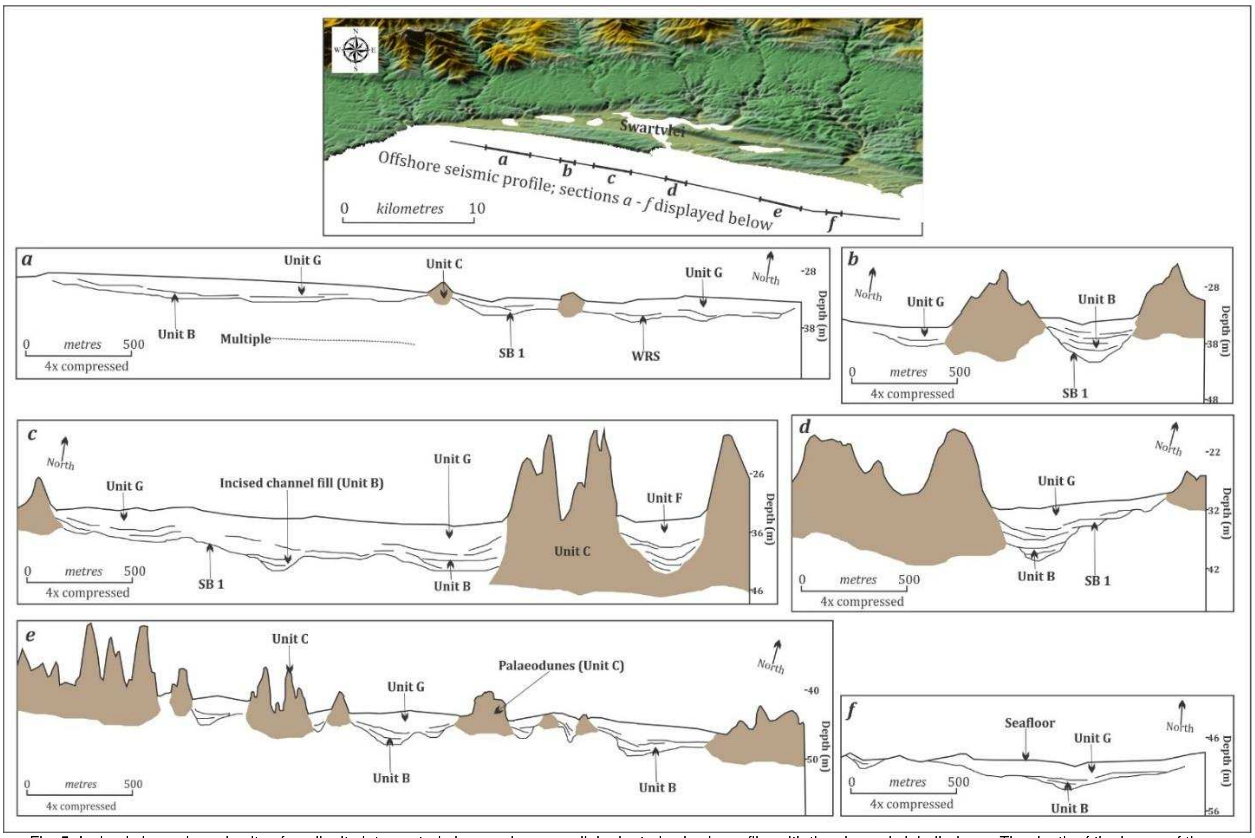

Fig. 5. Incised channels and units of aeolianite intercepted along a shore-parallel oriented seismic profile, with the channels labelled aee. The depth of the bases of these palaeodune barriers, when correlated to the global eustatic sea-level curves presented in Fig. 3 (after Waelbroeck et al., 2002; Bintanja et al., 2005; Clark et al., 2009; Rohling et al., 2009) indicate that they were likely deposited during MIS 3 (60e50 ka) when sea-level was 25e50 m lower than present base level. The most recent incision of these river channels, though separated spatially on the shelf, likely correlates to the regressive phase spanning MIS 5a e 4 (shown on this transect at approximately 90 ka in the case of channel a, 74 ka in the case of channels bee and 54 ka in the case of channel f).

I transgression, the seismic profiles (Fig. 4) and low nearshore shelf gradient suggests that a successive landward shift of Quaternary facies occurred on the low-gradient continental shelf. In conjunction with a steady sediment supply from the numerous fluvial systems draining the area and reworking of adjacent marine sediment, the Holocene dune and beach deposits are preserved in the modern-day Wilderness Embayment. The regressive palaeodunes in Fig. 4 were deposited as sea level fell from MIS 3 to MIS 2 and then drowned by the Termination I regression.

The majority of dating evidence from the modern terrestrial environment suggests that dune building occurred on the southern Cape during sea-level highstands and is essentially a function of sediment supply. Applying this model to the offshore evidence and considering the published Wilderness chronologies, offshore Barriers 1 and 2 (Fig. 4) should therefore post-date 75 ka (MIS 4) and are inferred to date to c. 70 and c. 62 ka respectively. These age inferences are derived from basal depths of geological units and correlation to published sea-level curves. These could also represent older deposits remnant of prior sea-level cycles. The morphology of offshore barriers (Fig. 5) displays some variability. These relatively flat-topped systems seen in some locations (e.g. in Fig. 5d and e) have experienced greater planation compared those observed in Fig. 5c, presumably as a result of the Termination I transgression. The basal depth of the deposits in Fig. 5c, d, e, and the fact that they lie along strike of a distinct bathymetric zone near 40 m BMSL, suggests that they are the composite representation of the dune-building event 1 along this submerged palaeoshoreline. The varied topography of dunes in Fig. 5c may also reflect remnants of stacked parabolic dune trail limbs, similar to recent dunes seen on the seaward barrier, accentuated in the orientation of the seismic profile. In this case, a possible post-depositional erosion and channelised flow in the interdune limb areas is suggested. The morphology in Fig. 5e (widely spaced, poorly developed palaeodunes) indicates that either the profile clipped the marginal portion of a larger barrier, or alternatively that the lower gradient on this specific area of the continental shelf meant that dune formation was less focused on a specific locale. The dunes further offshore likely young in a seaward direction, as is suggested on Fig. 4. Units 7 and 8 on Fig. 4 potentially represent a complex composite system formed around the LGM due to the shallowness of the continental shelf in this location, combined with the rapid base level changes at this time.

6.3. Incised channels/palaeodrainage

The Wilderness barriers (Fig. 6) have been dissected in several places by rivers (for example, the middle barrier breached by the Swart River). Interpretations of the seismic sequences reveals that, in addition to the depositional units, the stratigraphy of the Wilderness Embayment has been shaped by several erosive episodes resulting in the formation of prominent sequence boundaries and the incision of several channels. These palaeochannels truncate the bedrock, have been infilled with younger material during sea-level transgressions and can be traced onto the adjacent continental shelf.

Six incised channels are identified, which can be broadly linked to modern fluvial drainage systems. The oldest incisions probably pre-date the Last Interglacial, but in most cases the valleys were incised across the sub-aerially exposed shelf during MIS 4 and MIS 2. SB 2 is the basal surface of a series of incised valley systems that eroded both the embayment and shelf. These were likely carved during the regression towards the LGM. Based on their altitude/

depth these times correspond to phases at approximately 85 ka (Channel a), 74 ka (Channels b-e) and 54 ka (Channel f). subsequently these were filled first by fluvial and then by estuarine sediments as the shoreline migrated northwards during the Termination I transgression. The observed patterns are in accordance with the model of Nordfjord et al. (2006) and Ryan et al. (2007). The incised channels are correlated to the following respective rivers: a, b: Touws River; c: Diep River; d: Swart River; e, f: Goukamma River (Figs. 5 and 6). The three bathymetric depressions on the shelf (Fig. 4) are interpreted to be remnants of back-barrier morphology. These depressions are closely associated with dune deposits and are observed at depths of 70-110 m BMSL.

Buried incised valley systems are common features of Quaternary stratigraphy preserved on continental shelves (Foyle and Oertel, 1997; Nordfjord et al., 2006). Formed by incision while the shelf is exposed, they subsequently provide accommodation space for transgressive sediments (Van Wagoner et al., 1988). The infill sequences are also comparable to those described by Zaitlin et al. (1994), Nordfjord et al. (2006) and Green (2009) for wave dominated incised valleys; whereby the basal set of facies is separated from more acoustically transparent upper facies by reflectors, interpreted to represent a tidal ravinement surface. This surface is typically formed by inlet migration during transgression. This ravinement surface is, in turn, overlain by the Holocene sediment wedge, which is relatively poorly defined in this area compared to other localities on the South African continental shelf (Martin and Flemming, 1986; Cawthra et al., 2012a).

There is a strong contrast between deeply incised river valleys observed inland versus those identified offshore. This is partly the effect of planation by sea-level transgression(s) and subsequent

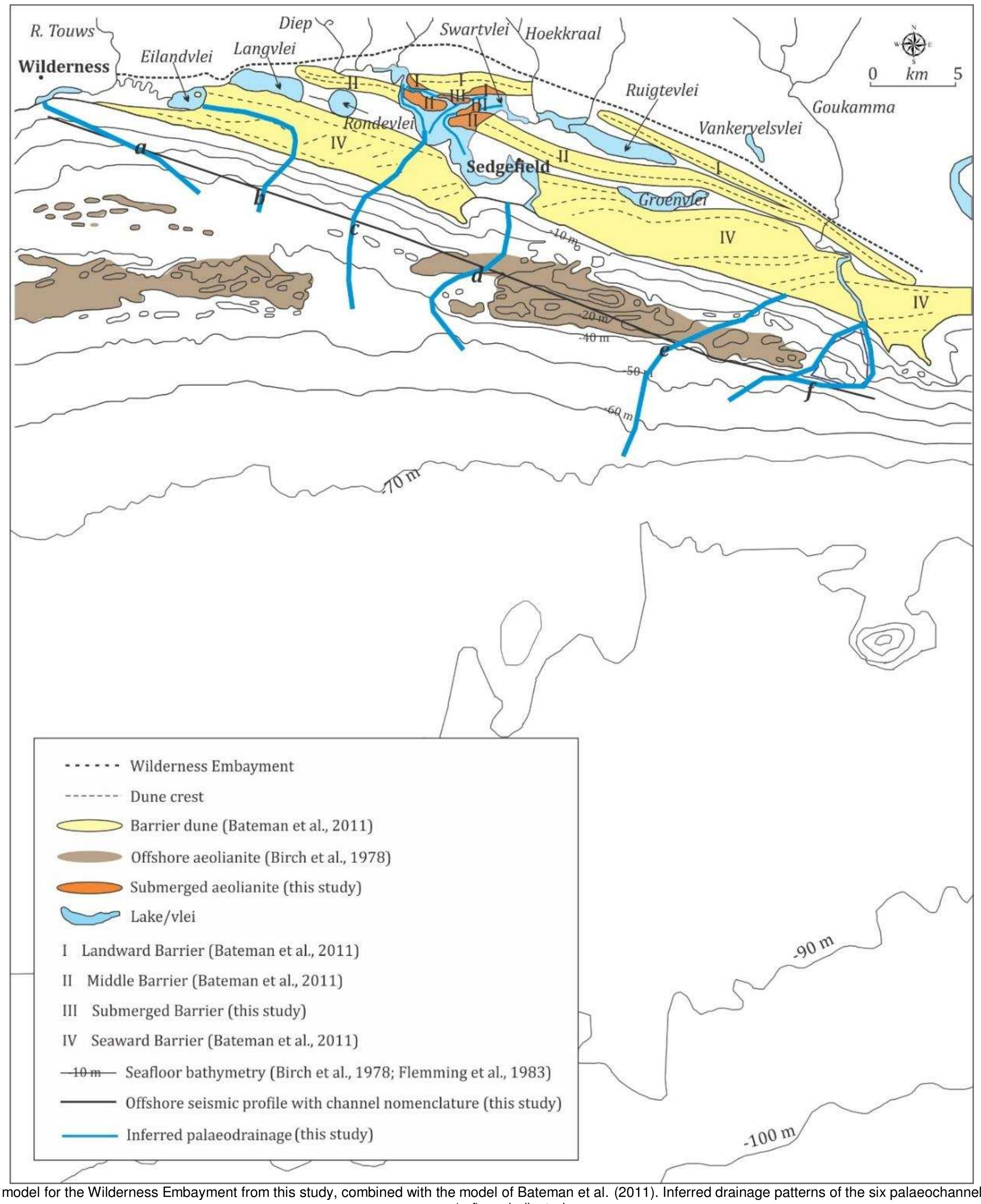

Fig. 6. Composite model for the Wilderness Embayment from this study, combined with the model of Bateman et al. (2011). Inferred drainage patterns of the six palaeochannels described in this paper (a-f) are indicated.

infilling with marine muds, but it may also reflect that once rivers flowed onto the low gradient of the continental shelf, beyond where barriers were vertically stacked, less incision took place and more lateral channel migration was possible. The bedrock control within the Wilderness Embayment is also suggested to have influenced the character of fluvial incisions compared to on the shelf.

7. Discussion

7.1. Late Quaternary evolution of the Wilderness Embayment

Sloss et al. (2005) presented a model of barrier-estuary evolution on wave-dominated coasts based on work from southeast Australia. Their model suggested that the dominant controls on the geomorphic evolution of such systems are the antecedent Late Pleistocene substrate (MIS 5e transgressive and remnant barriers) and fluctuations in Holocene sea levels. Last Interglacial (MIS 5e) successions are preserved at depth within incised valleys along the southeast Australian coast (Sloss et al., 2005). The South African coast is similar to the southern New SouthWales coast of southeast Australia (Cooper, 1994, 2001; Sloss et al., 2005) in that it is wave-dominated and tectonically stable. On the basis of the data presented here, a comparable model of Quaternary deposition is proposed for the Wilderness Embayment.

7.2. Palaeodrainage

The inferred channel courses shown in Fig. 6 were constructed based on the distribution of rivers within the modern fluvial system and the antecedent geological substrate which governs the flow pattern and the existence or absence of the dune barriers of the Wilderness Embayment. Deposition of the youngest seaward barrier (Bateman et al., 2011) would have been responsible for the most recent river drainage diversions. It seems that infilling of low stand river channels by subsequent sedimentation makes them less likely to be repeatedly incised and infilled as the river courses vary with contemporaneous sand dune development. Entry points to the embayment of rivers draining the wider hinterland were, as today, however strongly controlled by the hard rock geology.

Within the embayment, the oldest drainage system is interpreted to be the west-east oriented channel seaward of the modern Swartvlei and adjacent to the landward barrier. This is represented on Fig. 6 as River b (the Touws River palaeochannel). Given its incision associated with the middle barrier, the channel associated with River b was likely incised during MIS 6 when lower eustatic sea-levels would have increased the potential for fluvial incision. At this time the middle barrier sediments flanked channel b and it may have entered the sea at a palaeocoastline on the seaward edge of the middle barrier. Though definitive context is lacking in the case of channel a, it appears to link up with the Touws River, with the orientation of palaeoflow defined by the bedrock geology in the west. River channel c (the Diep River palaeochannel) post-dates the middle barrier as it has incised the base of middle barrier in Swartvlei (Fig. 6), which was deposited during MIS 7 (Bateman et al., 2011). River c may also have flowed towards a shoreline that existed prior to the deposition of the seaward barrier and have been fed by two rivers that flowed into the embayment and formed a confluence, which in the north re-used the existing depression from the very first/oldest landward channel. River d (the Swart River palaeochannel) has seemingly been relatively stable and seems to have maintained flow during dune construction. Given that intertidal beds within the Swartvlei Estuary are known to date to MIS 5e (Carr et al., 2010), this channel probably existed prior to MIS 5e. The channel of River d may, however, also have cut through the area of recent dunes to the west of the present river mouth (Fig. 6). Although only intercepted offshore, rivers e and f may be offshore extensions of the Goukamma and a palaeotributary now buried by the seaward barrier. From correlation with the global eustatic sea-level curves (Fig. 3), the timing of incision of the rivers on the shelf may date to three dominant clusters at MIS 5d and MIS 4a, as a function of rapid base level change and river incision.

7.3. Aeolianites and incised channels

The results from Wilderness have demonstrated a clear link between aeolianites and incised channels of barrier systems. These features are, in the seismic record, stacked vertically in response to fluctuating sea levels. Along the south coast, rivers provide a plentiful source for the coarser grade of sediment required to build coastal dune systems. Coastal dune ridges thus tend to reach their optimum development on the downdrift margin of river mouths (Roberts et al., 2008, 2009). This association has also been documented in the offshore environment through interpretation of seismic profiling (Cawthra et al., 2012b), where cores of aeolianite overlie or border incised palaeochannels on the continental shelf. On-going erosion of the seaward barrier, coupled with recycling during sea-level transgressions, was also a significant source of sediment to the Wilderness Embayment system (Roberts et al., 2008). In addition, south coast sediment supply is controlled by several large rivers, the Breede and Gouritz, with sediment discharged at river mouths and redistributed by eastwards longshore drift. The underlying bedrock and ability to create an embayment in response to available accommodation space is also a key requirement to dune-building.

The three bathymetric depressions on the shelf observed at depths of 70e110m BMSL (Fig. 4) are interpreted to be remnants of back-barrier morphology closely associated with dune deposits. These relative bathymetric lows within the transgressive surface suggest that back-barrier systems formed on the continental shelf during the LGM, presumably in association with aeolian sedimentary systems, as seen today in the sub-aerial embayment. Plausible reasons for the preservation of these features during transgressive ravinement (Swift, 1968) include (1) a slowing in the shoreline retreat during the final stages of the Termination I transgression, or (2) antecedent topography and shelf gradient. Nordfjord et al. (2009) suggest that pauses in sea-level rise may provide sufficient time to form these depressions. However, the preservation of sediments within these bathymetric depressions is likely to reflect the low gradient, broad south coast shelf. The adjacent dune ridges may have protected these sediments from erosion by the encroaching shoreline.

7.4. Evolution of barrier systems in a broader context

As found here, Brooke et al. (2010, 2014) have demonstrated that on the shallow Rottnest continental shelf palaeodunes systems can be deposited during sea-level regressions. Deposits on the inner shelf at 20 m BMSL were interpreted to date to MIS 5c and 5a, whereas the aeolianites on the outer shelf (50 m BMSL) were likely deposited during MIS 3 (Brooke et al., 2010). Similar ages are anticipated for the submerged systems off the Wilderness coastline. The role of offshore biogenic carbonate production and the delivery of this material to terrestrial environments has also been emphasised (James et al., 1999; Brooke et al., 2010). It is known that a large volume of biogenic carbonate is also produced off the southern Cape coastline (Birch, 1980) and although somewhat beyond the scope of the current study, the potential role of changing marine environmental conditions (temperature nutrient supply, upwelling) as well as wider environmental conditions (windiness and aridity) in driving variability in phases of dune formation within MIS 3 and MIS 2 on low gradient submerged shelves has been noted (Brooke et al., 2014).

Within back-barrier settings, the most recent (Holocene) phase of estuarine sedimentation was initiated on the southeast Australian coastline at the end of the Termination I transgression approximately 7e8 ka (Roy and Thom, 1981; Roy, 1984) consistent with of the timing of the mid- Holocene sea level highstand on the South African coastline (Compton, 2001). Since this highstand, Roy et al. (2001) suggested that rates of infilling of individual estuarine and back-barrier systems are dependent on the sediment load of associated rivers, and the near-shore hydrodynamic environment.

In areas having a relatively steep nearshore slope and rapid dispersal by wave action and currents, such as the Wilderness shelf, deltaic progradation is prevented (Cooper, 1993). During transgression estuarine sedimentation patterns are controlled by the balance between sedimentation rates and receiving basin volume. The results of this study are consistent with the findings of Birch et al. (1978) and indicate that Swartvlei is mantled by two distinct types of sediment; the lake margins are composed of quartzose sand while organic-rich muds blanket the floor of the lake. In accordance with the model outlined by Sloss et al. (2005), vast inundation of a large surface during the Termination I transgression may account for the relatively large dimensions of the modern Swartvlei. The sediment wedge that constitutes Unit G (Table 1, Fig. 2) and which now forms the back-edge margin of Swartvlei is interpreted to represent this middle- to late Holocene flooding of the embayment. The dipping beds of the progradational bank facies (Unit H) (Table 1, Fig. 2) indicate a system of higher energy during a period of relatively higher sea-level when the embayment was more exposed to nearshore marine processes. Thus the high-energy depositional environments were likely located further into the incised valley. This is inferred to reflect the peak of the Holocene highstand. Similar open embayment morphologies have been described by Sloss et al. (2007) and Switzer et al. (2010) where incised valleys are now occupied by barrier estuaries. According to this model, a significant volume of sediment entering the flooded valleys after the Termination I transgression would have been aeolian sediment, derived from poorly-vegetated dunes, with an increase in organic pelagic sedimentation in the central lake basin as dunes stabilised and the seaward barrier system was sufficiently large to produce low-energy environments within the lagoon. The geomorphological evolution of wave-dominated barrier estuaries on tectonically stable continental shelves has been described by Roy et al. (1980), Cooper (1993) and Sloss et al. (2005). The initial stages of valley-fill are generally a basal transgressive sand sheet, unconformably overlying the antecedent Pleistocene substrate, pinching out in a landward direction. Sloss et al. (2007) suggest that the source of the sediment is the continental shelf and that this material was transported landwards by the Termination I marine transgression. We propose that the Sequence 3 Wilderness Embayment sediments were deposited in similar manner, with an increased marine influence and that the WRS represents inundation of the embayment by past high sea levels.

With the associated dissipation of wave energy due to the establishment of the outer (seaward) barrier system, the accumulation of the present low-energy deposits accumulated as Unit I (Table 1, Fig. 2), with the dominant mechanism of sedimentation being suspension settling. Accumulation of lake bed muds was likely facilitated by the accretion of the adjacent coastal Holocene barriers, restricting the link to the ocean. Modern progressive sedimentary infilling and partial closure of the Swartvlei system may be responsible for the capacity to trap low-energy deposits (Unit I) in the central basin. Similarly Sloss et al. (2005) proposed that fine grained sediment from freshwater drainage into Lake Illawarra rapidly flocculated in the brackish/saline environment. This lake, as is the case at Swartvlei, is protected from circulating tidal currents, allowing preservation of this facies of silty estuarine mud. In addition, the limited catchments of the rivers make it unlikely that major floods could flush the system. In the shelf environment, analogous low energy lagoon systems appear to have existed during sea-level low stands, but preservation of such low-energy sediments is limited to the bathymetric depressions and adjacent to palaeodune ridges, as waves and currents likely removed these deposits.

8. Conclusions

Through offshore and lakefloor seismic profiling it has been possible to link the well-documented sub-aerially exposed stratigraphy and the currently submerged geological and sedimentological record on the South African south coast. This is a first attempt at a detailed integration of the marine-terrestrial interface Late Quaternary record in this region.

1. It is proposed that the accommodation space allowing the accretion of the barriers within the Wilderness Embayment is a function of basement geology, antecedent drainage pathways and gradient of the adjacent inner continental shelf, which facilitated sediment progradation during sea-level highstands.
2. Prior to the formation of the back-barrier lagoons of the Wilderness Embayment, part of the present-day Swart River flowed in an east-west direction, steeply incising into a narrow coastal plain. There may have been contemporaneous landward barrier construction controlling the east-est flow of the river.
3. During sea-level regressions MIS 6 and MIS 4 e 2 fluvial channels were incised and deposition of barrier dunes occurred on the continental shelf out to the LGM shoreline, c. 130 m BMSL. It is inferred that the incised-valley sequences on the continental shelf are the product of the last sea-level cycle (MIS 5e e 2). The orientation and inferred courses of incised channels of the palaeo- Touws, Diep and Goukamma Rivers observed in offshore seismic profiles suggest that the incision occurred prior to the deposition and lithification of the seaward barrier.
4. Eight palaeodune ridges are identified on the shelf at depths of 33, 42, 77, 93, 103, 108 and 115 m BMSL. These, we infer to have been deposited during sea level regression from Last Interglacial towards the LGM shoreline. Some of the dune ridges are associated with back-barrier lake bed deposits providing first evidence for back-barrier systems forming on the now submerged continental shelf during the Last Glacial cycle. These lake-floor facies survived the subsequently sea-level transgressions and are preserved at depths of 110e70 m BMSL.
5. During the early stages of the Termination I Marine transgression, shore-face advancement commenced. Channel incisions were submerged and filled with sediments (seismic Unit D) and eroded remnants of these incised valley fill sequences were preserved below WRS. As sea level neared present elevation, erosion of the mid shelf sediments and substrate resulted in the development of the Holocene sediment wedge. The preservation of the dunes during on the outer shelf was limited due to the erosional planation.
6. The sediments currently preserved in the Swartvlei most likely accumulated after the Holocene highstand (c. 6000-4000 cal yr BP; Compton, 2001, 2006). The sequence, though lacking detailed chronological control at present, bares some similarity to back barrier systems documented southeast Australia by Sloss et al. (2005). Rising sea level inundated shallowly incised

valleys and open ocean embayments, resulting in the deposition of a transgressive sand sheet. Progradation of these transgressive facies has continued through the Holocene highstand. Sedimentary infilling, dominated by fluvial input, continues in Swartvlei (seismic Unit I).

The methods and approach presented here, in conjunction with detailed coastal zone studies, clearly allow a unique opportunity to understand the complex land-ocean interface. When treated seamlessly, global coastal plain and continental shelf environments preserving Quaternary deposits comparable to those in the Wilderness Embayment can be placed into a holistic evolutionary model, which holds great potential, particularly through the application of suitable geochronological and appropriate geophysical techniques.

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