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Relict and contemporary influences on the postglacial geomorphology and evolution of a current swept shelf: the Eastern Cape Coast, South Africa

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Abstract:	Few stratigraphic models of continental shelves incorporate the process of geostrophic current-sweeping, consequently its role in the stratigraphic record is often overlooked. We examine the narrow, current-swept Eastern Cape shelf of South Africa using a combination of geophysical techniques, seafloor sampling and video observations and interpret the role of current action on the transgressive stratigraphy of this steep subtropical shelf. During the Last Glacial Maximum, fluvial valleys incised the acoustic basement rocks.During the subsequent transgression, two distinct shorelines were formed and preserved at -105 m and -60 m. Their development and preservation is linked to (i) high sediment supply from adjacent fluvial sources, (ii) early diagenesis and (iii) alternating sea-level stillstands and periods of rapid sea-level rise during melt water pulses 1A and 1B, respectively.The deeper shoreline formed in a sandy, wide coastal plain setting with limited bedrock influence, whereas the shallower shoreline comprised alternating rock headlands and embayments like the contemporary coast. Differences in antecedent topography and geology are responsible for the temporal variability in shoreline type. Between the two shoreline complexes, in the mid-shelf, the transgressive stratigraphy records initial valley infill by progradation of coast-parallel sandy spits . These are capped by a stiff lagoonal mud deposited as ongoing sea-level rise overspilled the valley interfluves, onlapping the adjacent aeolianites. The uppermost stratigraphy comprises mounds of rhodoliths which interfinger with a sandy inner to middle shelf highstand wedge. After sea-level reached its present position ca 7.4 ka yr BP, the shelf became subject to reworking by the high-energy, geostrophic Agulhas Current. This has had the following major effects on the shelf stratigraphy:1. the topographic relief of the cemented palaeo-shorelines has been emphasised by removal of the post-transgressive cover; and2. The shelf no longer acts as a depocenter; instead, the seabed consists of rhodoliths, gravel streamers, bedrock or gravel hash of the wave ravinement surface. Given the necessary antecedent conditions such as accommodation, sediment supply and favourable diagenetic climate, prominent shorelines can form and be preserved on the shelf. Strong current sweeping emphasises these morphological features on subtropical shelves.
Suggested Reviewers:	Scott Nichol scott.nichol@ga.gov.au Likewise, has worked on submerged shorelines similar to these

	Andy Plater gg07@liverpool.ac.uk Prof. Plater has been publishing much on similar processes of barrier overstepping on shelves
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	Francesco Chiocci francesco.chiocci@uniroma1.it Prof. Chiocci has wokred on numerous systems in the Mediterranean, including submerged beachrocks and shorelines
	Edward Anthony anthony@cerege.fr Prof. Anthony has much experience in coastal evolution which is what we deal with here
Response to Reviewers:	

Relict and contemporary influences on the postglacial geomorphology and evolution of a current swept shelf: the Eastern Cape Coast, South Africa

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Abstract

~~Few studies incorporate current sweeping into the~~Few stratigraphic models of continental shelves incorporate the process of geostrophic current-sweeping, consequently ~~their representation~~its role in the stratigraphic record is ~~poorly understood.~~often overlooked. We examine the narrow, current-swept Eastern Cape shelf of South Africa using a combination of geophysical techniques, seafloor sampling and video observations~~. A steeply seaward dipping acoustic basement is incised by valleys~~ and interpret the role of current action on the transgressive stratigraphy of this steep subtropical shelf. During the Last Glacial Maximum ~~that abut aeolianite pinnacles. A series of~~ , fluvial valleys incised the acoustic basement rocks. During the subsequent transgression, two distinct shorelines were formed and preserved at -105 m and -60 m. Their development and preservation is linked to (i) high sediment supply from adjacent fluvial sources, (ii) early diagenesis and (iii) alternating sea-level stillstands and

periods of rapid sea-level rise during melt water pulses 1A and 1B, respectively. The deeper shoreline formed in a sandy, wide coastal plain setting with limited bedrock influence, whereas the shallower shoreline comprised alternating rock headlands and embayments like the contemporary coast. Differences in antecendent topography and geology are responsible for the temporal variability in shoreline type.

Between the two shoreline complexes, in the mid-shelf, the transgressive stratigraphy records initial valley infill by progradation of coast-parallel sandy spits prograde into the valleys in the middle shelf,. These are capped by a stiff lagoonal mud thatdeposited as ongoing sea-level rise overspilled the valley interfluves, onlapping the adjacent aeolianites. The uppermost stratigraphy comprises mounds of rhodoliths which interfinger with a sandy inner to middle shelf highstand wedge. Multibeam and side-scan sonar data reveal the aeolianite pinnacles to form a variety of planform equilibrium palaeo-shorelines at -105 m and at -60 m. These, along with the adjacent middle to outer shelf are current-swept, with rhodoliths, gravel streamers, exposed bedrock or gravel hash of the wave ravinement exposed throughout.

The deeper shoreline formed in a sandy, wide coastal plain setting, whereas the shallower shoreline was constrained to rock embayments like the contemporary coast. The -105 m and -60 m shorelines were formed and preserved during stillstands and melt water pulses 1A and 1B, respectively, aided by subtropical diagenesis.

By ~7000 yr BP, the ensuing transgression had exposed the shelf to the effects of the Agulhas Current, and post-transgressive cover was removed by current whittling to expose the palaeo-shorelines.

After sea-level reached its present position ca 7.4 ka yr BP, the shelf became subject to reworking by the high-energy, geostrophic Agulhas Current. This has had the following major effects on the shelf stratigraphy: 1. the topographic relief of the cemented palaeo-shorelines has been emphasised by removal of the post-transgressive cover; and 2. The shelf no longer acts as a depocenter; instead, the seabed consists of rhodoliths, gravel streamers, bedrock or gravel hash of the wave ravinement surface.

Given the necessary antecedent conditions such as accommodation, sediment supply and favourable diagenetic climate, prominent shorelines can form~~. When coupled to rapid rates of sea-level rise~~ and be preserved on the shelf. Strong current sweeping~~, they are preserved as persistent~~ emphasises these morphological features ~~of current-swept~~on subtropical shelves.

Key words: palaeo-shorelines, barrier islands, melt water pulse, current-dominated shelf, Agulhas Current

1. Introduction

The southeastern shelf of South Africa, off the rocky and high-energy “Wild Coast” of the Eastern Cape Province, is little known in comparison to the adjacent shelves of KwaZulu-Natal (Green et al. 2018; Pretorius et al., 2019) to the north and the Southern Cape to the south (Cawthra et al., 2016; Flemming and Martin, 2018). The combination of a narrow and shallow shelf with the south-westward-flowing Agulhas Current, one of the fastest flowing boundary currents on the globe, results in a shelf that is strongly modified by current activity. To date, there are few studies that incorporate current sweeping into models of shelf stratigraphy and morphology (cf. Cawthra et al., 2012) and little is known of the processes that control the development and preservation of such features in the stratigraphic record. A key gap in knowledge is how coastal evolution is influenced by shelf-sweeping, coupled to sea-level rise, i.e. how does a coastline evolve as the shelf is drowned and becomes increasingly swept by oceanic currents?

The morphology and Quaternary/Holocene evolution of the Eastern Cape shelf is poorly studied, and little attention has been paid to shelf geomorphology and stratigraphy despite ~~Flemming (1980) first recognising~~ the current-swept nature of the area~~.~~ having been long identified (Flemming, 1980). Martin and Flemming (1987) notably documented a series of prominent outcropping palaeo-shorelines in the area, which along adjacent shelves, have since been more closely examined and recognised as exceptionally well-preserved and geomorphologically complex shoreline features (Green et al., 2018). These features provide abundant opportunities to examine shoreline changes in both time and space and importantly provide insight into long-term shoreline behaviour over ~~centurial~~centennial to millennial scales (Cooper et al., ~~2018~~2018a; Mellet and Plater, 2018). Such insights are often lacking from current-swept areas where sediment retention is limited by erosion.

Current-swept shelves ~~may~~typically comprise thin veneers of sandy/gravelly sediments (the palimpsest sediments of Swift, 1974), which mantle a relatively flat and low-relief bedrock outcrop (Shideler and Swift, 1972; Toscano and Sorgente, 2002; Coffey and Read, 2004; Green and Garlick, 2011; Flemming and Martin, 2018). However, under certain circumstances, e.g. sufficient antecedent accommodation and sediment supply, rapid sea-level rise and a climate that fosters rapid carbonate diagenesis, large-scale submerged shorelines may be preserved and exposed as spectacular seafloor features by the current action. Notable examples include the Loop Current-exposed Pulley Ridge of SW Florida (e.g. Locker et al., 1996; Jarrett et al., 2005), the Bass Cascade and Bass Strait-influenced Gippsland Shelf of SE Australia (Brooke et al., 2017), the Leeuwin Current-influenced Carnarvon (Nichol and Brooke, 2011) and Rottnest shelves of Western Australia (Brooke et al., 2017) and the Agulhas Current-dominated KwaZulu-Natal shelf of SE Africa (Green et al., 2013a; Green et al., 2014). In these instances, several drivers operate to define the shelf stratigraphy and geomorphology and may include longer-term allocyclic processes such as rate of sea-level fluctuation (Locker et al., 1996;

Salzmann et al., 2013), shorter term or near instantaneous allocyclic processes such as oceanographic forcing (Flemming, 1980; 1981), and long-term autocyclic conditioning of shelf gradient and palaeo-topography (e.g. Green et al., 2018; Kirkpatrick et al., 2019).

The broad aim of this paper is to investigate the morphological and stratigraphic evolution of a typical current-swept shelf, with focus on the Eastern Cape shelf of South Africa (Fig. 1). We examine the fundamental drivers of shelf evolution ~~such as~~including (i) sea-level changes during the last glacial cycle and (ii) contemporary ocean dynamics~~ with an~~. Thereby we aim to (1) describe the shelf stratigraphy and surface morphology; (2) identify modern and relict seafloor features (3) interpret the origin and genesis of seafloor features; and (4) present a model for current-swept shelf evolution driven by relict and modern forcing agents. This is ~~linked with~~compared to other similar shelves around the globe.

2. Regional setting

The southeast African continental margin is a sheared passive margin along which South America separated from southern Africa during the initial opening of the South Atlantic (Scrutton and Du Plessis, 1973). Regionally, it is exceptionally straight and narrow, but on a local scale, there are extensive variations in morphology, especially in the distribution of canyons and other irregularities on the continental slope (Flemming, 1981; Dingle et al., 1983). The East London shelf break occurs between 110 m and 120 m depth (Fig. 1), with a shelf width that varies between 19 km to 23 km, making it narrower and slightly shallower than the world average of 75 km and 130 m, respectively (Flemming, 1981). The shelf gradient varies, with a shallower gradient ca. 1.4° in the outer shelf, steepening up to 2.9° in the inner to middle shelf (Dlamini, 2018). The adjoining coastline is fragmented by a series of zeta (half-moon) bays of which their origin is related to the brittle deformation phases associated with the break-up of Gondwana (Watkeys, 2006).

The continental margin of southeast Africa is a high-energy environment dominated by south-westerly swells. The entire coast is subject to high-energy swells (Hs 2.1 m; T 11 s; HRU 1968), where the significant wave heights for 1, 0.1, and 0.01% exceedance are around 3.9 m, 5.0 m, and 6.0 m, respectively (Rossouw 1984). Swell heights commonly range between 1 and 2 m, with the largest recorded swell (12–13 June 1997) in the last 22 years having a significant wave height (Hs) of 9.3 m (Dixon et al., 2015). Spring tidal range is between 1.8 and 2.0 m, and neap tidal range is 0.6 to 0.8 m (HRU 1968). The mid-outer shelf is dominated by the Agulhas Current, a fast poleward-flowing geostrophic current that can reach surface velocities of >2.5 m/sec (Pearce et al., 1978). ~~The formation of giant waves~~ Along the shelf margin giant waves may be formed by the propagation of high swells into the current (Mallory, 1974; Smith, 1976).

The study area comprises Gondwana-age sedimentary rocks of the Karoo Supergroup that are onlapped by Cretaceous through to Quaternary age sedimentary rocks. Sandstones and shales of the Karoo Supergroup crop out along the coastline and are overlain by limestones of the Cretaceous Igoda Formation (Dingle et al., 1983). Calcareous sandstones of the Neogene Nanaga Formation occur locally, together with shelly sands, soils and middens of the Pleistocene-age Schelmhoek Formation (Roberts et al., 2006).

Along the coast and on the shelf, a variety of Pleistocene to Holocene age beachrocks and aeolianites are found (Roberts et al., 2006). These aeolianites comprise the Nahoon Formation, a former parabolic dune complex deposited at ~200 ka (Le Roux, 1989) and since bevelled into a series of raised shore platforms that occur at 4 to 5 m above mean sea level and mean sea level, respectively. The upper platform is mantled by a coquina of assumed Marine Isotope

Stage (MIS) 5e age (Roberts et al., 2006). Unconsolidated sediment mantles these in places and occurs as a narrow wedge of shelf sediment that forms the contemporary shoreface (Flemming, 1981).

Sediment is supplied to the coast via three main river drainage systems, the Kei, Mzimvubu and Great Fish Rivers (Table 1). The Great Fish and Kei River catchments supply 11.48 × 10^6 m^3 and 11.134 × 10^6 m^3 of sediment to the coast respectively (Table 1) (Flemming, 1981). The Mzimvubu River debouches to the north and when combined with the Mbashe River, provides a further 10.458 × 10^6 m^3 of fluvial sediment per year. The zone between the Great Fish and Mzimvubu Rivers was identified by Flemming (1981) as a discrete sediment compartment supplied by the above rivers and mostly dominated by current sweeping of the adjacent shelf. According to Rooseboom (1978), this entire coastal strip is characterised by annual sediment yields that range from 150 t/km^2 up to 800 150 t/km^2 per year.

Martin and Flemming (1987) identified a series of palaeo-coastlines on the shelf at a depth of 60-70 m, and at the shelf edge (-100-105 m). These shorelines extend for over 600 km to the north of the study area (Green et al., 2014) and are thought to have formed when sea levels occupied depths of 100 m ~ 14 600 yr BP (Green et al., 2014) and ~ 60 m between 13 000 and 12 500 cal yr BP (Cooper et al., ~~2018~~2018b).

3. Methods

Ultra-high-resolution seismic data were collected aboard the RV Meteor cruise M123 in February 2016. The data were acquired with an Atlas PARASOUND parametric echosounder using a primary low frequency of 4 kHz. Navigation was provided by a differential GPS (DGPS) capable of ~ 1 m accuracy in the X and Y domains.

The data were processed with Atlas PARASTORE, where the sea bottom was tracked, the data match-filtered and swell corrected, time varied gains were applied, and the processed data exported in SEGY format. All data were then interpreted in IHS Kingdom Suite or Hypack SBP utility. Sound velocity estimates of 1 500 ms^{-1} in water and 1 600 ms^{-1} in sediment were applied for all time-depth conversions.

Seismic units were defined by reflector packages, bound by distinct unconformity surfaces where the internal reflectors were either truncated, or where they downlapped, toplapped and onlapped the unconformities (see Mitchum et al., 1977). The units were described according to the internal reflector amplitudes, geometries and continuity and designated a unit name from Unit 1 to 4.

Multibeam data were collected using two different systems. Data offshore Morgan Bay, East London shelf edge and the Mazeppa Bay area were collected using a Reson 7125 multibeam echosounder coupled to a DGPS and Applanix POS-MV motion reference unit. The data were collected and processed by Marine Geosolutions Pty Ltd., and resolve to a 1 x 1 m grid, with a depth resolution of ~ 30 cm. Backscatter data were collected simultaneously with a Klein 3000 side scan sonar system with a scan range of 75 m using the 500 kHz channel. The data were processed using the Klein SonarPro software, where the bottom was manually tracked, the data were filtered, time varied gains applied, the channels colour balanced and the nadir zone removed for seamless mosaicking. The final data set resolve to a mosaic pixel approximating 1 x 1 m.

The second set of multibeam data were collected aboard the RV Ellen Khuzwayo, voyage 159, using a Reson 7101 ER multibeam system, coupled to a DGPS and a SBG Systems Ekinox-D INS motion reference unit. All soundings were reduced to mean sea level during processing. The final data were output as a 5 x 5 m resolution grid, with a depth resolution of ~ 50 cm. Co-registered pseudo-side scan sonar data were collected as Snippets for backscatter mapping, the final output of these on the same horizontal scale as the bathymetry data.

Seafloor materials were sampled using a benthic sled, a Shipek grab and a dredge, depending on the substrate; rocky substrate necessitated a dredge as opposed to the less consolidated materials such as mud and sandy material/gravels. Sampling was mainly done for biological purposes and as such, not all the bathymetric and backscatter features observed were sampled.

An intact rhodolith was selected for ^{14}C dating using accelerator mass spectrometry (AMS). Two samples, one from the centre of the rhodolith, the other from the exterior were analysed. Calibrated ages were calculated using the Southern Hemisphere atmospheric curve SHCal13 (Hogg et al., 2013). A reservoir correction (DeltaR) of 161 +/- 30 was applied to coralline material. Analyses were performed by Beta Analytic in their Florida radiocarbon facilities.

4. Results

4.1. Seismic stratigraphy

The seismic stratigraphy of the study area is shown in figure 2 (a-d). The acoustic basement comprises a series of moderate to high amplitude, inclined parallel reflectors. These dip seawards at ~ 2° and are truncated by an erosional surface, S1, marked by incised valleys up to 20 m deep in the middle shelf (Fig. 2c and d). These valleys abut a series of pinnacles and ridges of acoustically opaque material (Unit 1) that span the middle shelf to shelf edge, the bases of which occur at depths of 105 m. To seaward of the most landward ridge, a tangential oblique-prograding wedge of material onlaps the ridges (Unit 2) (Fig. 2a; c and d) and progrades into the valleys (Fig. 2d). In some areas, this wedge ~~may appear~~appears acoustically transparent (Fig. 2b). A thin (<2 m) body of discontinuous, wavy to horizontal, low amplitude reflectors (Unit 3) locally onlaps Unit 2 and interfingers with the overlying units (Fig. 2a and b).

Units 1, 2 and 3 are all in turn onlapped by a finely layered, low amplitude set of reflectors (Unit 4) that spill out of the middle shelf incised valleys (Fig. 3) and terminate behind the main ridges that comprise Unit 1 (Fig. 2b-d). This forms a meter-thick package~~,~~ that is exposed at the seafloor (Fig. 2b-d; 3). In the middle shelf, this forms an acoustically transparent, landward pinching wedge of material that onlaps the ridge on its landward side and overlies the incised valleys in the more proximal middle shelf regions (Fig. 2d).

Overlying Unit 4 in the middle to outer shelf is an internally complex mound ~~of~~characterised by chaotic and discontinuous, landward and seaward dipping reflectors (Unit 5) (Fig. 2). These interfinger to landward with moderate amplitude, sigmoidal prograding reflectors of Unit 6. Along coastal strike, Unit 6 forms a coast-parallel prograding body of sediment. These units are separated from the underlying units by a high amplitude erosional reflector, S2, that truncates the lower units (Units 1-4) (Fig. 2 and 3). S2 is exposed along the seafloor from the middle shelf to outer shelf.

4.2. Seafloor morphology

The spatial attributes of the main seafloor morphological features are described in table 2. Where Unit 1 crops out~~,~~ (see Figure 2 for example), the seafloor morphology comprises a variety of ridges that exhibit distinct plan ~~forms~~form morphologies (Fig. 4). The shallowest areas are characterised by a series of parabolic-shaped ridges and depressions (~~Fig.~~Figs 2, 3 and 4a) that crop out at their seaward edge at ~ 60 m depth. The ridge reliefs vary between 1 to 7 m, with the parabolic forms spaced ~ 500 m apart (Table 2). Along strike and at similar depths, Unit 1 takes the form of narrow (≤ 80 m) crenulate ridges 0.5 to 2 m in relief, superimposed on basement rocks that crop out as strongly SE-NW orientated, blocky seafloor (Fig. 4b).

In the middle shelf areas, between 60 and 80 m depth, the parabolic ridges and depressions of Unit 1 form cuspate features that separate semi-circular seafloor depressions, > 2 km-wide and up to 6 m in vertical relief (Fig. 4c and d; Table 2). The edges of these depressions are characterised by multiple, prograding arcuate ridges, up to 4 m in relief and spaced ~ 200 m apart (Fig. 4c).

The outer shelf is mostly characterised by subdued relief seafloor between 80 and 90 m deep. A large, coast parallel ridge of Unit 1 occurs throughout the study area, the seaward fringe of which occurs at -100 m (Fig. 4e and f; Table 2). In some areas, this ridge forms a feature with up to 15 m relief, with multiple recurved ridges attached to its landward flank (Fig. 4e). The recurved ridges are ~ 250 to 350 m-wide, with relief of up to 4 m. Depressions up to 2 m are evident in the ridge (Fig. 4e and f), forming low-lying areas on the seafloor in which smaller, prograded ridges of ~ 0.5 m relief and 40 m spacing occur (Fig. 4e). In other areas, cuspate, landward-narrowing ridges occur along the main ridge line ~~(Fig. 4f~~, forming triangular seafloor features 300 to 500 m long (Fig. 4f; Table 2).

The inner shelf ~~areas are~~is marked by ~~the surface expression of the~~several underfilled valleys ~~identified~~manifest as elongate seafloor depressions. These are correlated in seismic profile ~~as~~to the incisions associated with surface S1. These palaeo-valleys form topographic lows on the inner shelf where Unit 4 crops out. These areas are also characterised by the presence of mounds of Unit 5, where they form in some of the depressions. The palaeo-valleys extend into the semi-circular seafloor depressions and into the low-relief and deeper seafloor landward of the -100 m ridge (Fig. 4).

4.3. Seafloor backscatter and sediment characteristics

The more proximal middle shelf comprises even-toned high backscatter seafloor, confined to the topographic low of the underfilled incised valley (Fig. 5a). This merges with moderate and irregular backscatter where the valley widens towards the semi-circular depressions (Fig. 5a). On either side of the valley, high relief, irregular and alternating moderate to high backscatter seafloor marks the parabolic ridges and depressions of Unit 1, respectively. This seafloor texture ~~extends all the way~~ to the outer shelf. ~~Where~~ The lower relief areas of the semi-circular depressions ~~are encountered, these~~ are characterised by moderate, even toned backscatter.

Several coast-parallel elongate furrows are evident ~~from~~on the middle to outer shelf (Fig. 3b and 4b). These form linear depressions up to 30 cm deep and are associated with linear patches of high backscatter (Fig. 5). These overprint the low relief sea floor features and mark the surface exposure of S2. Throughout the study area, isolated patches of rippled, alternating high to low backscatter seafloor are apparent.

Seafloor inspections reveal the even-toned high backscatter areas to comprise weakly laminated, stiff, muddy deposits (Fig. 5; 6a). In the proximal underfilled incised valley, this is mantled by sandy material with mud cropping out in the depressions of current ripples (Fig. 1; 6b) The adjoining moderate and irregular backscatter seafloor is paved by a thin cover of rhodoliths (Fig. 5; 6c). In contrast, on the middle to outer shelf, the mounds of Unit 5 comprise stacked accumulations of rhodoliths (Fig. 2; 6c). AMS ^{14}C dates of the interior of the rhodoliths ranged from 7406 - 7225 cal yr BP, with their surface material dating to present day (150 cal yr BP to Post-Bomb).

The high relief, alternating high and moderate backscatter ridges and depressions correspond with aeolianites cropping out along the seafloor (Fig. 6d). The lower relief seafloor marks outcrop of subdued relief rocky material. The interleaving seafloor where S2 crops out is marked by pebbles and cobbles of reworked aeolianite, together with finer bioclastic material (Fig. 6e). The linear depressions of high backscatter are likewise lined by similar material (Fig. 6f). The isolated areas of rippled, alternating high to low backscatter represent isolated patches of rippled bioclastic material interspersed with quartzose sand.

5. Discussion

5.1. Seismic stratigraphic interpretation

Aeolianites of Unit 1 at -105 m and shallower abut and overlie S1, the last glacial maximum (LGM)-age subaerial unconformity that is commonly recognised across the SE African shelf (Green et al., 2013a). We refer to these as the -100 m and -60 m shorelines based on these previous works. Incised valleys formed in S1 relate to the LGM lowstand and constrain the age of the aeolianite sequences to the most recent postglacial period (Pretorius et al., 2016; Cooper et al., ~~2018~~2018b; Pretorius et al., 2019).

The tangential oblique-prograding wedge of Unit 2 that onlaps the aeolianites and enters the incised valleys is architecturally similar to spit systems recognised from multiple large incised valley systems, lagoons and lakes of the east coast of South Africa (Wright et al., 2000; Benallack et al., 2016) and from shelf to lake environments elsewhere around the world (Novak and Pederson, 2000; Raynal et al., 2009; Nutz et al., 2015). In keeping with this interpretation, the chaotic and discontinuous reflectors of Unit 3 are similar to features identified elsewhere as small-scale slump or mass wasting packages in waterbodies characterised by active spit progradation (Wright et al., 2000; Rucińska-Zjadacz and Wróblewski, 2018).

Seafloor sampling and observations reveal Unit 4 to comprise stiff muddy materials. The stratigraphic position as a capping and overspilling unit of the incised valleys points to deposition in a lagoonal environment that overtopped the interfluves and ponded along the shelf behind the barrier systems of Unit 1 (e.g. Green et al., 2013b; Benallack et al., 2016).

The intercalating upper units 5 and 6 represent the contemporary Holocene shelf sediment prism which interfingers with the rhodolith mounds indicating that the two were deposited and evolved contemporaneously. Studies of the Holocene sediment prism in SE Africa indicate a mid-Holocene to recent age (Pretorius et al., 2016) which correlates with the age at which Holocene sea level stabilized close to the present (Cooper et al., ~~2018~~2018b) and the rhodolith mounds began to form (7406 - 7225 cal yr BP).

Surface S2 outcrop represents the seafloor exposure of the Holocene wave ravinement surface. This surface truncates the spit/barrier/lagoon sequences and separates the post-transgressive Holocene material from the underlying transgressive succession. The mixed bioclastic and aeolianite pebbly material (Fig. 6f) is similar to the material forming from the contemporary wave ravinement of beachrocks and aeolianites in SE Africa (Cooper and Green, 2016). The exposure of this material in elongate furrows provides evidence for current furrowing that has denuded the mid to outer shelf of sandy sediment and exposed the underlying wave ravinement ~~to~~surface to geostrophic current reworking, forming gravel streamers and ribbons (Flemming, 1978).

The development of rhodolith fields since ca. 7.4 ka yr BP provides further evidence of strong Agulhas Current action since sea levels stabilised close to the present. Prior to this, the current ~~existed~~flowed seaward of the shelf edge and did not support the growth of rhodoliths in this position. Intact rhodoliths that interfinger with the Holocene sediment wedge indicate episodic wedge progradation into current-agitated waters where the rhodoliths nucleated, as opposed to punctuated re-deposition of the rhodoliths by gravity or storm driven processes (evidenced elsewhere by broken rhodoliths, interspersed with pebbly gravels~~-~~ (Brandano and Ronca, 2014~~).~~)). This conforms to Flemming's (1981) model of the regional shelf; an inner siliclastic wave-dominated system and an outer Agulhas Current-dominated shelf. In microcosm, this ~~reflects~~matches the shelf/carbonate platform-drowning model of Betzler et al. (2013), ~~where~~in which swift sea-level rise produces partial shelf drowning and current sweeping of the shelf. This thus places the timing of mid-shelf transgression to a minimum age of 7406 – 7225 cal yr BP and implies a sudden increase in the rate of sea-level rise that post-dates a regional sea-level slowstand recognised by De Lecea et al. (2017) ~ 8000 cal yr BP.

5.2. Seafloor morphology

Several seafloor features bear striking similarity in plan form ~~and scale~~ to contemporary shoreline features on the sandy and wide (40-100 km) Maputaland-Mozambique coastal plain (Fig. 7a), as well as coastal features that are not represented on the modern SE African coast. Below, following Gardner (2005, 2007), we compare the seafloor topographic features with contemporary coastal landforms as an aid to their interpretation.

5.2.1. -100 m shoreline

The large blocky aeolianite body that occurs at ~ 105 m at the shelf edge (Fig. 4e and f) is ~~equivalent~~similar in ~~scale and~~ shape to the modern barriers of the Maputaland coastline (Table 2), and to some modern barrier islands formed on ~~many~~other wave-dominated coastlines (see Mulhern et al., 2017). Regarding size, the aeolianite body is significantly narrower, with a lower elevation than the contemporary Maputaland coastal barrier. The seafloor depressions and recurved ridges that attach to the depressions and landward sides of the main ridge line are very similar in shape and ~~scale to~~conform to the lower size limits of inlets and associated cuspate and recurved spits of contemporary major barrier-inlet systems~~,~~ (Table 2), both in southern Mozambique and Maputaland (Fig. 7a and b) and from systems of the southern US Atlantic margin (Cooper and Pilkey, 2002; Pilkey, 2003; Davis and FitzGerald, 2009). Breaks in the ridge, marked by topographic lows are of a similar shape and dimension to tidal inlets ~~and~~, an interpretation that is supported by their location adjacent to recurved features (Fig 4e). These are up to 200 m-wide and ~ 5 m-deep, consistent with figures reported for inlets worldwide (Davis and FitzGerald, 2009). ~~This further supports such an interpretation.~~ The adjacent low relief areas landward of the main inferred barrier positions are interpreted as the palaeo-back barrier environments through which the incised valleys passed during the LGM lowstand (Fig. 6e).

The large, semi-circular seafloor depressions (Fig. 7c) that occur slightly distal to the barrier are interpreted as a series of drowned and segmented lagoons. The arcuate prograding ridges along the depression margins, together with the cuspate wedges of Unit 1 aeolianite that separate each lagoon, mark prograding lagoon shorelines and down-drift spit termini of the wave-driven littoral cells of the system, respectively (cf. Ashton and Murray, 2010) (Fig. 7c). These are mostly within the lower size range of the modern systems found along the SE African coast (Table 2). The depressions correlate directly to landwards with the outcropping, overspilled muddy facies of Unit 4.

These~~ apparently~~ segmented lagoons are fed by several underfilled incised valleys that clearly mark the palaeo-fluvial pathways that entered ~~into ~~these lagoons. These fluvial entrance points are similarly recognised in the contemporary setting of coastal waterbodies in SE Africa (Table 2) (Fig. 7d).

A significant modern barrier system extends from Richards Bay, ~ 650 km north of the study area into southern Mozambique (Jackson et al., 2014). This system is marked by a series of northeastward oriented, climbing parabolic dunes that can reach up to 120 m high, covered with multiple blowout features. The parabolic ridges and depressions that form in the aeolianite of Unit 1 are very similar in shape and planform scale to those dunes of the contemporary coast~~, with~~ (Table 2), though their elevations are markedly lower. Small, blowout-like features are also evident (Fig. 7e). We thus consider that a similar large dune system occurred at some point adjacent to and fringing the barrier islands and segmented waterbodies of the outer shelf. ~~This appears to be comparable in scale to~~Though of considerably lower elevation, the width is within the ranges reported for the dune fields of southern Mozambique (Fig. 7a) and marks an approximate shoreline depth of 105 m (c.f. Ramsay, 1995).

5.2.2. -60 m shoreline

At -60 m, a former shoreline lineation is also evident. In planform this is ~~arranged in a series of palaeo-embayments.~~manifest as a series of palaeo-embayments, fringed by small aeolianite ridges of similar widths to the lower limits of the primary dunes found along the embayed mixed-sand and rock coastlines of SE Africa (Jackson et al., 2014). The palaeoheadlands are formed in bedrock of the Karoo Supergroup, separated by crenulate ridges of Quaternary aeolianite (Fig. 8a) that also rest on Karoo bedrock. This is a~~ very~~ similar coastal morphology to that of the present day, where thin outcrops of aeolianite and beachrock rest with marked unconformity on older sedimentary rocks in embayments between prominent bedrock headlands (Fig. 8b and c).

Some of the embayments on the contemporary coast are also marked by modern barriers/Holocene age dunes (Table 2) (Fig. 8c) and this configuration too appears to be reflected on the seafloor (Fig. 8a). Their presence indicates that the coastal evolution at the time of their formation was strongly influenced by the bedrock framework, as is the modern coast (Watkeys, 2006). Similarly, their form and structure point to a shoreline occupation at a depth of 60 m where planform equilibrium forms developed in coastal re-entrants (Carter, 1980).

5.3. Postglacial evolutionary model

The contemporary shelf morphology reflects a combination of influences of wave and ocean current processes acting on the pre-existing basement geology. These have operated with varying intensity and at different locations as sea level fluctuated during the last glacial cycle and the deposits and geomorphic features of each successive interval have influenced subsequent evolution. The sequence of events and associated dynamics are discussed below in the context of an evolutionary model for the shelf.

Initially, the narrow and shallow shelf was dissected by several fluvial systems during lowstand conditions culminating in the LGM (Fig. 9a). Two main river systems in the area formed valleys of similar scale to those on the modern coast. At this time, wave action was focussed off the modern shelf break, as was the palaeo Agulhas Current. During subsequent sea-level rise wave processes reworked existing sediment and formed distinctive coastal landforms that are preserved at several specific levels on the seafloor. These shoreline features indicate marked differences in shoreline type at various stages of the transgression and their preservation or non-preservation is linked to rates of sea-level change.

The generation of a substantial barrier system at ~ 100 m depth (Fig. 9b) can be linked to patterns of stable sea level that allowed planform equilibrium for the palaeo-coastline to be reached. ~~Like~~It contains features similar to the contemporary highstand coastal systems of northern KwaZulu-Natal and southern Mozambique (Green et al., 2013b), ~~we see the same coastal forms~~ from which we infer similar conditions of sediment supply, energy and sea level state at the time of formation (~~expanded on~~see below). These strongly contrast with the sediment-poor, headland bound and rocky setting of the contemporary coastline of the Eastern Cape.

Stable or slowly rising early Holocene sea levels promoted barrier growth, overspilling of incised valleys and lateral extension of newly forming lagoons, with a general planform equilibrium reached for the lagoon bodies (Fig. 9c). New accommodation was not generated quickly, and the back barrier behind the -100 m barrier could be overfilled to compensate. The prograded lagoon margins on contemporary lagoons in SE Africa (Wright et al., 2000; Botha et al., 2018) are attributed to minor sea-level fall of +/- 2 m from a late Holocene highstand to the present (Cooper et al., ~~2018~~2018b). The prograded lagoon margin features at -100 m may indicate similar patterns of sea-level fall around the LGM (Fig. 9d). This is consistent with new findings regarding the nature of the LGM sea level which dropped from -100 m stillstand to a maximum of -118 m (Yokoyama et al., 2018) between 21 900 and 20 500 yr BP.

The behaviour of barrier shorelines in the context of rising sea level is discussed by Carter (2002), who considered three main modes of barrier response, erosion, rollover, and overstepping. A fourth possible mechanism is partial overstepping, whereby remnants of the barrier are left after a portion of the barrier is eroded as the shoreface translates over the barrier form. Overstepping has been considered the main mechanism responsible for the preservation of the palaeo-shorelines from SE Africa, associated with particularly abrupt phases of sea-level rise and in place drowning the coast (Green et al, 2014). We further this hypothesis by linking the overstepping of the -100 m shoreline to melt water pulse 1A (Fig. 9e). This rapid rise in sea level from ~ -100 m (~ 4 m per century, with a 95% probability of between 8.6 and 14.6 m rise globally-Liu et al., 2016) would have been sufficient to overstep the fronting barrier system (Fig. 9d). The lagoonal deposits landward of the -100 m barrier shoreline also bear witness to the rapid creation of accommodation space in the back barrier and an associated reduction in the efficacy of the bay-ravinement process as the barrier and back-barrier were submerged (cf. Storms and Swift, 2003; Storms et al., 2008). The high gradient of the wave ravinement surface (up to 4°), bounding the surface of the lagoonal/back barrier deposits (Fig. 2) indicates a steepened shoreline trajectory during overstepping. Salzmann et al. (2013) consider causes for steepened shoreline trajectories to include steep transgressed topographies, rapid rates of RSL rise and high rates of sediment supply (based on the work of Cattaneo and Steel, 2003). On this sediment-starved shelf, high sedimentation rates during infilling of the back barrier can be discounted (e.g. Green, 2009, 2011; Salzmann et al., 2013).

We hypothesise that relatively slower rates of sea-level rise then followed, with widespread shelf ravinement (denoted in red ~~on the figure~~in Figure 9) removing all but the cores of the barrier system surrounding the segmented lagoons and leaving the low-lying depressions of the lagoons intact (Fig. 9f). This slower rate of sea-level rise is linked to the Younger Dryas period that preceded a second meltwater pulse (MWP 1-B) (see Pretorius et al., 2016 for timing of other shoreline development at the same depth). At this time and where available accommodation occurred, shorelines developed within embayments (Fig. 9f). These were then overstepped by MWP 1-B (11.5–11.1 ka BP-Harrison et al., 2019) (Fig. 9g), leaving a subsequent set of smaller aeolian dune fields, some of which are preserved within embayments as relict shelf features. Sea level has since risen to present day, where the contemporary coast is strongly bedrock-dominated with multiple embayments bounded by rock headlands (Fig. 9h).

5.4. Local controls on stratigraphic and geomorphic evolution.

The model that has previously been ~~fitted~~developed to describe the occurrence and preservation of submerged postglacial shorelines~~ as presented here, follows one driven mostly by~~, is based on temporally varying rates of sea-level rise linked to paired slowstands (gradual and slowly rising sea level) and subsequent melt water pulses (see Green et al., 2014; 2018). The present study includes additional observations of submerged shorelines at depths consistently seen at 60 and 100 m across the narrow portions of the SE African shelf (c.f. Green et al., 2018; Pretorius et al., 2019). ~~We see a clear pattern forming in the data;~~Across the entire shelf, large volume, submerged planform equilibrium barriers and back barrier environments at -100 m and -60 m, ~~that~~ stretch for over 1000 kms ~~into~~alongshore from southern Mozambique (De Lecea et al., 2017~~).~~) to the present study area. This ~~even~~ mirrors to some degree, submerged relict shorelines on the ~~western~~southwestern African margin in Namibia (Kirkpatrick et al., 2019). Repeating forms such as drowned segmented lagoons (e.g. Green et al., 2013a), parabolic dune fields (Green et al., 2018) and underfilled incised valleys (Pretorius et al., 2019) are common, yet occupy areas of significant variation in antecedent shelf setting, e.g. narrow vs wider shelves, numerous steep-sided incised valleys vs flat planation surfaces.

Numerous similar examples of submerged shoreline features have been reported from other current-swept sub-tropical shelves. On the Gippsland and Lacepede shelves of SE Australia, a series of coast-parallel ridges are found at depths of ~65-75 m. These were interpreted as relict strandplains and barriers (Brooke et al., 2017). Other examples from similar depth ranges are found on the Recherche and Rottnest shelves of Western Australia, together with relict carbonate-cemented dunes (Brooke et al., 2014). On the Carnarvon shelf, coral reefs and carbonate-cemented dunes are similarly apparent at ~ 60 m (Nichol and Brooke, 2011). Around depths of ~ 100 m, erosional knickpoints (the Lacepede shelf, Hill et al., 2009), coral reefs and occasional associated lagoons (the NW Australian and Sahul shelves, Nichol et al., 2013; Howard et al., 2016) ~~are~~have also ~~found.~~been reported.

~~The landforms described above all follow a similar overstepping pattern in their inertial response to deglacial sea levels and it appears that the~~ An episodic ~~rate of~~ sea-level rise model ~~fits~~is required to develop these ~~well as a dominant driver in preservation of such a morphology~~submerged shoreline features at consistent depths and ages on ~~current-swept shelves throughout the subtropics.~~

a global scale. However, antecedent shelf geometry is also an important local consideration on shelf evolution~~ is antecedent shelf geometry. On the East London shelf, the high gradients~~. The steep gradient (up to 2.9°) of the SE African shelf would, theoretically, ~~foster weak~~lower the preservation potential of ~~the~~ shoreline ~~form~~features due to focused erosion along a steep profile for any given unit of time during transgression (Cattaneo and Steel, 2003). ~~In addition, the antecedent back barrier topography is particularly subdued. There are no clearly exposed palaeo-valleys and the seafloor directly landwards of the barrier appears remarkably smooth (Fig. 4e).~~ Where exposed, the barriers clearly comprise cemented sandy aeolianites and it is thus likely that it is the cementation, in conjunction with the driver of rapid rates of sea-level rise (c.f. Green et al., 2018), that is responsible for the preservation of these relict coastal forms on the shelf.

The overall weak preservation of shoreline forms, and a dominantly erosional or current swept seafloor between the outer barrier and the - 60 m shoreline can be related to strong ravinement processes, first by ~~waves~~the aggressive wave climate during landward translation of the wave base, and then by oceanic current denudation once sea level had passed over the palaeo-coastal profile. On this steep shelf (1-3°), the implication is that the shoreline migrated *slowly* between the landward edge of the -100 m shoreline and the seaward edge of the -60 m shoreline. During this period, transgressive erosion was maximised and only small remnants or cores of once much larger dune systems, were left.

This contrasts with the higher relief, outer shelf where the ~~barrier island and barrier ridges~~former coastal barriers are better preserved. ~~This also explains~~ The lack of sediment cover in these areas~~; as the shoreline transgressed the palaeo-coastal plain,~~ is attributed to sediment ~~is~~being held in the shoreface under sediment-deficit type conditions as the shoreline transgressed the palaeo-coastal plain (Mellet and Plater, 2018). Any sediment ~~left behind~~that was potentially deposited as a transgressive layer was subsequently removed by the current sweeping that formed the gravel streamers observed~~.~~ on the modern shelf. Simultaneously, the barrier system would continue to roll over to a point where ~~large~~smaller parabolic dunes and palaeo-embayments/shorelines could form ~~with a seaward depth of~~ (at -60 m~~.~~). This period marks a likely slowing of the rate of relative rise which ~~reconciles with~~is identified on other shorelines at depths of 60 m from the Durban shelf (Pretorius et al., 2016; Cooper et al., ~~2018~~2018b) and elsewhere e.g. SE and Western Australia (Brooke et al. 2017), SE Brazil (Cooper et al., 2016, 2018c).

When comparing the overall scale and size of the relict barrier features on the seafloor to the modern coastlines of SE Africa, we note that although broadly similar in morphology, the sizes of the relict features are smaller than their modern equivalents. The seafloor features are narrower (850 m vs 2 km), with significantly lower relief (15 m vs 170 m). This implies that a significant amount of sediment (~ an order of magnitude in terms of width and height) was lost as the shoreline translated over the shelf to where it is at present.

The current coastal configuration is mostly bedrock-controlled, with small rock-bound embayments that host isolated barrier-dune complexes. These are significantly smaller than the barriers preserved at -100 m and are more like the crenulate shorelines preserved at -60 m. The landward change in barrier size implies a shift from large and contiguous dune cordons forming during the early transgression, to isolated sandy barriers hosted amidst bedrock. This shift marks the increasing influence of bedrock control and coastal squeeze on shoreline adjustment during transgression. The net result is transformation of the Eastern Cape coast from a straight, littoral drift-dominated feature to a strongly compartmentalised shoreline with limited accommodation and littoral sediment supply.

The sediment for the early dune building phase appears to have been initially sourced from a well-fed littoral system that adjoined a sandy, linear coastline. The net supply of sediment to the coastline from the Kei River alone is likely to have been substantial, and when coupled to the other large quantities of sediment delivered by the adjoining fluvial systems (Table 2), the shelf and coastline should act as a major sediment depocentre. The Agulhas Current sweeping of the shelf, however, limits the potential for sediment accumulation and rather exposes relict features at -100 m that are indicative of former high sediment supply and retention rates. During the transgression, the landward effect of coastal pinch by the bedrock framework is also coupled to the progressive diminution of the seaward edge of the large quantity of sediment that was formerly hosted in the -100 m dune system. As the Agulhas Current has impinged further landward, this has steadily removed all but the relict and cemented barrier forms and produced the seafloor facies association discussed below. As Flemming (1981) recognised, coast-parallel sediment transport along the shelf and shelf edge extends to locations where a change in shelf orientation occurs and sediment is then lost off-shelf.

Rhodoliths began to develop when sea-level stabilised at its present level ca 7000 yrs BP, suggesting that the Agulhas Current was by this stage located on the shelf. During the subsequent 7000 years up to and including the present, thick accumulations of rhodoliths ~~have~~ accumulated in current-dominated conditions on the otherwise sediment-starved outer shelf. Sediment denudation has limited burial of the relict shorelines.

Multiple, current-controlled sedimentological features have similarly developed, resulting in a specific shelf morphology that comprises gravel-lined furrows and comet marks located in a largely sediment-denuded seascape. Strong current sweeping has further exacerbated the predominance of relict features associated with sea level fluctuations. Exposed wave ravinement surfaces, exhumed and relict incised valley features on the shelf, large exposed lagoonal systems, and intact barrier islands point to limited sediment retention on the shelf, since the repeated impingement of the Agulhas Current ~~on the shelf~~since ~ 7000 years ago. These seem likely to remain as persistent features in the shelf morphology and represent the nexus between relict geological and contemporary oceanographic processes.

Green et al. (2018) consider that subtropical climates particularly favour the preservation of relict shorelines on the shelf, and their occurrence may thus be a unique feature of current swept shelves of the sub tropics. This is strongly supported by the ~~examples outlined from the Western and SE Australian shelves.~~ distribution of examples outlined from the Western and SE Australian shelves. However, in those cases, the modern coastlines are wide and sandy and in most part reflect similar geomorphic elements as to the relict shorelines of the adjacent shelves. Likewise, where the submerged shorelines were bedrock controlled, such as in the case of the submerged cliffs offshore the Lacipede shelf (Brooke et al., 2017), these are reflected in the cliffs of the contemporary coastlines. Where bedrock control is reduced or not as extreme, the evolutionary pathway is not constrained, and modern shorelines may mirror the relict features of the shelf. Our study thus provides a unique case study that highlights changing coastal configuration and functioning due to progressive coastal squeeze, exacerbated by rising sea levels, an increased impingement by bedrock framework, and high levels of current sweeping.

6. Conclusions

This study marks the first in South Africa, to identify both the -60 and -100 m submerged shorelines in outcrop, with a degree of unprecedented continuity between the two. The lack of sediment cover and exceptional shoreline preservation makes this area an attractive one for testing the hypothesis of Green et al. (2014); that these features are geomorphic signatures of MWP-1A and 1B.

~~The contemporary shelf morphology reflects the combined effects of relict wave and littoral processes and modern ocean current processes as they were mediated by fluctuating rates of sea-level rise during the last transgression.~~ Shorelines developed at -100 and -60 are markedly different because of underlying geological influences, and reflect coastline adjustment to changing geological and allocyclic sea-level controls over millennial scales. A lack of shoreline preservation between each major shoreline reflects ravinement processes during slow relative sea-level rise.

Rhodolith growth began on the shelf when sea-level stabilised near the present and the Agulhas Current occupied its present position ~ 7000 yr BP. Up to 20 m thick rhodolith accumulations have developed and are strongly associated with other features indicative of sediment denudation and current whittling. Given the current-swept nature of the shelf, the surface expression of palaeoshorelines is exceptional.

This study suggests that given the necessary antecedent conditions such as accommodation, sediment supply and favourable diagenetic climate, prominent shorelines can form, and when coupled to rapid rates of sea-level rise and strong current sweeping, can be preserved as persistent morphological features. The coastal evolution can also be tracked using submerged shorelines. These appear to also remain lasting features in the shelf morphology and stratigraphy of current-swept subtropical shelves. Where prominent subsurface bedrock occurs on current-swept shelves, coastal squeeze will be exacerbated due to the increasing disruption of littoral cells, diminishing sediment supply to barrier-shoreline systems and increasing sediment losses to the shelf sediment supply by current sweeping.

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Figure captions

Figure 1. Locality map of the study area detailing multibeam bathymetric coverage, seismic tracklines (bold white lines) and locations of various seafloor samples or ROV observations (red stars-numbered as portrayed in Figure 6). The -60 m and -100 m isobaths are shown as dashed white lines, and the presence of a large rhodolith field is depicted by the blue polygon. Satellite images from Google Earth^{TM}.

Figure 2. Ultra-high-resolution coast-perpendicular seismic reflection profiles and interpretations. Note the pinnacles of Unit 1, underlain by incised valleys into which Unit 3 progrades. The abutting and onlapping acoustically transparent Unit 4 overspills the incised valleys and is overlain by the mounded accumulations of Unit 5, which interfinger with Unit 6. Inset shows line locations and sample intersections of a large rhodolith field corresponding to Unit 5. Red lines denote Holocene wave ravinement.

Figure 3. a) Ultra-high-resolution coast-parallel seismic reflection profile and interpretation detailing an incised valley that has overspilled unit 4 in the middle shelf. This occurs adjacent to pinnacles of Unit 1. Red lines denote Holocene wave ravinement. b) Multibeam bathymetry detailing the underfilled surface expression of the incised valley in a), together with the rugged seafloor expression of the pinnacles of Unit 1. Unit 4 and 5 were sampled from this valley.

Figure 4. Multibeam bathymetry showing a) an underfilled incised valley extending from the inner to middle shelf offshore the Kei River. b) A series of crenulate embayment-forming ridges at -60 m, with underfilled incised valleys offshore the Qnube River. c) Semi-circular seafloor depressions offshore the Kei River at ~ 80 m depth, bordered to either side by rugged seafloor of Unit 1. Note the arcuate prograded ridges on the margins of each depression. d) Weakly-developed semi-circular seafloor depression on the middle shelf at -80 m offshore

Qnube River. e) A coast-oblique ridge of Unit 1 at -100 m on the outer shelf offshore the Kei River, backed by recurved ridges to landward and intersected by a seafloor depression with subsidiary recurved ridges. f) A coast-oblique ridge of Unit 1 at -100 m on the outer shelf offshore the Qnube River intersected by similar seafloor depression. Note the recurved prograded ridges and single cuspate ridge developed to landward of the main ridge feature.

Figure 5. Acoustic facies derived from multibeam backscatter and side-scan sonar offshore the Kei River. High backscatter = black, low backscatter = white. The resulting seafloor qualitative interpretations are shown. a) The inner to middle shelf with smooth toned high backscatter interpreted as muddy deposits in the proximal incised valley depression. b) Rugged relief, high backscatter seafloor of Unit 1 in outcrop, interspersed by low relief seafloor of the semi-circular depressions. Occasional linear patches of high backscatter are interpreted as gravel-lined streamers. c) Rugged high relief seafloor of Unit 1 in outcrop, surrounding by lower relief rocky seafloor superimposed by gravel-lined streamers.

Figure 6. a) Remote Observation Video (ROV) imagery of stiff mud of Unit 4 cropping out at the seafloor in the underfilled incised valley offshore the Kei River. b) Stiff mud of Unit 4 exposed in the troughs of migrating sandy ripples in the most inshore region of the underfilled incised valley. c) Rhodoliths retrieved by seafloor dredging and grab sampling. d) Aeolianite retrieved from pinnacles of Unit 1 using a dredge. f) Mixed unconsolidated shell hash and aeolianite cobbles of surface S2. g) Shell hash and occasional aeolianite granules filling linear seafloor depressions.

Figure 7. a) The contemporary coastal geomorphic systems of the sandy Southern Mozambique coastal plain, with interpretative comparisons made to seafloor features of the Eastern Cape shelf (b-e). b) Recurved spits, cuspate spits and inlets of a -100 m barrier on the seafloor. c) Lagoon with prograded margins in the backbarrier of the -100 m barrier. d) Fluvial entrances

to the lagoons, marked by underfilled incised valleys. e) Parabolic dunes and blowouts formed in the -100 m seaward and landward barriers to the lagoon system. Satellite images from Google Earth™.

Figure 8. a) Interpreted multibeam bathymetry of the inner to middle shelf offshore the Qnube River, note how beachrocks and aeolianites comprise the embayment-forming ridges superimposed onto Karoo Supergroup-age strata. b) Contemporary coastal setting immediately adjacent to the above multibeam data. Here beachrock overlies sandstones of the Karoo Supergroup, backed by a Holocene age barrier-dune system (Holidaying Green for scale). c) Beachrocks overlying sandstones of the Karoo Supergroup, forming a headland to an embayment. Note the sandy Holocene-age barrier in the background separating another rocky headland to the north. Satellite images from Google Earth™.

Figure 9. A proposed evolutionary model for postglacial shoreline development of the Eastern Cape coast (timing inferred from Pretorius et al., 2016; 2019, details discussed in text).

Dear Prof. Anthony

I am deeply grateful for the opportunity to revise this paper. I must apologise, firstly to the second reviewer and then to you. I re-read my response and am deeply embarrassed. I say this not because I the paper's fate is in jeopardy, but rather because my reply was childish, rude and above all disrespectful to the reviewer who took the time to read the paper and provide feedback. Likewise, it is deeply unprofessional to place this on your desk. I do not have any excuse, this is not excusable and I am sincerely sorry. My response was rash, and in many instances, I did not truly give the comments their due consideration. Again, inexcusable.

Though some comments are hard to follow through on, I have given these all my full attention and am certain that I have addressed most of the issues that I can, that were highlighted by reviewer 2. I hope I have gone some way to show the novelty of the paper, especially now I have considered the comments on sediment source and sediment fate. I think this pays more than lip service to these comments and has elevated the paper a lot. My responses are all outlined in red below, and the revisions made very clear in the tracked change document.

As an aside to reviewer 2, if we ever meet, I would like to apologise in person and buy you the beverage of your choice (as long as it's not 100-year-old Scotch, remember our currency is weak!)

Kind regards

Andy Green

It was interesting to see a paper focused on the current-swept, passive margin setting of southeastern South Africa. Although the primary conclusions of the paper, which are summarized in the evolutionary model of Figure 9, seem to be generally correct (although need improvement as noted below), the presentation of the work is not up to the standards of a journal like Marine Geology.

I hope that this offering will be different. I have tried to bolster the various areas outlined below with clearer measurements, comparisons, logic and clarity wherever possible.

There are a number of factors that have led to this decision. A primary reason was the manuscript text needs significant improvements. It took several readings to understand the work, its purpose and the details of the results. These elements should be clear with a single reading. These problems seem to arise because the authors know their study area so well that they have forgotten to include important details for the newcomer.

I think this is a good point, overfamiliarity with the paper, I hope this is better portrayed now.

Additionally, there are several leaps made in the logic (e.g., "Units" being defined or described) that are not explained thoroughly in the text.

These have been refined accordingly in the results, and made clear with links to figures, especially the outcrop of Unit 1 and its relating seafloor morphology.

More specifically,

Currently, the paper is written as a summary report, not a scientific paper. No hypotheses are proposed and tested, no research questions are asked.

From what I can gather, there are really few examples in the literature on current-swept shelves and their geomorphic facets. I tried to frame the paper so that we present on an area well-known for its current sweeping, and then try to relate what this may do to the stratigraphic evolution over time, and now, to how this may also produce clear and distinct changes to coastal morphology and dynamics.

We set up the knowledge gap as follows :

Line 52 to 58 " To date, there are few studies that incorporate current sweeping into models of shelf stratigraphy and morphology (cf. Cawthra et al., 2012) and little is known of the processes that control the development and preservation of such features in the stratigraphic record. A key gap in knowledge is how coastal evolution is influenced by shelf-sweeping, coupled to sea-level rise, i.e. how does a coastline evolve as the shelf is drowned and becomes increasingly swept by oceanic currents?"

We then examine both the development and the preservation of shorelines exposed at the seafloor, a rarity in itself, to state:

Line 65-68"These features provide abundant opportunities to examine shoreline changes in both time and space and importantly provide insight into long-term shoreline behaviour over centennial to millennial scales (Cooper et al., 2018; Mellet and Plater, 2018). Such insights are often lacking from current swept areas where sediment retention is limited by erosion."

We end our introduction with:

Line 86-93 "(i) sea-level changes during the last glacial cycle and (ii) contemporary ocean dynamics with an aim to (1) describe the shelf stratigraphy and surface morphology; (2) identify modern and relict seafloor features (3) interpret the origin and genesis of seafloor features; and (4) present a model for current-swept shelf evolution driven by relict and modern forcing agents. This is linked with other similar shelves around the globe"

We take this further in the discussion by then demonstrating how over time, sediment retention and barrier building is influenced by increasing bedrock control, coupled with vigorous shelf sweeping. We then compare and contrast to the Australian shelf and how the submerged shorelines evolve towards the modern day coastline.

(i) The 'aim' of the paper as provided in L77-83 is to "investigate the morphological and stratigraphic evolution" of the site in question. However, for what purpose? What fundamental research question will be addressed?
I hope that this is answered in the above. A key gap in knowledge is how coastal evolution is influenced by shelf-sweeping, coupled to sea-level rise, i.e. how does a coastline evolve as the shelf is drowned and becomes increasingly swept by oceanic

currents?" We have also rewritten the abstract to reflect a leaner and more focused research question.

(ii) What broader scientific understanding could be gained from this investigation? As noted in the Marine Geology Editorial Policies, "Although most papers are based on regional studies, they must demonstrate new findings of international significance."

Likewise, I really hope this is answered in the above statement.

(ii) The Introduction (L39-83) makes the reader believe that 'current sweeping' will be the focus of the work, owing to statements such as, "To date, there are few studies that incorporate current sweeping into model of shelf stratigraphy and morphology…" (L45). However, the paper does not distinguish the effective roles of waves and currents in the sediment transport, the sediment mass balance, or the morphological and stratigraphic evolution of the site (L443-460). As such, no new understanding is provided about current-swept settings.

I hope we have done this adequately now. Its hard to bring address the waves, but the overall littoral transport role, the sediment budget (e,g. from where and to where) and how the coastline evolves is now included.

We include the following sections:

Regional setting:

Line 132-140 Sediment is supplied to the coast via three main river drainage systems, the Kei, Mzimvubu and Great Fish Rivers (Table 1). The Great Fish and Kei River catchments supply 11.48 × 106 m3 and 11.134 × 106 m3 of sediment to the coast respectively (Table 1) (Flemming, 1981). The Mzimvubu River debouches to the north and when combined with the Mbashe River, provides a further 10.458 × 106 m3 of fluvial sediment per year. The zone between the Great Fish and Mzimvubu Rivers was identified by Flemming (1981) as a discrete sediment compartment supplied by the above rivers and mostly dominated by current sweeping of the adjacent shelf. According to Rooseboom (1978), this entire coastal strip is characterised by annual sediment yields that range from 150 t/km2 up to 800 150 t/km2 per year.

Results:

We include a table showing comparison between measured aspects of the various features observed on the seafloor, vs what we consider to be there contemporary equivalents. We emphasize these dimensions later in the discussion as a means of examining changing sediment budget and changing impacts of bedrock on the littoral regime and sediment supply to barrier.

Discussion:

We have emphasized the aspects the reviewer pointed out as deficiencies.

We retooled our "identical" comparisons and give a much better picture of exactly how similar and different these features are between modern and relict, please see Table 2.

Line 324 to 328 “Several seafloor features bear striking similarity in plan form to contemporary shoreline features on the sandy and wide (40-100 km) Maputaland-Mozambique coastal plain (Fig. 7a), as well as coastal features that are not represented on the modern SE African coast. Below, following Gardner (2005, 2007), we compare the seafloor topographic features with contemporary coastal landforms as an aid to their interpretation.”

Line 330-339 “The large blocky aeolianite body that occurs at ~ 105 m at the shelf edge (Fig. 4e and f) is similar in shape to the modern barriers of the Maputaland coastline (Table 2), and to some modern barrier islands formed on many wave-dominated coastlines (see Mulhern et al., 2017). Regarding size, the aeolianite body is significantly narrower, with a lower elevation. The seafloor depressions and recurved ridges that attach to the depressions and landward sides of the main ridge line are very similar in shape and conform to the lower size limits of inlets and associated cuspate and recurved spits of major barrier-inlet systems (Table 2), both in southern Mozambique and Maputaland (Fig. 7a and b) and from systems of the southern US Atlantic margin (Cooper and Pilkey, 2002; Pilkey, 2003; Davis and FitzGerald, 2009)”.

Line 347-353. The arcuate prograding ridges along the depression margins, together with the cuspate wedges of Unit 1 aeolianite that separate each lagoon, mark prograding lagoon shorelines and down-drift spit termini of the wave-driven littoral cells of the system, respectively (cf. Ashton and Murray, 2010) (Fig. 7c). These are mostly within the lower size range of the modern systems found along the SE African coasts (Table 2).

Line 360-367. The parabolic ridges and depressions that form in the aeolianite of Unit 1 are very similar in shape and planform scale to those dunes of the contemporary coast (Table 2), though their elevations are markedly lower. Small, blowout-like features are also evident (Fig. 7e). We thus consider that a similar large dune system occurred at some point adjacent to and fringing the barrier islands and segmented waterbodies of the outer shelf. Though of considerably lower elevation, the width is within the ranges reported for the dune fields of southern Mozambique (Fig. 7a) and marks an approximate shoreline depth of 105 m (c.f. Ramsay, 1995).

We have also added new sections as below:

Lines 503-531:

“When comparing the overall scale and size of the relict barrier features on the seafloor to the modern coastlines of SE Africa, we note that although broadly similar in morphology, the sizes of the relict features are diminished when compared to their modern equivalents. The seafloor features are narrower (850 m vs 2 km), with significantly lower relief (15 m vs 170 m). This implies a significant amount of sediment (~ an order of magnitude) was lost as the shoreline translated over the shelf to where it is at present.

The current coastal configuration is mostly bedrock-controlled, with small rock-bound embayments that host isolated barrier-dune complexes. These are significantly smaller than the barriers preserved at -100 m and are more like the crenulate shorelines preserved at -60 m. The landward change in barrier size implies a shift from large and contiguous dune cordons forming during the early transgression, to isolated sandy barriers hosted amidst bedrock. This shift marks the increasing influence of bedrock control and coastal squeeze on shoreline adjustment during transgression. The net result is transformation of the Eastern Cape coast from a straight, littoral drift-dominated feature to a strongly compartmentalised shoreline with limited accommodation and littoral sediment supply.

The sediment for the early dune building phase appears to have been initially sourced from a well-fed littoral system that adjoined a sandy, linear coastline. The net supply of sediment to the coastline from the Kei River alone is substantial, and when coupled to the other large quantities of sediment delivered by the adjoining fluvial systems (Table 2), the shelf and coastline should act as a major sediment depocentre. The current sweeping of the shelf however limits this and rather only exposes relict features at -100 m that are indicative of higher sediment supply and retention rates. During the transgression, the landward effect of coastal pinch by the bedrock framework is also coupled to the progressive diminution of the seaward edge of the large quantity of sediment that was hosted in the -100 m dune system. As the Agulhas Current has impinged further landward, this has steadily removed all but the relict and cemented barrier forms and produced the seafloor facies association discussed below. As Flemming (1981) recognised, coast-parallel sediment transport along the shelf and shelf edge will continue until a change in shelf orientation occurs where the sediment is then lost off-shelf.

(iii) In the end, it is concluded that, "the contemporary shelf morphology reflects the combined effects of relict wave and littoral processes and modern ocean current processes as they were mediated by fluctuating rates of sea-level rise during the last transgression." (L31-33). This general conclusion statement could be written for just about any continental shelf setting, active or passive margin.

This is true, and reflects a weak conclusion. We remove this statement and add the following:

Line 578 to 583 "The coastal evolution can also be tracked using submerged shorelines. These appear to also remain lasting features in the shelf morphology and stratigraphy of current-swept subtropical shelves. Where prominent subsurface bedrock occurs on current-swept shelves, coastal squeeze will be exacerbated due to the increasing disruption of littoral cells, diminishing sediment supply to barrier-shoreline systems and increasing sediment losses to the shelf sediment supply by current sweeping".

(iv) Important parts of the Methods are not reproducible as written. For example, it is stated that, "all (geophysical) data were then interpreted in HIS Kingdom Suite or Hypack SBP…" No information is given about how interpretations were defined and made, how 'Units' were defined and delineated, how existing literature was incorporated into the interpretations, etc. Please be descriptive here.

Remedied to include Line 157-161 " Seismic units were defined by reflector packages, bound by distinct unconformity surfaces where the internal reflectors were either truncated, or where they downlapped, toplapped and onlapped the unconformities (see Mitchum et al., 1977). The units were described according to the internal reflector amplitudes, geometries and continuity and designated a unit name from Unit 1 to 4."

(v) Several results are not shown or observable in the figures. For example, readers are told of "several coast-parallel elongate furrows" in Figures 3b and 4b (L225), but none are readily seen.

These are now very clearly pointed out with arrows and labels in 3c and 4b, with the aid of new, higher relief sunshaded images and more transparent colour overlays.

Also, "the proximal shelf areas are marked by the surface expression of the S1 paleo-valley that form topographic lows where Unit 4 crops out… " (L212). Huh? Proximal to what?

We rephrase this now to say " Inner shelf".

"S1 Paleo-valleys" (1st time these are mentioned)? What are these?

I looked at this very carefully and then rephrased it to Line 237-239 "The inner shelf is marked by several underfilled valleys manifest as elongate seafloor depressions. These are correlated in seismic profile to the incisions associated with surface S1. These palaeo-valleys form topographic lows on the inner shelf where Unit 4 crops out"

These valleys are mentioned earlier.

(vi) The data availability ("made available upon request") does not appear to be consistent with Marine Geology standards. What happens if the communicating author changes email, retires, or is no longer with us?

Unfortunately, we are not allowed to release data before publication by all authors working on these data, but this can be treated on a case by case basis if requests are made. Given the difficulty in collecting even one seismic line here, data is considered sacrosanct.

(vii) Figures are incomplete or not consistent. For example, some of the bathymetric panels in Fig. 4 have relief shading, others do not.

I amended all of these with greater relief exaggeration and more transparent colour overlays.

Different depth ranges are used in most panels of Fig. 4.

These are all now uniform.

The profile in Fig. 2a does not seem to be complete; it should be approximately the same length as b,c,d.

It is the correct length.

No horizontal scales are provided in Fig. 2 and 3.

Thank you for pointing that out, they were on a hidden layer!!! They are now visible.

No geographic information (lat/long) are provided in Fig. 4 and 5.

-These are amended now.

Insets would be very helpful for Fig. 3, 4, 5, just like the inset for Fig. 2.

Amended figure 5, but the other figures are shown in figure 1 and I would rather not clutter things too much.

Many of the key geographical sites are not included in Fig. 1, including these from the Introduction section: Wild Coast, Eastern Cape Province, KwaZulu-Natal, and the locations of previous studies highlighted. Readers will not know the locations of these places.

I have now included the locations for previous studies too, as well as the rivers etc in a new figure 2.

Figure 9 is not complete. The panels are not labeled with a,b,c, etc. Each panel needs an approximate date range. What is the red zone in the 6th panel, and why does it go inland of the water level? Also, include rhodoliths (Unit 5) and new sedimentation (Unit 6), as these are significant features of the study area? Label the final panel with Unit names to show how these were formed/modified?

Have amended as recommended, I am embarrassed I missed that originally.

(viii) The Results define “Units” without presenting the logic for why these are characterized as specific entities.

This is explained in the methods now based on standard seismic stratigraphic procedure.

Presentation of Unit 1 is most problematic, as it is found broadly and intermittently across the shelf (Fig. 2); Unit 4 is similarly intermittent.

These are now very clearly defined on the basis of reflector geometry and spatial distribution

The reader must assume that the authors define the Units with local knowledge, etc., because there is no logic provided for their definition. Please help the reader understand how/why these Units are defined.

We state as above: Seismic units were defined by reflector packages, bound by distinct unconformity surfaces where the internal reflectors were either truncated, or where they downlapped, toplapped and onlapped the unconformities (see Mitchum et al., 1977). The units were described according to the internal reflector amplitudes, geometries and continuity and designated a unit name from Unit 1 to 4. We used the standard practice for defining units.

On a related note, Figure 2 provides a confusing compilation of the Units. Some Units are shown with color, others with text labels.

This is so that the figure is not overwhelmed and only the most important units are coloured so as to draw attention to them. This is mentioned in the figure caption now.

Labels are split between the two panels for each profile. Because Units are an interpretation, shouldn’t they solely be placed on the 2nd (ie interpreted) panel? Using color for each Unit would be nice.

These are split like this so as to avoid cramping of labels. I hope this is ok to leave.

(ix) Interpretation of the data is hindered by the general lack of overlapping data collection to ‘tie’ the geophysics data with the bathymetry data (Fig. 1). This makes connecting the dots between geophysical and bathymetric features difficult, if not impossible, for the reader. Although this cannot be remedied, please keep in mind that readers will be significantly challenged with comparison and interpretation of the two data sets.

This is a tough point to address. We simply have such limited budget to get complete coverage of anything, so this is as best I can do. The area itself is so wild, that surveying is a serious challenge given the small vessels (skiboats) we use to collect data. Perhaps in time we will receive a proper oceanographic vessel and that would help a lot. Until then, I wish I could better address this.

(x) The descriptions in the Results are incomplete. For example, the first description of the bathymetric data states, "Where Unit 1 crops out, the seafloor morphology comprises a variety of plan forms (Fig. 4)" (L194). Note that the authors have already concluded that the bathy data has Unit 1 outcrops without describing to the reader how this conclusion was made.

I am still really unsure of this comment, but I amended this to read:

Where Unit 1 crops out (see Figure 2 for example), the seafloor morphology comprises a variety of ridges that exhibit distinct plan form morphologies (Fig. 4).

Where it breaks the surface is where the various ridges etc. are.

Additionally, Fig. 4 does not include any labels with "Unit 1". Thus, the reader is left confused with questions… Is the entire seafloor shown in Fig. 4 part of Unit 1?

Are the forms labeled in Fig. 4 all Unit 1? These kinds of confusing statements are repeated throughout the Results section.

Amended to show unit 1 outcrop with full labels and arrows.

(xi) Several fundamental research questions should be raised about the evolutionary model (Fig. 9). Why did the massive sand dune fields form during lowstand? What sediment source(s) are attributed to their formation? How is their formation related to the broader coastal morphodynamics? Where did the dune sands go during transgression? Where are they now? A simple order-of-magnitude sediment mass balance would be helpful for this understanding.

I have added much to this, as per the above replies in lines 503-531.

(xii) A number of landforms are described to be "identical", and these comparisons are overstated. The reader is told that the seafloor characteristics are "identical in shape and scale to inlets and associated cuspate and recurved spits of major barrier-inlet systems" (L306), "identical in shape and scale to those dunes of the contemporary coast" (L330), and "identical coastal forms.." (L369). First, measurements of landscape features must be provided to make comparisons, but no measurements were given. These measurements (size, volume, angles, slopes, relief, etc.) would greatly improve the paper. Second, "identical" has a fairly rigorous definition, and it is unlikely to have been met.

You are right, this was not correct. I added a table 2 showing these measurements and their comparisons.

The 'identical' coastal forms (L369) are used to infer similar conditions of "sediment supply, energy and sea level state." Are there instances in coastal morphology where 'identical' coastal forms are developed from different conditions?

This is another toughie, I hope I covered it with caveats etc., though I think we provide a convincing argument.

(xii) There are numerous errors, typos, misspellings, although the authors should be able to clean these up.

Noted and cleaned up.

Highlights

Palaeo-lagoons, inlets and barrier islands mark a -100 m palaeo-shoreline

Barrier complexes formed within embayments mark a -60 m palaeo-shoreline

Rhodolith accumulations, gravel streamers and bedrock exposure signify current-dominated conditions

Current sweeping began ~ 7000 BP

Contemporary morphology reflects relict influences like sea level stillstands, and meltwater pulses

Now strongly current-dominated exposing older shelf morphologies

Relict and contemporary influences on the postglacial geomorphology and evolution of a current swept shelf: the Eastern Cape Coast, South Africa

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Abstract

Few stratigraphic models of continental shelves incorporate the process of geostrophic current-sweeping, consequently its role in the stratigraphic record is often overlooked. We examine the narrow, current-swept Eastern Cape shelf of South Africa using a combination of geophysical techniques, seafloor sampling and video observations and interpret the role of current action on the transgressive stratigraphy of this steep subtropical shelf. During the Last Glacial Maximum, fluvial valleys incised the acoustic basement rocks. During the subsequent transgression, two distinct shorelines were formed and preserved at -105 m and -60 m. Their development and preservation is linked to (i) high sediment supply from adjacent fluvial sources, (ii) early diagenesis and (iii) alternating sea-level stillstands and periods of rapid sea-level rise during melt water pulses 1A and 1B, respectively. The deeper shoreline formed in a sandy, wide coastal plain setting with limited bedrock influence, whereas the shallower shoreline comprised alternating rock headlands and embayments like the contemporary coast. Differences in antecedent topography and geology are responsible for the temporal variability in shoreline type.

Between the two shoreline complexes, in the mid-shelf, the transgressive stratigraphy records initial valley infill by progradation of coast-parallel sandy spits . These are capped by a stiff lagoonal mud deposited as ongoing sea-level rise overspilled the valley interfluves, onlapping the adjacent aeolianites. The uppermost stratigraphy comprises mounds of rhodoliths which interfinger with a sandy inner to middle shelf highstand wedge.

After sea-level reached its present position ca 7.4 ka yr BP, the shelf became subject to reworking by the high-energy, geostrophic Agulhas Current. This has had the following major effects on the shelf stratigraphy: 1. the topographic relief of the cemented palaeo-shorelines has been emphasised by removal of the post-transgressive cover; and 2. The shelf no longer acts as a depocenter; instead, the seabed consists of rhodoliths, gravel streamers, bedrock or gravel hash of the wave ravinement surface. Given the necessary antecedent conditions such as accommodation, sediment supply and favourable diagenetic climate, prominent shorelines can form and be preserved on the shelf. Strong current sweeping emphasises these morphological features on subtropical shelves.

Key words: palaeo-shorelines, barrier islands, melt water pulse, current-dominated shelf, Agulhas Current

1. Introduction

The southeastern shelf of South Africa, off the rocky and high-energy “Wild Coast” of the Eastern Cape Province, is little known in comparison to the adjacent shelves of KwaZulu-Natal (Green et al. 2018; Pretorius et al., 2019) to the north and the Southern Cape to the south (Cawthra et al., 2016; Flemming and Martin, 2018). The combination of a narrow and shallow shelf with the south-westward-flowing Agulhas Current, one of the fastest flowing boundary currents on the globe, results in a shelf that is strongly modified by current activity. To date, there are few studies that incorporate current sweeping into models of shelf stratigraphy and morphology (cf. Cawthra et al., 2012) and little is known of the processes that control the development and preservation of such features in the stratigraphic record. A key gap in knowledge is how coastal evolution is influenced by shelf-sweeping, coupled to sea-level rise, i.e. how does a coastline evolve as the shelf is drowned and becomes increasingly swept by oceanic currents?

The morphology and Quaternary/Holocene evolution of the Eastern Cape shelf is poorly studied, and little attention has been paid to shelf geomorphology and stratigraphy despite the current-swept nature of the area having been long identified (Flemming, 1980). Martin and Flemming (1987) notably documented a series of prominent outcropping palaeo-shorelines in the area, which along adjacent shelves, have since been more closely examined and recognised as exceptionally well-preserved and geomorphologically complex shoreline features (Green et al., 2018). These features provide abundant opportunities to examine shoreline changes in both time and space and importantly provide insight into long-term shoreline behaviour over centennial to millennial scales (Cooper et al., 2018a; Mellet and Plater, 2018). Such insights are often lacking from current-swept areas where sediment retention is limited by erosion.

Current-swept shelves typically comprise thin veneers of sandy/gravelly sediments (the palimpsest sediments of Swift, 1974), which mantle a relatively flat and low-relief bedrock outcrop (Shideler and Swift, 1972; Toscano and Sorgente, 2002; Coffey and Read, 2004; Green and Garlick, 2011; Flemming and Martin, 2018). However, under certain circumstances, e.g. sufficient antecedent accommodation and sediment supply, rapid sea-level rise and a climate that fosters rapid carbonate diagenesis, large-scale submerged shorelines may be preserved and exposed as spectacular seafloor features by the current action. Notable examples include the Loop Current-exposed Pulley Ridge of SW Florida (e.g. Locker et al., 1996; Jarrett et al., 2005), the Bass Cascade and Bass Strait-influenced Gippsland Shelf of SE Australia (Brooke et al., 2017), the Leeuwin Current-influenced Carnarvon (Nichol and Brooke, 2011) and Rottnest shelves of Western Australia (Brooke et al., 2017) and the Agulhas Current-dominated KwaZulu-Natal shelf of SE Africa (Green et al., 2013a; Green et al., 2014). In these instances, several drivers operate to define the shelf stratigraphy and geomorphology and may include longer-term allocyclic processes such as rate of sea-level fluctuation (Locker et al., 1996; Salzmann et al., 2013), shorter term or near instantaneous allocyclic processes such as oceanographic forcing (Flemming, 1980; 1981), and long-term autocyclic conditioning of shelf gradient and palaeo-topography (e.g. Green et al., 2018; Kirkpatrick et al., 2019).

The broad aim of this paper is to investigate the morphological and stratigraphic evolution of a typical current-swept shelf, with focus on the Eastern Cape shelf of South Africa (Fig. 1). We examine the fundamental drivers of shelf evolution including (i) sea-level changes during the last glacial cycle and (ii) contemporary ocean dynamics. Thereby we aim to (1) describe the shelf stratigraphy and surface morphology; (2) identify modern and relict seafloor features (3) interpret the origin and genesis of seafloor features; and (4) present a model for current-swept shelf evolution driven by relict and modern forcing agents. This is compared to other similar shelves around the globe.

2. Regional setting

The southeast African continental margin is a sheared passive margin along which South America separated from southern Africa during the initial opening of the South Atlantic (Scrutton and Du Plessis, 1973). Regionally, it is exceptionally straight and narrow, but on a local scale, there are extensive variations in morphology, especially in the distribution of canyons and other irregularities on the continental slope (Flemming, 1981; Dingle et al., 1983). The East London shelf break occurs between 110 m and 120 m depth (Fig. 1), with a shelf width that varies between 19 km to 23 km, making it narrower and slightly shallower than the world average of 75 km and 130 m, respectively (Flemming, 1981). The shelf gradient varies, with a shallower gradient ca. 1.4° in the outer shelf, steepening up to 2.9° in the inner to middle shelf (Dlamini, 2018). The adjoining coastline is fragmented by a series of zeta (half-moon) bays of which their origin is related to the brittle deformation phases associated with the break-up of Gondwana (Watkeys, 2006).

The continental margin of southeast Africa is a high-energy environment dominated by south-westerly swells. The entire coast is subject to high-energy swells (Hs 2.1 m; T 11 s; HRU 1968), where the significant wave heights for 1, 0.1, and 0.01% exceedance are around 3.9 m, 5.0 m, and 6.0 m, respectively (Rossouw 1984). Swell heights commonly range between 1 and 2 m, with the largest recorded swell (12–13 June 1997) in the last 22 years having a significant wave height (Hs) of 9.3 m (Dixon et al., 2015). Spring tidal range is between 1.8 and 2.0 m, and neap tidal range is 0.6 to 0.8 m (HRU 1968). The mid-outer shelf is dominated by the Agulhas Current, a fast poleward-flowing geostrophic current that can reach surface velocities of >2.5 m/sec (Pearce et al., 1978). Along the shelf margin giant waves may be formed by the propagation of high swells into the current (Mallory, 1974; Smith, 1976).

The study area comprises Gondwana-age sedimentary rocks of the Karoo Supergroup that are onlapped by Cretaceous through to Quaternary age sedimentary rocks. Sandstones and shales of the Karoo Supergroup crop out along the coastline and are overlain by limestones of the Cretaceous Igoda Formation (Dingle et al., 1983). Calcareous sandstones of the Neogene Nanaga Formation occur locally, together with shelly sands, soils and middens of the Pleistocene-age Schelmhoek Formation (Roberts et al., 2006).

Along the coast and on the shelf, a variety of Pleistocene to Holocene age beachrocks and aeolianites are found (Roberts et al., 2006). These aeolianites comprise the Nahoon Formation, a former parabolic dune complex deposited at ~200 ka (Le Roux, 1989) and since bevelled into a series of raised shore platforms that occur at 4 to 5 m above mean sea level and mean sea level, respectively. The upper platform is mantled by a coquina of assumed Marine Isotope Stage (MIS) 5e age (Roberts et al., 2006). Unconsolidated sediment mantles these in places and occurs as a narrow wedge of shelf sediment that forms the contemporary shoreface (Flemming, 1981).

Sediment is supplied to the coast via three main river drainage systems, the Kei, Mzimvubu and Great Fish Rivers (Table 1). The Great Fish and Kei River catchments supply 11.48×10^6 m^3 and 11.134×10^6 m^3 of sediment to the coast respectively (Table 1) (Flemming, 1981). The Mzimvubu River debouches to the north and when combined with the Mbashe River, provides a further 10.458×10^6 m^3 of fluvial sediment per year. The zone between the Great Fish and Mzimvubu Rivers was identified by Flemming (1981) as a discrete sediment compartment supplied by the above rivers and mostly dominated by current sweeping of the adjacent shelf. According to Rooseboom (1978), this entire coastal strip is characterised by annual sediment yields that range from 150 t/km^2 up to 800 150 t/km^2 per year.

Martin and Flemming (1987) identified a series of palaeo-coastlines on the shelf at a depth of 60-70 m, and at the shelf edge (-100-105 m). These shorelines extend for over 600 km to the north of the study area (Green et al., 2014) and are thought to have formed when sea levels occupied depths of 100 m ~ 14 600 yr BP (Green et al., 2014) and ~ 60 m between 13 000 and 12 500 cal yr BP (Cooper et al., 2018b).

3. Methods

Ultra-high-resolution seismic data were collected aboard the RV Meteor cruise M123 in February 2016. The data were acquired with an Atlas PARASOUND parametric echosounder using a primary low frequency of 4 kHz. Navigation was provided by a differential GPS (DGPS) capable of ~ 1 m accuracy in the X and Y domains.

The data were processed with Atlas PARASTORE, where the sea bottom was tracked, the data match-filtered and swell corrected, time varied gains were applied, and the processed data exported in SEGY format. All data were then interpreted in IHS Kingdom Suite or Hypack SBP utility. Sound velocity estimates of 1 500 ms^{-1} in water and 1 600 ms^{-1} in sediment were applied for all time-depth conversions.

Seismic units were defined by reflector packages, bound by distinct unconformity surfaces where the internal reflectors were either truncated, or where they downlapped, toplapped and onlapped the unconformities (see Mitchum et al., 1977). The units were described according to the internal reflector amplitudes, geometries and continuity and designated a unit name from Unit 1 to 4.

Multibeam data were collected using two different systems. Data offshore Morgan Bay, East London shelf edge and the Mazeppa Bay area were collected using a Reson 7125 multibeam echosounder coupled to a DGPS and Applanix POS-MV motion reference unit. The data were collected and processed by Marine Geosolutions Pty Ltd., and resolve to a 1 x 1 m grid, with a depth resolution of ~ 30 cm. Backscatter data were collected simultaneously with a Klein 3000 side scan sonar system with a scan range of 75 m using the 500 kHz channel. The data were processed using the Klein SonarPro software, where the bottom was manually tracked, the data were filtered, time varied gains applied, the channels colour balanced and the nadir zone removed for seamless mosaicking. The final data set resolve to a mosaic pixel approximating 1 x 1 m.

The second set of multibeam data were collected aboard the RV Ellen Khuzwayo, voyage 159, using a Reson 7101 ER multibeam system, coupled to a DGPS and a SBG Systems Ekinox-D INS motion reference unit. All soundings were reduced to mean sea level during processing. The final data were output as a 5 x 5 m resolution grid, with a depth resolution of ~ 50 cm. Co-registered pseudo-side scan sonar data were collected as Snippets for backscatter mapping, the final output of these on the same horizontal scale as the bathymetry data.

Seafloor materials were sampled using a benthic sled, a Shipek grab and a dredge, depending on the substrate; rocky substrate necessitated a dredge as opposed to the less consolidated materials such as mud and sandy material/gravels. Sampling was mainly done for biological purposes and as such, not all the bathymetric and backscatter features observed were sampled.

An intact rhodolith was selected for ^{14}C dating using accelerator mass spectrometry (AMS). Two samples, one from the centre of the rhodolith, the other from the exterior were analysed. Calibrated ages were calculated using the Southern Hemisphere atmospheric curve SHCal13

(Hogg et al., 2013). A reservoir correction (DeltaR) of 161 +/- 30 was applied to coralline material. Analyses were performed by Beta Analytic in their Florida radiocarbon facilities.

4. Results

4.1. Seismic stratigraphy

The seismic stratigraphy of the study area is shown in figure 3 (a-d). The acoustic basement comprises a series of moderate to high amplitude, inclined parallel reflectors. These dip seawards at ~ 2º and are truncated by an erosional surface, S1, marked by incised valleys up to 20 m deep in the middle shelf (Fig. 3c and d). These valleys abut a series of pinnacles and ridges of acoustically opaque material (Unit 1) that span the middle shelf to shelf edge, the bases of which occur at depths of 105 m. To seaward of the most landward ridge, a tangential oblique-prograding wedge of material onlaps the ridges (Unit 2) (Fig. 3a; c and d) and progrades into the valleys (Fig. 3d). In some areas, this wedge appears acoustically transparent (Fig. 3b). A thin (<2 m) body of discontinuous, wavy to horizontal, low amplitude reflectors (Unit 3) locally onlaps Unit 2 and interfingers with the overlying units (Fig. 3a and b).

Units 1, 2 and 3 are all in turn onlapped by a finely layered, low amplitude set of reflectors (Unit 4) that spill out of the middle shelf incised valleys (Fig. 4) and terminate behind the main ridges that comprise Unit 1 (Fig. 3b-d). This forms a meter-thick package that is exposed at the seafloor (Fig. 3b-d; 3). In the middle shelf, this forms an acoustically transparent, landward pinching wedge of material that onlaps the ridge on its landward side and overlies the incised valleys in the more proximal middle shelf regions (Fig. 3d).

Overlying Unit 4 in the middle to outer shelf is an internally complex mound characterised by chaotic and discontinuous, landward and seaward dipping reflectors (Unit 5) (Fig. 3). These interfinger to landward with moderate amplitude, sigmoidal prograding reflectors of Unit 6. Along coastal strike, Unit 6 forms a coast-parallel prograding body of sediment. These units are separated from the underlying units by a high amplitude erosional reflector, S2, that truncates the lower units (Units 1-4) (Fig. 3 and 4). S2 is exposed along the seafloor from the middle shelf to outer shelf.

4.2. Seafloor morphology

The spatial attributes of the main seafloor morphological features are described in table 2. Where Unit 1 crops out (see Figure 3 for example), the seafloor morphology comprises a variety of ridges that exhibit distinct plan form morphologies (Fig. 5). The shallowest areas are characterised by a series of parabolic-shaped ridges and depressions (Figs 3, 4 and 5a) that crop out at their seaward edge at ~ 60 m depth. The ridge reliefs vary between 1 to 7 m, with the parabolic forms spaced ~ 500 m apart (Table 2). Along strike and at similar depths, Unit 1 takes the form of narrow (≤ 80 m) crenulate ridges 0.5 to 2 m in relief, superimposed on basement rocks that crop out as strongly SE-NW orientated, blocky seafloor (Fig. 5b).

In the middle shelf areas, between 60 and 80 m depth, the parabolic ridges and depressions of Unit 1 form cuspate features that separate semi-circular seafloor depressions, > 2 km-wide and up to 6 m in vertical relief (Fig. 5c and d; Table 2). The edges of these depressions are characterised by multiple, prograding arcuate ridges, up to 4 m in relief and spaced ~ 200 m apart (Fig. 5c).

The outer shelf is mostly characterised by subdued relief seafloor between 80 and 90 m deep. A large, coast parallel ridge of Unit 1 occurs throughout the study area, the seaward fringe of which occurs at -100 m (Fig. 5e and f; Table 2). In some areas, this ridge forms a feature with up to 15 m relief, with multiple recurved ridges attached to its landward flank (Fig. 5e). The recurved ridges are ~ 250 to 350 m-wide, with relief of up to 4 m. Depressions up to 2 m are evident in the ridge (Fig. 5e and f), forming low-lying areas on the seafloor in which smaller, prograded ridges of ~ 0.5 m relief and 40 m spacing occur (Fig. 5e). In other areas, cuspate, landward-narrowing ridges occur along the main ridge line, forming triangular seafloor features 300 to 500 m long (Fig. 5f; Table 2).

The inner shelf is marked by several underfilled valleys manifest as elongate seafloor depressions. These are correlated in seismic profile to the incisions associated with surface S1. These palaeo-valleys form topographic lows on the inner shelf where Unit 4 crops out. These areas are also characterised by the presence of mounds of Unit 5, where they form in some of the depressions. The palaeo-valleys extend into the semi-circular seafloor depressions and into the low-relief and deeper seafloor landward of the -100 m ridge (Fig. 5).

4.3. Seafloor backscatter and sediment characteristics

The more proximal middle shelf comprises even-toned high backscatter seafloor, confined to the topographic low of the underfilled incised valley (Fig. 6a). This merges with moderate and irregular backscatter where the valley widens towards the semi-circular depressions (Fig. 6a). On either side of the valley, high relief, irregular and alternating moderate to high backscatter seafloor marks the parabolic ridges and depressions of Unit 1, respectively. This seafloor texture to the outer shelf. The lower relief areas of the semi-circular depressions are characterised by moderate, even toned backscatter.

Several coast-parallel elongate furrows are evident on the middle to outer shelf (Fig. 4b and 4b). These form linear depressions up to 30 cm deep and are associated with linear patches of high backscatter (Fig. 6). These overprint the low relief sea floor features and mark the surface exposure of S2. Throughout the study area, isolated patches of rippled, alternating high to low backscatter seafloor are apparent.

Seafloor inspections reveal the even-toned high backscatter areas to comprise weakly laminated, stiff, muddy deposits (Fig. 6; 7a). In the proximal underfilled incised valley, this is mantled by sandy material with mud cropping out in the depressions of current ripples (Fig. 1; 7b) The adjoining moderate and irregular backscatter seafloor is paved by a thin cover of rhodoliths (Fig. 6; 7c). In contrast, on the middle to outer shelf, the mounds of Unit 5 comprise stacked accumulations of rhodoliths (Fig. 3; 7c). AMS ^{14}C dates of the interior of the rhodoliths ranged from 7406 - 7225 cal yr BP, with their surface material dating to present day (150 cal yr BP to Post-Bomb).

The high relief, alternating high and moderate backscatter ridges and depressions correspond with aeolianites cropping out along the seafloor (Fig. 7d). The lower relief seafloor marks outcrop of subdued relief rocky material. The interleaving seafloor where S2 crops out is marked by pebbles and cobbles of reworked aeolianite, together with finer bioclastic material (Fig. 7e). The linear depressions of high backscatter are likewise lined by similar material (Fig. 7f). The isolated areas of rippled, alternating high to low backscatter represent isolated patches of rippled bioclastic material interspersed with quartzose sand.

5. Discussion

5.1. Seismic stratigraphic interpretation

Aeolianites of Unit 1 at -105 m and shallower abut and overlie S1, the last glacial maximum (LGM)-age subaerial unconformity that is commonly recognised across the SE African shelf (Green et al., 2013a). We refer to these as the -100 m and -60 m shorelines based on these previous works. Incised valleys formed in S1 relate to the LGM lowstand and constrain the age of the aeolianite sequences to the most recent postglacial period (Pretorius et al., 2016; Cooper et al., 2018b; Pretorius et al., 2019).

The tangential oblique-prograding wedge of Unit 2 that onlaps the aeolianites and enters the incised valleys is architecturally similar to spit systems recognised from multiple large incised valley systems, lagoons and lakes of the east coast of South Africa (Wright et al., 2000; Benallack et al., 2016) and from shelf to lake environments elsewhere around the world (Novak and Pederson, 2000; Raynal et al., 2009; Nutz et al., 2015). In keeping with this interpretation, the chaotic and discontinuous reflectors of Unit 3 are similar to features identified elsewhere as small-scale slump or mass wasting packages in waterbodies characterised by active spit progradation (Wright et al., 2000; Rucińska-Zjadacz and Wróblewski, 2018).

Seafloor sampling and observations reveal Unit 4 to comprise stiff muddy materials. The stratigraphic position as a capping and overspilling unit of the incised valleys points to deposition in a lagoonal environment that overtopped the interfluves and ponded along the shelf behind the barrier systems of Unit 1 (e.g. Green et al., 2013b; Benallack et al., 2016).

The intercalating upper units 5 and 6 represent the contemporary Holocene shelf sediment prism which interfingers with the rhodolith mounds indicating that the two were deposited and evolved contemporaneously. Studies of the Holocene sediment prism in SE Africa indicate a mid-Holocene to recent age (Pretorius et al., 2016) which correlates with the age at which Holocene sea level stabilized close to the present (Cooper et al., 2018b) and the rhodolith mounds began to form (7406 - 7225 cal yr BP).

Surface S2 outcrop represents the seafloor exposure of the Holocene wave ravinement surface. This surface truncates the spit/barrier/lagoon sequences and separates the post-transgressive Holocene material from the underlying transgressive succession. The mixed bioclastic and aeolianite pebbly material (Fig. 7f) is similar to the material forming from the contemporary wave ravinement of beachrocks and aeolianites in SE Africa (Cooper and Green, 2016). The exposure of this material in elongate furrows provides evidence for current furrowing that has denuded the mid to outer shelf of sandy sediment and exposed the underlying wave ravinement surface to geostrophic current reworking, forming gravel streamers and ribbons (Flemming, 1978).

The development of rhodolith fields since ca. 7.4 ka yr BP provides further evidence of strong Agulhas Current action since sea levels stabilised close to the present. Prior to this, the current flowed seaward of the shelf edge and did not support the growth of rhodoliths in this position. Intact rhodoliths that interfinger with the Holocene sediment wedge indicate episodic wedge progradation into current-agitated waters where the rhodoliths nucleated, as opposed to punctuated re-deposition of the rhodoliths by gravity or storm driven processes (evidenced elsewhere by broken rhodoliths, interspersed with pebbly gravels (Brandano and Ronca, 2014)). This conforms to Flemming's (1981) model of the regional shelf; an inner siliclastic wave-dominated system and an outer Agulhas Current-dominated shelf. In microcosm, this matches the shelf/carbonate platform-drowning model of Betzler et al. (2013), in which swift sea-level rise produces partial shelf drowning and current sweeping of the shelf. This thus places the timing of mid-shelf transgression to a minimum age of 7406 – 7225 cal yr BP and implies a sudden increase in the rate of sea-level rise that post-dates a regional sea-level slowstand recognised by De Lecea et al. (2017) ~ 8000 cal yr BP.

5.2. Seafloor morphology

Several seafloor features bear striking similarity in plan form to contemporary shoreline features on the sandy and wide (40-100 km) Maputaland-Mozambique coastal plain (Fig. 8a), as well as coastal features that are not represented on the modern SE African coast. Below, following Gardner (2005, 2007), we compare the seafloor topographic features with contemporary coastal landforms as an aid to their interpretation.

5.2.1. -100 m shoreline

The large blocky aeolianite body that occurs at ~ 105 m at the shelf edge (Fig. 5e and f) is similar in shape to the modern barriers of the Maputaland coastline (Table 2), and to some modern barrier islands formed on other wave-dominated coastlines (see Mulhern et al., 2017). Regarding size, the aeolianite body is significantly narrower, with a lower elevation than the contemporary Maputaland coastal barrier. The seafloor depressions and recurved ridges that attach to the depressions and landward sides of the main ridge line are very similar in shape and conform to the lower size limits of inlets and associated cuspate and recurved spits of contemporary major barrier-inlet systems (Table 2), both in southern Mozambique and Maputaland (Fig. 8a and b) and from systems of the southern US Atlantic margin (Cooper and Pilkey, 2002; Pilkey, 2003; Davis and FitzGerald, 2009). Breaks in the ridge, marked by topographic lows are of a similar shape and dimension to tidal inlets, an interpretation that is supported by their location adjacent to recurved features (Fig 4e). These are up to 200 m-wide and ~ 5 m-deep, consistent with figures reported for inlets worldwide (Davis and FitzGerald, 2009). The adjacent low relief areas landward of the main inferred barrier positions are interpreted as the palaeo-back barrier environments through which the incised valleys passed during the LGM lowstand (Fig. 7e).

The large, semi-circular seafloor depressions (Fig. 8c) that occur slightly distal to the barrier are interpreted as a series of drowned and segmented lagoons. The arcuate prograding ridges along the depression margins, together with the cuspate wedges of Unit 1 aeolianite that separate each lagoon, mark prograding lagoon shorelines and down-drift spit termini of the wave-driven littoral cells of the system, respectively (cf. Ashton and Murray, 2010) (Fig. 8c). These are mostly within the lower size range of the modern systems found along the SE African coast (Table 2). The depressions correlate directly to landwards with the outcropping, overspilled muddy facies of Unit 4.

These segmented lagoons are fed by several underfilled incised valleys that clearly mark the palaeo-fluvial pathways that entered these lagoons. These fluvial entrance points are similarly recognised in the contemporary setting of coastal waterbodies in SE Africa (Table 2) (Fig. 8d).

A significant modern barrier system extends from Richards Bay, ~ 650 km north of the study area into southern Mozambique (Jackson et al., 2014). This system is marked by a series of northeastward oriented, climbing parabolic dunes that can reach up to 120 m high, covered with multiple blowout features. The parabolic ridges and depressions that form in the aeolianite of Unit 1 are very similar in shape and planform scale to those dunes of the contemporary coast (Table 2), though their elevations are markedly lower. Small, blowout-like features are also evident (Fig. 8e). We thus consider that a similar large dune system occurred at some point adjacent to and fringing the barrier islands and segmented waterbodies of the outer shelf. Though of considerably lower elevation, the width is within the ranges reported for the dune fields of southern Mozambique (Fig. 8a) and marks an approximate shoreline depth of 105 m (c.f. Ramsay, 1995).

5.2.2. -60 m shoreline

At -60 m, a former shoreline lineation is also evident. In planform this is manifest as a series of palaeo-embayments, fringed by small aeolianite ridges of similar widths to the lower limits of the primary dunes found along the embayed mixed-sand and rock coastlines of SE Africa (Jackson et al., 2014). The palaeoheadlands are formed in bedrock of the Karoo Supergroup, separated by crenulate ridges of Quaternary aeolianite (Fig. 9a) that also rest on Karoo bedrock. This is a similar coastal morphology to that of the present day, where thin outcrops of aeolianite and beachrock rest with marked unconformity on older sedimentary rocks in embayments between prominent bedrock headlands (Fig. 9b and c).

Some of the embayments on the contemporary coast are also marked by modern barriers/Holocene age dunes (Table 2) (Fig. 9c) and this configuration too appears to be reflected on the seafloor (Fig. 9a). Their presence indicates that the coastal evolution at the time of their formation was strongly influenced by the bedrock framework, as is the modern coast (Watkeys, 2006). Similarly, their form and structure point to a shoreline occupation at a depth of 60 m where planform equilibrium forms developed in coastal re-entrants (Carter, 1980).

5.3. Postglacial evolutionary model

The contemporary shelf morphology reflects a combination of influences of wave and ocean current processes acting on the pre-existing basement geology. These have operated with varying intensity and at different locations as sea level fluctuated during the last glacial cycle and the deposits and geomorphic features of each successive interval have influenced subsequent evolution. The sequence of events and associated dynamics are discussed below in the context of an evolutionary model for the shelf.

Initially, the narrow and shallow shelf was dissected by several fluvial systems during lowstand conditions culminating in the LGM (Fig. 10a). Two main river systems in the area formed valleys of similar scale to those on the modern coast. At this time, wave action was focussed off the modern shelf break, as was the palaeo Agulhas Current. During subsequent sea-level rise wave processes reworked existing sediment and formed distinctive coastal landforms that are preserved at several specific levels on the seafloor. These shoreline features indicate marked differences in shoreline type at various stages of the transgression and their preservation or non-preservation is linked to rates of sea-level change.

The generation of a substantial barrier system at ~ 100 m depth (Fig. 10b) can be linked to patterns of stable sea level that allowed planform equilibrium for the palaeo-coastline to be reached. It contains features similar to the contemporary highstand coastal systems of northern KwaZulu-Natal and southern Mozambique (Green et al., 2013b), from which we infer similar conditions of sediment supply, energy and sea level state at the time of formation (see below). These strongly contrast with the sediment-poor, headland bound and rocky setting of the contemporary coastline of the Eastern Cape.

Stable or slowly rising early Holocene sea levels promoted barrier growth, overspilling of incised valleys and lateral extension of newly forming lagoons, with a general planform equilibrium reached for the lagoon bodies (Fig. 10c). New accommodation was not generated quickly, and the back barrier behind the -100 m barrier could be overfilled to compensate. The prograded lagoon margins on contemporary lagoons in SE Africa (Wright et al., 2000; Botha et al., 2018) are attributed to minor sea-level fall of +/- 2 m from a late Holocene highstand to the present (Cooper et al., 2018b). The prograded lagoon margin features at -100 m may indicate similar patterns of sea-level fall around the LGM (Fig. 10d). This is consistent with new findings regarding the nature of the LGM sea level which dropped from -100 m stillstand to a maximum of -118 m (Yokoyama et al., 2018) between 21 900 and 20 500 yr BP.

The behaviour of barrier shorelines in the context of rising sea level is discussed by Carter (2002), who considered three main modes of barrier response, erosion, rollover, and overstepping. A fourth possible mechanism is partial overstepping, whereby remnants of the barrier are left after a portion of the barrier is eroded as the shoreface translates over the barrier form. Overstepping has been considered the main mechanism responsible for the preservation of the palaeo-shorelines from SE Africa, associated with particularly abrupt phases of sea-level rise and in place drowning the coast (Green et al, 2014). We further this hypothesis by linking the overstepping of the -100 m shoreline to melt water pulse 1A (Fig. 10e). This rapid rise in sea level from ~ -100 m (~ 4 m per century, with a 95% probability of between 8.6 and 14.6 m rise globally-Liu et al., 2016) would have been sufficient to overstep the fronting barrier system (Fig. 10d). The lagoonal deposits landward of the -100 m barrier shoreline also bear witness to the rapid creation of accommodation space in the back barrier and an associated reduction in the efficacy of the bay-ravinement process as the barrier and back-barrier were submerged (cf. Storms and Swift, 2003; Storms et al., 2008). The high gradient of the wave ravinement surface (up to 4^{o}), bounding the surface of the lagoonal/back barrier deposits (Fig. 3) indicates a steepened shoreline trajectory during overstepping. Salzmann et al. (2013) consider causes for steepened shoreline trajectories to include steep transgressed topographies, rapid rates of RSL rise and high rates of sediment supply (based on the work of Cattaneo and Steel, 2003). On this sediment-starved shelf, high sedimentation rates during infilling of the back barrier can be discounted (e.g. Green, 2009, 2011; Salzmann et al., 2013).

We hypothesise that relatively slower rates of sea-level rise then followed, with widespread shelf ravinement (denoted in red in Figure 10) removing all but the cores of the barrier system surrounding the segmented lagoons and leaving the low-lying depressions of the lagoons intact (Fig. 10f). This slower rate of sea-level rise is linked to the Younger Dryas period that preceded a second meltwater pulse (MWP 1-B) (see Pretorius et al., 2016 for timing of other shoreline development at the same depth). At this time and where available accommodation occurred, shorelines developed within embayments (Fig. 10f). These were then overstepped by MWP 1-B (11.5–11.1 ka BP-Harrison et al., 2019) (Fig. 10g), leaving a subsequent set of smaller aeolian dune fields, some of which are preserved within embayments as relict shelf features. Sea level has since risen to present day, where the contemporary coast is strongly bedrock-dominated with multiple embayments bounded by rock headlands (Fig. 10h).

5.4. Local controls on stratigraphic and geomorphic evolution.

The model that has previously been developed to describe the occurrence and preservation of submerged postglacial shorelines, is based on temporally varying rates of sea-level rise linked to paired slowstands (gradual and slowly rising sea level) and subsequent melt water pulses (see Green et al., 2014; 2018). The present study includes additional observations of submerged shorelines at depths consistently seen at 60 and 100 m across the narrow portions of the SE African shelf (c.f. Green et al., 2018; Pretorius et al., 2019). Across the entire shelf, large volume, submerged planform equilibrium barriers and back barrier environments at -100 m and -60 m, stretch for over 1000 kms alongshore from southern Mozambique (De Lecea et al.,

2017) to the present study area. This mirrors to some degree, submerged relict shorelines on the southwestern African margin in Namibia (Kirkpatrick et al., 2019). Repeating forms such as drowned segmented lagoons (e.g. Green et al., 2013a), parabolic dune fields (Green et al., 2018) and underfilled incised valleys (Pretorius et al., 2019) are common, yet occupy areas of significant variation in antecedent shelf setting, e.g. narrow vs wider shelves, numerous steep-sided incised valleys vs flat planation surfaces.

Numerous similar examples of submerged shoreline features have been reported from other current-swept sub-tropical shelves. On the Gippsland and Lacepede shelves of SE Australia, a series of coast-parallel ridges are found at depths of ~65-75 m. These were interpreted as relict strandplains and barriers (Brooke et al., 2017). Other examples from similar depth ranges are found on the Recherche and Rottnest shelves of Western Australia, together with relict carbonate-cemented dunes (Brooke et al., 2014). On the Carnarvon shelf, coral reefs and carbonate-cemented dunes are similarly apparent at ~ 60 m (Nichol and Brooke, 2011). Around depths of ~ 100 m, erosional knickpoints (the Lacepede shelf, Hill et al., 2009), coral reefs and occasional associated lagoons (the NW Australian and Sahul shelves, Nichol et al., 2013; Howard et al., 2016) have also been reported.

An episodic sea-level rise model is required to develop these submerged shoreline features at consistent depths and ages on a global scale. However, antecedent shelf geometry is also an important local consideration on shelf evolution. The steep gradient (up to 2.9°) of the SE African shelf would, theoretically, lower the preservation potential of shoreline features due to focused erosion along a steep profile for any given unit of time during transgression (Cattaneo and Steel, 2003). Where exposed, the barriers clearly comprise cemented sandy aeolianites and it is thus likely that it is the cementation, in conjunction with the driver of rapid rates of sea-level rise (c.f. Green et al., 2018), that is responsible for the preservation of these relict coastal forms on the shelf.

The overall weak preservation of shoreline forms, and a dominantly erosional or current swept seafloor between the outer barrier and the - 60 m shoreline can be related to strong ravinement processes, first by the aggressive wave climate during landward translation of the wave base, and then by oceanic current denudation once sea level had passed over the palaeo-coastal profile. On this steep shelf (1-3°), the implication is that the shoreline migrated *slowly* between the landward edge of the -100 m shoreline and the seaward edge of the -60 m shoreline. During this period, transgressive erosion was maximised and only small remnants or cores of once much larger dune systems, were left.

This contrasts with the higher relief, outer shelf where the former coastal barriers are better preserved. The lack of sediment cover in these areas is attributed to sediment being held in the shoreface under sediment-deficit type conditions as the shoreline transgressed the palaeo-coastal plain (Mellet and Plater, 2018). Any sediment that was potentially deposited as a transgressive layer was subsequently removed by the current sweeping that formed the gravel streamers observed on the modern shelf. Simultaneously, the barrier system would continue to roll over to a point where smaller parabolic dunes and palaeo-embayments/shorelines could form (at -60 m). This period marks a likely slowing of the rate of relative rise which is identified on other shorelines at depths of 60 m from the Durban shelf (Pretorius et al., 2016; Cooper et al., 2018b) and elsewhere e.g. SE and Western Australia (Brooke et al. 2017), SE Brazil (Cooper et al., 2016, 2018c).

When comparing the overall scale and size of the relict barrier features on the seafloor to the modern coastlines of SE Africa, we note that although broadly similar in morphology, the sizes of the relict features are smaller than their modern equivalents. The seafloor features are narrower (850 m vs 2 km), with significantly lower relief (15 m vs 170 m). This implies that a significant amount of sediment (~ an order of magnitude in terms of width and height) was lost as the shoreline translated over the shelf to where it is at present.

The current coastal configuration is mostly bedrock-controlled, with small rock-bound embayments that host isolated barrier-dune complexes. These are significantly smaller than the barriers preserved at -100 m and are more like the crenulate shorelines preserved at -60 m. The landward change in barrier size implies a shift from large and contiguous dune cordons forming during the early transgression, to isolated sandy barriers hosted amidst bedrock. This shift marks the increasing influence of bedrock control and coastal squeeze on shoreline adjustment during transgression. The net result is transformation of the Eastern Cape coast from a straight, littoral drift-dominated feature to a strongly compartmentalised shoreline with limited accommodation and littoral sediment supply.

The sediment for the early dune building phase appears to have been initially sourced from a well-fed littoral system that adjoined a sandy, linear coastline. The net supply of sediment to the coastline from the Kei River alone is likely to have been substantial, and when coupled to the other large quantities of sediment delivered by the adjoining fluvial systems (Table 2), the shelf and coastline should act as a major sediment depocentre. The Agulhas Current sweeping of the shelf, however, limits the potential for sediment accumulation and rather exposes relict features at -100 m that are indicative of former high sediment supply and retention rates. During the transgression, the landward effect of coastal pinch by the bedrock framework is also coupled to the progressive diminution of the seaward edge of the large quantity of sediment that was formerly hosted in the -100 m dune system. As the Agulhas Current has impinged further landward, this has steadily removed all but the relict and cemented barrier forms and produced the seafloor facies association discussed below. As Flemming (1981) recognised, coast-parallel sediment transport along the shelf and shelf edge extends to locations where a change in shelf orientation occurs and sediment is then lost off-shelf.

Rhodoliths began to develop when sea-level stabilised at its present level ca 7000 yrs BP, suggesting that the Agulhas Current was by this stage located on the shelf. During the subsequent 7000 years up to and including the present, thick accumulations of rhodoliths accumulated in current-dominated conditions on the otherwise sediment-starved outer shelf. Sediment denudation has limited burial of the relict shorelines.

Multiple, current-controlled sedimentological features have similarly developed, resulting in a specific shelf morphology that comprises gravel-lined furrows and comet marks located in a largely sediment-denuded seascape. Strong current sweeping has further exacerbated the predominance of relict features associated with sea level fluctuations. Exposed wave ravinement surfaces, exhumed and relict incised valley features on the shelf, large exposed lagoonal systems, and intact barrier islands point to limited sediment retention on the shelf, since the repeated impingement of the Agulhas Current since ~ 7000 years ago. These seem likely to remain as persistent features in the shelf morphology and represent the nexus between relict geological and contemporary oceanographic processes.

Green et al. (2018) consider that subtropical climates particularly favour the preservation of relict shorelines on the shelf, and their occurrence may thus be a unique feature of current swept shelves of the sub tropics. This is strongly supported by the distribution of examples outlined from the Western and SE Australian shelves. However, in those cases, the modern coastlines are wide and sandy and in most part reflect similar geomorphic elements as to the relict shorelines of the adjacent shelves. Likewise, where the submerged shorelines were bedrock controlled, such as in the case of the submerged cliffs offshore the Lacipede shelf (Brooke et al., 2017), these are reflected in the cliffs of the contemporary coastlines. Where bedrock control is reduced or not as extreme, the evolutionary pathway is not constrained, and modern shorelines may mirror the relict features of the shelf. Our study thus provides a unique case study that highlights changing coastal configuration and functioning due to progressive coastal squeeze, exacerbated by rising sea levels, an increased impingement by bedrock framework, and high levels of current sweeping.

6. Conclusions

This study marks the first in South Africa, to identify both the -60 and -100 m submerged shorelines in outcrop, with a degree of unprecedented continuity between the two. The lack of sediment cover and exceptional shoreline preservation makes this area an attractive one for testing the hypothesis of Green et al. (2014); that these features are geomorphic signatures of MWP-1A and 1B.

Shorelines developed at -100 and -60 are markedly different because of underlying geological influences, and reflect coastline adjustment to changing geological and allocyclic sea-level controls over millennial scales. A lack of shoreline preservation between each major shoreline reflects ravinement processes during slow relative sea-level rise.

Rhodolith growth began on the shelf when sea-level stabilised near the present and the Agulhas Current occupied its present position ~ 7000 yr BP. Up to 20 m thick rhodolith accumulations have developed and are strongly associated with other features indicative of sediment denudation and current whittling. Given the current-swept nature of the shelf, the surface expression of palaeoshorelines is exceptional.

This study suggests that given the necessary antecedent conditions such as accommodation, sediment supply and favourable diagenetic climate, prominent shorelines can form, and when coupled to rapid rates of sea-level rise and strong current sweeping, can be preserved as persistent morphological features. The coastal evolution can also be tracked using submerged shorelines. These appear to also remain lasting features in the shelf morphology and stratigraphy of current-swept subtropical shelves. Where prominent subsurface bedrock occurs on current-swept shelves, coastal squeeze will be exacerbated due to the increasing disruption of littoral cells, diminishing sediment supply to barrier-shoreline systems and increasing sediment losses to the shelf sediment supply by current sweeping.

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Figure captions

Figure 1. Locality map of the study area detailing multibeam bathymetric coverage, seismic tracklines (bold white lines) and locations of various seafloor samples or ROV observations (red stars-numbered as portrayed in Figure 7). The -60 m and -100 m isobaths are shown as dashed white lines, and the presence of a large rhodolith field is depicted by the blue polygon. The Agulhas Current is portrayed as an idealised cartoon representing shelf sweeping of the area. Satellite images from Google Earth^{TM}.

Figure 2. Fluvial sediment supply to the shelf. The main rivers and sub-catchments that contribute to the study area, as outlined in table 1, are depicted (Q-T). The sediment yield in tonnes per km^2 per year are provided based on Rooseboom's (1978) data, modified after Flemming and Martin (2018). Red line denotes the 100 m isobath which approximates the shelf break for the study area. Note the shelf sediment compartment identified by Flemming (1981). The terrain model is based on the data of Dorschel et al. (2018).

Figure 3. Ultra-high-resolution coast-perpendicular seismic reflection profiles and interpretations. Note the pinnacles of Unit 1, underlain by incised valleys into which Unit 3 progrades. The abutting and onlapping acoustically transparent Unit 4 overspills the incised valleys and is overlain by the mounded accumulations of Unit 5, which interfinger with Unit 6. Inset shows line locations and sample intersections of a large rhodolith field corresponding to Unit 5. Red lines denote Holocene wave ravinement. Only the most important units are depicted in colour overlay.

Figure 4. a) Ultra-high-resolution coast-parallel seismic reflection profile and interpretation detailing an incised valley that has overspilled unit 4 in the middle shelf. This occurs adjacent to pinnacles of Unit 1. Red lines denote Holocene wave ravinement. b) Multibeam bathymetry detailing the underfilled surface expression of the incised valley in a), together with the rugged seafloor expression of the pinnacles of Unit 1. Unit 4 and 5 were sampled from this valley. Only the most important units are depicted in colour overlay.

Figure 5. Multibeam bathymetry showing a) an underfilled incised valley extending from the inner to middle shelf offshore the Kei River. b) A series of crenulate embayment-forming ridges at -60 m, with underfilled incised valleys offshore the Qnube River. c) Semi-circular seafloor depressions offshore the Kei River at ~ 80 m depth, bordered to either side by rugged seafloor of Unit 1. Note the arcuate prograded ridges on the margins of each depression. d) Weakly-developed semi-circular seafloor depression on the middle shelf at -80 m offshore Qnube River. e) A coast-oblique ridge of Unit 1 at -100 m on the outer shelf offshore the Kei River, backed by recurved ridges to landward and intersected by a seafloor depression with subsidiary recurved ridges. f) A coast-oblique ridge of Unit 1 at -100 m on the outer shelf offshore the Qnube River intersected by similar seafloor depression. Note the recurved prograded ridges and single cuspate ridge developed to landward of the main ridge feature.

Figure 6. Acoustic facies derived from multibeam backscatter and side-scan sonar offshore the Kei River. High backscatter = black, low backscatter = white. The resulting seafloor qualitative interpretations are shown. a) The inner to middle shelf with smooth toned high backscatter interpreted as muddy deposits in the proximal incised valley depression. b) Rugged relief, high backscatter seafloor of Unit 1 in outcrop, interspersed by low relief seafloor of the semi-circular depressions. Occasional linear patches of high backscatter are interpreted as gravel-lined streamers. c) Rugged high relief seafloor of Unit 1 in outcrop, surrounding by lower relief rocky seafloor superimposed by gravel-lined streamers.

Figure 7. a) Remote Observation Video (ROV) imagery of stiff mud of Unit 4 cropping out at the seafloor in the underfilled incised valley offshore the Kei River. b) Stiff mud of Unit 4 exposed in the troughs of migrating sandy ripples in the most inshore region of the underfilled incised valley. c) Rhodoliths retrieved by seafloor dredging and grab sampling. d) Aeolianite retrieved from pinnacles of Unit 1 using a dredge. f) Mixed unconsolidated shell hash and aeolianite cobbles of surface S2. g) Shell hash and occasional aeolianite granules filling linear seafloor depressions.

Figure 8. a) The contemporary coastal geomorphic systems of the sandy Southern Mozambique coastal plain, with interpretative comparisons made to seafloor features of the Eastern Cape shelf (b-e). b) Recurved spits, cuspate spits and inlets of a -100 m barrier on the seafloor. c) Lagoon with prograded margins in the backbarrier of the -100 m barrier. d) Fluvial entrances to the lagoons, marked by underfilled incised valleys. e) Parabolic dunes and blowouts formed in the -100 m seaward and landward barriers to the lagoon system. Satellite images from Google Earth^{TM}.

Figure 9. a) Interpreted multibeam bathymetry of the inner to middle shelf offshore the Qnube River, note how beachrocks and aeolianites comprise the embayment-forming ridges

superimposed onto Karoo Supergroup-age strata. b) Contemporary coastal setting immediately adjacent to the above multibeam data. Here beachrock overlies sandstones of the Karoo Supergroup, backed by a Holocene age barrier-dune system (Holidaying Green for scale). c) Beachrocks overlying sandstones of the Karoo Supergroup, forming a headland to an embayment. Note the sandy Holocene-age barrier in the background separating another rocky headland to the north. Satellite images from Google Earth™.

Figure 10. A proposed evolutionary model for postglacial shoreline development of the Eastern Cape coast (timing inferred from Pretorius et al., 2016; 2019, details discussed in text).

Table 1. Physical characteristics of the regional drainage basins for the Fish, Kei and Mzimvubu Rivers. Sediment yield for each sub-catchment is based on figures reported by Flemming (1981).

Table 2. Dimensions of relict seafloor features. Wherever possible the seismic unit, relief, width, length and spacing are provided and compared to dimensions of modern systems from the contemporary coastline of SE Africa.

Figure 1

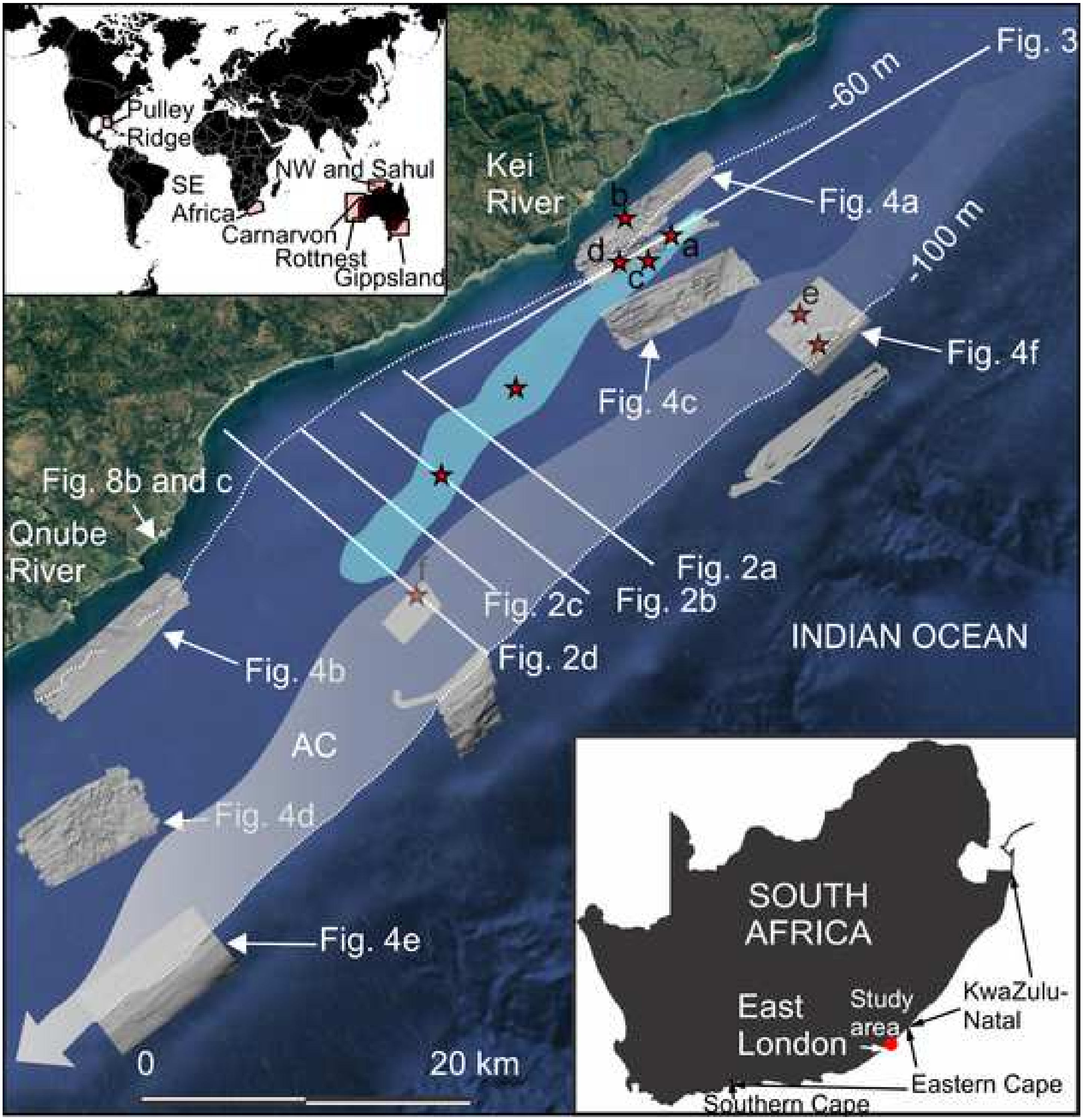
Pulley
Ridge
SE
Africa
NW and Sahul
Carnarvon
Rottnest
Gippsland
Kei
River
-60 m
Fig. 3
Fig. 4a
-100 m
b
a
d
c
e
Fig. 4f
Fig. 4c
Fig. 8b and c
Qnube
River
Fig. 2a
Fig. 2c
Fig. 2b
INDIAN OCEAN
Fig. 2d
Fig. 4b
AC
Fig. 4d
Fig. 4e
0
20 km
SOUTH
AFRICA
East
London
Study
area
KwaZulu-
Natal
Eastern Cape
Southern Cape

Figure 2

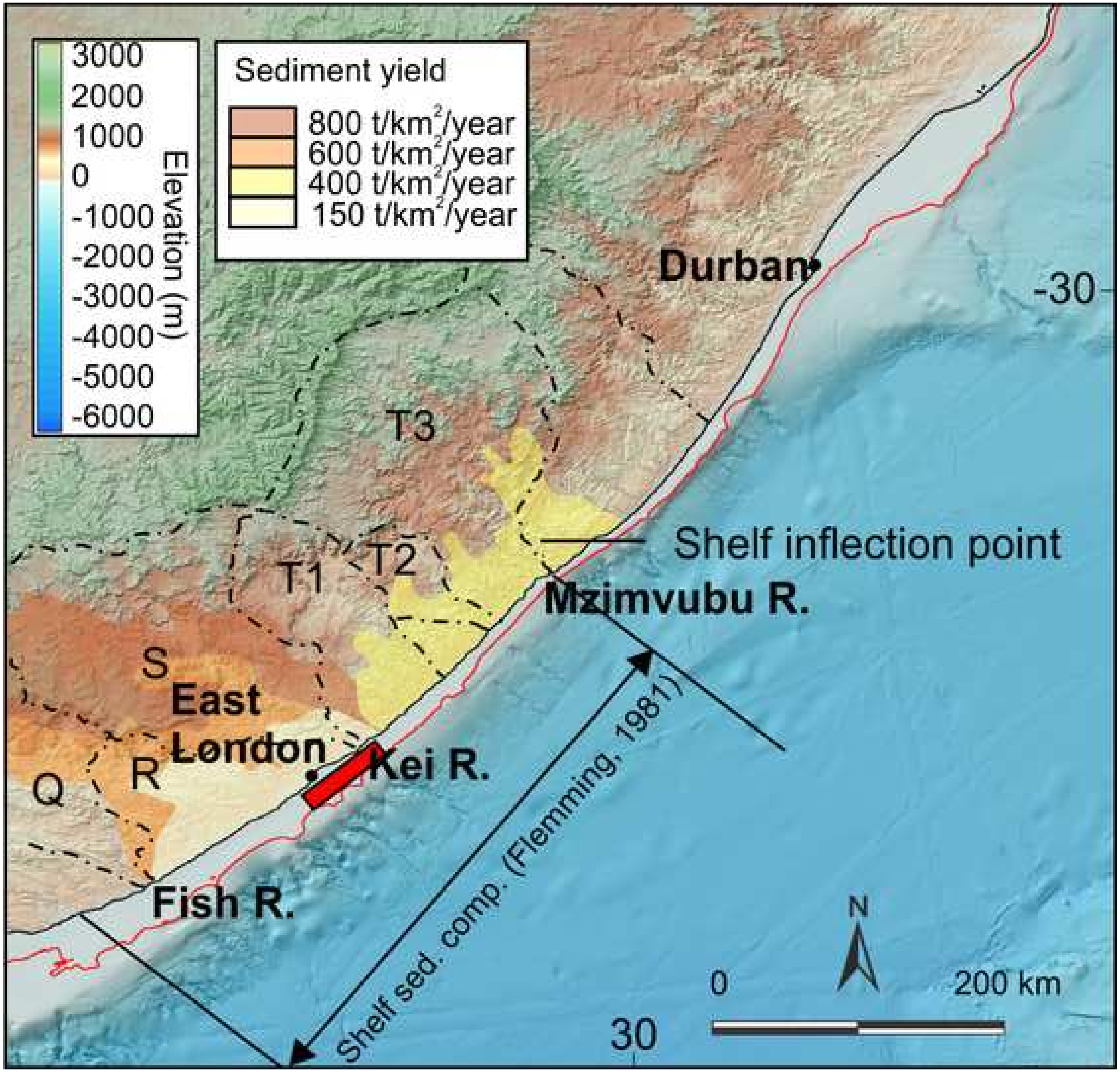
3000
2000
1000
0
-1000
-2000
-3000
-4000
-5000
-6000
Elevation (m)
Sediment yield
800 t/km²/year
600 t/km²/year
400 t/km²/year
150 t/km²/year
Durban
-30
T3
T1
T2
Shelf inflection point
Mzimvubu R.
S
East London
Kei R.
Q
R
Fish R.
Shelf sed. comp. (Flemming, 1981)
N
0
200 km
30

Figure 3

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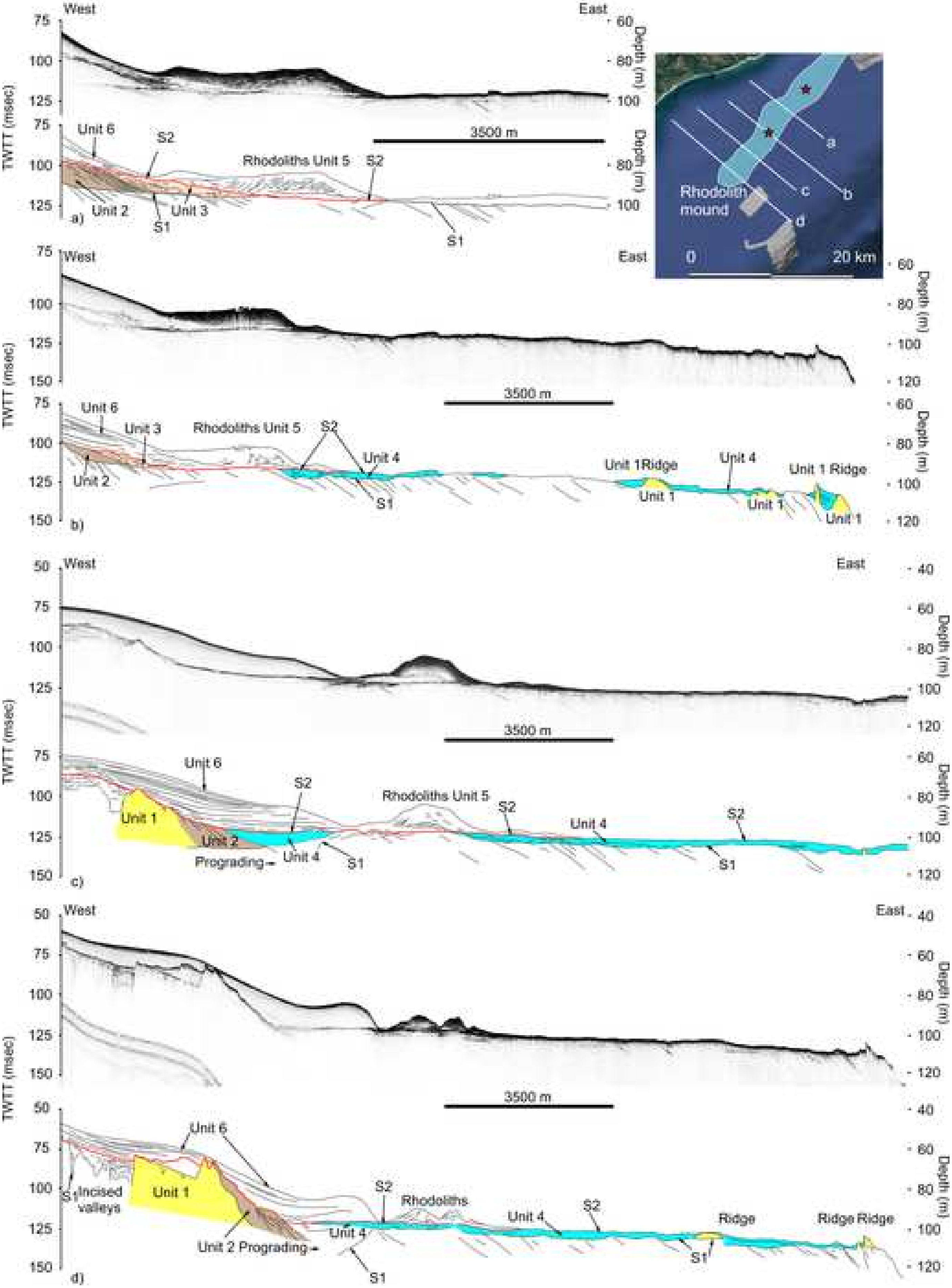

Figure 4

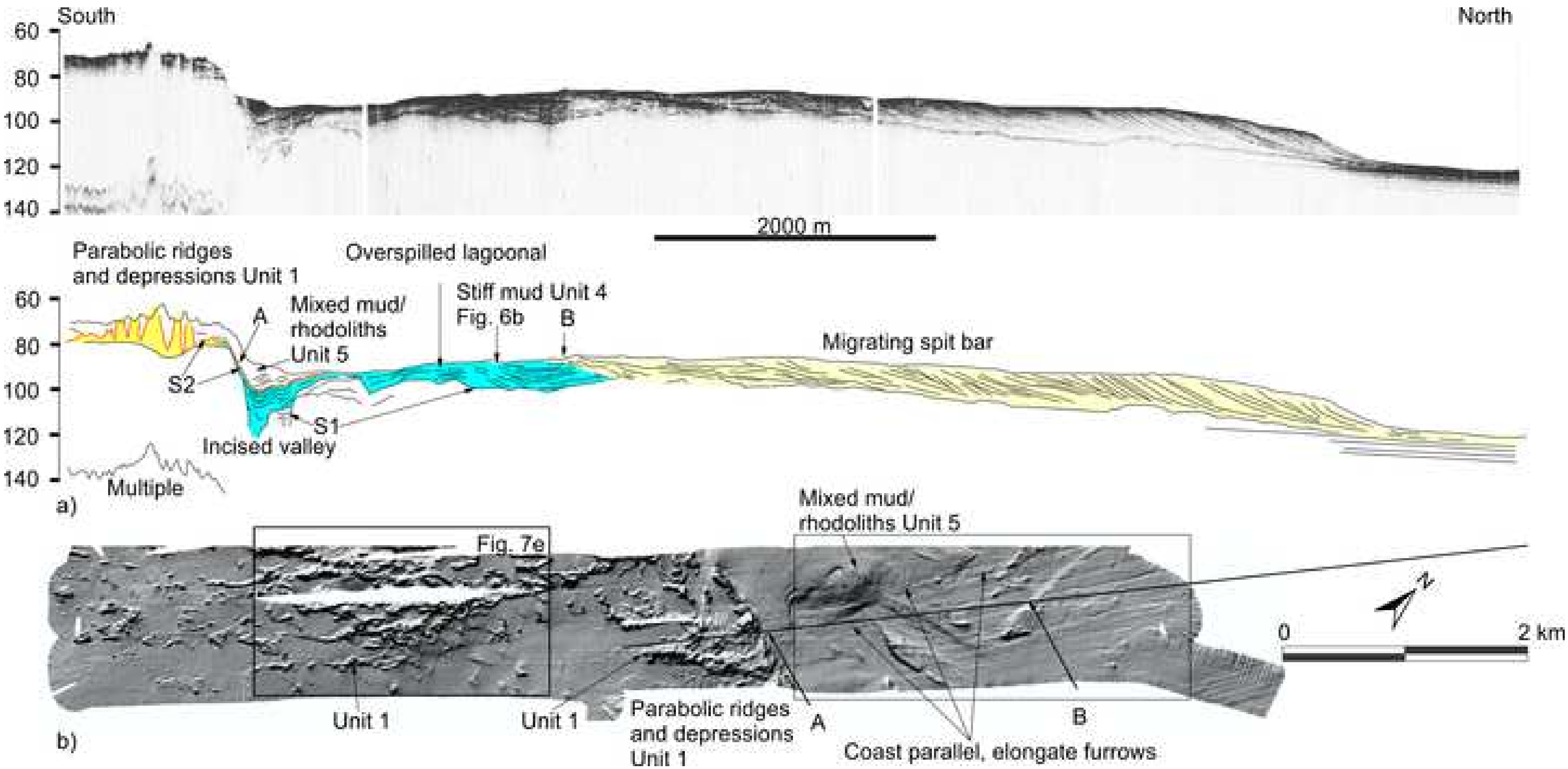
South
North
60
80
100
120
140
2000 m
Parabolic ridges and depressions Unit 1
Overspilled lagoonal
Stiff mud Unit 4
Fig. 6b
A
B
Mixed mud/ rhodoliths Unit 5
Migrating spit bar
S2
S1
Incised valley
Multiple
a)
Mixed mud/ rhodoliths Unit 5
Fig. 7e
N
0
2 km
Unit 1
Unit 1
Parabolic ridges and depressions Unit 1
A
B
Coast parallel, elongate furrows
b)

Figure 5

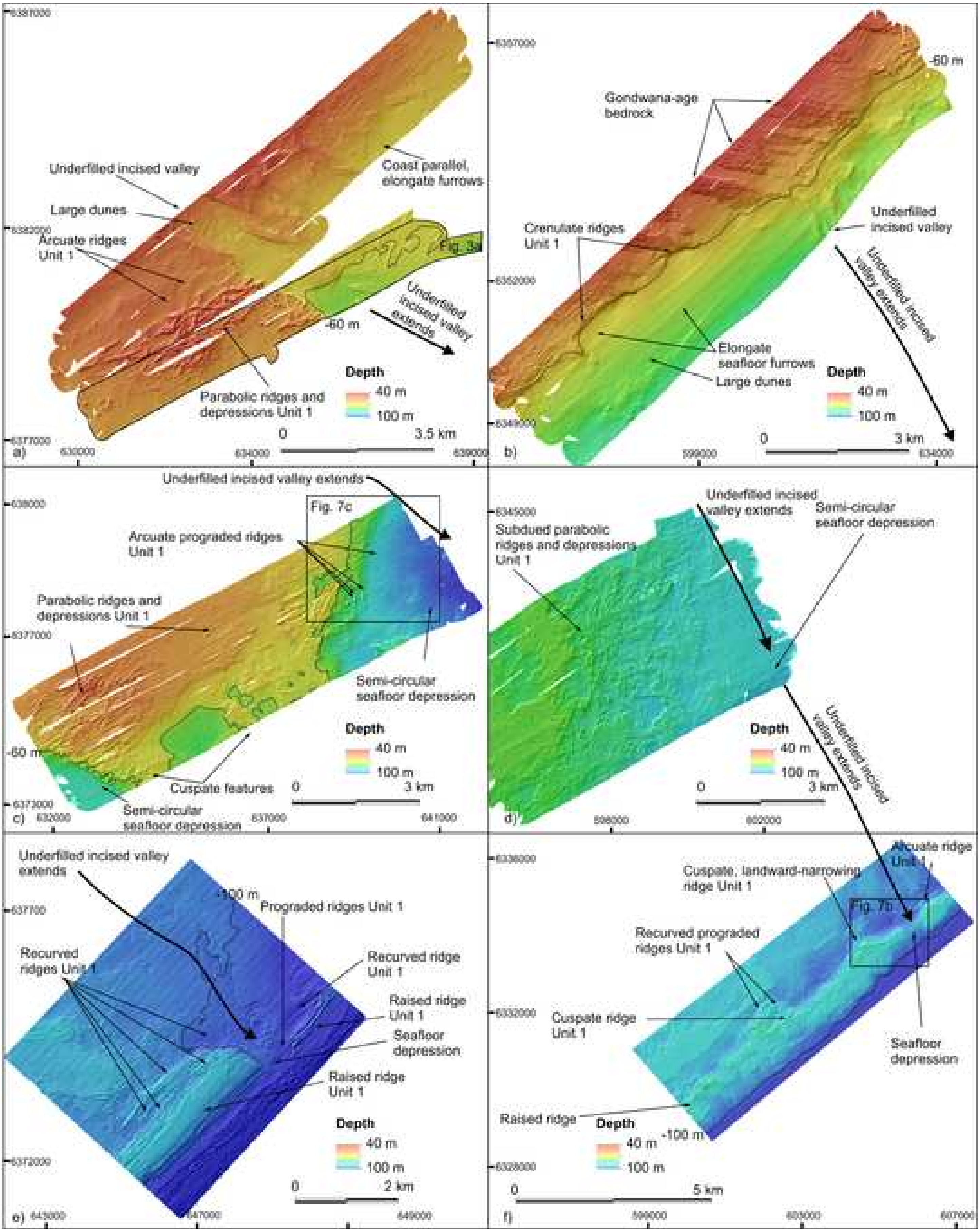
Underfilled incised valley
Large dunes
Arcuate ridges Unit 1
Coast parallel, elongate furrows
Fig. 3a
Underfilled incised valley extends
-60 m
Parabolic ridges and depressions Unit 1
Depth
40 m
100 m
0
3.5 km
a)
Gondwana-age bedrock
-60 m
Crenulate ridges Unit 1
Underfilled incised valley
Underfilled incised valley extends
Elongate seafloor furrows
Large dunes
Depth
40 m
100 m
0
3 km
b)
Underfilled incised valley extends
Fig. 7c
Arcuate prograded ridges Unit 1
Parabolic ridges and depressions Unit 1
Semi-circular seafloor depression
-60 m
Cuspate features
Semi-circular seafloor depression
Depth
40 m
100 m
0
3 km
c)
Underfilled incised valley extends
Semi-circular seafloor depression
Subdued parabolic ridges and depressions Unit 1
Underfilled incised valley extends
Depth
40 m
100 m
0
3 km
d)
Underfilled incised valley extends
-100 m
Prograded ridges Unit 1
Recurved ridges Unit 1
Recurved ridge Unit 1
Raised ridge Unit 1
Seafloor depression
Raised ridge Unit 1
Depth
40 m
100 m
0
2 km
e)
Arcuate ridge Unit 1
Cuspate, landward-narrowing ridge Unit 1
Fig. 7b
Recurved prograded ridges Unit 1
Cuspate ridge Unit 1
Seafloor depression
Raised ridge
Depth
40 m
100 m
-100 m
0
5 km
f)

Figure 6

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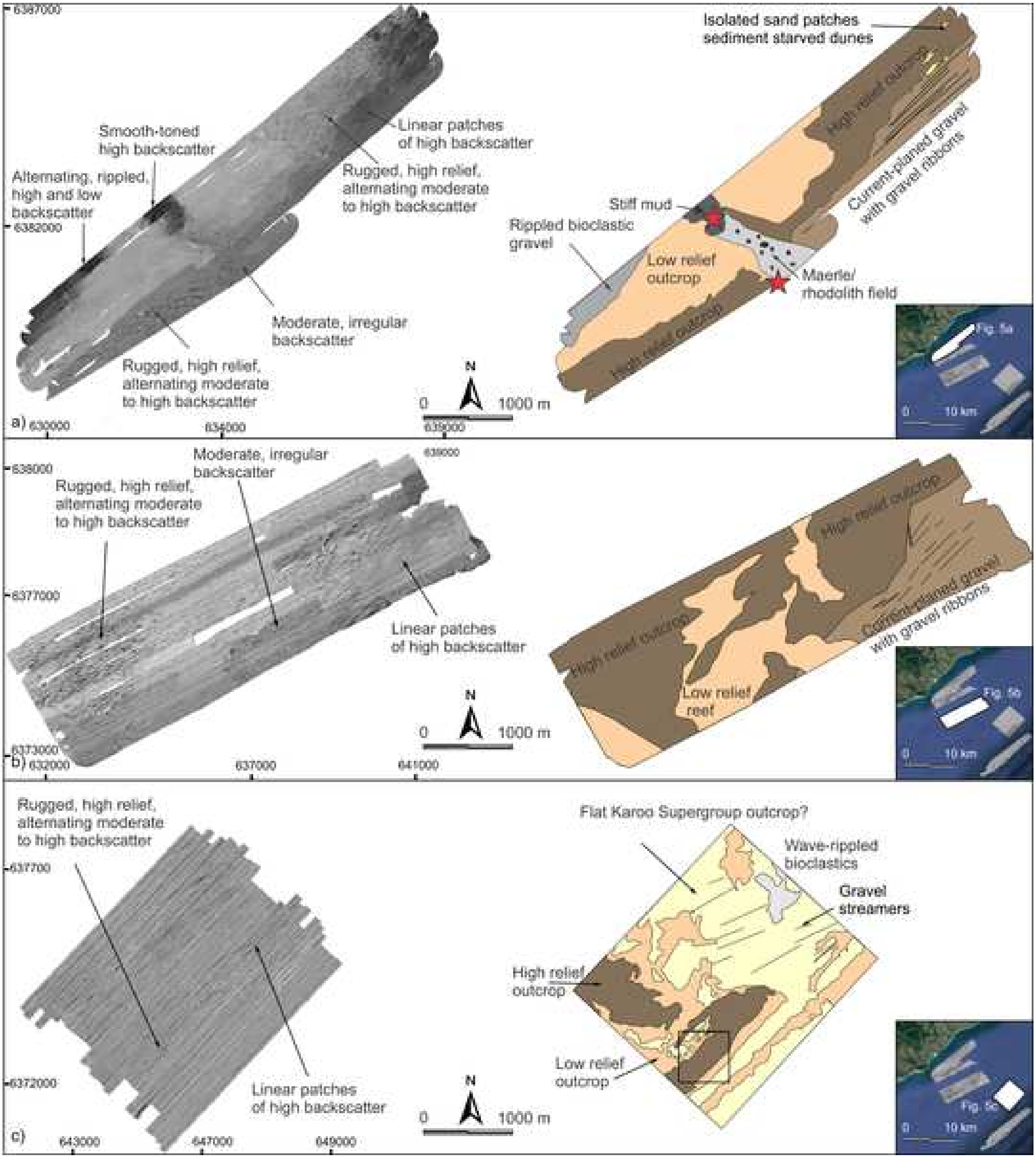

Figure 7

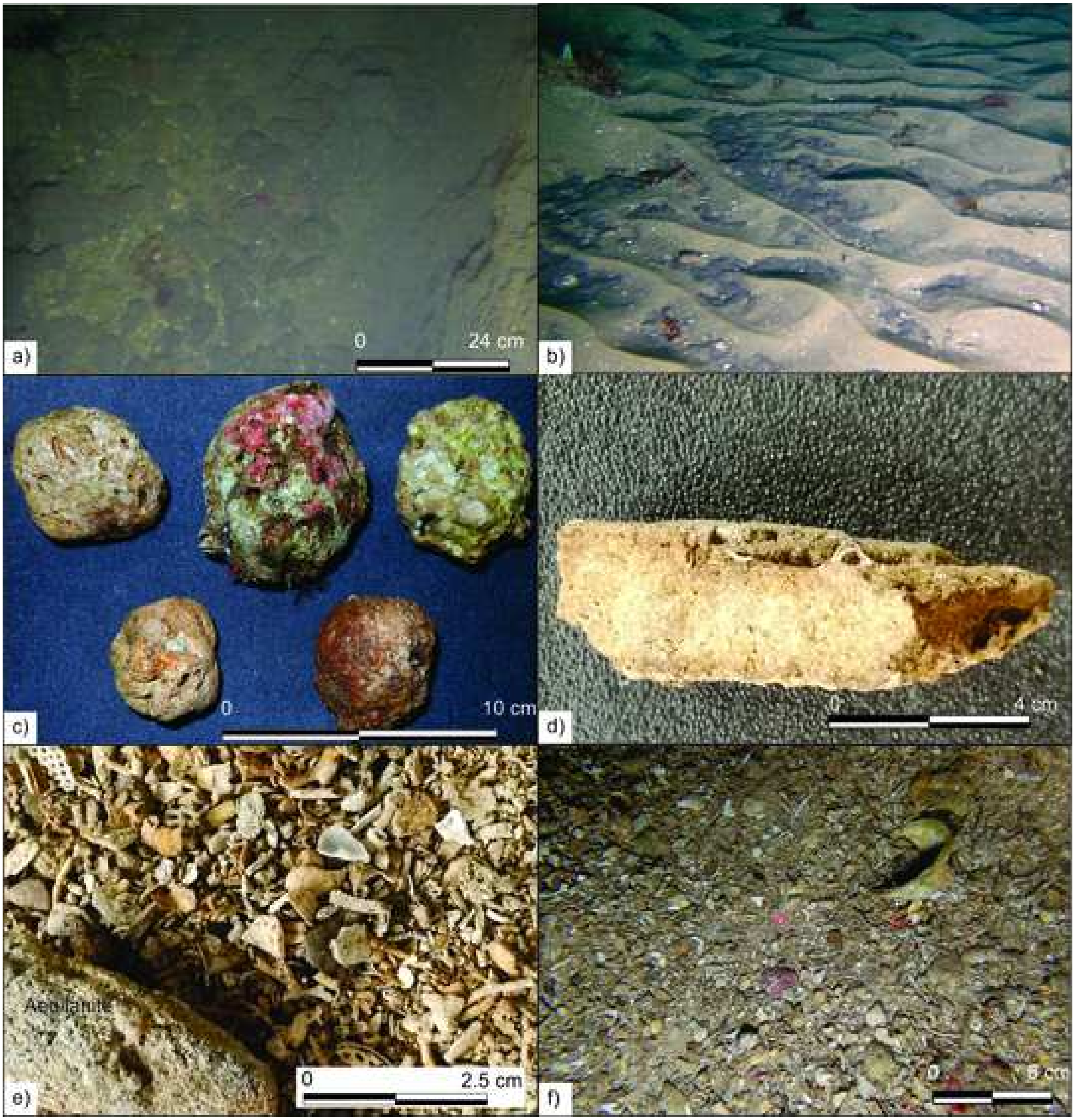

Figure 8

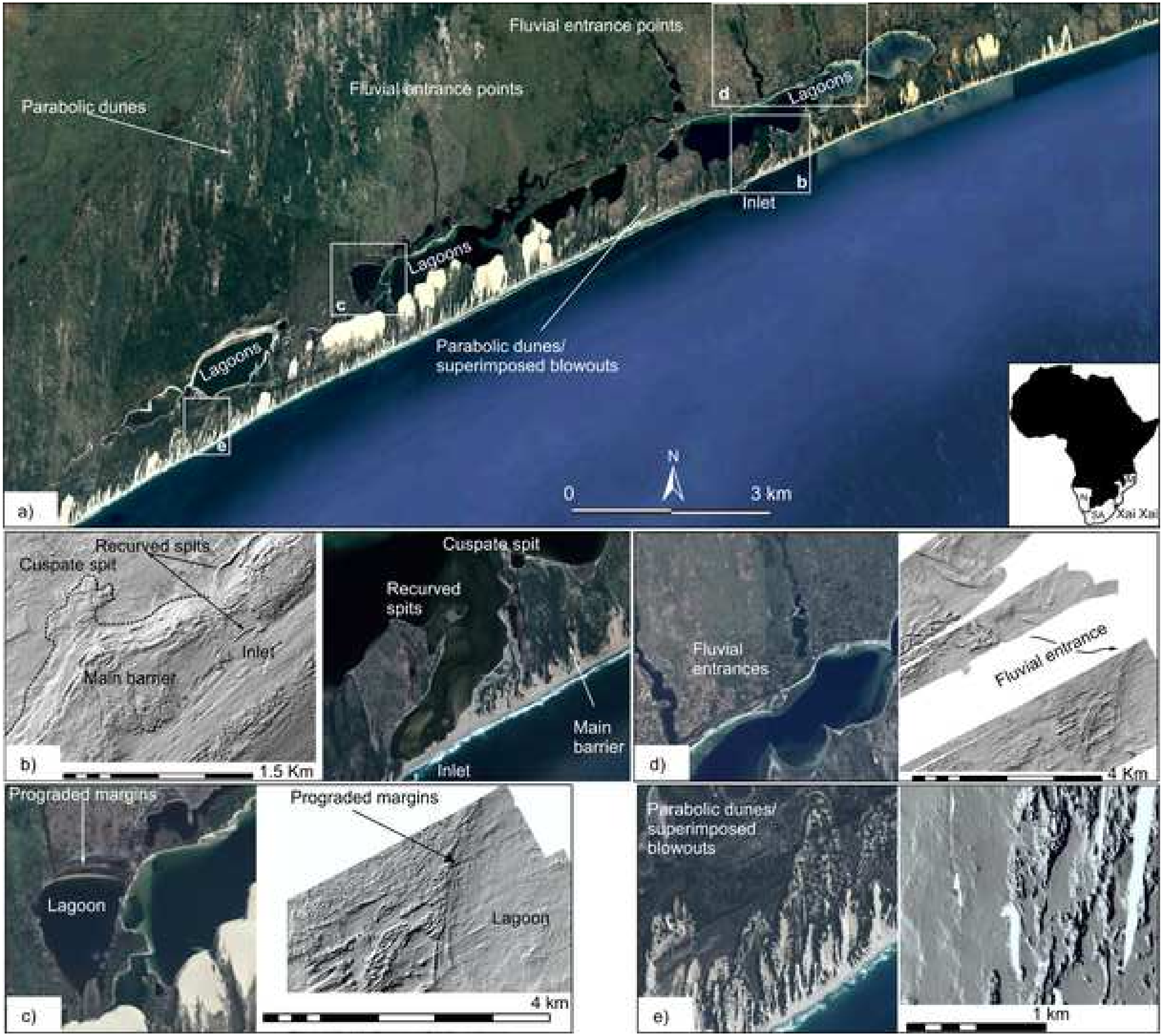
Fluvial entrance points
Fluvial entrance points
Parabolic dunes
Lagoons
Lagoons
Lagoons
Inlet
Parabolic dunes/
superimposed blowouts
a)
b)
c)
d)
e)
N
0
3 km
Xai Xai
Recurved spits
Cuspate spit
Inlet
Main barrier
1.5 Km
Cuspate spit
Recurved spits
Main barrier
Inlet
Fluvial entrances
Fluvial entrance
4 Km
Prograded margins
Lagoon
Prograded margins
Lagoon
4 km
Parabolic dunes/
superimposed
blowouts
1 km

Figure 9

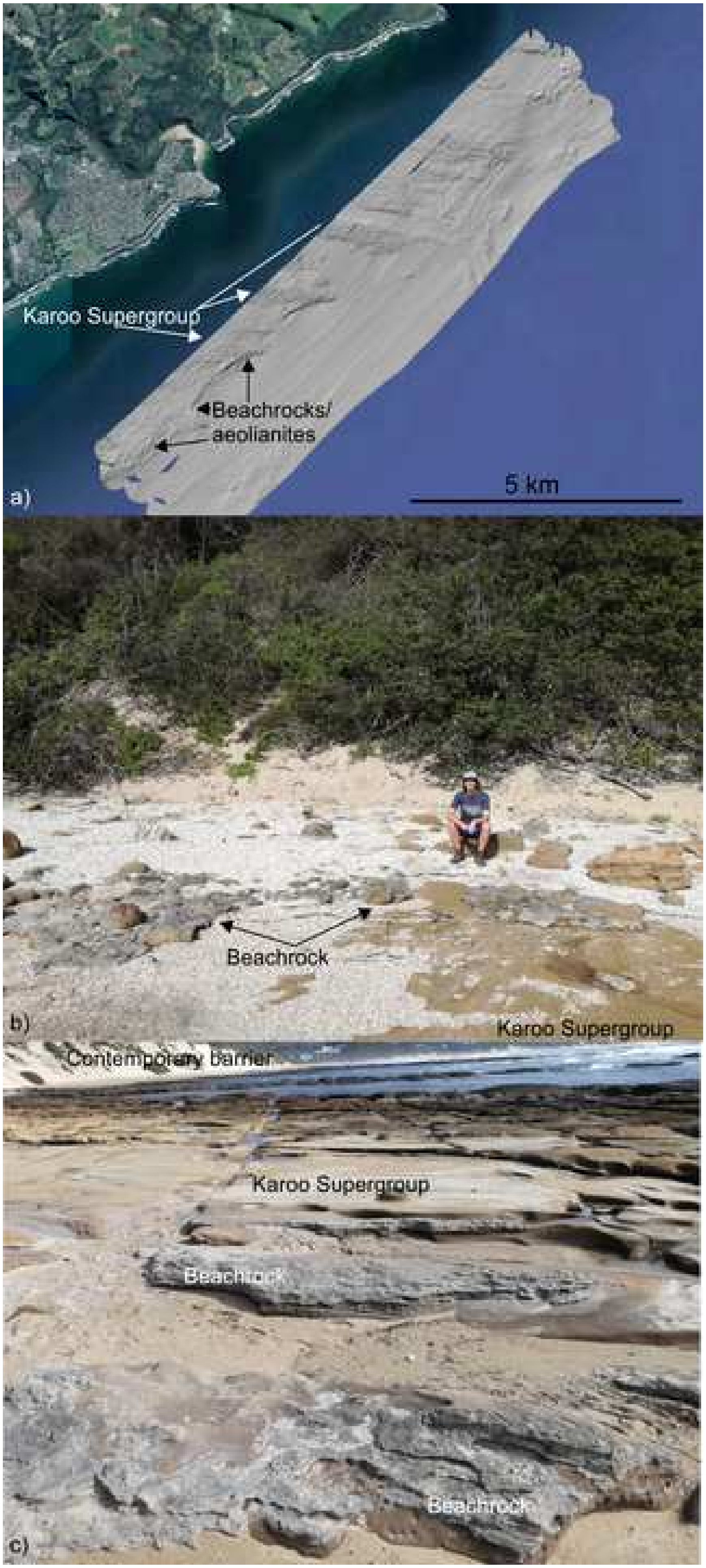
Karoo Supergroup
Beachrocks/
aeolianites
5 km
a)
Beachrock
b)
Karoo Supergroup
Contemporary barrier
Karoo Supergroup
Beachrock
Beachrock
c)

Figure 10

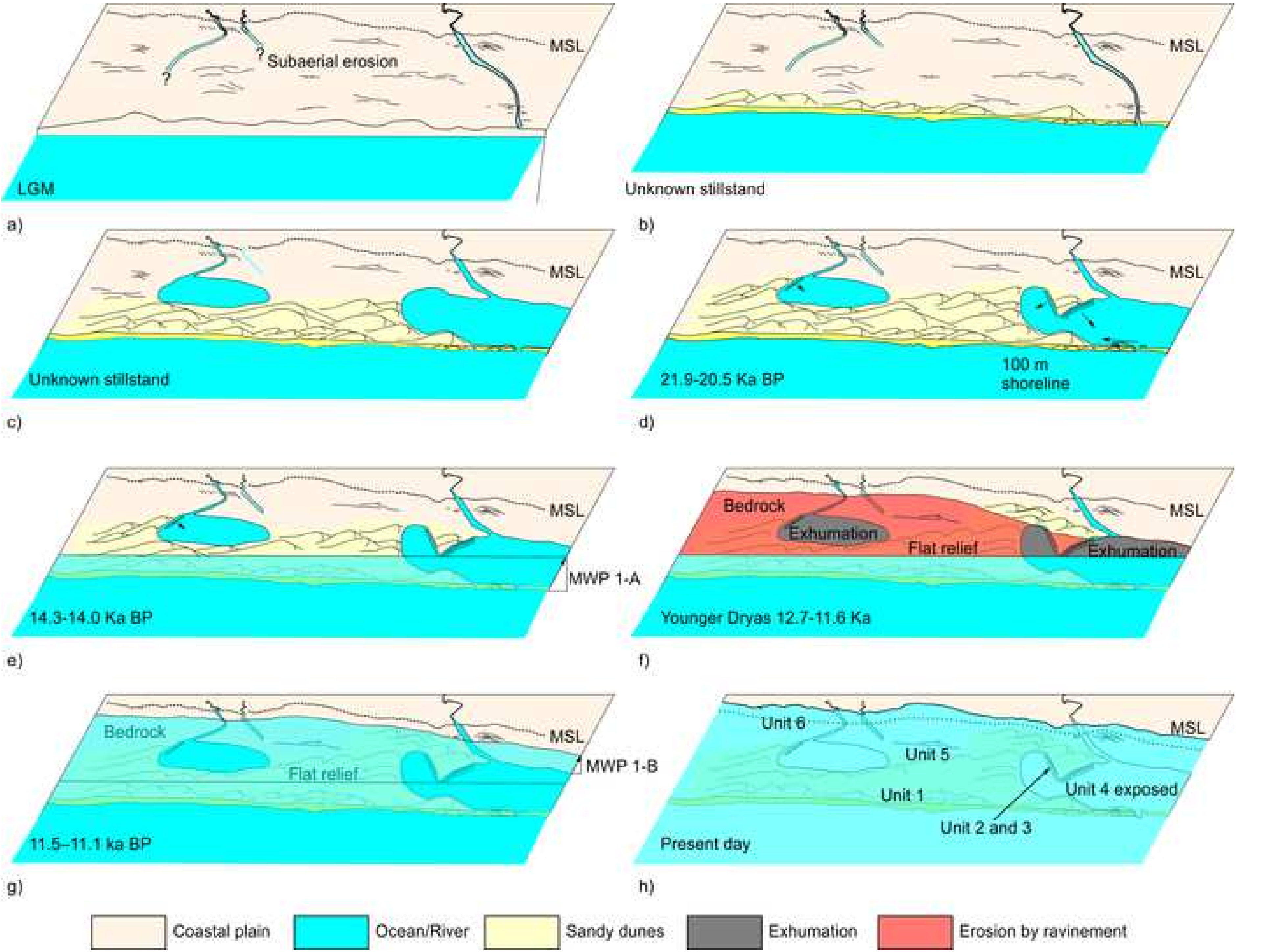
MSL
? Subaerial erosion
?
?
LGM
a)
MSL
Unknown stillstand
b)
MSL
Unknown stillstand
c)
MSL
21.9-20.5 Ka BP
100 m
shoreline
d)
MSL
MWP 1-A
14.3-14.0 Ka BP
e)
Bedrock
Exhumation
Flat relief
Exhumation
MSL
Younger Dryas 12.7-11.6 Ka
f)
Bedrock
Flat relief
MSL
MWP 1-B
11.5–11.1 ka BP
g)
Unit 6
Unit 5
MSL
Unit 1
Unit 4 exposed
Unit 2 and 3
Present day
h)
Coastal plain
Ocean/River
Sandy dunes
Exhumation
Erosion by ravinement

Table 1

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Table
Table 1.docx

Table 2

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