A morphological classification of coastal forelands, with examples from South Africa

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Abstract

Alongshore variations in the cross-shore width, and therefore volume, of sandy beaches are important because these reflect spatial variability in the operation of wave- and wind-driven processes taking place both at the shoreface and in the supratidal zone. One key geomorphic signature of variations in cross-shore beach width is the development of coastal forelands. Different foreland types have been described in the literature from very specific geomorphic contexts, but hitherto there has been no overarching classification scheme that genetically links these different foreland types, or considers them in the wider context of sandy beach dynamics. In order to achieve this aim, this study maps and inventorises 87 forelands from the South African coast (~2600 km long), and classifies these into four morphological types: salients, tombolos, cuspate forelands, and ramp forelands. These foreland types have different morphological properties, reflecting the interplay of coastal erosional and depositional processes and any antecedent conditions; and a varying balance of morphodynamic controls on their development and behaviour. These include variations in wave (and to a lesser extent wind) energy, sediment supply, and the presence of bedrock outcrops of different sizes, shapes and positions along the shoreline. Analysis of foreland morphology and dynamic behaviour, based on examples from South Africa, enables a better understanding of coastal

forelands globally as integrated sediment systems and responsive to the range of forcings driving coastal change.

Keywords: Coastal dynamics; Forelands; Headland bypass systems; Longshore processes; Supratidal zone; Wave processes

Introduction

Longshore and cross-shore variations in sandy coast sediment budgets result in, amongst other outcomes, changes in beach width, width of the intertidal, supratidal and shoreface elements of beaches, and development of distinctive sedimentary landforms (Sanderson et al., 2000). This dynamic behaviour of sandy beaches is achieved mainly through wave and wind process regimes, and also influenced by longshore currents, tides, incoming rivers, and headland bypass systems (Boeyinga et al., 2010; Goodwin et al., 2013; Vieira da Silva et al., 2018). One key geomorphic expression of this alongshore variation in cross-shore sediment accumulation is the *coastal foreland*. Forelands are shoreline protuberances formed by the seaward progradation of the littoral shoreline, often mirrored by backshore accommodation of dunes and/or beach ridges, along a certain coastal stretch. This development takes place as a combination of wave and current processes to form 'promontories of the mainland', to use Gulliver's (1896, p.400) original definition. The most well-known foreland type reported in the literature is the cuspate foreland. This develops where shoreline progradation takes place in the form of nested gravel beach ridges that have a consistent alignment at an oblique angle to the shore (e.g., Semeniuk et al., 1988; McNinch and Leuttich, 2000; Alcántara-Carrió and Fontán, 2009). Cuspate forelands thus have a regular progradational character controlled by the linear and nested nature of these beach ridges (Carter, 1980; Fontolan and Simeoni, 1999; Roberts and Plater, 2007; Lampe and Lampe, 2018) and driven by differential wave action

(Falqués et al., 2018). These forelands therefore develop a distinctive triangular-shaped morphology with generally symmetrical lateral margins, and may have backbarrier lagoons or wetlands behind the foreland or between individual beach ridges within the foreland itself. Cuspate forelands exhibiting these general characteristics are noted in particular along the glaciated northwest Europe and northeast North America coasts (Long and Hughes, 1995; Roberts and Plater, 2007; Clemmensen et al., 2011; Xhardé et al., 2011; St-Hilaire-Gravel et al., 2015; Hesp et al., 2016) and this foreland type can thus be classified as a paraglacial landform linked to the deposition of gravel beach ridges from glacigenic sediment sources during phases of sea-level change. Cuspate forelands can be considered as accommodation-limited systems controlled by longshore processes along the foreland margins. Other cuspate forelands, however, can be considered as sediment-limited systems where sediment is stored on nearshore shoals and where waves, and to a lesser extent tides and fluvial pumping, drive seasonal onshore sediment transport to the foreland apex (McNinch and Luettich, 2000; Park and Wells, 2005, 2007; Kumar et al., 2013).

Despite this historical emphasis in the literature on cuspate forelands, similar progradational morphologies are also found along sandy coasts (Fig. 1). These include tombolos and salients that develop as a result of wave refraction around offshore islands or reefs (Semeniuk et al., 1988; Sanderson and Eliot, 1996; Sanderson et al., 2000; Black et al., 2020; de Macêdo et al., 2022), and ramp forelands (defined in this study) that develop where wave- and wind-deposited sediments prograde across a low-elevation bedrock surface. Therefore, coastal forelands (*sensu lato* and as defined below) are part of a continuum of sandy coastal beach morphologies that reflect the interplay among sediment availability, the presence of bedrock outcrops or protuberances, and different forcing factors (waves, sediment supply, sea-level trajectory) that can result in long- to short-term patterns of differential coastal aggradation or erosion along any coastal stretch (Heron et al., 1984; Sanderson et al., 2000; Falqués et al., 2018; Orlando et al., 2019; Gallop et al., 2020). Because of the presence of these morphological types along a continuum of forms, the non-genetic term *coastal foreland* is used in this study for all foreland types. Coastal forelands are defined herein as *a prominent and persistent (decadal-scale) protrusion of a littoral shoreline in response to the differential action of wave erosion and deposition processes*. This is a broader yet more precise definition than the encyclopaedia definition given by Craig-Smith (2005). The broad structure of all types of forelands as defined in this study, including their key associated geomorphic elements in plan form and cross profile, is shown in Figure 1.

Because there are limitations of the currently narrow definition and understanding of forelands, the main aim of this study is to propose a typology of sandy coastal forelands (*sensu lato*) applicable globally, based on examples observed along the South African coast (~2600 km long). This study is unique for three reasons: (1) it proposes an integrated global classification for coastal foreland types (Fig. 1) that considers them as a morphological continuum of forms and not as simple evolutionary endmembers. This has not been achieved before; (2) no previous study has mapped and classified coastal forelands at a national scale; and (3) this is the first study that examines these landform types in South Africa (or indeed in Africa).

In detail this paper (1) maps the distribution and properties of forelands along the South African coast in order to distinguish and classify the forelands into different morphological types; (2) describes the morphodynamics and properties of the foreland types; and (3) proposes an evolutionary model for coastal foreland systems that focuses on the sediment dynamics that contribute to their development. The foreland classification scheme presented in this study can be usefully applied to sandy coasts globally, and represents a significant advance in how longshore variations in the width of these sedimentary accumulations can be conceptualised. This is particularly important given the sensitivity of sandy coasts to climate forcing (Knight and Harrison, 2009; Luijendijk et al., 2018) and thus the role of sandy beaches as a buffer to the effects of storm waves and ongoing sea-level rise (Nordstrom and Terich, 1986; Dolphin et al., 2007, 2011; Orlando et al., 2019).

Study area

The geomorphology of the South African coast has only been examined at a regional scale (Tinley, 1985; Dardis and Grindley, 1988) and thus there is still much information lacking about its detailed coastal landforms and their dynamics. Long and uninterrupted sandy coasts are present on different sectors of the South African coast, and exposed to different prevailing wind and wave climates (Mitchell et al., 2005) (Fig. 2). The nature of these coastal sediment systems varies significantly. Laterally extensive sandy beaches have a consistent width, backed variably by unvegetated transverse dune complexes, and exhibit a sharp and often linear landward boundary that is marked by vegetated foredunes. Along the southeast-facing coastline of South Africa in particular, sandy beaches are dissected by small perennial rivers that result in the formation of microtidal estuaries (Cooper, 2001; Bate et al., 2017). Along all coastal sectors, sandy beaches including pocket beaches may be constrained by bedrock headlands that influence the size and shape of sediment cells (Tinley, 1985; Meeuwis and van Rensburg, 1986; Dardis and Grindley, 1988). There are spatial differences in external forcing by wind, waves and tides between the south/east (Indian Ocean) and west (Atlantic) coasts in South Africa (Corbella and Stretch, 2012a; Rautenbach et al., 2019; Veitch et al., 2019). Winds are predominantly shore-parallel along all coastal sectors (Schumann and Martin, 1991). Tides are semi-diurnal and high microtidal/low mesotidal (range ~2.0–2.5 m) with a non-residual component that increases from west to east (Searson, 1994). Waves (H_s >5 m; Corbella and Stretch, 2012c; Wepener and Degger, 2019) exert a significant forcing on shoreline dynamics in South Africa (Corbella and Stretch, 2012a, b). Despite this background, there have been relatively few studies on beach morphodynamics and the sensitivity and responses of beach systems to storm and wave forcing (Harris et al., 2011; Corbella and Stretch, 2012a, b; Guastella and Smith, 2014; Green et al., 2019). More frequently there have been studies that examine the dynamics of coastal sediment systems, especially dune–beach systems (La Cock et al., 1992; Olivier and Garland, 2003; Mitchell et al., 2005; Knight and Burningham, 2021) and headland–embayment systems (Meeuwis and van Rensburg, 1986), but these specific and localised case studies have not been compared to each other or integrated into a wider coastal sediment systems model.

Methods

In order to map and identify the large-scale properties of coastal forelands in South Africa, the country's coastline was systematically examined using Google Earth imagery. This is similar to methodologies used in other studies of coastal forelands, including assessing their changes over time (e.g., Kunte and Wagle, 1993; Clemmensen et al., 2011; Xhardé et al., 2011; Allen et al., 2012; Hesp et al., 2016). In this coastal survey, the locations and general geomorphic properties of individual forelands were identified and then digitised from the most recent (2020) Google Earth imagery, and key metrics calculated were *length, width*, *area* and *skewness* of the foreland. *Length* (in m) is defined as the alongshore distance between the up- and down-drift limits of any single foreland system. These limits, essentially representing the sediment closure width of that foreland system, are located where the beach is narrowest which often coincides with the position of (ephemeral or perennial) river mouths (Fig. 3a) or rocky headlands. These act as barriers to continuous longshore sediment transport and thus their positions along the shoreline can be used to compartmentalise the relatively continuous beach systems. *Width* refers to the maximum seaward extent (in m) of the sandy foreland at its apex point, as measured perpendicular to the landward boundary between the beach and the vegetated dunes. Commonly the foreland apex is anchored on a bedrock outcrop. *Area* is calculated as the area (in m^2) enclosed within the digitised polygon of the outer margin of the foreland, which includes its longshore limits, and the landward and seaward extents of the functional (dynamical) components of the forelands, thus excluding thickly vegetated dunes for example. Axial *skewness* or asymmetry of the foreland refers to the position, along its length, of the greatest foreland width (apex point). If the greatest width is located half way along the length, like an isosceles triangle, then the foreland is broadly symmetric. If the greatest width is located nearer to the up- or down-drift limits, like a scalene triangle, then the foreland is asymmetric or skewed in a certain longshore direction (Fig. 3b, c). 'Foreland activity' identified in Table 1 is a generalised qualitative evaluation of the foreshore, shoreline, and backshore dynamics of each foreland based on a simple visual comparison of recent (last 5 years) Google Earth images. If the shorelines of each foreland vary significantly over this timeframe the foreland is classified as *active*; if they appear static the foreland is *inactive*; and if they vary only to some extent the foreland is classified as *partly active*. A more rigorous quantitative evaluation of foreland dynamics was not undertaken in this study.

After identification as described above, the forelands were systematically examined for the presence of key geomorphic features including the presence and properties of transverse, fixed (contemporary, vegetated), and ramp dunes (cf., Carter and Wilson, 1993); any smaller aeolian depositional forms such as minor humps and undulations in the supratidal zone; bedrock outcrops within the varied sediment accumulations; any vegetated and inactive dunes at the back of the beach; evidence for erosional or progradational features of the beach shoreface; and the presence of absence of a river mouth as a significant sediment source. In addition to the previously described foreland morphometrics, the length of bedrock along the foreland shoreline was calculated as a proportion of the total foreland length. In combination, a principal component analysis (PCA) was then undertaken to explore the parameter space (feature presence/absence was presented as binary measures) and establish key gradients across the multiple variables. The program PAST (Hammer et al., 2001) was used for this purpose to calculate the eigenvalues of the correlation matrix. The first two principal components captured 34% of the total variance in the parameters used here to describe foreland morphology.

Results

Distribution and properties of forelands along the South African coast

In total, 87 forelands are identified along the South African coast (Fig. 4). Their key geomorphic characteristics are shown in Table 1. Forelands are found mainly along sand-dominated stretches of the coastline where sediment supply is greatest, but are also found along predominantly rocky stretches where sediment accumulates around river mouths. Four different foreland types are identified (Fig. 1).

Foreland type 1 – salient. This is formed where wave refraction takes place around an offshore bedrock island or reef, resulting in enhanced seaward sediment deposition in the wake of the reef. In this study four salients were identified (5% of all forelands), three of which are on the west coast (Fig. 4).

Foreland type 2 – tombolo. This most commonly forms by initial development of a salient, where an offshore island that forces wave refraction becomes linked to the mainland by the continued accumulation of wave-transported sediment. In this study nine tombolos were identified (10% of all forelands) (Fig. 4).

Foreland type 3 – cuspate foreland. This is a distinctive triangular-shaped foreland formed by longshore processes, driven by wave erosion and sediment transport on the two sides of the foreland. Classically, cuspate forelands show the development of nested parallel beach ridges that are commonly overlain by sand dunes (high sand sediment supply), which may contain wetlands in ridge swales (low sediment supply or gravel-dominated systems). In this study 46 cuspate forelands were identified (Fig. 4), making them the most common foreland type (53% of the total) (Table 1). Cuspate forelands often reflect local alongshore sediment transport patterns and may be symmetric in plan view, or asymmetric (skewed). Of these forelands, 21 (46%) are symmetric, 21 (46%) are skewed to the north and only four (9%) are skewed to the south. Of the four cuspate forelands along the south coast, two are symmetric and two are skewed to the east.

Foreland type 4 – ramp foreland. This landform is specifically named and described in this study for the first time. Ramp forelands occur where sand covers the surface of a low-elevation bedrock platform, allowing the beach to extend farther seaward. In a longshore direction, sediment thins as it rises up the bedrock ramp surface to the top of the foreland, which corresponds to the location of its maximum width, and then thickens down the leeside. Ramp forelands are therefore distinct from cuspate forelands (*sensu stricto*) in the elevated nature of the bedrock bench or shelf that raises the supratidal deposits above the tidal frame. In this study 28 ramp forelands were identified (32% of all forelands) and these are mainly located on the south and east coasts (Fig. 4). Considering all the ramp forelands, five (18%) are symmetric whereas of those that are skewed, the majority (20 of 23) are skewed to the north with only a few (3 of 23) to the south. Of the five ramp forelands on the south coast, four are skewed to the east, and one to the west.

The key morphometric properties of all 87 forelands (of all types) identified in this study are illustrated spatially in Figure 5. There are no systematic spatial (alongshore) patterns in foreland properties between different coastlines. Comparison of the generalised morphometry of the four foreland types is given in Figure 6. There is less variability in foreland width than there is in length. Cuspate forelands are the largest landforms and several of these are significant landforms in terms of their length and area, with nine of the ten forelands over 2 million m^2 (200 ha) in area being cuspate forelands (Table 1). This may suggest that cuspate forelands, by virtue of their size, have different morphodynamic behaviours to other foreland types. Salients are largely near-symmetrical, whilst ramp forelands are more significantly skewed because they reflect longshore processes and alongshore winds. Both cuspate and ramp forelands are more elongated (larger length relative to width) in comparison to salients and tombolos, which are more equidimensional. Forelands comprise a range of bedrock shoreline controls, with cuspate and ramp forelands tending to have the potential for greater extents of bedrock shorelines compared to salients and tombolos. Comparison of some of these morphometric factors in a geographical context suggests that west coast forelands are more compact (have somewhat higher width/length values; Fig. 5) than east coast forelands (average of 0.261 compared to 0.190, respectively), which may reflect the more vigorous wave regime and lower sediment availability.

Some specific examples illustrate the properties of these forelands. The salient at Visagiesfontein (#1 on Table 1 and Fig. 4) (Fig. 7a) is developed at around 100 m distance in the lee of a bedrock outcrop and is broadly symmetric in plan view but with a slight southward skew. Observation over multiple time periods (in Google Earth) shows waves to be shore parallel, suggesting that the salient is morphodynamically at equilibrium with respect to wave regime. The surface of the salient is relatively flat, with no supratidal dune development. A notable feature at this site is evidence for sand mining on the coastal plain behind the salient. Borrow pits are visible at the north end and at the apex of the salient (3 February 2016), but these pits have disappeared in the subsequent image (24 November 2018). Further, the stable morphology of the salient suggests that sand mining has not affected its morphodynamics over recent last decades.

The tombolo at Robberg (#26) (Fig. 7b) is connected to an offshore island comprised of aeolianite. This aeolianite was dated by Carr et al. (2019) using the luminescence method to the period ~35–41 ka (middle of marine isotope stage (MIS) 3), suggesting that today's tombolo developed in response to progressive marine erosion and development of this island as a topographic feature, in the post-MIS 3 period. Aeolianite on this island and on the landward Robberg peninsula have helped anchor this system, and force refraction, with tombolo sediment provided by reworking of recent dunes in the centre of the peninsula, or where tombolo surface sediments are blown inland into this dune system (Hellström and Lubke, 1993). The width of the tombolo appears to vary seasonally, narrowing on both sides in the winter as likely result of bigger waves. The shoreface around the tombolo margins is steep and sharp-crested.

The cuspate foreland at Oceana Beach (#39) (Fig. 7c) is asymmetric and anchored on a broad intertidal shore platform. This is defined as a cuspate foreland because sediment availability does not vary along the length of the foreland, in contrast to ramp forelands where sediment thins up the bedrock ramp. The ramp foreland at Fort D'Acre (#42) (Fig. 7d) has a broader shoreface than the cuspate forelands.

The PCA results of morphometric and geomorphic analysis of each of the forelands identified (Table 1) are shown in Figure 8. The results show that there is wide variability in the composition, structure and size of the contemporary forelands along this coast. The PCA allows six morphometric form types to be identified – these are labelled types a–f on Figure 8 and correspond to the morphological continuum between cuspate and ramp foreland types (mostly types b and c, respectively). Tombolos and salients are not resolved as discrete morphotypes in Figure 8, but are mainly represented by type e. In total, around one third of the total variance is captured by the parameters of foreland size, the presence and absence of specific aeolian forms, and the role of rock within the foreland. Larger forelands (types a–c) generally comprise significant areas of unvegetated transverse dunes, backed in many cases by densely vegetated and inactive (fossilised) dunes (see Knight, 2021), and their shape is notably skewed in an alongshore down-drift direction. These foreland types are all found on the east coast, and can be secondarily differentiated by the presence of bedrock close to, or protruding above, the contemporary aeolian surface. A wider range of forelands are found across all shorelines, and these are more generally characterised as more compact and symmetrical forms (types d–f) and are found mainly along the west coast. Some relate to significantly rocky shorelines, and exist as unvegetated, small aeolian deposits at the rear of the beach. With reduced dominance of rock along the shoreline, the forelands are generally more vegetated, but are further distinguished by the presence or absence of erosional features such as deflation hollows. A smaller group of forelands is differentiated by the presence of specific progradational forms such as beach ridges; bedrock is still evident within the nearshore zone, but these are the closest geomorphologically to cuspate forelands. Specific examples of form types a–f are presented in Figure 9. These illustrate schematically the main geomorphic elements of these types that allow them to be distinguished from each other, and therefore why they plot in different areas of the PCA.

Although there is a broad association of forelands with sandy coastal stretches (Fig. 4) there is essentially a random pattern of foreland size and shape over space despite closely located forelands commonly having similar properties (Fig. 5). This appears true for both north–south oriented coastlines (along the west and east coasts), and the west–east oriented coastline along the southern Cape coast. In addition, the different foreland types are found along all sectors of the coast apart from the limited number of salient found mainly along the west coast. There is a clustering of forelands along the Eastern Cape and northern KwaZulu-Natal coasts of South Africa, with densities of <16 forelands/100 km.

Of note here is that both cuspate and ramp foreland types have well developed transverse dunes (defined by Hunter et al., 1983) within the supratidal zone (e.g., Knight and Burningham, 2019, 2021; Jackson et al., 2020). Erosion of the vegetated dunes to the rear of these forelands is evidenced by the ragged dune edge and shows that sediment can be transferred from the dunes to the beach, and *vice versa*. It is also notable that over time the margins of these foreland systems are stable with a continuous shoreface, suggesting they are largely at equilibrium with respect to wave forcing (but this is discussed below).

Discussion

Forelands can be considered as locations along extensive sandy coastlines where sediments show net accumulation leading to seaward progradation and therefore development of the foreland shape. Forelands are shown here to be relatively common, but underreported, landforms along the South Africa coast, and are located along both sand-dominated and rock-dominated coastal stretches (Figs. 2, 4). Sand-dominated stretches have generally linear and narrow sandy beaches with well-vegetated backing dunes (Tinley, 1985; Dardis and Grindley, 1988). Along the east coast where a narrow shelf and steep coastal hinterland is usually present, forelands are found particularly in association with river mouths (Table 1) where sediment supply overwhelms the limited accommodation space. It is notable that the sand-dominated west (Atlantic) coast contains significantly fewer forelands in total and by density per 100 km (values of 2 to 4) compared to much higher values (5 to 16/100 km) along the east (Indian) coast. However, the west coast contains most of the (4) salients identified in this study, which is indicative of high wave energy conditions (Sanderson and Eliot, 1996). The role of wave energy in shaping the lateral margins of forelands as well as supplying longshore sediment to the foreland apex is well established (Carter, 1980; Heron et al., 1984; Ashton et al., 2001). Seasonal changes in wave direction and height can lead to beach rotation (Dolphin et al., 2011), asymmetric foreland shapes (Sanderson et al., 2000) and formation of 'travelling forelands' where the entire foreland shape migrates alongshore (Escoffier, 1954; Burningham and French, 2014; Hesp et al., 2016). There is no evidence to suggest this is happening at the multiannual time scale (i.e., within last 20 years) as this was not examined in this study, but the generally high energy wave regime, narrow shelf and limited sediment supply may mean that aggradational landforms are quickly 'flattened' against the coast (e.g., Corbella and Stretch, 2012b). Indeed, the forelands identified in this study are generally of greater length and shorter width when compared to those reported elsewhere globally (see for example Sanderson and Eliot, 1996; Klein et al., 2002, for different evolutionary models).

This property also has implications for evaluating foreland dynamics (e.g., width/length ratio) and the extent to which the lateral margins of the forelands may be exposed to wave action (Alcántara-Carrió and Fontán, 2009; Xhardé et al., 2011). It is notable that the greatest morphodynamic changes occurring in the forelands examined here are found in association with river mouth/bar locations. Bedrock is clearly imposing a key role in either anchoring or delineating many of the South African forelands which leads to a strong tendency for them to be largely fixed in their alongshore position.

One significant difference between the cuspate and ramp forelands in this study is that 46% of the former are symmetric in plan view, whereas only 18% of the latter are (Table 1). The reason for this is the rising bedrock surface underlying ramp forelands acts to disrupt longshore transport, leading to differential erosion of the foreland margins and an asymmetric plan form shape (Boeyinga et al., 2010; Vieira da Silva et al., 2018; Gallop et al., 2020). Cuspate forelands, even if they are anchored on a shore platform (as 44 of 46 cuspate forelands in this study area), appear to be better able to operate as headland bypass systems because they retain an active sedimentary foreshore along their entire length (Fig. 7), and this process works through feedback to maintain foreland systems at morphological equilibrium. This may be facilitated by storage of sediment in, and sediment transport to and from, subtidal bars and shoals, in particular around river mouths (Fig. 10). The varied typologies of cuspate to ramp foreland systems, that can be considered to exist along a continuum, highlight the role of bedrock control within the lower shoreface or intertidal zone (Fig. 7). The presence of antecedent bedrock outcrops controls where shoreface pinning will take place, resulting in enhanced erosion of loose sand outside of these areas (Dillenburg et al., 2000; Valvo et al., 2006; Gallop et al., 2020). Over time, therefore, the shoreface becomes more indented and bedrock-influenced forelands develop. This means that macroscale geologic structure can be considered as the major control on foreland development and geometry along sandy coasts. Silveira et al. (2010) describe different styles of sandy coastline response to bedrock outcrops along the coast of Brazil, which they classified as headland-bypassing systems, but this principle works exactly the same for smaller-scale outcrops as described from South Africa in this present study. An interesting point is that, especially along the northeast coast of South Africa, this bedrock influence is commonly provided by aeolianite and, less commonly, by beachrock that may exist across the subtidal to supratidal zones (Miller and Mason, 1994; Knight, 2021). The relief and extent of the bedrock surface largely controls accommodation space on the beach behind.

In detail, this mechanism of sediment storage in headland bypass systems has been previously described in the literature (Moslow and Heron, 1981; Goodwin et al., 2013; Kumar et al., 2013). Almost all the forelands identified here are contemporary and thus appear to be morphologically active under today's conditions (44 of 87, 50%), or partly active with contemporary geomorphic change taking place in some parts of the system only (42 of 87, 48%). All foreland types are also equally split between active and partly active systems. Only one system (Cape Recife, #32) is considered to be largely inactive. This system comprises headland-bypass dunefields that show mid-Holocene stabilised dune ridges overlying earlier coarse beach ridges (Illenberger and Burkinshaw, 2008). These geomorphic elements correspond to the Schelm Hoek Formation, which is of (undifferentiated) late Pleistocene age (Roberts et al., 2014).

Many of the forelands along the northeast coast of South Africa, and the adjacent coastal plains, are anchored on aeolianite and gravel/sand beach ridges that span MIS 11 to Holocene (Porat and Botha, 2008; Botha et al., 2018). For example, the Cape Vital foreland (#71) is located immediately seaward of Lake Bhangazi that has, at its southern end, a beach berm <6 m asl dated by the luminescence method to 1800±160 yr (Botha et al., 2018). Progradational development of the Cape Vital foreland therefore postdates this period. Further, all of these forelands on this northern sector of the KwaZulu-Natal coast (n=15) are the youngest and smallest coastal elements of the Middle to Late Pleistocene coastal aggradational record in this location where the relict coastal plain extends >12 km inland (Sudan et al., 2004; Porat and Botha, 2008). It is also notable that extensive beach ridge sets here are mainly linear, building an aggradational and parallel shoreline rather than a large cuspate foreland shoreline (cf., Dungeness: Long and Hughes, 1995; Roberts and Plater, 2007). This may suggest that today's forelands are only reworking sediment along this largely relict coast (Knight, 2021).

Forelands and coastal geomorphic systems

The different types of forelands identified in this study have not been described systematically in the literature, and this study is the first to formalise and define these four foreland types (Fig. 1). These different types represent the interplay amongst sediment supply, accommodation space and the presence of bedrock outcrops of different sizes, elevations and locations (Heron et al., 1984; Boeyinga et al., 2010; Goodwin et al., 2013; Vieira da Silva et al., 2018; de Macêdo et al., 2022), and thus these foreland types can be considered to exist along a morphological continuum. This interplay is shown through the development of ramp forelands, where the rise of the bedrock surface towards the foreland apex leads to thinning of the surficial sediment cover which is maintained mainly by supratidal aeolian deposition, with wave-deposited sediments located on the foreland flanks (e.g., at Kaysers Beach (#52) and Rockclyffe-on-Sea (#56)). Ramp forelands therefore also reflect the interplay between wave and wind sediment transport processes that maintain the stability of the foreland as a whole.

A sediment systems approach can frame the analysis of these relationships (Fig. 10). For example, on the east coast of South Africa, beach recovery after storms takes around two years on average, and is modified by beach–dune interactions (Corbella and Stretch, 2012a, b). This suggests that storms move beach sediment both landward into the dunes and offshore onto the shelf, and that this sediment is then recirculated back to the beach system under fairweather conditions. Along the Eastern Cape coast, Lubke and Webb (2016) described the sediment circulation patterns between the beach–dune system (part of the Boknes Boesman ramp foreland, #35) and the Bushmans River at the north end of this system. Changes in river mouth position from ~1955 onwards led to growth of the beach and dune areas adjacent to the mouth, and this subsequently led (~1970–1980) to new dune areas being stabilised by vegetation in this marginal sector of the foreland. Presently (from ~1997 onwards) dunes are being reactivated at the south end of this system, giving rise to spatial differences along the foreland in sediment availability and supratidal dune dynamics. Along the southern Cape coast, Hellström (1996) showed that changes in the position of the Goukamma River outlet from ~1930 resulted in development of a large 'spit delta' which was then naturally vegetated, reducing downdrift sediment supply to the adjacent Buffelskop foreland (#25). Thus, any potential narrowing of this foreland system could be interpreted as a response to this river mouth behaviour. Similar behaviour has also been described adjacent to small rivers flowing into the Río de la Plata estuary, Uruguay (Gutíerrez et al., 2018). These examples illustrate how within-system sediment supply and transport can significantly modify foreland dynamics, independent of direct external forcing. Figure 10 also depicts the main drivers of foreland sediment systems and their dynamical controls. Of note here is that there are functional connections between different landforms within the foreland system that are driven by both wind and water processes. There are also feedbacks between these landforms and therefore the processes that influence them – for example, erosion of vegetated dunes releases more sediment to transverse dunes of the upper beach, building ramp dunes and protecting vegetated dunes inland from further erosion (e.g., He et al., 2022). The present vegetated dunes at the rear of most beaches can be considered as essentially fossilised systems as they are largely not functionally connected to the present beach system (Knight, 2021). Likewise, foreland erosion can also reduce accommodation space for transverse dune development (e.g., at Kaysers Beach, #52). Although there is high variability in dune migration rates within the foreland systems, this appears to be cyclic in behaviour but not strictly seasonal, and there is limited evidence for net alongshore movement of the foreland through dune migration (Knight and Burningham, 2021). The comparison between forelands suggests that at the foreland scale, these systems are actually behaving in a similar fashion. Bigger winter waves, however, may both enhance sediment supply to and increase erosion from the foreland shoreface (Fig. 10), which may be reflected in the geomorphology of foreland margins and, subsequently, on transverse dune geomorphology and sediment supply. Examining foreland sediment budgets is a useful area of future research.

Conclusions

This study for the first time identifies four different types of coastal forelands and then inventorises these through a systematic survey of the South African coast. These foreland types are found in different coastal contexts in South Africa, and likely repeated globally, and their distributions and large-scale geomorphic properties illustrate the interplay amongst the different forcing factors that contribute to foreland dynamics, including wind/wave regime and sediment supply. Of the 87 forelands identified across South Africa in this study, 5% are salients, 10% tombolos, 53% cuspate and 32% ramp forelands. These have different locations and geomorphic properties, and it is only cuspate and ramp forelands that are associated with transverse dunes in their supratidal zones. A sediment systems approach – considering the interplay among fluvial, nearshore, shoreface, supratidal and vegetated dune elements – can usefully inform on foreland sediment budgets and dynamics, and the role of forelands in influencing the dynamics of sandy coasts more generally. The methods presented in this study can be deployed worldwide, and this is a useful research strategy to inform on sandy beach dynamics, with implications for the sensitivity of such beaches to climate forcing.

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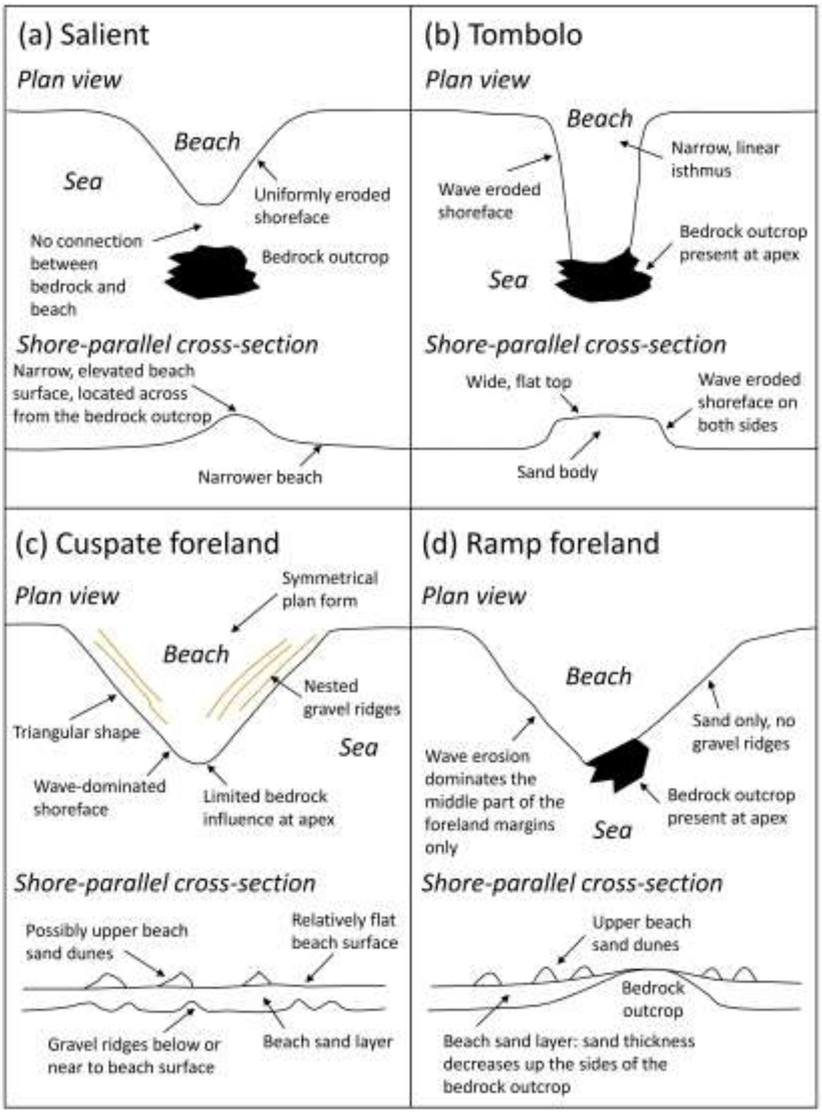

Figure 1. Schematic illustration of coastal foreland types and their major morphology properties. Schematic shore-parallel cross-sections are not to scale.

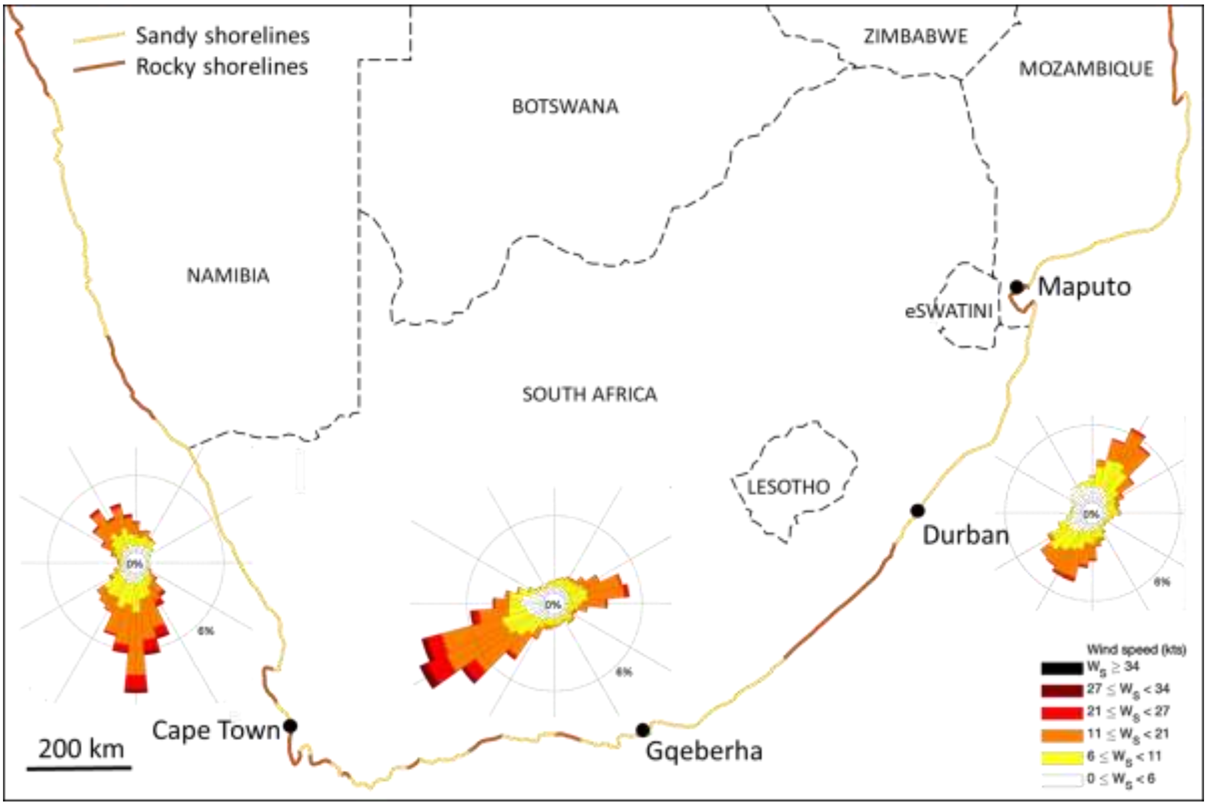

Figure 2. Map of southern Africa showing the broad differentiation between sandy and rock shorelines (after Tinley, 1985; Dardis and Grindley, 1988). Illustrative wind roses for the west coast (Cape Town, 1975 to 2020), south coast (Port Elizabeth, 2001 to 2020) and east coast (Durban, 1975 to 2020) are also shown.

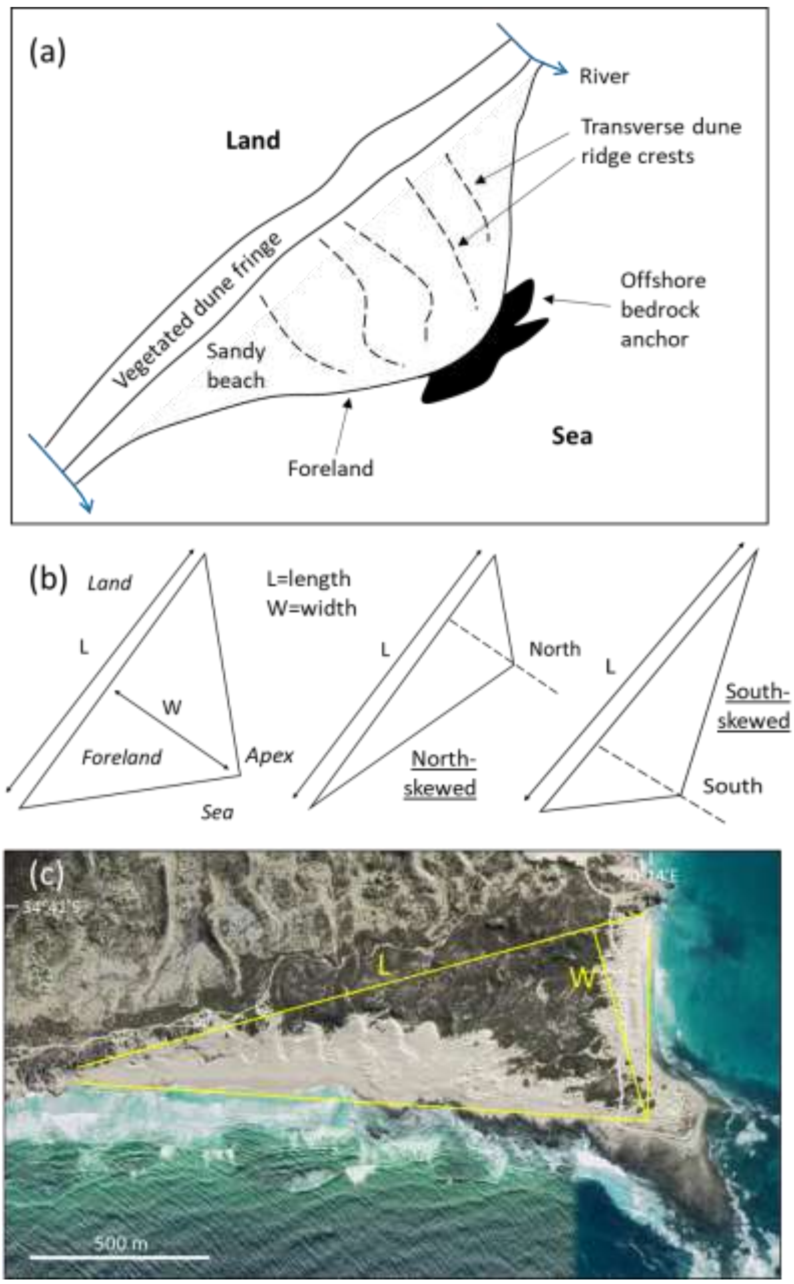

Figure 3. (a) Sketch of the main geomorphic elements of a coastal foreland, (b) schematic view of (top) foreland length and width, as measured in this study, and (bottom) asymmetry or skewness of the foreland shape where the position of the greatest width is skewed to the north or south part of the foreland, (c) example of morphometric analysis from Arniston foreland (#24).

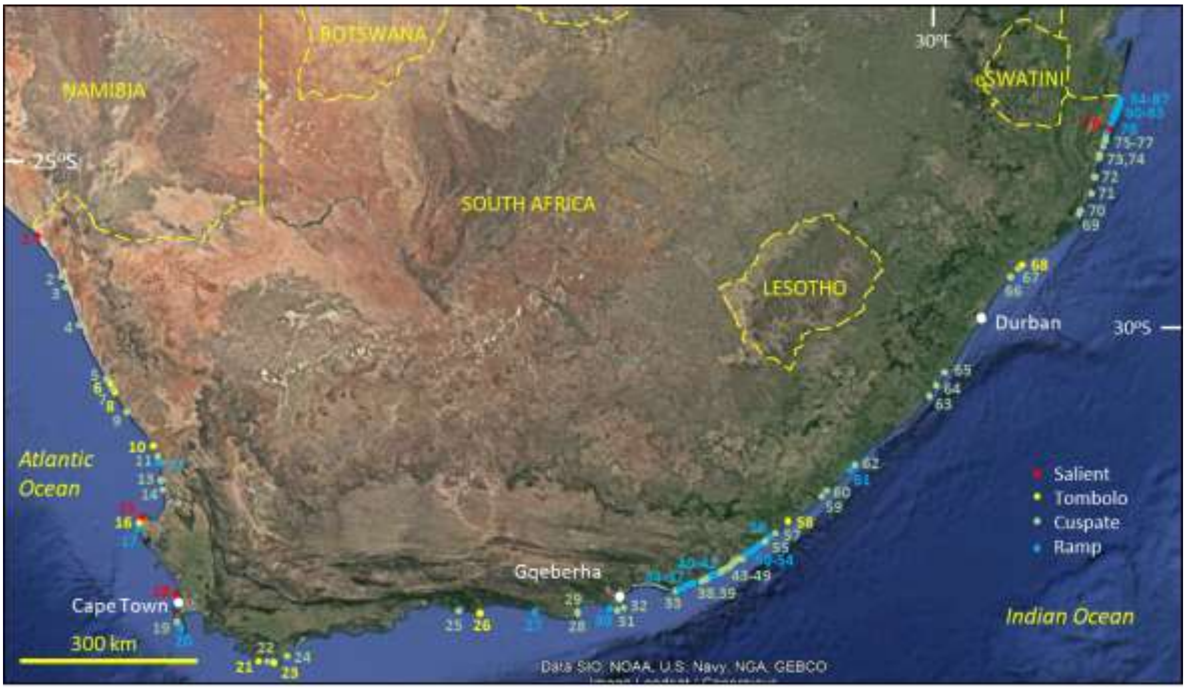

Figure 4. Map of the South African coast showing the position of coastal forelands identified in this study using Google Earth imagery. Numbered forelands 1–87 classified into the four different foreland types are listed in Table 1.

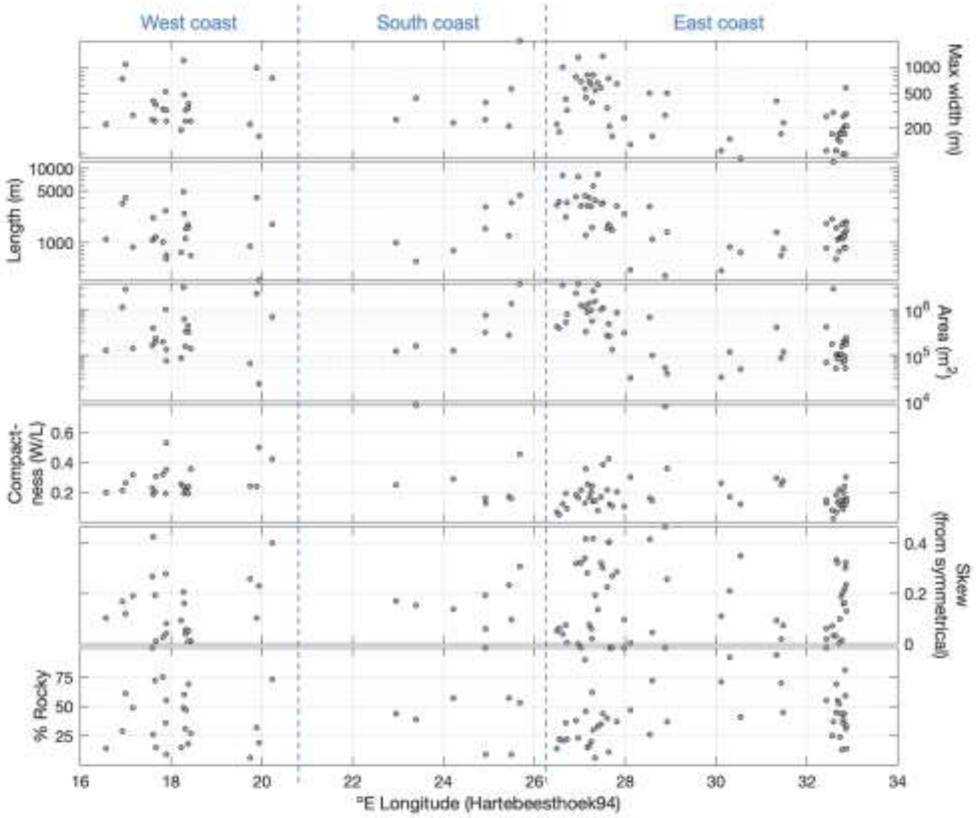

Figure 5. Plot of longshore (from west to east) variations in foreland morphometric properties along the South African coast.

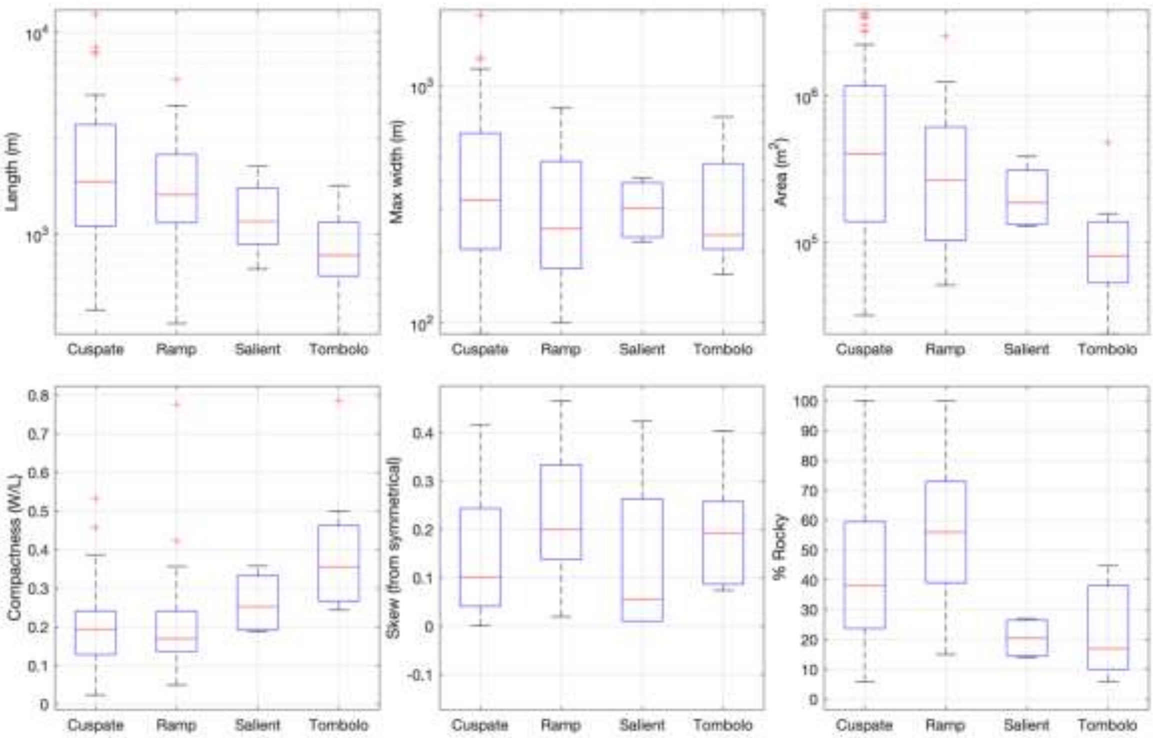

Figure 6. Examination of key foreland properties: length, width at the apex, area, compactness (width/length), skewness (from symmetrical), and proportion of the foreland shoreline comprising bedrock.

Figure 7. Examples of different foreland types along the South African coast. (a) Salient foreland (#1 Visagiesfontein), (b) tombolo foreland (#26 Robberg), (c) cuspate foreland (#39 Oceana Beach), (d) ramp foreland (#42 Fort D'Acre). Locations are marked on Figure 4.

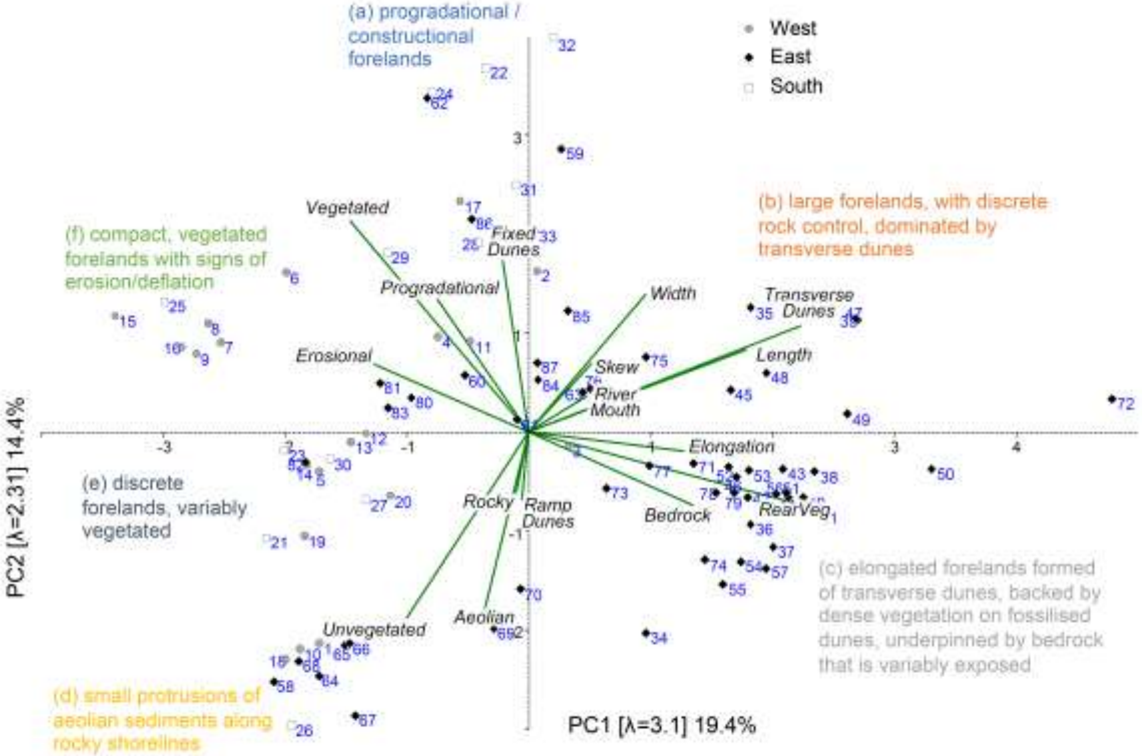

Figure 8. PCA results based on foreland morphometric and geomorphic properties from the South African coast, from which six endmembers (a–f) are identified (shown in Fig. 9). The morphometrics shown in Figures 5 and 6, except for area (as it correlates strongly with length), are used in addition the pseudo (binary) variables representing presence / absence of different properties and features: river mouth, transverse dunes, fixed dunes, ramp dunes, exposed bedrock, deflation zone, contemporary progradational forms, distinct aeolian bedforms, vegetation present on the foreland, vegetation only present at the rear (mainland), and unvegetated forelands.

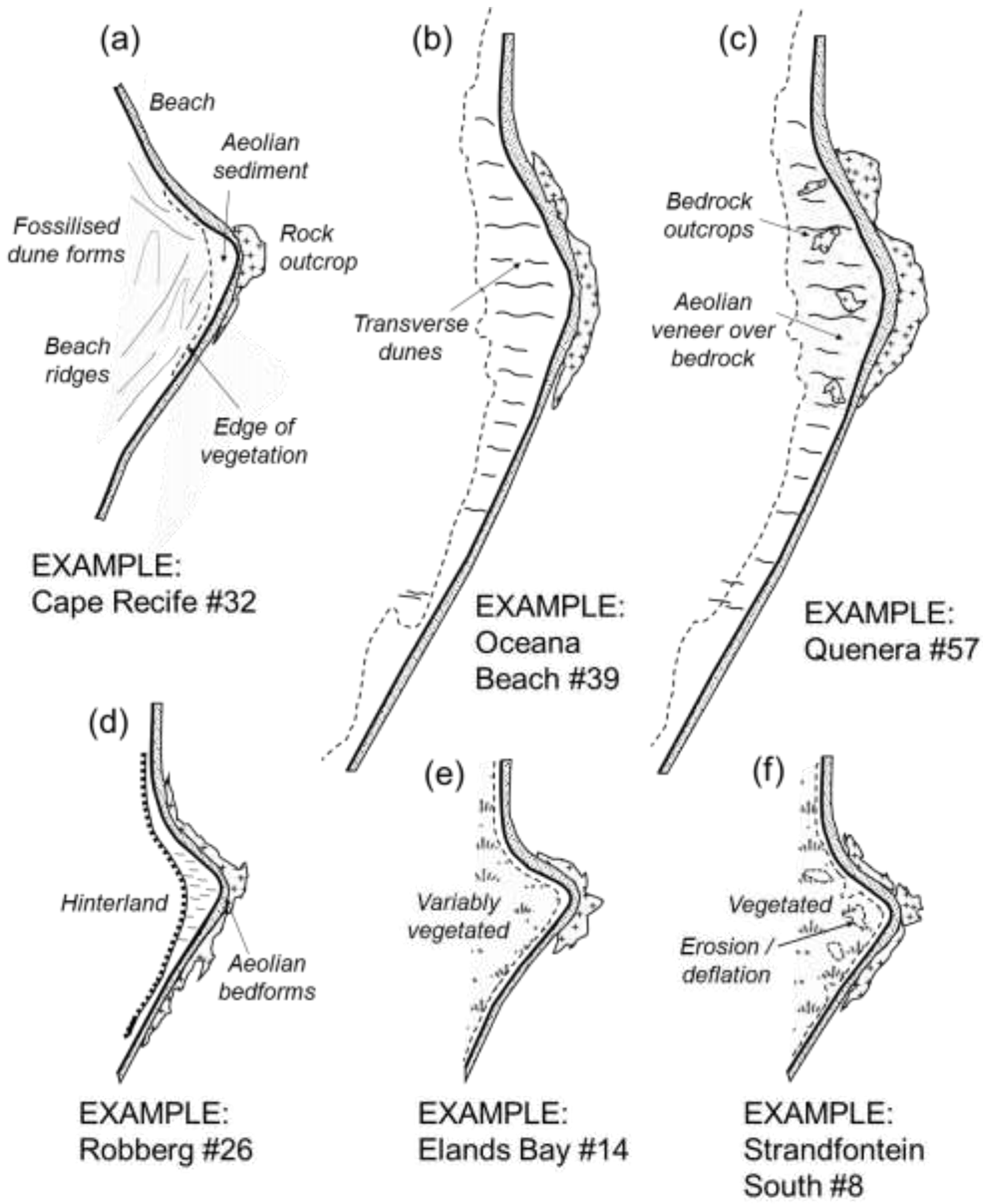

Figure 9. Sketches of the major geomorphic characteristics of the six endmembers identified by PCA analysis of foreland morphometric and geomorphic properties.

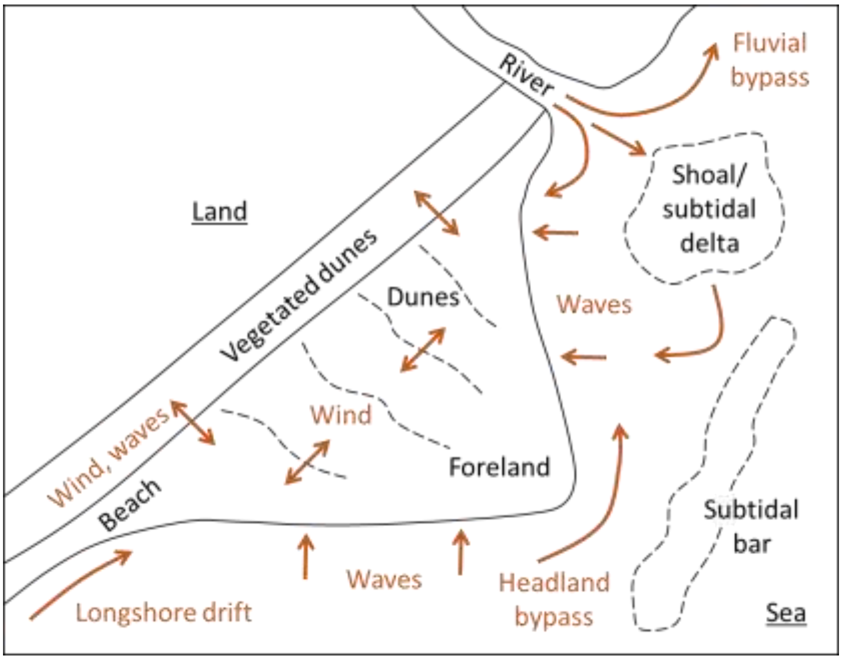

Figure 10. Schematic representation of physical processes (brown text) leading to sediment transport within a coastal foreland system (brown arrows).

Table 1. List of forelands identified along the coast of South Africa (numbered in Figure 4) and their major geomorphic properties.

Supplementary Data File. Google Earth kzm file of the locations of the forelands examined in this study.