SEISMIC STRATIGRAPHY OF THE BROAD, LOW-GRADIENT CONTINENTAL SHELF OF THE PALAEO-AGULHAS PLAIN, SOUTH AFRICA

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Keywords

South Africa, continental shelf, seismic stratigraphy, Pleistocene, Post-glacial Marine Transgression, Palaeo-Agulhas Plain

ABSTRACT

The continental shelf of the Palaeo-Agulhas Plain (PAP) is scattered with Pleistocene deposits with subdued topography. Their exaggerated lateral extension is the expression of a flat underlying substrate and availability of accommodation space, depositional processes and response to glacio-eustatic sea-level change have influenced deposition and distribution of these units. We present new results for the upper ~30 m (up to ~200 ka) of the stratigraphic record in this area and show that this shelf offers the opportunity to examine the response of a stable tectonic setting to the effects of sea-level change. This paper presents the results of extensive sub-bottom profiling surveys and chronostratigraphic investigations from marine sediment vibracores. Radiocarbon and Optically stimulated Luminescence dates are integrated into a seismic stratigraphic model composed of twenty Quaternary units, where two depositional sequences are bounded by shelf-wide unconformities. The upper sequence was cored where Pleistocene deposits were observed to be close to the seafloor and are draped in a thin veneer of marine shelf sediment and allow us to describe the environments of deposition of the PAP. The most pervasive stratigraphic pattern in these shelf deposits is made up of the depositional sequence remnant of the Falling Stage Systems Tract (FSST) forced regression from Marine Isotope Stage 5e–2. The other dominant stratigraphic group is the Transgressive Systems Tract (TST) associated with the Postglacial Marine Transgression. Surprisingly, the TST makes up an almost equal proportion of deposits in both sequences in the sedimentological record as the FSST, despite the shorter temporal span of the TST. The sub-bottom profiles were acquired on regional surveys extending from the Breede River in the west to Plettenberg Bay in the east, and to a maximum depth of 110 m below Mean Sea Level, with the exception of one ~200 m deep shelf-edge profile.

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INTRODUCTION

During the Quaternary Period, Earth has experienced rapid and abrupt climate changes that have been associated with sea-level fluctuations of varying duration and amplitude (e.g., Shackleton and Opdyke, 1973; Ruddiman, 2003). Milankovitch cyclicity was first detected in the marine geological record through the recognition that past variations in the ocean's oxygen isotope composition occur in line with glacially-driven changes in ocean volumes (Emiliani, 1955; Shackleton and Opdyke, 1973). This theory (Milankovitch, 1930; 1941) proposed that summer insolation at high Northern Hemisphere latitudes drives the glacial cycles, and statistical tests have demonstrated that the glacial cycles are indeed linked to eccentricity, obliquity and precession cycles (Lisiecki, 2010). The growth and decay of Northern Hemisphere ice sheets over the past 0.9 Ma is dominated by an approximately 100 kyr periodicity and a ‘sawtooth’ pattern (characterised by slow growth and rapid termination) (Hays et al., 1976; Clark et al., 2009). Depositional cycles in Quaternary sediments are often an expression of these major ice-volume changes (Lisiecki and Raymo, 2005). The timing and duration of maximum ice cap growth and decay from oxygen isotope records indicate that the 100 kyr sea-level cycle exhibits a short-lived (~10% of the cycle) maximum lowstand phase, followed by abrupt terminations which lead to high-amplitude interglacial sea-level transgressions (e.g., Broecker, 1984; Ruddiman, 2003). These culminate in a maximum highstand, also of relatively short duration. Interglacial highstands give way to a longer-lasting sea-level regression (~70 – 80% of the sea-level cycle duration) which results in the following glacial maximum lowstand.

Passive continental shelf settings are relatively common in the geological record (Catuneanu et al., 2011). The sedimentary successions of these settings are controlled by amplitude and rate of sea-level change, clastic inputs, sediment transport and erosion, and oceanographic conditions (e.g. Catuneanu et al., 2011). Although sea-level highstand conditions prevail today on most coasts, passive margin settings are important locations to study the lowstand depositional record of sea level (e.g., Storms et al., 2008; Nordfjord et al., 2009; Bosman, 2012; Brooke et al., 2014; Cawthra et al., 2018), which can be achieved through seismic stratigraphic interpretation (e.g., Dalrymple, 2006). The antiquity of the Pleistocene geological record on the Cape South Coast’s Palaeo-Agulhas Plain (PAP) – with a sea-level highstand record extending back to Marine Isotope Stage (MIS) 11 (Roberts et al., 2012) – allows for a unique opportunity to map older Pleistocene sequences on this broad shelf. The PAP shelf was not glaciated in the Quaternary, and this makes for a suitable analogue to unravel the record of middle- to Late Pleistocene deposition in a context of sea-level change and consequent deposition. Since the Last Glacial Maximum (LGM), the PAP shelf has been progressively submerged and marine deposits have accumulated.

Seismic stratigraphic procedures have been developed and refined by Mitchum and Vail (1977), Vail (1987), Posamentier and Vail (1988) and recently readdressed by Coe and Church (2003) and Catuneanu (2006) and Catuneanu et al. (2009; 2011). The nomenclature and associations presented here are based on the proposed standardised terminology of Catuneanu et al. (2009). The interpretations in this work recognise four systems tracts in each complete sequence (as per Coe and Church, 2003; Catuneanu et al., 2009): the FSST, the lowstand systems tract (LST), the Transgressive Systems Tract (TST) and the highstand systems tract (HST). Within this classification scheme, we recognise and describe the FSST and the TST in the study area.

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We describe the uppermost units on a siliciclastic passive continental shelf as an analogue for a broad shelf system. We aim to investigate which elements of a coastal landscape are preserved on the continental shelf. This paper provides detailed seismic and sequence stratigraphy to gain new insights into processes of deposition and ravinement and provides context to the structural framework of the PAP. Specifically, we aim to (1) Define and describe deposits associated with the FSST and TST systems tracts, and the relationship of these progradational and retrogradational units with reference to glacio-eustatic sea-level curves, and (2) Define how, and to what extent, the seismic stratigraphy of the upper continental shelf affects the surficial deposits of the PAP and use these data towards the production of a geological map of the LGM (Cawthra et al., QSR under review).

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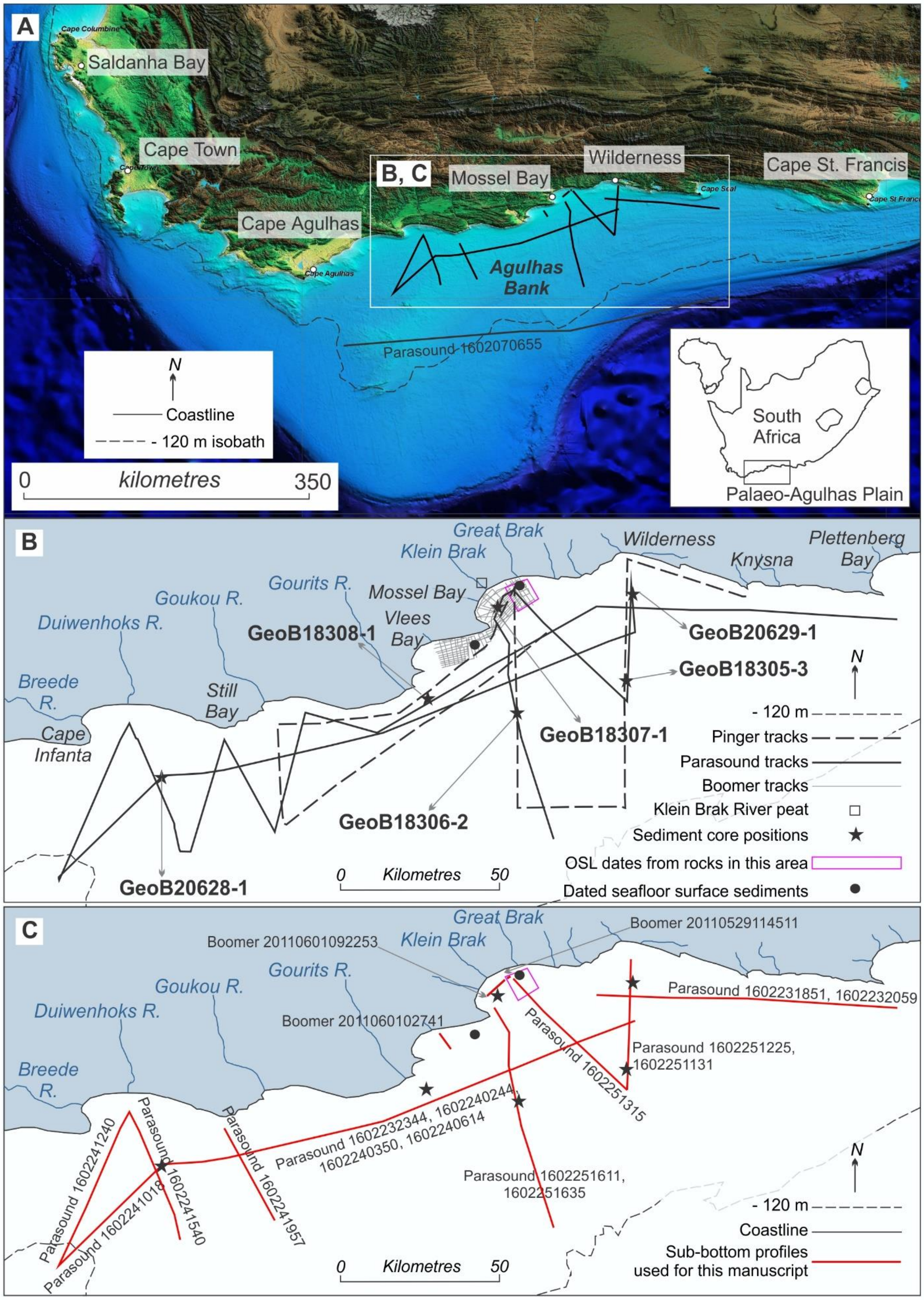

Figure 1. (A) Locality of the study area, core locations and sub-bottom profiles. The bathymetry is from de Wet (2013). (B) Three separate surveys are listed and these tracks are shown relative to the 120 m isobath, which marks the approximate Last Glacial Maximum shoreline. Boomer

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sub-bottom profiles are shown as an area of full-coverage, as the line spacing was set at 500 m. all sampling locations (cores, dated units) are marked. (C) A total of seventeen sub-bottom profiles are presented in this paper (nine parasound and three boomer profiles). Abbreviations: R. – River.

PHYSICAL SETTING AND PREVIOUS INVESTIGATIONS

The PAP has a subdued landscape with a low gradient, composed mostly of an erodible substrate of Mesozoic rocks. It is a passive margin, within a trailing-edge intraplate tectonic setting (Dingle et al., 1983) and relative tectonic stability has been demonstrated for the latter part of the Cenozoic (e.g. Wildman et al., 2015). With a width of up to 270 km off Cape Agulhas, the Agulhas Bank shelf is considerably broader than the global average of 78 km (Shepard, 1963; Kennett, 1982). The shelf breaks are at a depth of ~200 m off Cape Agulhas and ~140 m off Port Elizabeth (Martin and Flemming, 1986; Figure 1A; Figure 2), which reflects variability in basement outcrops on the shelf.

The shallow stratigraphy of the South African South Coast shelf has been mapped and investigated since the early 1970s (e.g. Rogers, 1971; Dingle et al., 1975; 1987; Gentle, 1987). Recent seismic stratigraphic studies on the South Coast have concentrated on continental margin processes (e.g. Uenzelmann-Neben and Huhn, 2009), or the continental slope in pursuit of oil and gas relying on deeper penetrating lower resolution seismic data (e.g. Brown, 1995; Broad et al., 2006; 2012; PASA, 2012). A high-resolution seismic stratigraphy focused on the Holocene sediment wedge and the location of submerged aeolianite was provided by Birch (1980) and Martin and Flemming (1986; 1987). The Holocene sediment wedge is described to have accreted in response to coastal morphology of sediment prisms adjacent to river mouths, and well-developed sediment spits extend eastwards from selected headlands (Birch, 1980). Following this earlier work, a seismic record was published for the Wilderness Embayment (Figure 1B) and adjacent Pleistocene units on the adjacent shelf which focussed on land-sea interactions through the Late Pleistocene and the development of barrier complexes (Cawthra et al., 2014). This seismic stratigraphic framework for the seafloor offshore of the Wilderness Embayment showed two marine sequences, two sequence boundaries (SB 1: MIS 7-6 and SB 2: MIS 5e-2) and a wave ravinement surface (WRS), interpreted to be Holocene in age.

What has remained unknown in this broader Cape South Coast area is the relationship between cemented and unconsolidated sediments, the relationship between stratigraphic units in a continental shelf-wide seismic stratigraphy, and the main mechanism of process-driven deposition, i.e. what controls preservation and, preferential erosion.

Pleistocene stratigraphy is relatively well-represented. Shelf sedimentation has taken place since at least MIS 7 (Cawthra, 2014), and evolution of shifting shorelines, dominate the offshore and littoral zone record of the Agulhas Bank shelf and form part of the Bredasdorp Group. The high amplitude (up to 130 m of vertical base-level change) 80 - 120 kyr glacial/interglacial cycles were initiated by 0.9 Ma, with relatively steady 40 kyr, 20 - 80 m amplitude sea-level cycles from 2.7 to 0.9 Ma (Elderfield et al., 2012). Thus, the impact of changes in sea-level underwent a major shift at 0.9 Ma and as a result much of what was deposited before that time was eroded away or is covered by younger deposits, unless, like during the early Pliocene and MIS 11, it was deposited at high sub-aerial elevation.

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The concept of a submerged landscape has been suggested by Dingle and Rogers (1972), further investigated by van Andel (1989) and most recently explored by Compton (2011) and Cawthra et al. (2015). In all cases, the marine geology of the shelf has been described. With new data, this work has been continued and for the first time that this shelf has been cored for research purposes.

MATERIALS AND METHODS

Reflection seismic data

A total of 245 sub-bottom profiles (~1500 line km of data, Figure 1B) have been collected from 2011 to 2016 for an ongoing investigation on the PAP. But in this study we present seventeen key profiles in nine figures that were selected because they demonstrate the stratigraphy (five figures presented in the main text; four in supplementary material), that are evenly spread across regions of specific interest and adequately display the regional stratigraphy. A high-frequency boomer was used to collect medium penetration seismic profiling data in Mossel Bay and Vlees Bay. Two pinger sub-bottom profiling surveys were carried out in Mossel Bay, and from Knysna to Stil Bay. Lastly, a Parasound survey was conducted on RV Meteor cruise M123. These parasound profiles were acquired from Plettenberg Bay in the east, to the Breede River in the west. The sub-bottom profile lines are all vertically exaggerated.

Stacking, filters and time-varied gain were applied to enhance the seismic records. Post-processing of the reflection seismic data involved the application of time-varied gain, a bandpass filter generally optimised between 900 and 8000 Hz, swell filter and seafloor tracking. Sound velocity through the water column was set at 1500 ms^{-1} to constrain time-depth conversions. Vertical thicknesses were computed with a constant nominal two-way speed of sound of 1650 ms^{-1} in unconsolidated sediments. Positioning was constrained using a differential GPS and depths surveyed ranged from 20 – 130 m below Mean Sea level (bMSL). The geodetic parameters applied to the 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 facies assemblages were interpreted to represent depositional environments (Figure 3). Seismic interpretations were supported by published data where possible. Our nomenclature is based on the two major sequences described (Pleistocene and Post-glacial Marine Transgression [PMT]) and the units are named according to environment of deposition. We anticipate that this nomenclature will allow for later addition of new units, should they be recognised and documented.

The lower floodplain on the Cape South Coast is interpreted here to consist of a combination of alluvial sediments, estuarine and lacustrine deposits. We grouped these units' environments of deposition into the 'lower floodplain' as we argue that to distinguish the units based on seismic impedance and microfossil evidence is often difficult. In the case of seismic characteristics, we suggest that there is ambiguity between 'estuarine' and marine littoral or alluvial floodplain. Although microfossils may provide reliable evidence of depositional environment and palaeosalinity (cf. Fürstenberg et al., 2017), it is difficult to differentiate within the outer

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estuarine regions as reworking through currents and waves mixes and destroys microfauna from marine littoral, estuarine and even fluvial habitats.

In the investigation of seismic units within the sub-bottom profiling record, we relied on (1) principles of sequence stratigraphy, (2) correlation to the cores and microfossils, (3) close correlation to the dated surficial deposits, (4) context compared to the modern coastal plain, and (5) previous marine geological investigations which have been carried out on the South Coast shelf. We identify five dominant environments of deposition, namely: mixed siliciclastic-calcareous coastal beaches and dunes; incised fluvial channels; back-barrier lagoons; lower floodplain and mobile shelf sediments (Table 2).

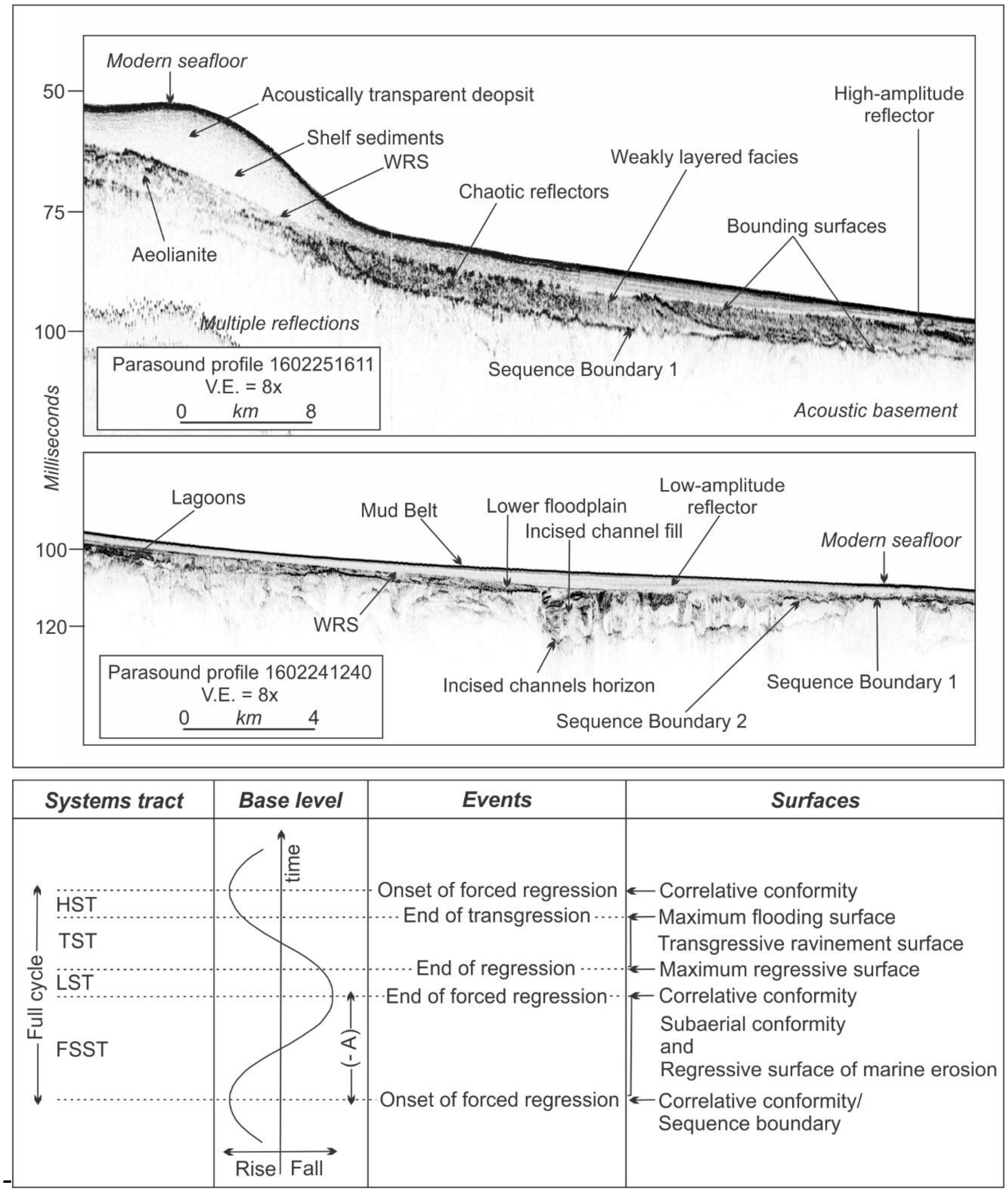

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Figure 2. (Top) Representative sub-bottom profiles to demonstrate how the bounding horizons (e.g. ‘WRS’/Wave Ravinement Surface and Sequence Boundaries, as well as seismic units and facies were delineated in this study. The data example comes from sub-bottom profiles

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1602251611 and 1602241240, displayed in Figures 6 and 4, respectively. See Figure 1C for location. (Bottom) Schematic showing the basis for definition of units and surfaces. Abbreviations: (–A) negative accommodation space. Bottom panel modified from Coe and Church (2003).

Sediment coring, seafloor sampling and analyses

A total of six sediment vibrocores were recovered from the vessel R/V Meteor on voyages M102 and M123 in 2013 and 2016 after, and in parallel with, seismic investigations (cruise reports: Ekau et al., 2014; Zabel et al., 2017). The core locations are spread across the three dominant shelf zones (inner-, mid- and outer-shelf) at depths ranging from 40 – 85 m bMSL. The cores were sited where low-energy sediment fills were thickest in protected valley fills and drowned back-barrier settings observed from seismic profiling. The cores in this investigation are only used to correlate seismic units and facies. Detailed analyses and interpretation of one of these cores (GeoB18308-1) has been published as a multi-proxy investigation by Hahn et al. (2017). To provide full multi-proxy records of each core exceeds the purpose of this paper, but data from the six marine sediment cores (Table 1; Figures 4-8) correlate to the regional stratigraphy and assisted in the development of both the seismic record and a stratigraphic column for the PAP.

Micropalaeontological analyses are based on a few selected samples only. These have a spacing of ~50 cm up to a maximum spacing of ~1 m through the cores. Samples were washed over a 200 µm sieve and the retained grain size fraction of the sediment was searched for microfossils. All interpretation is based on qualitative analysis only, i.e. foraminifer and ostracod taxa as well as macrofossil remains were used to interpret palaeoenvironments based on ecological preferences of the taxa found. A microfossil plate, containing dominant taxa, is presented in Supplementary Data Figure 1 and has formed the basis of a Masters dissertation (Gander, 2016).

Geochronology

Organic material from all six marine cores, one subaerial peat sample, and two surface sediment samples from the seafloor, were all dated at C-14-Laboratory of the Alfred-Wegener Institute in Bremerhaven, Germany (results in Table 1). The subaerial (~5 m above Mean Sea Level/aMSL) peat deposit is from the back-beach environment, and two submerged surface seafloor sediments are from the inner and mid-continental shelf. The peat sample was taken on the western bank of the Klein Brak River (Figure 1B) and a bulk sample was dated. Two marine sediment grab samples were obtained from the South Coast mud belt offshore of Mossel Bay, and were obtained from depths of 38 m and 47 m bMSL (Figure 1B). Organic material was extracted from the grab samples for dating (a bivalve from MB15 and a coral fragment from MB91). For marine samples the Marine13 – calibration curve was used (Reimer et al. 2013) with a local reservoir age of 187±18 ^{14}C yrs calculated for the South African south coast by Maboya et al. (2017). For terrestrial samples, the SHCal13 (Hogg et al. 2013) calibration curve was applied (Table 1).

Calcarenite rocks (aeolianite and cemented beach deposits) dated using Optically Stimulated Luminescence (OSL) (Cawthra et al., 2018) were used as chronological control points in the seismic stratigraphic record. Outcrops preserved on the shelf have a range of OSL ages from 200 ka – 60 ka (Cawthra, 2014; Cawthra et al., 2018) and were utilised to constrain seismic units, as their stratigraphic context is clearly visible in the seismic records. Reference to their specific ages is provided in Table 2, where relevant.

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RESULTS AND INTERPRETATION

Continental shelf sediment cores

The stratigraphy preserved in all cores broadly points towards a comparable sedimentary sequence, made up of two units (Table 1). Coarse-grained marine littoral shelf sediments laid down during the PMT, containing a high percentage of shell hash, overlie fine-grained Late Pleistocene material derived from different environments of deposition but made up of mud and silt. In the case of core GeoB10305-3, only the marine littoral deposits are present. Cores GeoB18306-1, GeoB18308-1 and GeoB20629-1, contain a hiatus between the two sedimentary units, but in the case of cores GeoB18307-2 and GeoB20628-1, deposition from the Late Pleistocene to the Present is semi-continuous (Table 1).

Marine microfossil analyses (Table 1; Supplementary Data Figure 1) allowed for interpretation of environments of deposition. The basal units of cores GeoB18306-1, GeoB18307-2 and GeoB20628-1 were laid down in a brackish estuary or lagoon. The bases of cores GeoB18308-1 and GeoB20628-1 are outer estuarine deposits and the basal portion of core GeoB20629-1 was deposited in a lagoon (Table 1; Supplementary Data Figure 1).

Table 1. Details of six marine sediment vibrocores and three sediment samples which were obtained from the south coast shelf and coastal plain. Depths are reported bMSL.

Core- or Sample number	Co-ordinates	Depth & core length	Calibrated ages at selected	Environment of deposition	Dominant microfossil taxa
MB15 (grab sample)	34°14'16.9"S, 22°6'51.04"E South Coast mud belt: Vlees Bay	47 m Grab sample	118 cal. yrs BP	South coast mud belt shelf sediment	*Ammonia* spp., *Ammotium morenoi*
MB91 (grab sample)	34°4' 59.3"S, 22°15'26.65"E Within an incised palaeo-channel: Great Brak	38 m Grab sample	187 cal. yrs BP	South coast mud belt shelf sediment	*Ammonia* spp., *Textularia* spp.
GeoB18305-3	34°21'27.03"S, 22°34'58.40"E Offshore of Wilderness	86.5 m Core length 4.67 m	0.5 m: 4072 cal. yrs BP 1.77 m: 22,571 cal. yrs BP 4.02 m: 25,282 cal. yrs BP	4.5 – 0.2 m: Marine littoral shelf sediments	Planktic forams, *Ammonia* spp., *Elphidium macellum*, *Pararotalia nipponica*, *Quinqueloculina* spp.

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GeoB183 06-1	34°25'15.42"S, 22°14'34.79"E Offshore of Mossel Bay	80.1 m Core length 4.74 m	2.36 m: 22,811 cal. yrs BP	3.0 – 1.0 m: marine littoral shelf sediments	Marine-brackish forams
			4.44 m: 23,768 cal. yrs BP	4.0 m: brackish estuary or lagoon	Marine-brackish forams and ostracods
GeoB183 07-2	34° 8'22.10"S, 22°10'26.80"E Offshore of Mossel Bay	29.2 m Core length 5 m	0.75 m: 1695 cal. yrs BP	1.0 – 0.5 m: marine littoral shelf sediments	Planktic forams, *Pararotalia nipponica*, *Cytherella* spp.
			2.32 m: 8944 cal. yrs BP 4.05 m: 10,541 cal. yrs BP	4.6 – 2.0 m: brackish-marine estuary or lagoon	*Ammonia* spp., *Pararotalia nipponica*, *Cyprideis remanei*
GeoB183 08-1 (core record publishe d in Hahn et al., 2017)	34°22'24.11"S, 21°55'44.70"E Offshore of the Gourits River	39.8 m Core length 4.94 m	1.25 m: 598 cal. yrs BP	1.1 – 0.6 m: marine sub-littoral sediments with event layers	Planktic forams, *Ammonia* spp., *Cibicides/Cibicidoides, Planorbulina mediterranensis, Quinqueloculina* spp., *Textularia, Aurila kliei, Mutilus bensonmaddocksorum, Neocytherideis boomeri, Paradoxostoma* sp.
			1.46 m: 991 cal. yrs BP	2.0 – 1.4 m: outer estuary or marine littoral	*Ammonia* spp. *Quinqueloculina* spp.
			2.85 m: 1481 cal. yrs BP 4.9 m: 4058 cal. yrs BP	4 – 3 m: marine (sub)littoral	Planktic forams, *Pararotalia nipponica*, *Quinqueloculina* spp., *Aurila kliei*, *Garciella knysnaensis*, *Mutilus bensonmadocksorum*
GeoB206 28-1	34°33′52,80″S, 21°5′40,2″E Offshore of the Breede River	70.5 m Core length 4.36 m	0.2 m: 851 cal. yrs BP 0.5 m: 6183 cal. yrs BP 1.5 m: 7181 cal. yrs BP 1.8 m: 11,035 cal. yrs BP	Upper 3.8 m: marine sub-littoral	Planktic forams, *Ammonia* spp., *Cassidulina laevigata*, *Elphidium* spp., *Pararotalia nipponica*, *Cytherella*, *Xestoleberis*

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			2.8 m. 12,743 cal. yrs BP		
			-	4.3 m: outer estuarine	Marine-brackish forams
			-	Lower section: Upper Cretaceous deposits	Prisms of inoceramids (Cretaceous mussels)
GeoB206 29-1	34°5′36,30″S, 22°35′59,58″E Offshore of Wilderness	49.6 m Core length 4.99 m	1.1 m: 11,455 cal. yrs BP	2.2 – 0.1 m: marine sub-littoral	planktic forams, *Elphidium* spp., *Pararotalia nipponica*, *Quinqueloculina* spp.
			3.0 m: 12,714 cal. yrs BP 4.5 m: 13,113 cal. yrs BP	4.7 – 2.7 m: lagoon, open to the ocean	*Ammonia* spp., *Cyprideis remanei*, *Cytheromorpha milleri*
Klein Brak River sample	34° 5'32.38"S 22° 8'50.48"E From the bank of the Klein Brak River	N/A	40,311 cal. yrs BP	Reworked fluvial and beach barrier material	*Cibicides/Cibicidoides, Elphidium* spp., *Neo-/Pararotalia, Neonesidea, Xestoleberis*

Geochronology of core and surface sample material

The Klein Brak River peat sample from the present-day coastal plain yielded an AMS-radiocarbon age of 40,311 cal. yrs BP (Table 1). The peat deposit is terrestrial but composed of reworked marine fragments such as echinoid spines, balanid plates, broken marine bryozoans, mollusc shells and some marine benthic foraminifers as *Elphidium* (Table 1). Two surface sediment samples from the submerged shelf (South Coast Mud Belt) yielded AMS-radiocarbon ages of 118 and 187 cal. yrs BP (Table 1), and they consist of fine-grained sand and silt, with a composition dominated by quartz. All dated core material is listed in Table 1, at the down-core depths from which material was obtained, where applicable.

Seismic stratigraphy

The seismic stratigraphic investigation of the South Coast revealed twenty units within two sequences laid down from the Late Pleistocene to the Present, with repeated environments of deposition (Figure 3; Table 2). The two sequences are bounded by regional sequence boundaries (SB 1, SB 2). Two ‘new’ reflectors, not previously described for this shelf, are also identified: channels i, channels ii.

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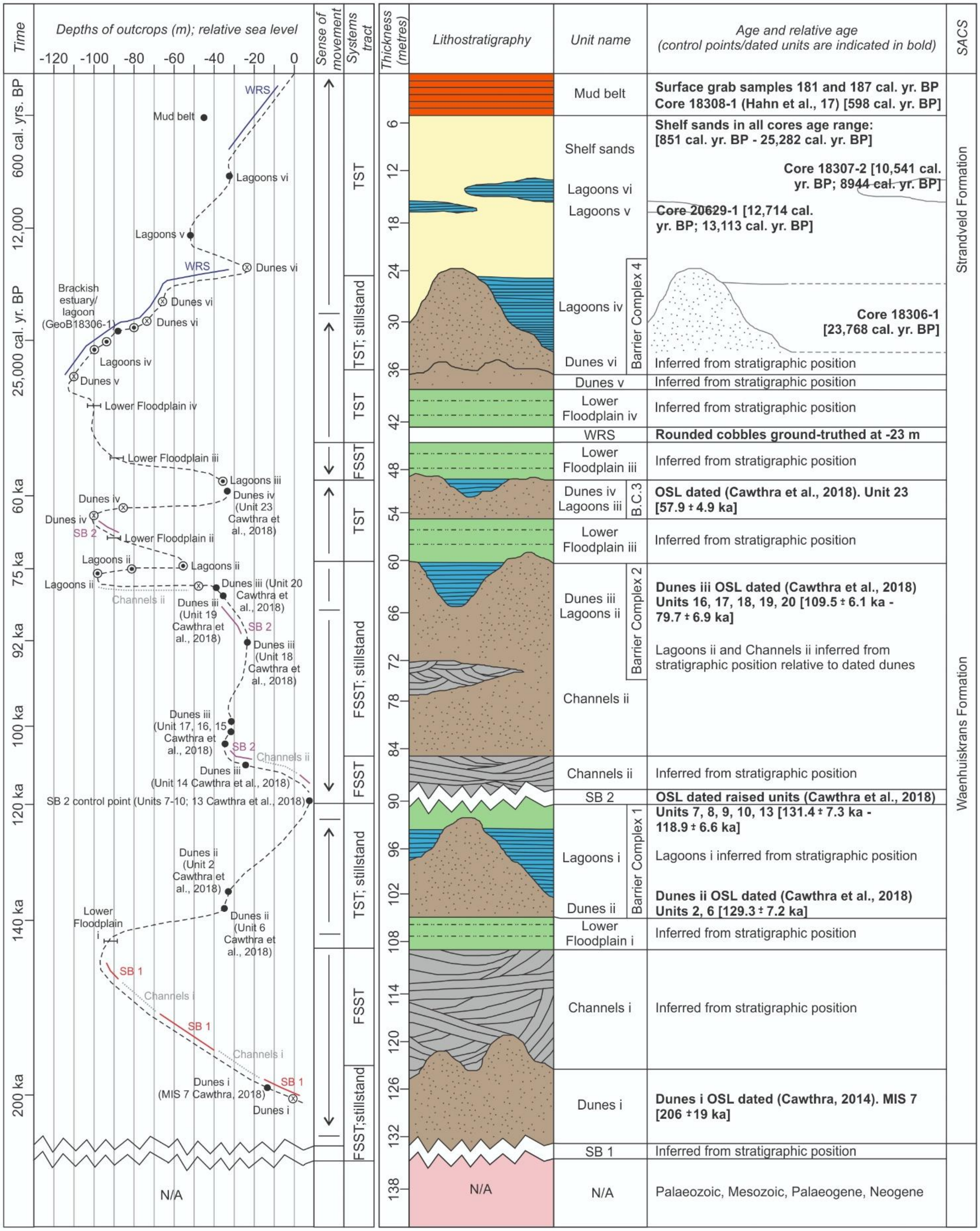

Figure 3. Stratigraphic column showing all seismic and lithostratigraphic units on the Palaeo-Agulhas Plain.

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Table 2. Seismic units and interpreted ages of the south coast shelf deposits. Abbreviations: FSST- Falling Stage Systems Tract, TST- Transgressive Systems Tract, SB – Sequence Boundary, WRS – Wave Ravinement Surface, Seq. – Sequence, PMT – Post-glacial Marine Transgression, Fm – Formation. Abbreviations of areas for location: C. – Cape; S. Bay – Stil Bay, G. Mond – Gouritsmond, V. Bay – Vlees Bay, M. Bay – Mossel Bay, P. Bay – Plettenberg Bay. Seismic facies interpretation and interpreted environments of deposition are derived from the sediment cores taken for this study (Table 1) and dated control points from dated Pleistocene strata in the region.

Seq	**Seismic unit**		**Stratal characteristics of clinoforms**	**Sys-tems tract**	**Thi ck-ness**	**Actual or inferred age; stratigraphic context within the Bredasdorp Group**	**Location**
	Unconsolidated sediment wedge	South Coast Mud belt	Acoustic blanking with fine lamination where visible. Always overlies shelf sands.		≤ 5 m	Late Holocene – Recent. Surface samples: 118 & 187 cal. yrs BP (Table 1); 598 cal. yrs. BP (Hahn et al., 2017; core GeoB18308-1)	C. Infanta – S. Bay, G. Mond –M. Bay. Depths of 75-30 m.
		Lag-oons vi	Low amplitude, horizontal clinoforms; semi transparent	TST	≥ 11 m	Early Holocene. 10,541 - 8944 cal. yrs. BP (Table 1: core GeoB18306-2)	M. Bay
		Lag-oons v	Low amplitude, horizontal clinoforms; semi transparent			PMT & Early Holocene. Core GeoB20629-1 (Table 1): 13,113 cal. yr. BP; 12,714 cal. yr. BP	Wilderness
2		Shelf sands	Acoustically transparent, low amplitude divergent clinoforms.		≤ 8 m	PMT shoreface sediments: Late Pleistocene to Recent Strandveld Fm 'Unit G' (Cawthra et al., 2014); 25,282 – 598 cal. yrs. BP (Table 1)	Depths across the entire shelf & present in all marine cores.
	Dunes vi		Acoustically semi-transparent to impenetrable, low amplitude clinoforms.		≥ 10 m	PMT *[Age inferred from stratigraphic context]*	C. Infanta – S. Bay, Wilderness – P. Bay. 75 m; 62-67 m; 25 m.
	Lagoons iv		Acoustically semi-transparent. Occasional parallel- to sub-parallel reflectors.	TST and stillst and	≥ 11 m	PMT: Early Holocene 'Unit F' (Cawthra et al., 2014). (Table 1: core GeoB18306-2)	C. Infanta – S. Bay, M. Bay, Wilderness – P. Bay. Depths of 110 m; 95 m; 80 m.
	Dunes v		Structureless, relatively high acoustic impedance.			Late Pleistocene *[Stratigraphic context]*. 'Unit E' (Cawthra et al., 2014)	C. Infanta – S. Bay, M. Bay, Wilderness – P. Bay. Depths of 110 m; 95 m; 80 m; 75 m.
	Lower Floodplain iv		Low-amplitude, continuous, inclined to horizontal parallel to sub-parallel reflectors	TST	≥ 8 m	PMT: Late Pleistocene to mid Holocene. 12,743 - 6183 cal. yrs. BP (Table 1: core GeoB20628-1)	C. Infanta – V. Bay, M. Bay, Wilderness – P. Bay. Depths of 105-95 m.

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WRS: Regional marine flooding event across the rapidly drowning continental shelf – PMT Ravinement Surface						
	Lower Floodplain iii	Acoustically transparent	FSST	≤ 4 m	MIS 2 (Table 1: core GeoB18306-2) 23,768 – 22,811 cal. yrs. BP	M. Bay, Wilderness – P. Bay. Depths of 90 m; 72 m.
	Lagoons iii	Low amplitude, horizontal clinoforms; semi transparent		≤ 5 m	MIS 3*[Stratigraphic context]* Cawthra et al. (2018)	C. Infanta – G. Mond, M. Bay. Depths of 70-75 m; 55 m; 35-40 m.
	Dunes iv	Structureless, relatively high acoustic impedance.	Short -lived TST		MIS 3 Waenhuiskrans Fm; 60 ka (Cawthra et al., 2018)	C. Infanta – G. Mond, M. Bay. Depths of 100 m; 85 m.
2	Lower Floodplain ii	Low-amplitude, continuous, inclined to horizontal parallel-sub-parallel reflectors.			MIS 3 *[Stratigraphic context]*	C. Infanta – S. Bay. Depths of 90 m; 80-85 m.
	Lagoons ii	Semi-transparent deposits	Stillst and	≤ 5 m	MIS 5 d-c *[Stratigraphic context]*	C. Infanta – V. Bay, M. Bay, Wilderness. 100-95 m; 80 m; 55 m; 25 m.
	Dunes iii	High to medium amplitude discontinuous, chaotic reflectors	FSST and stillst and	≤ 20 m	MIS 5e – 2. Waenhuiskrans Fm; 90 – 70 ka (Cawthra et al., 2018)	C. Infanta – S. Bay, M. Bay, Wilderness – P. Bay. Depths of 95 m; 78 m, 55 m; 45-40 m; 38 m; 25 m.
	Channel Fill ii	Parallel and sub-parallel chaotic reflectors infilling structural depressions	FSST	≤ 4 m	MIS 5e – 2. *[Stratigraphic context],* 'Unit D' (Cawthra et al., 2014)	C. Infanta – G. Mond, M. Bay, Wilderness – P. Bay. Depths of 100-105 m; 25-40 m.
Incised Channels 2 (horizon)						
Sequence Boundary SB2: Erosional truncation of underlying surface; MIS 5e-2. Associated with 'Incised Channels ii'						
	Lagoons i	Parallel & sub-parallel reflectors infilling structural depressions, or acoustically transparent.	TST	≥ 6 m	MIS 6 – 5e. 140 – 130 ka (Cawthra et al., 2018)	S. Bay – G. Mond, M. Bay. Depths of 90 m.
1	Dunes ii	High to medium amplitude discontinuous, chaotic reflectors. Acoustic blanking of underlying strata.	TST (?) and stillst and	≤ 12 m	MIS 6 – 5e Waenhuiskrans Fm. 'Unit C' (Cawthra et al., 2014); 140 - 130 ka (Cawthra et al., 2018)	C. Infanta –V. Bay, M. Bay, Wilderness. Depths of: 105 m, 90 m; 80 m; 55 m; 37-25 m.
	Lower Floodplain i	Acoustically transparent unit, infills depressions on SB1.	TST/ Stillst and	≤ 3 m	MIS 6 – 5e *[Stratigraphic context]*	S. Bay – G. Mond, M. Bay. Depths of 95-90 m; 80 m.
	Channel Fill i	Poorly defined high amplitude, chaotic	FSST	≤ 15 m	MIS 7 – 6 'Unit B' (Cawthra et al., 2014). *[Stratigraphic context]*	C. Infanta – S. Bay, M. Bay. Depths of 100 m; 80-85 m.

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		reflectors, truncated against channel margins.				
	Dunes i	High- to medium amplitude discontinuous, chaotic reflectors.	FSST & stillst and	≤ 10 m	MIS 7 Waenhuiskrans Fm. 200 ka (OSL dating: Cawthra, 2014)	C. Infanta – S. Bay, M. Bay. Depths of 110 m; 30 m; 12 m.
Incised Channels 1 (horizon)						
Sequence Boundary SB1: MIS 7 – 6. Associated with 'Incised Channels i'						
Bedrock (earlier Cenozoic, Mesozoic and Palaeozoic deposits – not considered here) 'Unit A' (Cawthra et al., 2014)						

Bedrock

The basal units mapped in the stratigraphic record have been referred to as 'bedrock'. These units include all pre-Quaternary units (Cretaceous, Palaeogene, Neogene: Dingle et al., 1983) but for the purposes of this work and are not described further in this paper.

Bounding surfaces

A total of five bounding surfaces are recognised in this study. **Sequence Boundary 1** (SB 1) (Figure 3; Table 2) unconformably overlies the basement sequences and underlies Dunes i and Dunes ii, which are dated and provided a minimum age of the surface (MIS 7–MIS 6). SB 1 marks the base of Sequence 1 and is not represented across the entirety of the shelf. In places, SB 1 is observed in association with overlying SB 2 (Supplementary Data Figures 2; 4) but in most areas SB 1 pinches out on the mid-shelf (Figures 4; 6; 7).

Incised Channels i (Figure 3; Table 2) interrupts the overall smooth texture of SB 1 and is incised into SB 1 in places (Figures 4-6; Supplementary Data Figure 4). This horizon is filled by the seismic unit 'Channel Fill i' and has not been sampled.

Sequence Boundary 2 (SB 2) marks the commencement of Sequence 2 and is widespread across the PAP shelf, from depths of 25-120 m bMSL. SB 2 is directly overlain by Channels ii and Dunes iii. Dunes iii is dated to MIS 5a-c, providing stratigraphic context (Figure 3; Table 2). SB 2 truncates underlying units (e.g., Channel Fill i).

The reflector **Incised Channels ii** incises SB 2 and is infilled by unit 'Channel Fill ii' (Figure 3; Table 2). Incised Channels ii has carved up to 10 m into the basement deposits and has troughs that reach up to 20 km in lateral extent (Figure 6; Supplementary Data Figure 2). The poorly defined, high-amplitude reflectors of Channel Fill i and ii which are truncated against the margins of incised channels on the shelf (e.g., Figure 5) are interpreted to be composed of fluvial deposits, remnant of FSST conditions, laid down on the sea-level regressions from MIS 7–6 and MIS 5e–2.

This study identifies one **Wave Ravinement Surface** (WRS) (Figure 3; Table 2) which has been sampled offshore of the Great Brak River and confirmed to be made up of cobbles (Cawthra, 2014). WRS is indicated on Figure 4 and in Supplementary Data Figures 3 and 4, at depths of 20-60 m. although WRS may be present on the outer- and middle shelf, it is only clearly mapped on the inner shelf on the profiles presented.

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Sequence 1 (Middle- to Late Pleistocene)

Sequence 1 is confined between the horizons SB 1 and SB 2 and is composed of five units (Figure 3; Table 2). OSL dates on 'Dunes i and Dunes ii' show that this sequence was laid down between MIS 7 and MIS 5e (Cawthra, 2014; Cawthra et al., 2018; Table 2). The oldest unit within Sequence 1 is Dunes i. Discontinuous outcrops of Dunes i overlie SB 1 and are composed of high- to medium-amplitude reflectors, which are generally chaotic in nature and produce acoustic blanking of underlying strata. These deposits are less than 10 m in thickness and are widespread at selected depths (100 m, 85-80 m) on the shelf (Figure 5; Supplementary Data Figure 5). A compilation of field relationships onshore, OSL dates onshore and offshore (Cawthra, 2014) and the continuity of these deposits below the water, suggest that Dunes i is associated with sea-level stillstands which periodically prevailed on an overall FSST. Channel Fill i, preserved from Cape Infanta to Still Bay and offshore of Mossel Bay, is characterised by high-amplitude reflectors infilling incised channels on the shelf. Channel Fill i appears to be closely associated with Dunes i, and is also linked to FSST forced regression by the dating of Dunes i to provide stratigraphic context. Dunes ii is dated to MIS 6 (Cawthra et al., 2018; Table 2) and is interpreted from sampling, dating and seismic context to have been deposited during a fast sea-level rise TST event during Termination-II with prevailing stillstands on this overall transgression. Lagoons i is closely associated with Dunes ii, in that it is nestled within depressions of Dunes ii (Figure 6C). The clinoforms within Lagoons i are generally semi-transparent and lie within the swales of Dunes ii and together they make up Barrier Complex 1. Lower Floodplain i crops out between Still Bay and Gouritsmond (Figures 5, 6) and offshore of Mossel Bay in close association with incised palaeochannels (Figure 6; Supplementary Data Figure 4). This unit is acoustically transparent and contains no visible clinoforms. Lower Floodplain i reaches a maximum of only 3 m in thickness and is laterally widespread where it occurs, extending up to 16 km in width across the plain (Figure 5; Cawthra et al., this volume). Lower Floodplain i is considered a TST from stratigraphic context and the preservation is not in a continuous sheet across the entire shelf. SB 2 caps the deposits of Sequence 1 and is a prominent surface across almost the entire shelf (Figures 5-8).

Sequence 2 (PMT)

Sequence 2 (Table 2) is bounded between SB 2 and the modern seafloor and holds a total of fifteen seismic units. Seven of the thirteen units are linked to FSST conditions and eight to TST, though geochronological control points show that there is extensive oscillation within the FSST and minor TST deposition has ensued on the overall forced regression (Figure 3). SB 2 is sporadically cut by Incised Channels ii (Figures 4-8). At the base of Sequence 2, FSST clinoforms of Channel Fill ii and within a parallel- to sub-parallel arrangement are preserved within incised channel pathways, much like the older and comparable Channel Fill i (Table 2). These are relatively widespread, occurring semi-continuously from Cape Infanta to Plettenberg Bay. Packages of Dunes iii (dated to MIS 5c-a: Cawthra et al., 2018; Table 2) and Lagoons ii [Barrier Complex 2; Figures 5 and 6] are preserved at depths of 100-95 m, 80 m, 55 m, 45-38 m and 25 m. These units are up to 6 km wide perpendicular to strike and the basal Dunes iii is made up of chaotic, discontinuous reflectors which are generally acoustically impenetrable. Lagoons ii consists of semi-transparent deposits within natural depressions of Dunes iii. Lower Floodplain ii (Supplementary Data Figure 2), attaining a maximum thickness of 5 m, occurs as widespread deposits from Cape Infanta to Still Bay, adjacent to incised palaeochannels. This unit is interpreted to be associated with a brief transgression of TST origin. Dunes iv is dated to MIS 3

(Cawthra et al., 2018; Table 2). Lagoons iii (Figure 7) is comparable in character and also in context to Lagoons i and Lagoons ii, having been laid down in depressions associated with its linked Dunes iv [Barrier Complex 3]. Dunes v is closely related to Dunes vi and is interpreted from stratigraphic context to represent deposition on an overall TST. The deposits are preserved across the shelf, from Cape Infanta to Mossel Bay (Table 2). Lower Floodplain iii, as determined through stratigraphic context with dated unit Dunes iv (Figure 3), was deposited on a FSST regression in sea level and has been dated offshore of Mossel Bay to 23,768 – 22,811 cal. years BP using AMS radiocarbon in core GeoB18306-1 (Table 1; Table 2) (Figures 4-8). Lower Floodplain iii is preserved at Mossel Bay and Wilderness. In addition to these dates from marine cores, a terrestrial peat deposit associated with the same unit has left remnant sediments ~5 m above MSL on the western bank of the Klein Brak River and this sediment yielded a radiocarbon age of 40,311 cal. yrs. BP (Table 1).

The depositional units of Sequence 2 are interrupted by a prominent erosional horizon, WRS. WRS sampled offshore of Mossel Bay and found to be composed predominantly of cobbles. It is interpreted to be a transgressive surface which indicates the rise in sea level during the PMT. The surface WRS forms the base of the PMT and is made up of high-energy deposits such as poorly sorted conglomerates with clasts up to cobble size (Cawthra, 2014).

The uppermost six units of Sequence 2 are associated with PMT deposition (Figure 3; Table 2) and were laid down under transgressive and stillstand regimes after the termination of the LGM. These deposits have been sampled and dated in all marine cores (Table 1) and plotted independently (Figure 3) as well as against global sea-level curves (e.g., Waelbroeck et al., 2002), correspond to transgression. We suggest that sea-level stillstands provide an opportunity to preserve low-energy features on an overall high-energy shelf. Lower Floodplain iv is a widespread unit, which is mapped across the PAP shelf and is generally in close association with incised channels (Figures 4-8). It is made up of low-amplitude, horizontal to gently inclined, parallel reflectors. Lower Floodplain iv has been cored offshore of the Breede River and dates to 12,743 – 6183 cal. yrs. BP (this study: core GeoB20628-1). Dunes v, vi and Lagoons iv make up a composite back-barrier complex [Barrier Complex 4; Figure 4]. Dunes v is acoustically impenetrable and where visible, has chaotic reflectors (Tables 1 and 2). Dunes vi forms the youngest of these deposits on the PAP shelf. Lagoons iv consists of parallel- to sub-parallel clinoforms. This facies has been cored and dated, and ranges in age from 13 – 11 ka (Core GeoB20629-1, Table 2) and Dunes vi crops out sporadically near Cape Infanta, Mossel Bay and Wilderness at depths of 75 m, 67-62 m and 25 m bMSL (Supplementary Data Figure 2). The thickness is a maximum of 10 m and this facies is made up of chaotic reflectors.

The unconsolidated marine sediment wedge is made up of two units: Shelf sands and the South Coast Mud belt (Figures 4-8). These are the youngest units mapped on the shelf. Deposition of Shelf Sands commenced at the start of the PMT and continued throughout the Holocene in association with a rising sea level. Shelf sands form an acoustically transparent wedge, with faintly visible low-amplitude divergent clinoforms. These sediments drape almost all underlying units on the PAP shelf and are thickest within embayments and in inshore areas. The oldest age of this unit (Table 1; Table 2) is determined to be 22,571 cal. years BP at a depth of 82 m (core GeoB18305-3). Up-sequence dates are 7181 cal. years BP at a depth of 69.5 m (Core GeoB20628-1), 4058 cal. years BP (Core GeoB18308-2) at a depth of 34 m and 1695 cal. years BP at a depth of 28 m (Core GeoB18307-2). The South Coast Mud belt is the uppermost stratigraphic unit in the area. AMS radiocarbon dates on two surface samples (MB15 and MB91,

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Table 1), yielded ages of 118 and 187 cal. years BP, in water depths of 47 and 38 m bMSL, respectively. The stratal characteristics of this facies are made up of high-impedance and finely laminated clinoforms. The mudbelt overlies sand in all areas of occurrence and it is most prominent at Cape Infanta to Still Bay and in the region from Gouritsmond to Mossel Bay.

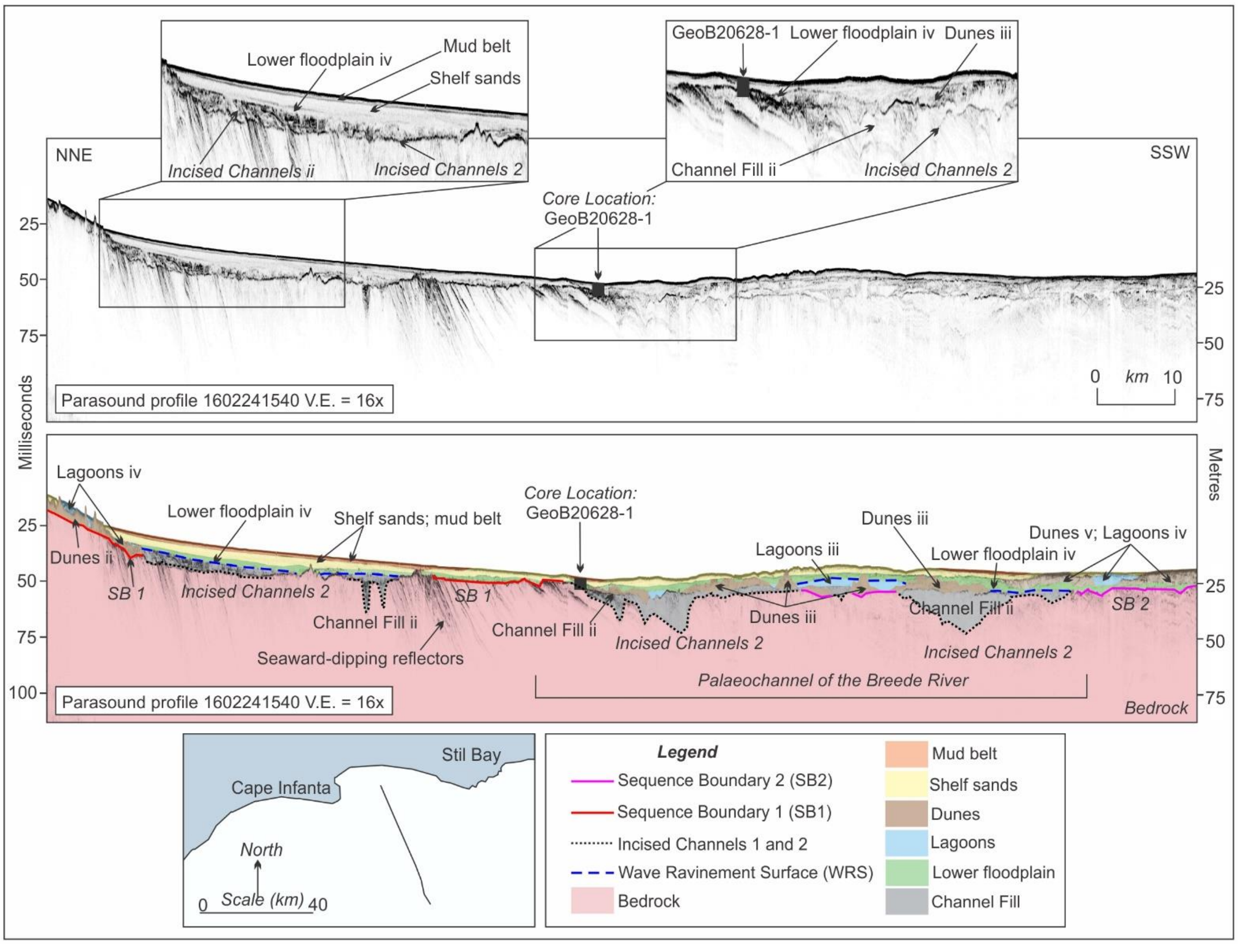

Figure 4. Sub-bottom profile intercepting the palaeochannel of the Breede River near Cape Infanta. The site of core GeoB20628-1 is shown. For relative location of this profile, please refer to Figure 1C.

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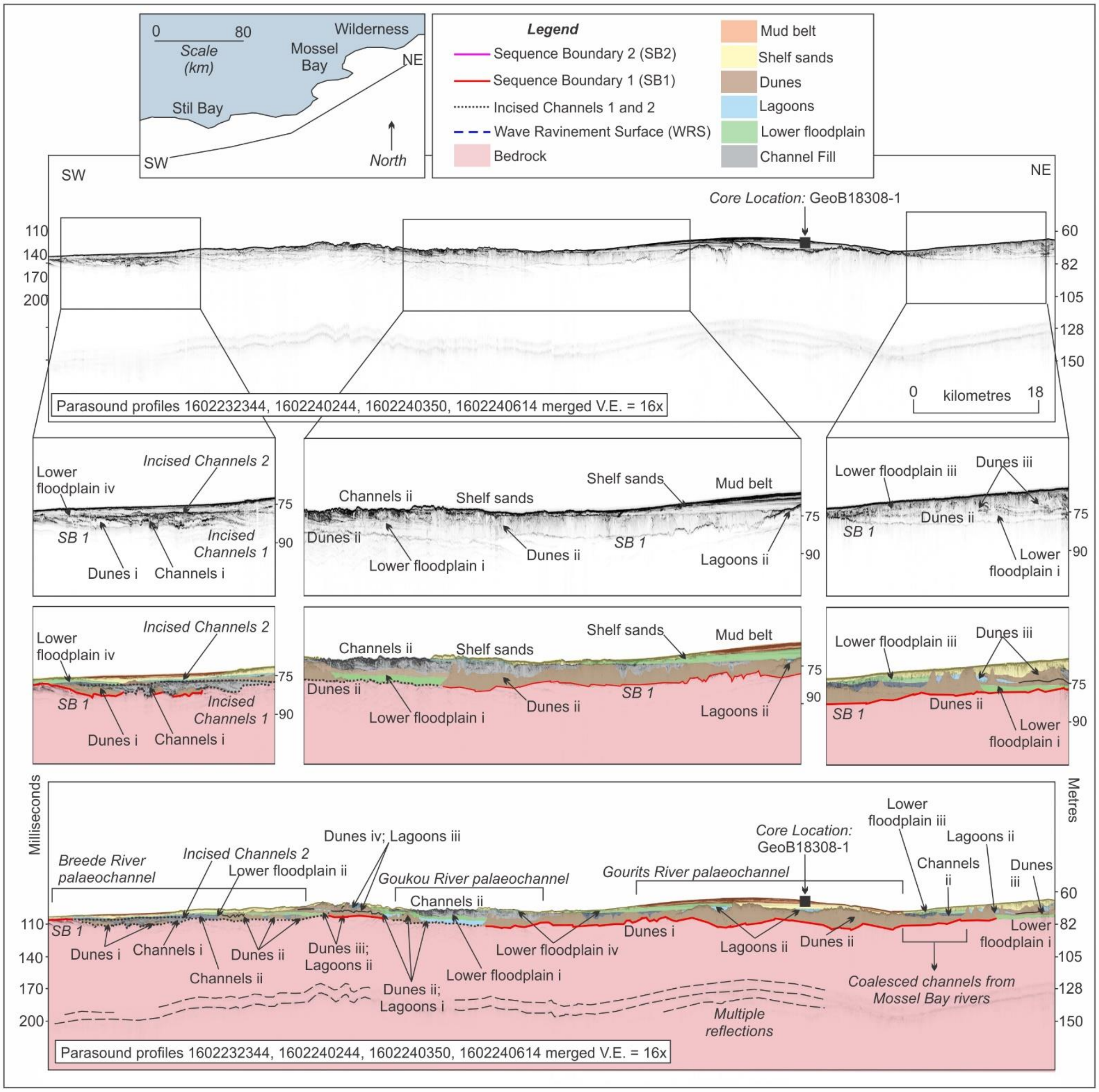

Figure 5. Sub-bottom profiles from between the Breede River (Cape Infanta) and Wilderness, with the context of core site GeoB18308-1. Palaeochannels of the Breede, Goukou, Gourits, and Mossel Bay rivers (Hartenbos, Klein Brak and Great Brak) are visible. For relative location of this profile, please refer to Figure 1C.

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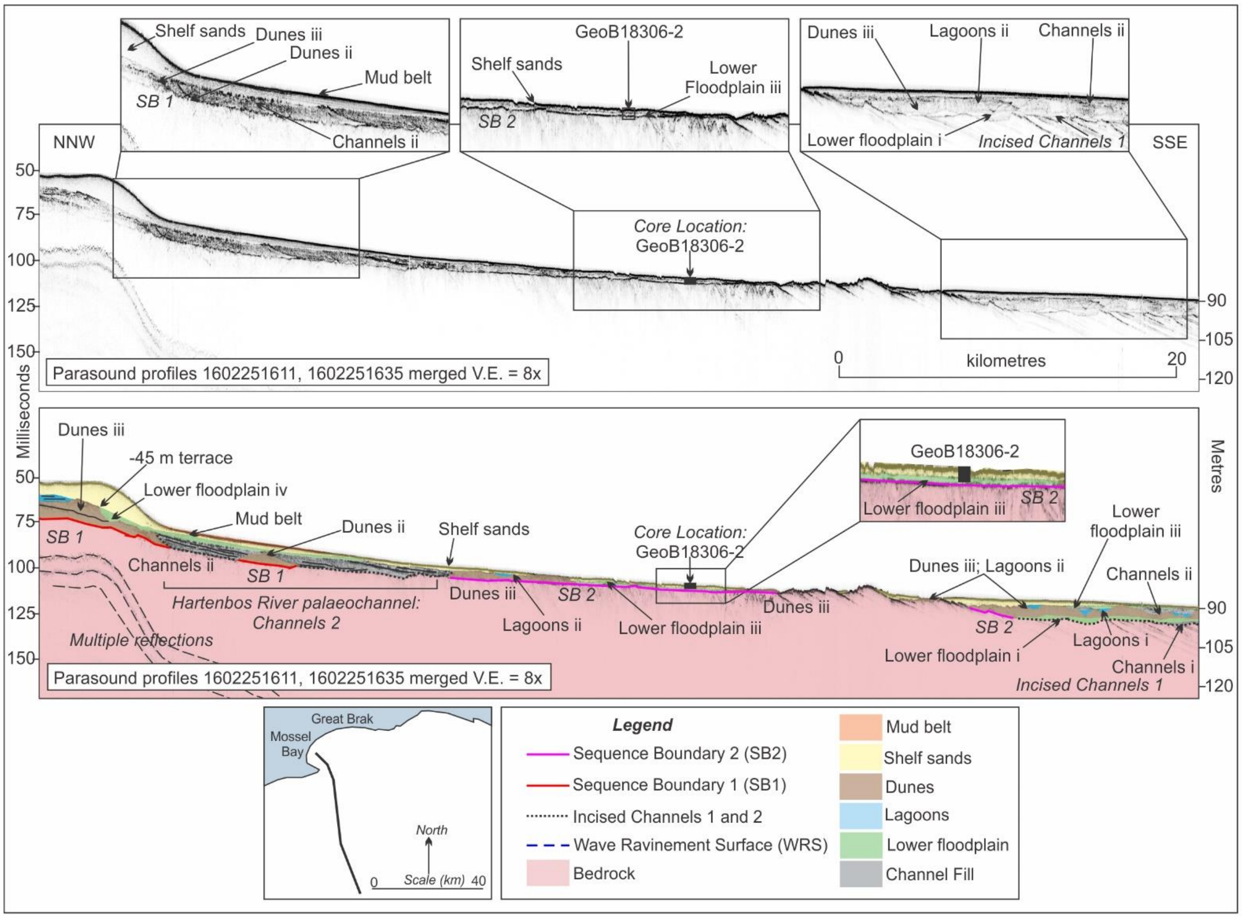

Figure 6. Sub-bottom profile offshore of Mossel Bay and showing the location of core GeoB18306-2. For relative location of this profile, please refer to Figure 1C. The location of core GeoB18306-2 is shown in inset.

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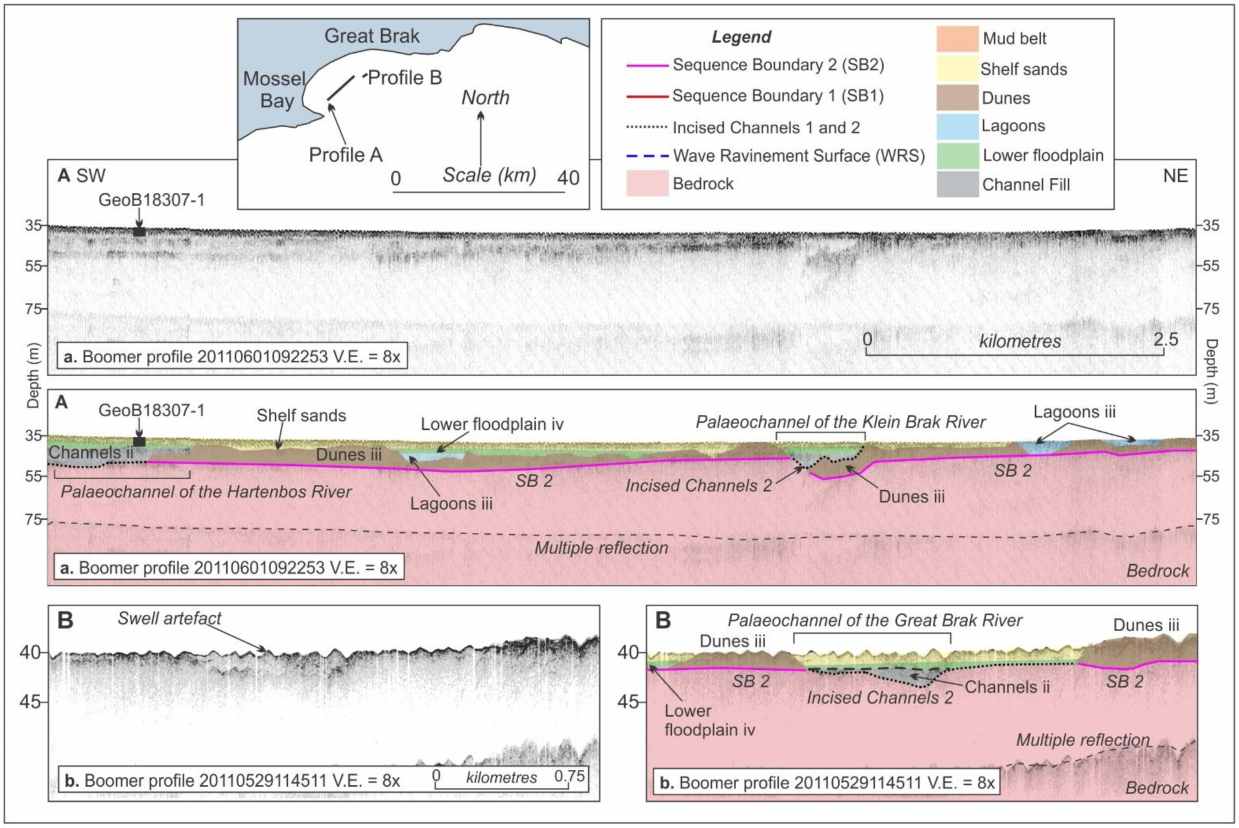

Figure 7. Sub-bottom profiles from within the embayment of Mossel Bay. For relative location of this profile, please refer to Figure 1C. The location of core GeoB18307-1 is shown in the inset.

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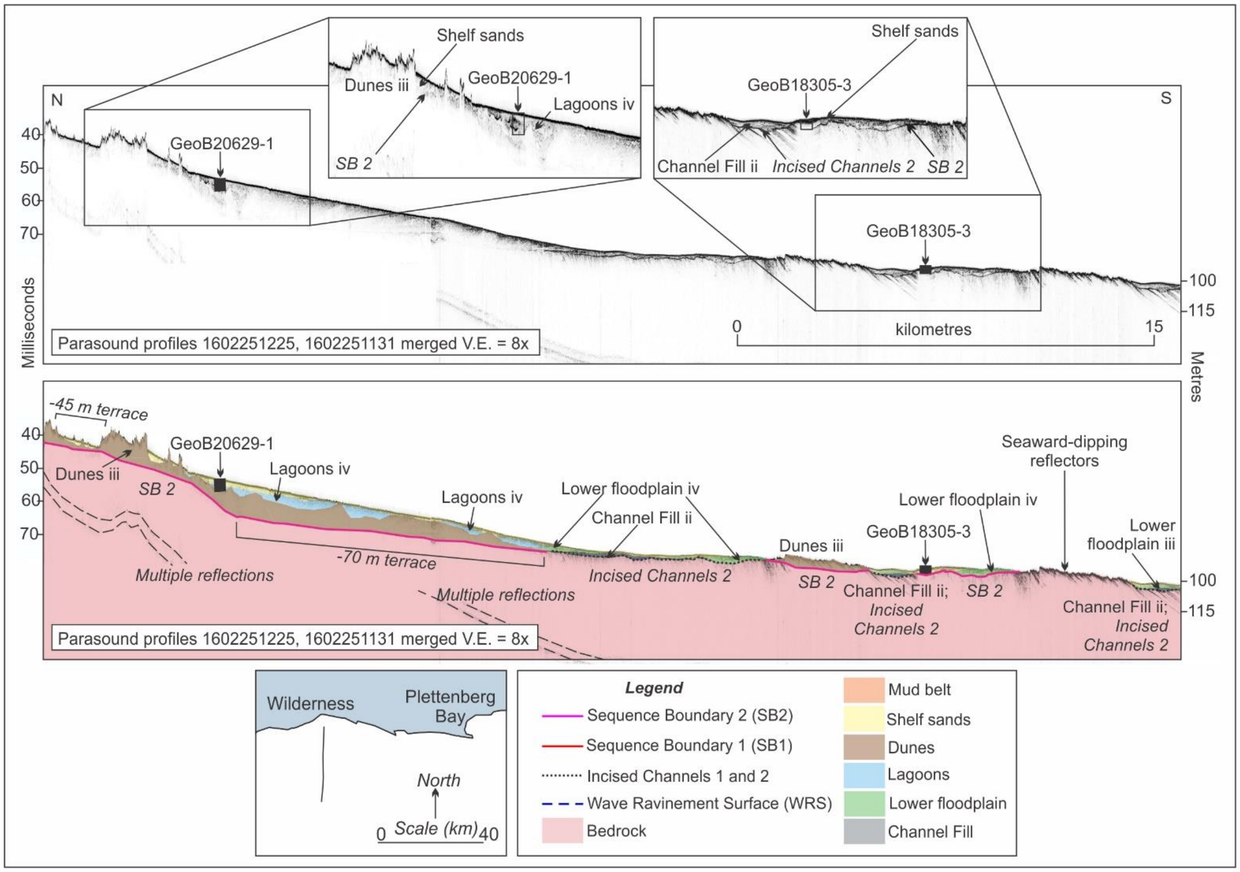

Figure 8. Coast-perpendicular oriented sub-bottom profile from the eastern region at Wilderness. Locations of cores GeoB18305-3 and GeoB20629-1 are shown.

Rivers on the Palaeo-Agulhas Plain

‘Lower Floodplain i’ is interpreted in this study as alluvial and estuarine sedimentation of the major PAP palaeo-river channels (notably the Breede, Gourits and Goukou rivers). Younger Lower Floodplain deposits were cored (Lower Floodplain iii; iv), and the comparable seismic signature down-record allowed their classification within Sequence 1.

We describe the ‘Incised Channels’ horizon from the Cape South Coast for the first time. There are two visible generations of incised channels on this shelf (Channel Fill i; Channel Fill ii), associated with each of the respective Sequence Boundaries. Incised channels are well described in marine geological literature (e.g. Nordfjord et al., 2009; Green, 2009) and have been investigated for their complex geometries, nested deposits, sedimentary environments and hydrocarbon potential (Boyd et al., 2006). We provide a conceptual model for the formation of these fluvial systems and their associated features on a low-gradient shelf (Figure 9). They show straight incision on the inner shelf area, tending to become increasingly anastomosed down the depositional profile towards the outer shelf. There is no clear evidence for barrier island preservation within fluvial channels. The channels are truncated by TST deposits in both sequences. As base level rose more rapidly through subsequent transgression, we propose that fine-grained deposits were preserved and formed the deposits of a lower floodplain. As transgression ensued, estuarine/floodplain conditions migrated up-profile in a landward direction. The regressive channel incision resulted in high-energy geomorphic forms such as anastomosing channels (e.g. Breede River: Figure 4).

Channel pathways were mapped and the distribution of the palaeodrainage network on the PAP is shown in Figure 9. This schematic representation was constructed by linking interception points along sub-bottom profiles and also taking into account features visible on surficial bathymetry (of de Wet, 2013; Figures 1, 9). We interpret anastomosing river flow for this region during times of lowered sea levels and from the interception of sub-bottom profiles and mapped incised channels we demonstrate (Figure 9) that the Gourits River splayed into a delta when falling sea level reached the -120 m isobath.

We correlated the channels with the Rosgen (1994) classification scheme of channel types, where possible, and low gradients and sinuosities typical of PAP rivers is typical of the C- and DA-type rivers (a braided or anastomosing drainage system: Figure 9C). Type 'C' is characterised by low gradient, meandering, point-bar alluvial channels with well-defined floodplains. These are interpreted for what is now the inner- and mid-shelf, with a gradient of <0.02. Type DA is interpreted for the outer continental shelf. In this case, anastomosing channels are associated with broad floodplains and extensive wetlands. The gentle relief promotes high sinuosities. The deposition of these fluvial sediments takes place on slopes of <0.05° and a width: length ratio that is greater than 40.

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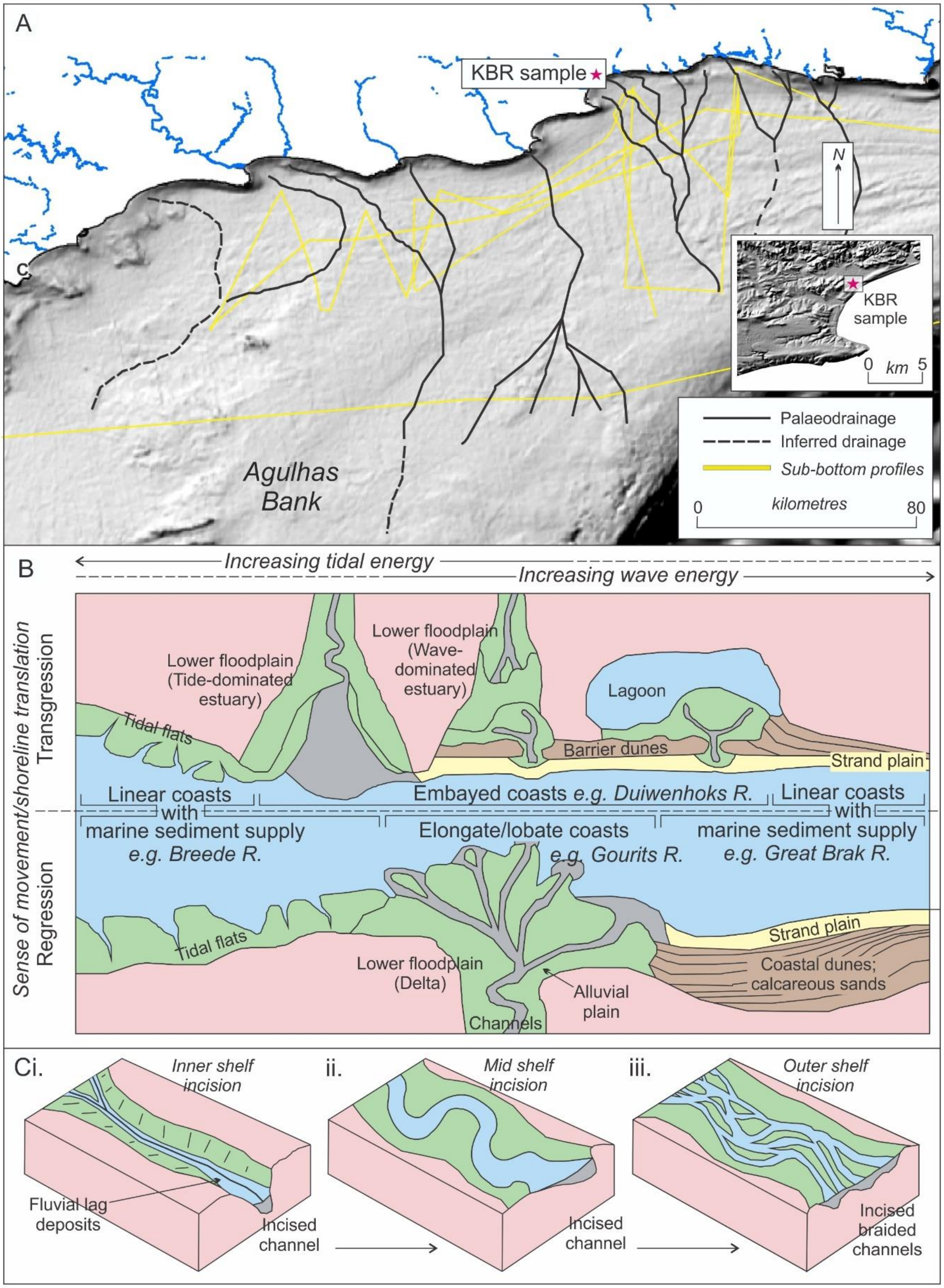

Figure 9. A. Interpreted palaeodrainage network for the Cape South Coast shelf for the LGM. Actual channels which crossed sub-bottom profiles are shown as solid lines and inferred pathways, stippled lines and the bathymetry source is de Wet (2013). **B.** Conceptual classification of major coastal depositional environments based on the direction of shoreline translation

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(regression or transgression), with examples of the Cape South Coast rivers during the Pleistocene. Schematic representation modified from Boyd et al. (1992). **C.** Style of incision across the shelf, depending on gradient. Fluvial styles derived from Rosgen (1994).

DISCUSSION

Systems tracts in a spatial-temporal framework

The recovered stratigraphy is relatively complex (Figure 3) as a result of the relatively high-amplitude, rapid sea-level changes during the Quaternary (Figure 10), coupled with abrupt spatial and temporal environmental conditions in the last sea-level cycle (~120 ka). The full range of depositional environments that exists on the modern coastal plain were all subaerially preserved for varying periods of time on what is now the continental shelf.

Seismic units and bounding surfaces SB 1, Dunes i, Channel Fill i, Dunes ii, SB 2, Channel Fill ii, WRS, Dunes v, Lagoons iv and Shelf Sands have been described in the Wilderness Embayment by Cawthra et al. (2014) and we include the addition of thirteen seismic units and a new horizon, 'incised channels'.

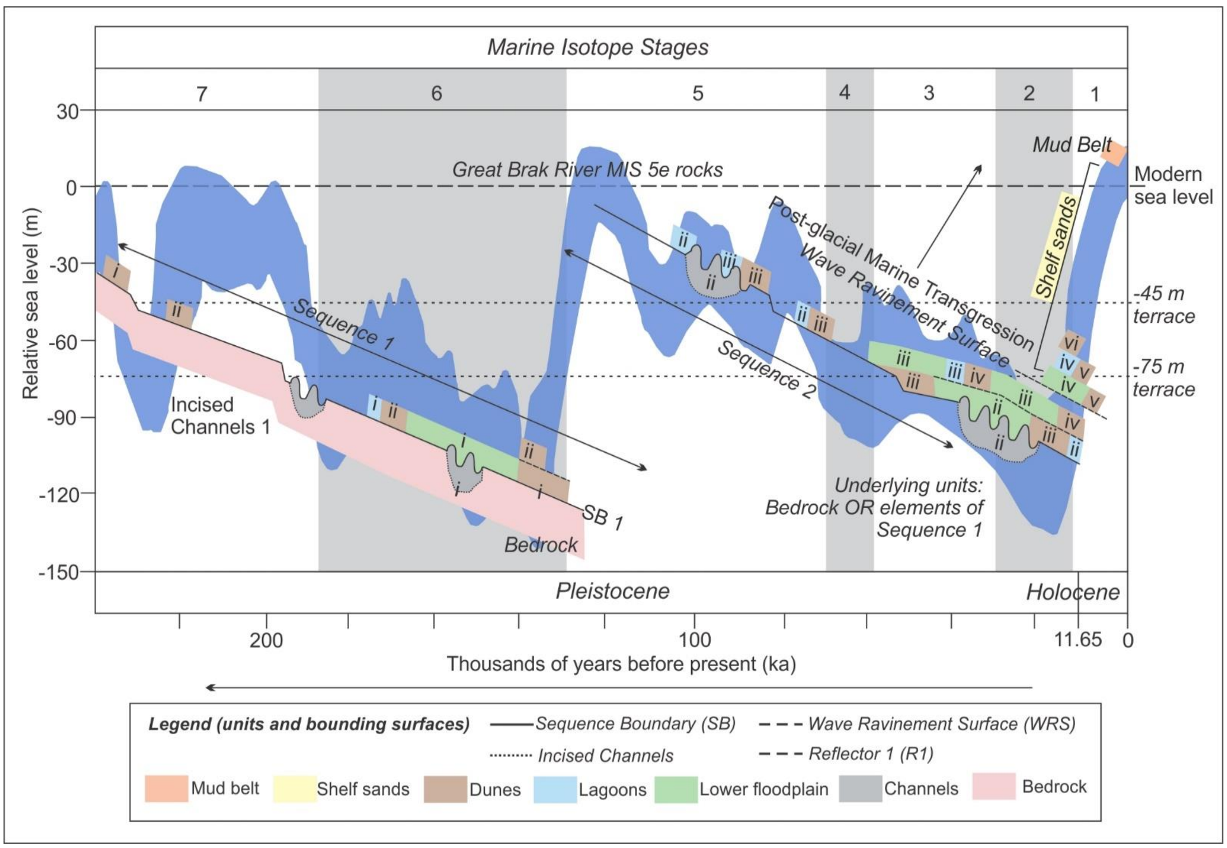

Figure 10. Schematic temporal representation of the South Coast shelf units relative to global sea-level curves (blue: background plot). The sea-level band of curves represents a compilation of the datasets from Waelbroeck et al. (2002), Bintanja et al. (2005), Kopp et al. (2009) and Rohling et al. (2009).

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All seismic units on this shelf are linked to deposition on one of two systems tracts: FSST and TST, with overall regressive and transgressive regimes punctuated by sea-level stillstands. Depositional sequences are bounded by unconformities, after the definitions of Vail, 1987; Posamentier and Vail, 1988; Van Wagoner et al. (1988; 1990) and Hunt and Tucker (1992). Unconformities *within* the sequences are only demonstrated by the surface WRS. The sequence boundaries are closely associated with the incised channels horizons Incised Channels i and ii, respectively. The incised channels on the PAP were coastal plain rivers and exhibit compound fill by units Channel Fill i and ii (Figures 4-8).

Forced regression leads to forestepping and downstepping at the shoreline, whereas transgression results in backstepping at the shoreline (Catuneanu et al., 2011). Our work demonstrates relative complexity within the TST which generally differs to published records in the Northern Hemisphere (e.g. Lobo and Ridente, 2014) that record bias towards the FSST. Our records do not map the HST nor the LST, as the HST lies landward of this study (see Cawthra et al., 2014) and the LST, seaward, in water depths exceeding 120 m bMSL.

The **FSST** lies directly on the Sequence Boundaries in our interpretation, as per Posamentier and Allen (1999). As a function of this low-gradient profile shelf, the architecture is commonly detached; meaning that there are units deposited down-profile and there is not always connectivity. The dunes are generally closely associated with fluvial systems (Figures 4-8; Supplementary Data Figures 2-5), such as the case on the Cape West Coast coastal plain (e.g., Roberts et al., 2009).

Stratigraphy and positions of palaeo river channels in the depositional record are modified by downstream controls and in this case, changes in sea level. We interpret the incision of rivers to be associated with the FSST and the subsequent infill to be a function of deposition on a rise in sea level, as per the models of Zaitlin et al. (1994) and Boyd et al. (2006). The mechanism we propose to cause the sedimentation on transgression is that a rise in sea level elevates the downstream portion of the buffer zone of fluvially-related deposition and creates new accommodation, and allows for the development of estuaries (part of the Lower Floodplain). The longitudinal profiles of the incised channels are generally smooth (Figures 4-8). Pauses in the regression – stillstands or slowing in the overall rate of sea-level rise – allowed for broad floodplains to develop on the PAP (Figures 4-8; Cawthra et al., QSR under review).

All width: depth ratios of South Coast palaeorivers are in excess of 40, and some (e.g. the Gourits River) up to 1800. High width: depth ratios are typically recorded on subdued coastal plains and in some cases, being characteristic of tidal systems. An example is the modern Delaware Estuary in eastern USA which ranges from 250 – 2500 (Walsh, 2004). There is no direct modern analogue for this magnitude on the modern South African coastal plain. In strong contrast to steeply incised river channels on the PAP today (see Figure 10), the river channels on the emergent coastal plain would have had extremely low gradients and sediment supply a key factor in the build-up of deposits (dunes) or infilling of channels.

Dated lagoons from the lower floodplain, the accretion of the PMT sediment wedge and OSL-dated cemented dunes demonstrate rising sea level and **TST** conditions. The TST in this study is deposited on transgression and sediments are laid down and preserved in the continental shelf record when an increase in accommodation outpaced the rate of sediment supply (e.g., Catuneanu et al., 2009). On the PAP, the TST is composed of deposits that accumulated from the onset of

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transgression up to the time of maximum transgression of the coast. Sea-level **stillstands** are periods of paucity in the overall sea-level states of rise or fall, when well-developed shorelines have the opportunity to accrete.

Transgressive Ravinement Surfaces (after Nummedal and Swift, 1987) are erosional surfaces that form by wave- or tidal scouring during transgression in coastal areas and shallow marine settings. These surfaces young in a landward direction. The **Wave Ravinement Surface** WRS is a regional flooding event which affected the entire shelf sequence from the LGM depth to present sea level (Figures 4-8). This PMT surface has been sampled with sediment grab samplers and diving surveys and is known to consist predominantly of gravels and cobbles. Given its position on the shelf, we suggest here that the WRS formed from the Late Pleistocene and through the PMT. The erosive nature of this landward-migrating high-energy shoreline, is postulated to have been responsible for planation of underlying unconsolidated sequences and deposits from the time of the termination of the LGM to the present. WRS was therefore considered responsible for truncation of Pleistocene units in marine cores GeoB18306-1, GeoB18308-1 and GeoB20628-1. Although ravinement surfaces can also be dominated by tidal encroachment (e.g., Catuneanu et al., 2006), we propose that the governing scouring mechanism of a WRS in this area was more likely to be wave action in the shoreface (e.g. Swift, 1975), based on the analogy that the present hydrodynamic conditions most likely prevailed through the late Pleistocene. Currently, the Cape South Coast has a micro-tidal range in this area of <2 m (Davies, 1980; South African Navy, 2017) and southwesterly-dominated swell (Heydorn and Tinley, 1980; Whitfield, 1983) which modify the sediments of shoreface and foreshore by longshore drift (Wiles et al., 2017).

Palaeoenvironments preserved on the Palaeo-Agulhas Plain

Elements of palaeoenvironments best represented on this shelf are from coastal plain, marginal marine and fluvial hydrodynamic regimes. Three broad groups of geomorphological features are recognised, namely (1) barrier complexes, (2) fluvial channel fills, and (3) sheet-type units.

(1) (i) A total of four back-barrier complexes are identified; each composed of a cemented dune or beach ridge and a back-barrier lagoon, and (ii) stand-alone calcarenite deposits laid down on sea-level stillstands are scattered across the shelf at set depths. Barrier complexes were the focus of Cawthra et al. (2014) and these new data corroborate the relationship between cemented dunes and lagoonal back-barrier deposits.

(2) Fluvial channel fills consist of the incised channels and associated sedimentary infill.

(3) Sheet-type units are further divided into (i) lower floodplain sediments and (ii) the unconsolidated marine sediment wedge which is made up of two units.

Barrier systems (siliciclastic-calcareous beaches and dunes; lagoons)

'Dunes' consists of cemented aeolian and beach material and these units have been sampled and dated in places using OSL (Cawthra et al., 2018), where these deposits outcrop at the seafloor. These units consist of Late Pleistocene calcarenite (aeolianite and cemented beaches) belonging to the Waenhuiskrans Formation, Bredasdorp Group.

The period from the termination of MIS 5e and overall regression into MIS 2 was characterised by multiple oscillations of sea-level within a depth range of 70–20 m bMSL, which are superimposed on an overall regression towards the LGM (e.g., Lambeck and Chappell, 2001; Yokoyama et al., 2001). Aeolianites and unconsolidated dune deposits preserved along this

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trajectory are punctuated outcrops (Cawthra et al., 2014). The ~90 and 74 ka clusters of OSL ages of dunes are noted here to be the most pervasive units in the MIS 5–4 stratigraphic record, and are seismically associated with an overall normal regression punctuated by sea-level stillstands. With the contemporary coast being relatively far from these dunefields at the time of their deposition, we suggest that this environment with large dunefields on a low-gradient coastal plain may have been comparable to the Duynefontein dune plume (Roberts et al., 2009) or the Alexandria dunefield in the Eastern Cape. The source of sediment for the dunefields was likely from their contemporary coastal plains, as per the model of Bateman et al. (2004) for the Wilderness dunes. Mobile dunes, with a propensity to migrate landward, are interpreted to have covered much of what is now the continental shelf, particularly on the middle shelf (~72 m bMSL).

Marine regressions and transgressions allowed carbonate-rich sediment movement and subsequent aeolian re-working to occur at similar points in the landscape. The initial accumulation of sediment must favour large-scale entrainment and deposition of calcareous sand and subsequently, subaerial conditions favourable to cementation prevailed. Dunes and aeolian sediments appear to have been deposited when sea-levels were rapidly changing and this corresponds to the findings reported by Cawthra et al. (2018) in the suggestion that large-scale sediment deposition occurred as pulses during glacial terminations. In addition to this, there is no clear preference for coastal sediments to have been deposited during a preferred sea-level regime, but they are laid down on both sea-level regressions and transgressions.

Incised fluvial channels

Two fluvial channel-fill units are mapped in the record (Figure 9; Cawthra et al., QSR under review). These are the deposits nested within the horizons ‘Incised Channels’.

Lower Floodplain

Seismically, these ‘Lower Floodplain’ deposits are often weakly layered and the units were laid down in estuarine, lagoonal and marine littoral settings according to the identification of microfossils (Table 1; Supplementary Data Figure 1). Where there are hiatuses, all but the deepest portions of estuaries and lagoons remained (Table 1; Supplementary Data Figure 1), while most of the deposits would have been removed by the subsequent ravinement process.

For the most part, the Lower Floodplain successions are anticipated to be composed of estuarine deposits at the base, with floodplain alluvium adjacent to the river mouth. Although estuaries and incised valleys have a fluvial input by definition, estuarine facies models reflect the balance between wave and tidal processes (Dalrymple et al., 1992; Zaitlin et al., 1994). As transgression prevailed, this sequence would have shifted landward. The relative thickness or maturity of the Lower Floodplain is linked to the rate and nature of the transgression – i.e. the step-like nature of the last deglacial sea-level rise in particular is characterised by relatively slower rates of rise punctuated by short rapid accelerations of sea-level rise (e.g., Meltwater Pulses).

In order to improve the refinement of estuarine and incised-valley facies models, the ability to distinguish brackish water deposits and sub-divide compound fills has been cited as a need (e.g. Boyd et al., 2006).

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Mobile shelf sediments

The unconsolidated marine sediment wedge is the youngest part of the sequence, which is interpreted to represent a TST unit. This unit is further divided into a basal transparent unit of shelf sands (Tables 1 and 2) and a Recent deposit of mud-belt deposits (surficial samples MB15 and MB91 dated to less than 200 cal. yrs B.P.). Dated sediments in our marine cores suggest that these shelf sands were deposited on the PMT and through ongoing processes of sedimentation on this shelf. The South Coast Mud belt is derived from the Breede and Gourits rivers, entrained by currents and transported towards the east (Rogers, 1971; Birch, 1980).

Global relevance of the stratigraphy of the Palaeo-Agulhas Plain shelf

Sequence 1, commencing with SB 1, preserves systems tracts providing insight into the depositional and erosional processes from MIS 7 to the MIS 5e. Sequence 2, the most complete sequence documented in this study, commenced with the retreat of sea-level from MIS 5e and extends to the Present. Comparable seismic signatures can be noted in other parts of the South African continental shelf and linked over distance with offsets in timing of deposition (e.g. Green, 2009; Green and Garlick, 2011; Bosman, 2012) and variation in sediment supply from different fluvial catchments. This continental shelf is unique compared to other areas of South Africa (e.g. the narrow East Coast: Green, 2009; Cawthra et al., 2012) and the West Coast shelf (e.g. Rogers, 1977; Compton and Wiltshire, 2009) in that the chronology presented here from dating of marine cores and recent publication of surficial seafloor deposits (Cawthra et al., 2018) allowed the opportunity to tie a high-resolution seismic stratigraphy into a chronological framework showing the character of the preserved deposits on an expanded shelf.

Comparable broad passive shelf settings have been mapped and documented globally (e.g. the New Jersey Margin: Nordfjord et al., 2009 and the southeast Australian Margin: Heap and Harris, 2008) and with relative tectonic stability through the Cenozoic, Pleistocene sequences can be mapped with relative success. The structural substrate of the PAP can be considered to be comparable to the New Jersey continental shelf in the USA in a morphological sense, but with subtle differences as the New Jersey shelf was ice-rafted at the time of the LGM (Duncan, 2000) which gives it a bias towards younger strata (e.g. Emery and Uchupi, 1984; Austin et al., 1998). The PAP therefore provides a unique opportunity to correlate depositional events to palaeoenvironments of relevance to the Pleistocene.

Although transgressive units in internal Quaternary seismic architecture have been shown in the Northern Hemisphere to have reduced thickness and limited lateral extent (e.g. Hernandez-Molina et al., 2000; Hanebuth et al., 2002; Lobo et al., 2002; Ridente et al., 2008) the PAP has good evidence of the TST as well as the FSST. In studies such as from the Western Adriatic margin (Trincardi and Correggiari, 2000), Gulf of Lions (Posamentier et al., 1998), Gulf of Mexico (Boyd et al., 1989; Plint, 1991), and Korea (Yoo et al., 2003), these authors have shown that the TST deposits are patchy, discontinuous, and characterised by confined sediment fills, thin sheets or wave-dominated nearshore ridges. Lobo and Ridente (2014) suggest that the variety and style of depositional patterns within the TST is controlled by wave energy during transgression. These processes are interpreted to remove earlier units, and in particular fluvial deposits, which results in the poor preservation of major incised valleys on continental shelves. We propose that the lack of ice sheets during Pleistocene glacials in southern Africa, and the open-ocean setting, have allowed for this unique preservation of the TST to be well preserved on the PAP shelf in both sequences. Another factor that we consider an important part of their preservation is the low

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shelf gradient, as a minor rise in sea level translates to a sizeable area which could support overstepping and therefore preservation of existing deposits.

CONCLUSIONS

Five depositional environments are recognised in this study through sedimentary investigations using marine cores, seismic data, and confirmed by microfossil analysis. These environments include siliciclastic-calcareous coastal beaches and dunes; incised fluvial channels and peat; back-barrier lagoons; lower floodplain and mobile shelf sediments. We introduce the 'Lower Floodplain' environment seismically, which consists of a composite grouping of alluvial, estuarine and floodplain sediments. Although the sediments are introduced to the coastal areas and later the continental shelf by rivers, the primary control on subsequent distribution and preservation is considered to be sea level.

What the sub-bottom profiling has allowed in conjunction with geochronological investigations is an overview of the distribution of palaeocoastlines ('Dunes') on the shelf. Incised fluvial channels are closely associated with the locations of modern river systems on the coastal plain and were carved on the shelf during times of regression, preserving these erosional and infill features as part of the FSST. There are two generations of channel erosion and infill, both contemporaneous with the planation of the Sequence Boundaries SB 1 and SB 2, respectively. The horizons called 'Incised Channels' are recognised on all profiles.

Our work demonstrates relative complexity within the TST. This differs to published records in the Northern Hemisphere which record bias towards the FSST. We suggest that the depositional setting on a high-energy open coast may account for this difference, as well as the lack of ice in this area during Pleistocene glaciations.

Despite an erodible substrate and varying amounts of modification of Pleistocene deposits by sea-level fluctuations, we have provided a method for siting core locations on passive margins where relatively localised deposits are preserved as a function of the morphology. Low- energy terrestrial deposits have been protected on this current-swept shelf where nestled within river valleys and where rapid transgression has facilitated deposition of PMT sediments to protect the underlying units (Figures 4-8). In addition to protection within palaeo-river channels, cemented dune ridges of barrier systems from times of sea-level lowstand provide a buffer against subsequent transgressions, where they shelter the low-energy back-barrier sediments on their seaward margins. The benefit of this approach of combining acoustic survey data with core data lies in the ability to decipher the development history of this highly complex and highly dynamic area. Valuable information for following targeted sampling campaigns can be achieved through detailed seismic profiling on continental shelves. These sub-bottom profiling data have been used towards the compilation of a geological map of the LGM for the PAP shelf (Cawthra et al., QSR under review).

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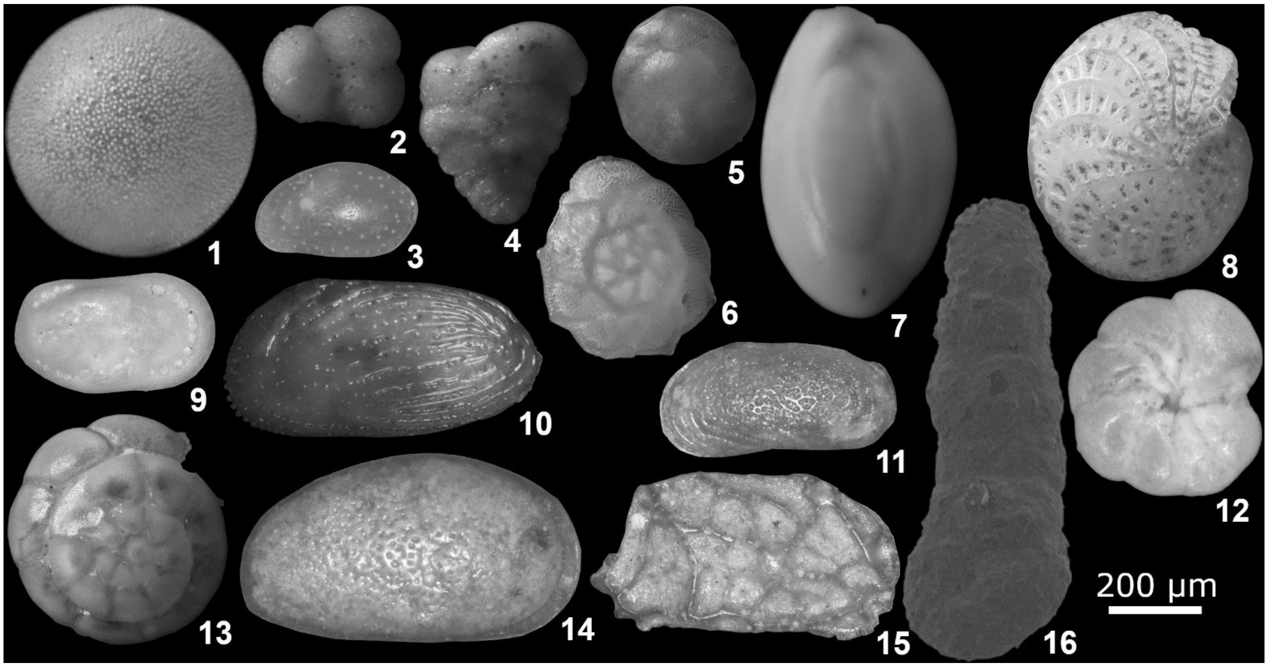
SUPPLEMENTARY MATERIAL

The supplementary material consists of a total of five figures. First, a plate of microfossils present in the sediment cores, and four additional annotated sub-bottom profiles to supplement the Results. The positions of these four profiles are located on Figure 1.



Supplementary Data Figure 1. Characteristic microfossil taxa from the Mossel Bay region. Planktic taxa: 1) *Orbulina universa* d'Orbigny, 1839; 2) Globigerininae, gen. et sp. indet. Marine benthic taxa: 3) *Xestoleberis* sp., 4) *Textularia* sp., 5) *Cassidulina laevigata* d'Orbigny, 1826, 6) *Pararotalia nipponica* Asano, 1936, 7) *Quinqueloculina* sp., 8) *Elphidium macellum* (Fichtel & Moll, 1798), 9) *Cytherelloidea compuncta* Dingle, 1993, 10) *Garciaella knysnaensis* Benson & Maddocks, 1964. Estuarine taxa: 11) *Cytheromorpha milleri* Dingle & Honigstein, 1994, 12) *Ammonia tepida* (Cushman, 1926), 13) *Ammonia parkinsoniana* (d'Orbigny, 1839), 14) *Cyprideis remanei* Klie, 1940, 15) *Mutilus bensonmaddocksorum* Hartmann, 1974, 16) *Ammotium morenoi* (Acosta, 1940).

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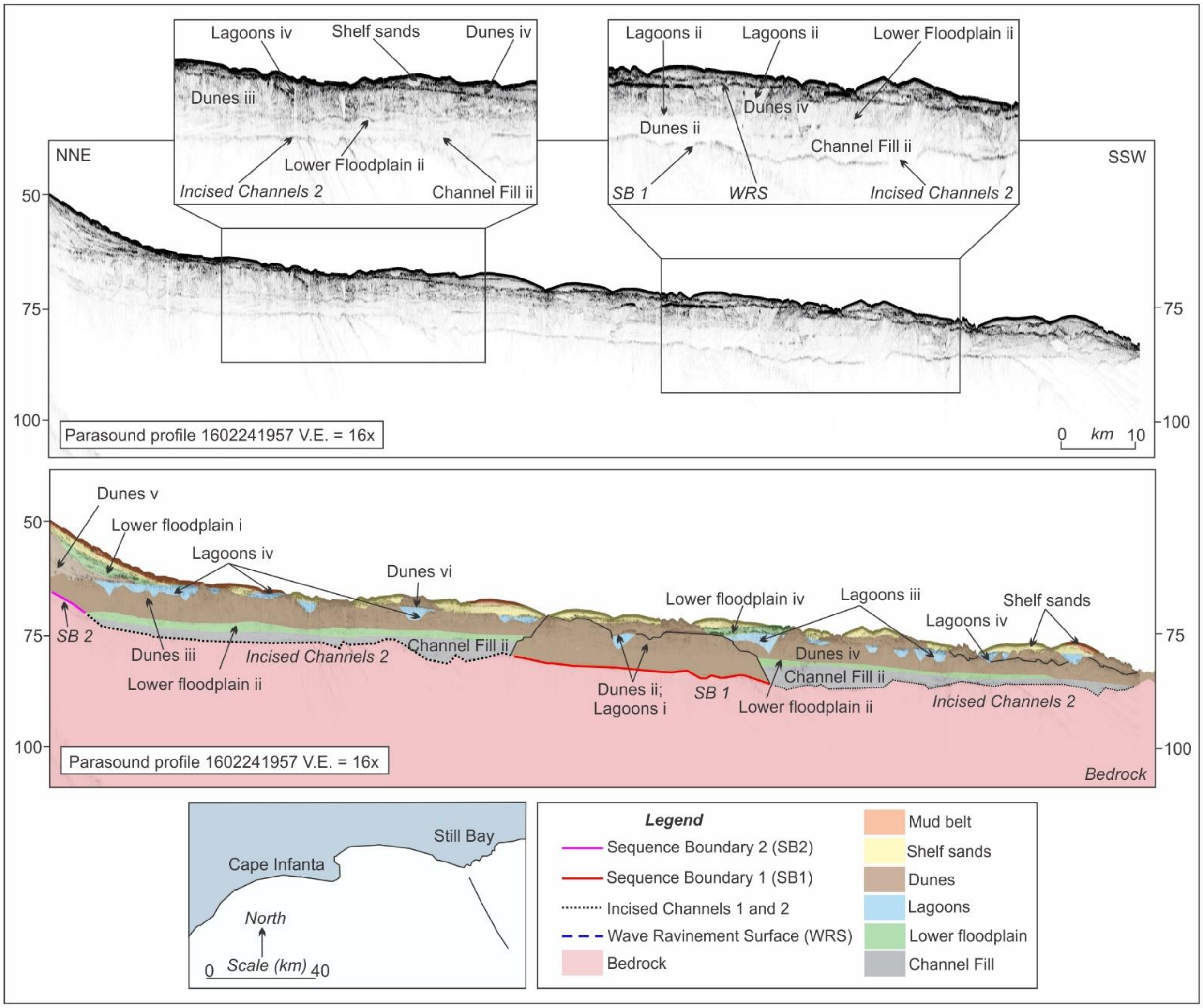

Supplementary Data Figure 2. Sub-bottom profile offshore of Stil Bay, demonstrating a dominance of dunes on the Agulhas Bank, with pockets of Lagoon sediments.

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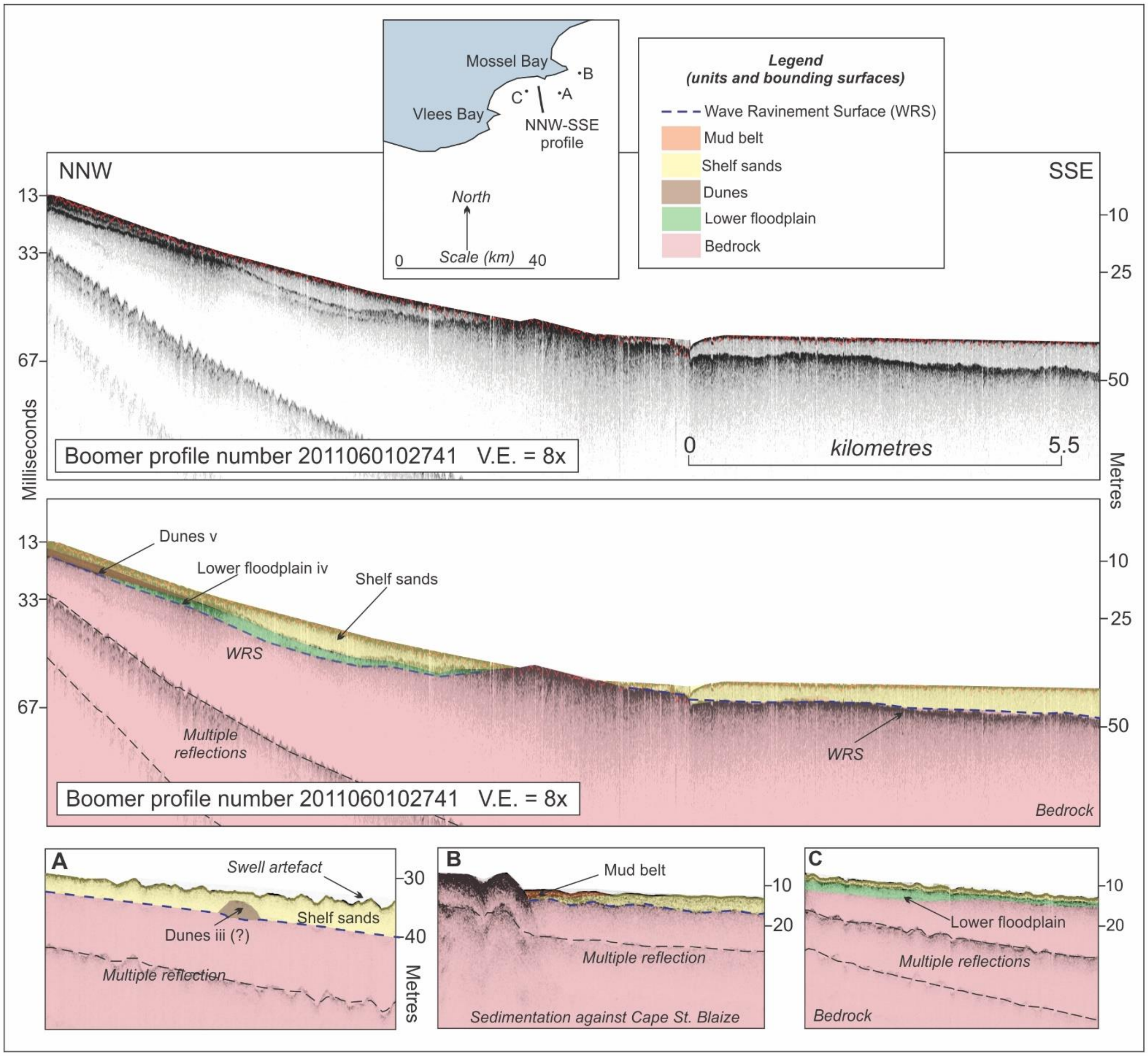

Supplementary Data Figure 3. Sub-bottom profile from Vlees Bay, indicating the Lower Floodplain and shallow bedrock.

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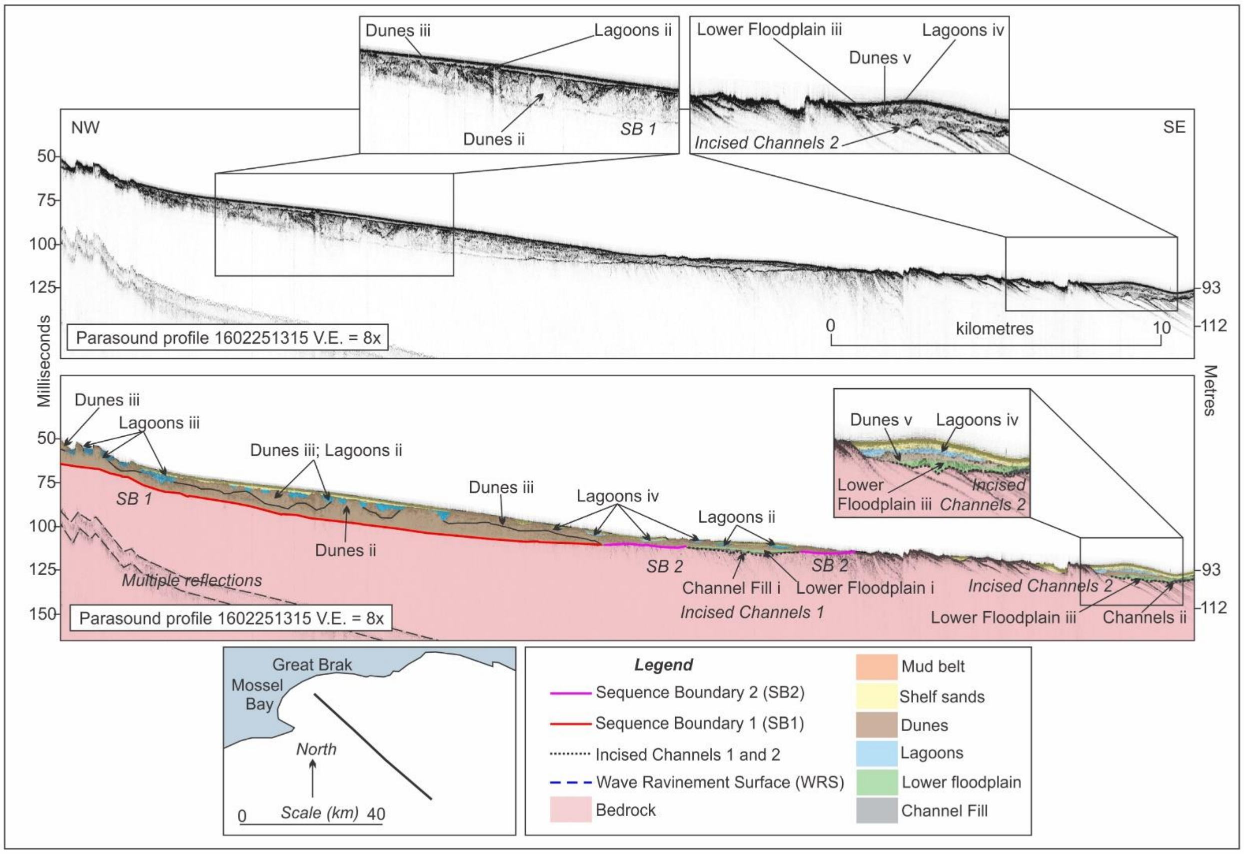
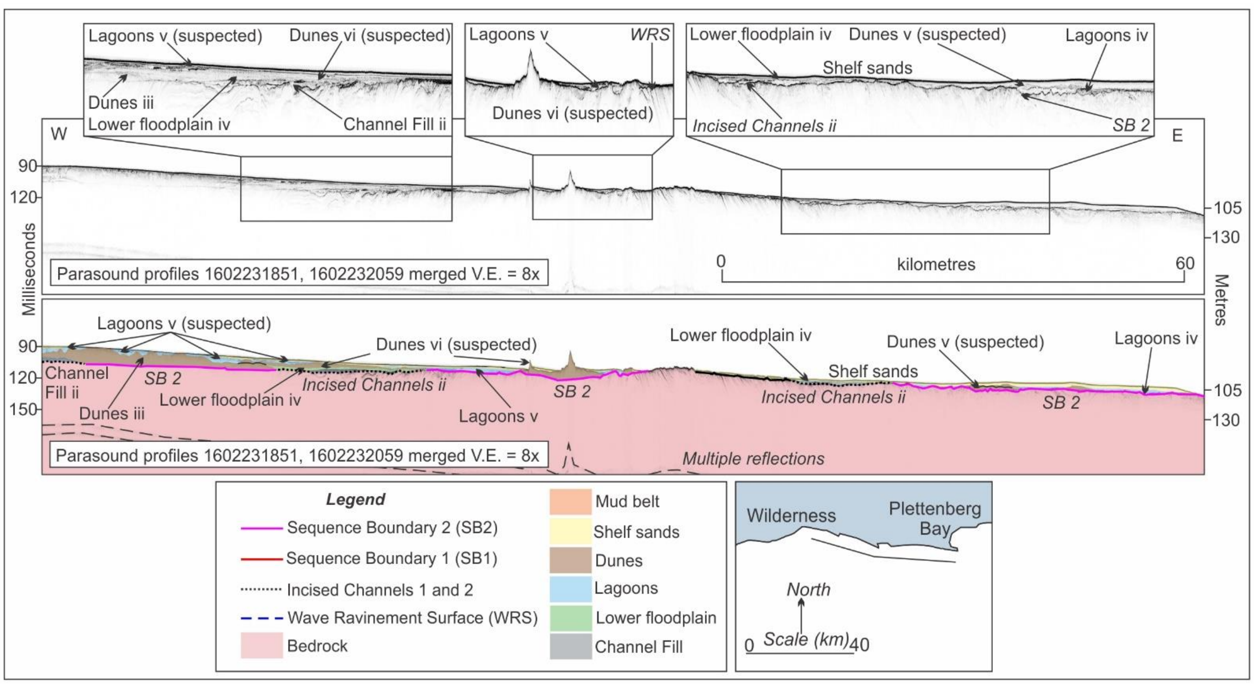


Supplementary Data Figure 4. Coast-parallel oriented sub-bottom profile offshore of Mossel Bay.



Supplementary Data Figure 5. Sub-bottom profile offshore of Wilderness to Plettenberg Bay.

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