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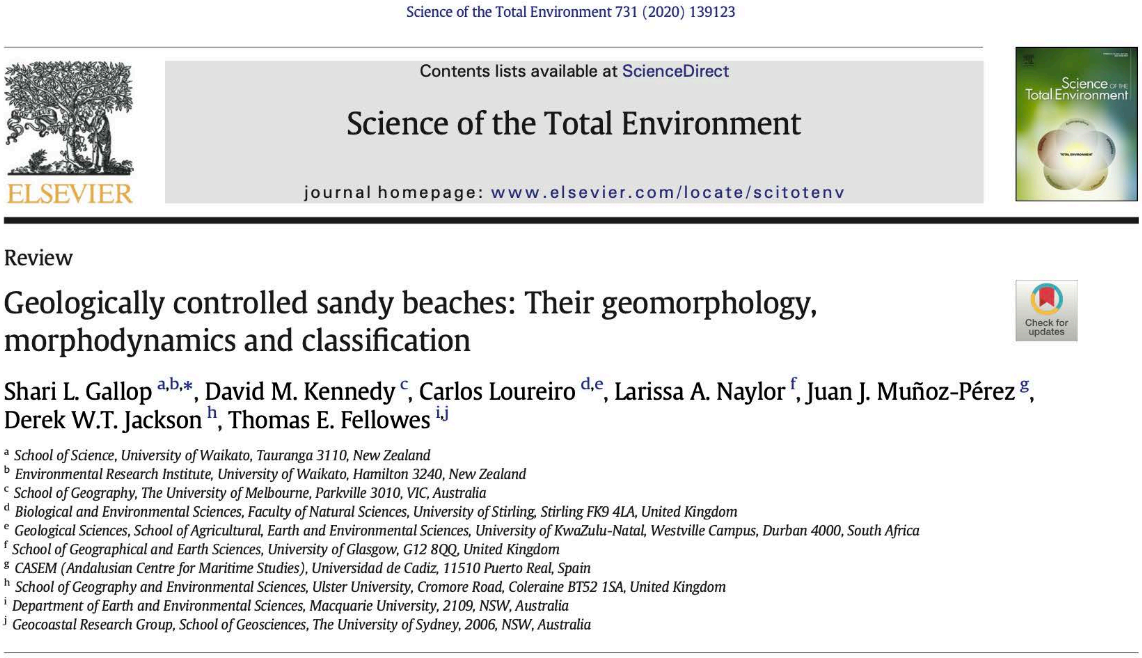

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Review

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Geologically controlled sandy beaches: Their geomorphology, morphodynamics and classification

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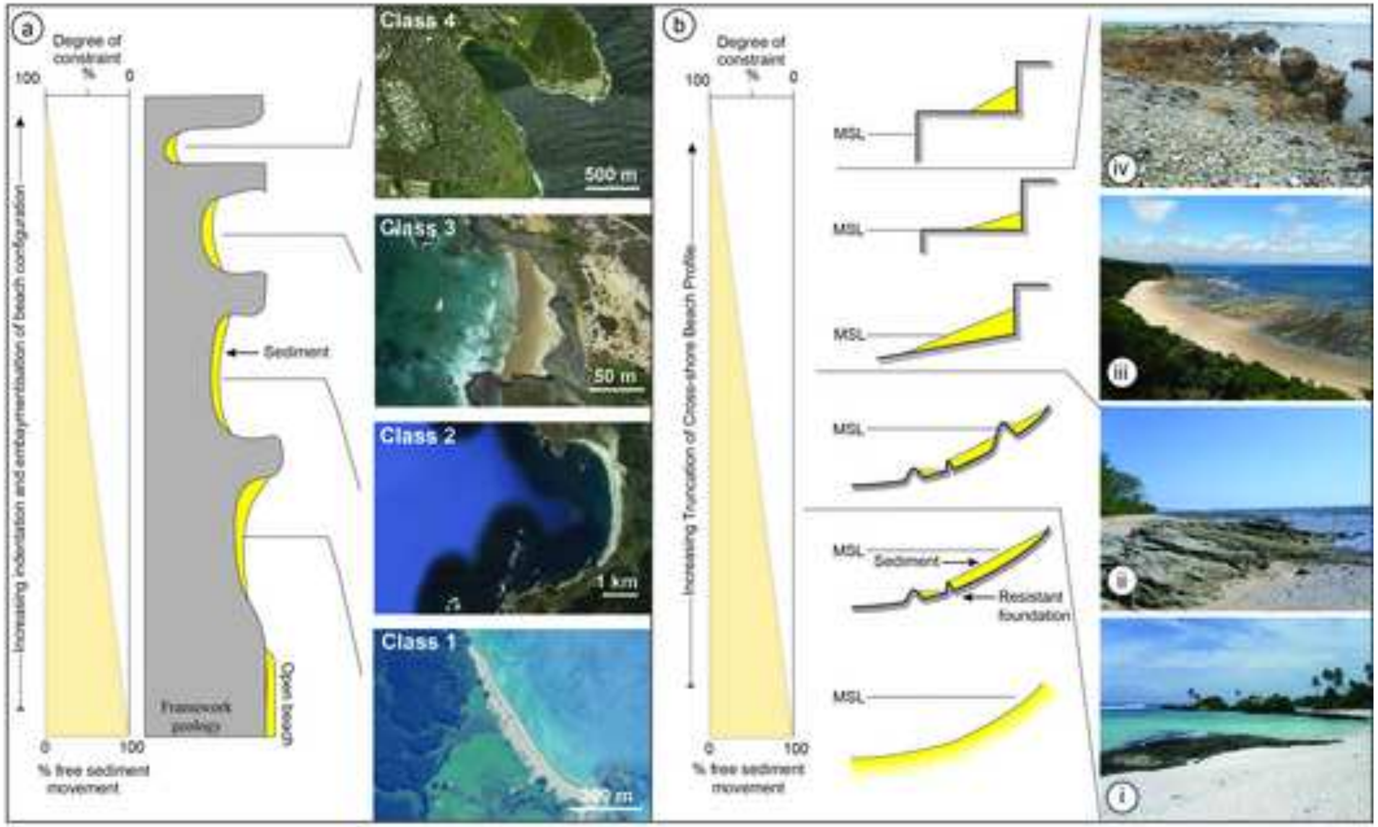

a
Degree of constraint %
100
0
Increasing indentation and embaymentisation of beach configuration
0
100
% free sediment movement
Sediment
Framework geology
Open beach
Class 4
500 m
Class 3
50 m
Class 2
1 km
Class 1
200 m
b
Degree of constraint %
100
0
Increasing Truncation of Cross-shore Beach Profile
0
100
% free sediment movement
MSL
Sediment
Resistant foundation
iv
iii
ii
i

- Beaches geologically controlled by rock and coral formations are common globally.
- We review the state of knowledge of geological control of sandy beaches.
- There was no encompassing classification system for these beaches.
- We present longshore and cross-shore models from low to high geological control.
- There is poor applicability of models for management of this common beach type.

Abstract

Beaches that are geologically controlled by rock and coral formations are the rule, not the exception. This paper reviews current understanding of geologically controlled beaches, bringing together a range of terminologies (including embayed beaches, shore platform beaches, relict beaches, and perched beaches among others) and processes, with the aim of exploring the multiple ways in which geology influences beach morphology and morphodynamics. We show how in addition to sediment supply, the basement geology influences where beaches will form by providing accommodation, and in the cross-shore, aspects of rock platform morphology such as elevation and slope are also important. Geologically controlled beaches can have significant variations in sediment coverage with seasons and storms, and geological controls have fundamental influences on their contemporary morphodynamics. This includes wave shadowing by headlands and rocky/coral formations inducing strong alongshore gradients in wave energy, resulting in corresponding variations in morphodynamic beach state and storm response. Geologically-induced rip currents such as shadow rips and deflection rips, and even mega-rips that can develop on embayed beaches during storms, are an integral feature of the nearshore circulation and morphodynamics of geologically controlled beaches. We bring these processes together by presenting a conceptual model of alongshore and cross-shore levels of geological control. In the longshore dimension, this ranges from beaches that are slightly embayed, through to highly embayed beaches where headlands dominate the entire beach morphodynamic response. In the cross-shore dimension, this ranges from beaches without discernible geological controls, through to relict beaches above the influence of the contemporary littoral zone. Given the prevalence of geologically controlled beaches along the world's coasts, it is paramount for coastal management to consider how these beaches differ from unconstrained beaches and avoid applying inappropriate models and tools, especially with our uncertain future climate.

Keywords: Beach morphodynamics; shore platform; coral reef; headlands; perched beach; equilibrium profile

1. Introduction

Strong feedback loops exist within sandy beach systems, where a change in a single driver such as wave period and height, or sediment size, may result in an adjustment to beach form, whose interaction was termed morphodynamics by Wright and Thom (1977) and synthetized by Wright and Short (1984) for sandy beach environments. Most research on beach morphodynamics focuses on cross-shore and alongshore sediment exchange that is (at least assumed to be) unconstrained by geology or other hard substrates (Cowell and Thom, 1994; Short and Jackson, 2013; Feal-Pérez et al., 2014; Trenhaile, 2018). Classic examples include the beach change frameworks developed for single, double (Wright and Short, 1984; Wright et al., 1985) and multi-barred (Short and Aagaard, 1993) wave-dominated beaches, and the model of Masselink and Short (1993) that accounts for tidal range using the Relative Tidal Range (RTR) parameter. In these models, the surf zone and beach morphology is essentially a function of grain size, wave and tide hydrodynamics, conveniently described through the surf scaling parameter, Dean's parameter and RTR (Jackson et al., 2005; Jackson and Cooper, 2009). However, many beaches have significant geological controls due to headlands, reefs, platforms, rock outcrops and islets (Short, 2006), which determine beach boundaries, beach morphology, morphodynamics and long-term evolution (Jackson et al., 2005; Gómez-Pujol et al., 2007; Short, 2010). An increasing number of studies show that beaches with geological controls have distinctly different behaviour compared to unconstrained beaches (González et al., 1999; Muñoz-Pérez et al., 1999; Jackson et al., 2005; Jackson and Cooper, 2009; Gallop et al., 2011b; Gallop et al., 2012, 2013; Loureiro et al., 2013; Gallop et al., 2015a; Trenhaile, 2016), which causes significant complications for coastal managers as traditional erosional models are not directly applicable in such settings. However, geologically controlled beaches are still largely not classified as a distinct type, there is still a fundamental lack of data on their behaviour, and there is no commonly-accepted terminology and classification system of their morphology.

Thus, the aims of this critical review are to understand our current state of knowledge on how geological control affects sandy beach morphology and morphodynamics, to identify key research needs and management implications of these understudied, globally distributed coastal systems. In Section 2 we review the terminology used for geologically controlled beach systems. Section 3 focuses on the morphodynamics of sandy geologically controlled beaches, starting with conditions necessary for beach accumulation in terms of the underlying geological surface morphology (Section 3.1), followed by a discussion of the sometimes stark temporal variations in sediment coverage that can occur in these systems (Section 3.2). This is followed by the analysis of how geological controls can reduce beach wave exposure, and also filter wave energy increasing the dominance of infragravity waves (Section 3.3). We then discuss the range of geologically controlled rip currents in Section 3.4, followed by a summary of beach rotation in Section 3.5. Section 4 presents conceptual models of geological control in longshore directions (existing models) and in a cross-shore direction (a new model developed in this review). This is followed by conclusions in Section 6.

2. Defining geologically controlled beaches

Various terms have been applied in the geomorphological and engineering domains to describe geologically controlled beaches and their morphology (Table 1, Figure 1). The terms *geologically controlled* and *geologically constrained* have been used interchangeably, both to describe beaches with alongshore geological controls (Short, 2006, 2010) and/or where there is a geologically influenced cross-shore beach profile (Jackson and Cooper, 2009; Muñoz-Pérez and Medina, 2010). In particular, alongshore geological control is an important concept in delineating coastal sediment compartments (or cells) for coastal management (Gallop et al., 2015b), particularly where boundaries are located at rock headlands (Cooper and Pontee, 2006; Thom et al., 2018). It is a fundamental principle behind the development of headland control as an engineering solution for coastal stabilization (Silvester and Hsu, 1997).

In contrast, beaches without geological control in the cross-shore dimension, termed *unconstrained* by Jackson and Cooper (2009), have a sedimentary profile envelope that does not intersect or interact with the basement geology or semi-consolidated Quaternary lithologies (Jackson and Cooper, 2009) over contemporary morphodynamic time-scales. A typical example are the wave-dominated sandy beaches analysed in the classic Wright and Short (1984) morphodynamic model, where there is abundant sediment and the beach profile is assumed to adjust freely and fully to local hydrodynamic forcing by waves and tides (Jackson and Cooper, 2009). Some examples of geologically controlled beaches are given in Figure 1. While this paper focuses on hard substrates such as rock and coral, beach morphodynamics may also be influenced by other types of bioherms such as reefs built by gastropods, fan worms and molluscs such as oysters (Milliman, 1974; Piazza et al., 2005). Moreover, seagrass meadows (and associated litter) can also have a direct influence on the morphodynamics of geologically controlled beaches (Basterretxea et al., 2004; Gómez-Pujol et al., 2007; Aragonés et al., 2016) and may act in a similar way to a rock or coral reef (Gómez-Pujol et al., 2011). These features are an important consideration in the management of many geologically controlled beaches but are beyond the scope of this paper.

Figure 1. *Examples of geologically controlled beaches: (a) sandy embayed beach on rock reef at Man O'War Bay, Dorset, England (Photo: S.L. Gallop); (b) Sandy beach on rock pavement and intertidal outcrops at Rottnest Island, Western Australia (Photo: S. L. Gallop); (c) Sandy beach behind intertidal rock platform in Cuba (Photo: M.I. Vousdouskas); (d) Sandy pocket beach and beach rock platform at Motu Tuamotu, French Polynesia (Photo: S.L. Gallop); (e) Sandy beach behind Ningaloo fringing coral reef, Western Australia (Photo: S. Bauer); and (f) Sandy beach on calcareous sandstone platform at Victoria Beach, Cadiz, SW Spain (Photo: J.J.* Muñoz-Pérez*).*

Other key terms in the literature describe sub-types of geologically controlled beaches. This includes beaches constrained by beach rock formed by *in situ* cementation (Russell, 1959; Cooper, 1991; Vousdoukas et al., 2007; Vousdoukas et al., 2009; Vousdoukas et al., 2012), typically in the intertidal zone of tropical/subtropical and low latitude microtidal coasts (Vousdoukas et al., 2007). On some beaches, geological control occurs due to submerged or emergent (elevated about MSL) rock or coral reefs (Muñoz-Pérez et al., 1999; Sanderson, 2000), which may be naturally-occurring or artificial predominantly for coastal protection (Ranasinghe et al., 2006). Beaches on top of shore platforms, or platform beaches (Taborda and Ribeiro, 2015), are also subjected to strong geological controls (Stephenson, 2000; Short, 2006; Trenhaile, 2016). The term ‘hard bottom’ has often been used in the literature to describe rock outcrops (whether natural or engineered) on the beach and shoreface (Cleary et al., 1996; Larson and Kraus, 2000; Hanson and Militello, 2005)

Of relevance in the context of geological control are also raised/stranded/relict beaches, although these terms are also applied to unconstrained beaches. For a beach to become relict, a change in base level is required to strand the beach above the reach of modern marine processes, which can be eustatically, glacio-isostatically or tectonically driven (Blackburn et al., 1967; Kidson and Wood, 1974; Sprigg, 1979; Huntley et al., 1993; Alonso and Pagés, 2007; Benedetti et al., 2009; Trenhaile, 2016). Raised beaches are particularly common in tectonically active areas where instantaneous base level change strands beaches so that they can no longer be reworked by contemporary marine processes, such as Turakirae Head (McSaveney et al., 2006) and Wellington (Olson et al., 2012) in New Zealand and Kujikuri, Japan (Tamura et al., 2008).

Some geologically controlled beaches are described as ‘perched beaches’ with various definitions of ‘perched’ existing from both the geomorphological and engineering literature. In the 1960’s, the concept of engineered perched beaches was introduced by Inman and Frautschy (1966), who explored the idea that an artificially-steep beach (often due to sediment nourishment) could be maintained if it was ‘perched’ on an engineered submerged dike. The inspiration for this design was based on observations in nature at Algodones in the Gulf of California where the presence of a natural sedimentary rock outcrop ~2.75 m below MSL enabled a wider beach than on the neighbouring coast (Moreno et al., 2018). Nowadays, in coastal engineering, the term 'perched' beach is typically defined as a beach or wedge of sand retained above the otherwise normal profile level by a submerged dike (US Army Corps of Engineers, 1984) (Figure 2). According to this definition, perched beaches are essentially an engineered raised beach with an artificial cross-shore geological control that aims to prevent offshore leakage of sediment.

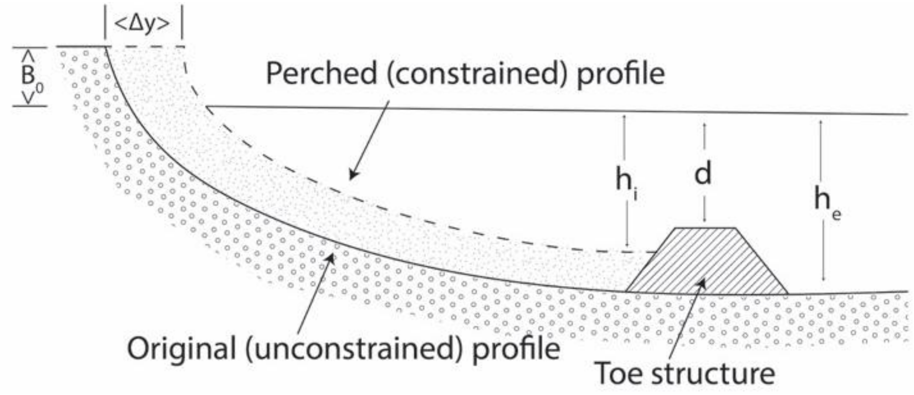


Figure 2. *Schematic of an engineered perched beach (based on (González et al., 1999), where the main variables are indicated including (d) water depth over the toe structure (e.g., breakwater), water depth on the shoreward (h_i) and seaward sides (h_e) of the structure, the change in beach width (Δy) and berm height (B_o).*

In a geomorphological context, the term 'perched beach' is sometimes used more broadly to describe beaches and other coastal landforms such as beach-barrier sequences (Pilkey et al., 1993; Riggs et al., 1995; Cleary et al., 1996), which have a hard substrate (e.g. rock or coral substrates) outcropping on the beach profile (Alexandrakis et al., 2013). The term perched beach has also been applied to beaches on shore platforms (Cleary et al., 1996), including those made of relatively soft, erodible materials such as soft mudstone and soft clay (Walkden and Hall, 2005) when the underlying and beach materials differ and there is limited exchange of sediment between the units (Shand et al., 2013). To avoid confusion between engineering and geomorphological terminology, we suggest that 'geologically controlled' is more appropriate than 'perched' to collectively describe beaches with *cross-shore* geological constraints. The geology in our definition can be both artificial and engineered and refers to substrate which is more resistant to erosion than the overlying unconsolidated beach sand.

Table 1. *Summary of terms used to describe types of geologically controlled beaches.*

Term	**Definition**
Geologically controlled/constrained beach	Beach where the physical boundaries such as headlands, outcrops, reefs, shore platforms and islets (Short, 2006) determine beach boundaries (accommodation space), sediment supply, nature of sediments and morphological change (McNinch, 2004; Jackson et al., 2005). Geology may also intrude into the cross-shore idealised equilibrium beach profile envelope (Jackson et al., 2005; Short, 2010).
Unconstrained/open beach	Beach where the sedimentary profile does not intersect or interact with the basement geology or semi-consolidated lithologies (Jackson and Cooper, 2009) over decadal time-scales. Beach can adjust freely to local hydrodynamic forcing by waves and tides (Jackson and Cooper, 2009).
Embayed/pocket/crenulated /headland-bay beach	Beach bound laterally in one or both extremities by physical barriers such as headlands, rock platforms or artificial structures such as groins, jetties and breakwaters (Hsu and Evans, 1989; Fellowes et al., 2019).
Reef-protected beaches/beaches with submerged structures such as breakwaters	Beaches with natural or artificial submerged or emergent (elevated about MSL) rock or coral reefs (Muñoz-Pérez et al., 1999; Sanderson, 2000; Moschella et al., 2005), or lithified submerged barriers/ paleo shorelines in the nearshore (McNinch, 2004; Gómez-Pujol et al., 2019). See Ranasinghe et al. (2006) for a review of shoreline response to nearshore submerged structures.

Shore platform beaches	Beaches where the underlying beach substrate is an erosional rocky shore platform. These beaches occur above MLWS elevation (Stephenson, 2000; Trenhaile, 2004; Doucette, 2009; Kennedy and Milkins, 2015).
Relict/raised/stranded beach	Beach that is elevated well-above current MSL and even extreme storm conditions, as a result of eustatically, glacio-isostatically or tectonically driven change in base level (Blackburn et al., 1967; Kidson and Wood, 1974; Sprigg, 1979; Huntley et al., 1993; Alonso and Pagés, 2007; Benedetti et al., 2009; Trenhaile, 2016). These terms can be applied to geologically controlled and unconstrained beaches alike.
Perched beach	*Engineering*: "a beach or wedge of sand retained above the otherwise normal profile level by a submerged dike" (US Army Corps of Engineers, 1984) *Geomorphology*: broad term describing beaches with either a hard substrate outcropping on the beach profile such as submerged beach rock and coral reefs (Gallop et al., 2011b; Gallop et al., 2012; Alexandrakis et al., 2013; Gallop et al., 2013) or where material underlying the beach has a different composition, such as soft clay (Walkden and Hall, 2005).

It is important to consider that geological beach control will occur in any situation where bedrock is outcropping on the beach profile. As a result, it is more likely to occur in areas of high coastal relief and in instances where there is restricted sediment supply (Cooper et al., 2018). Changes to sediment supply which would lead to a reduction in total beach volume could potentially shift beaches from being unconstrained to geologically controlled as bedrock becomes exposed (Masselink et al., 2016) (discussed further in Section 3.2). Globally, this may become more common as sediment supply to the coast is reduced (Syvitski et al., 2005), however, exploration of this topic is beyond the scope of this study.

3. Geological control of beach morphodynamics

3.1. Beach accumulation on shore platforms

Beaches that develop through sand accumulation on shore platforms are probably the most well-studied form of cross-shore geologically controlled beach (Trenhaile, 2016). On shore platform beaches, a rocky surface occupies at least part of the intertidal zone. The degree to which sediment can accumulate, and therefore the level of beach profile development, is a product of the elevation of the platform and its slope (Trenhaile, 2004; Kennedy and Milkins, 2015). Trenhaile (2004) modelled the accumulation of beach sediment on shore platforms and found that sediment will only accumulate when the slope of the platform is less than the slope of the beach. This is because a higher platform angle will favour offshore rather than onshore sediment transport. If the platform gradient is low enough, beach development initiates at the cliff base and extends seaward if sediment is available. If the platform is sloping, the beach can only develop on sections of the platform with a gradient less than the equilibrium beach face gradient, which depends on breaker height, wave period and sediment grain size (Sunamura, 1989). This relationship of beach development and platform slope means that the sub-horizontal platforms found in micro- and lower meso-tidal ranges are particularly conducive to beach formation (Trenhaile, 2004). Beaches are also more likely to develop on the lower-gradient regions of convex platforms (seaward end) and concave platforms (landward end). In addition, platform gradient has an influence on the sediment grain size that can accumulate to form the beach, where smaller grain sizes can build up on more gently-sloping platforms, compared to larger grain sizes on steeper platforms. Trenhaile (2004) also suggested that only pebbles and other coarse material can accumulate on platforms with a gradient of more than 5°, and coarse sand can accumulate when the platform gradient is between 2° and 5°.

Shore platform gradient tends to increase with tidal range, although local factors are also important (Trenhaile and Layzell, 1981), which implies that the potential for platform beach formation is higher on microtidal rocky coasts. In such low tide range settings in Victoria, SE Australia, Kennedy and Milkins (2015) found that shore platform elevation was a critical determinant of beach accumulation. Sand was only able to accumulate when the platform dropped below the combined elevation of the mean annual wave height and the Mean High Water Springs (MHWS) tide level. Once sand could accumulate on the shore, the width of the platform then became a significant factor in determining beach volume. Wider platforms dissipate more wave energy (Trenhaile, 2005; Marshall and Stephenson, 2011) and therefore encourage sediment deposition. In SE Victoria, there was a positive relationship between platform width and beach volume once the platform was low enough for sediment to accumulate (Kennedy and Milkins, 2015). In this region, at Cape Paterson (Figure 5iii), where a wide platform at low tide elevation is found, a steep beachface with cusps developed, however in Lorne, where the platform is at MSL and has half the width of the previous case, only a featureless upper beachface is present.

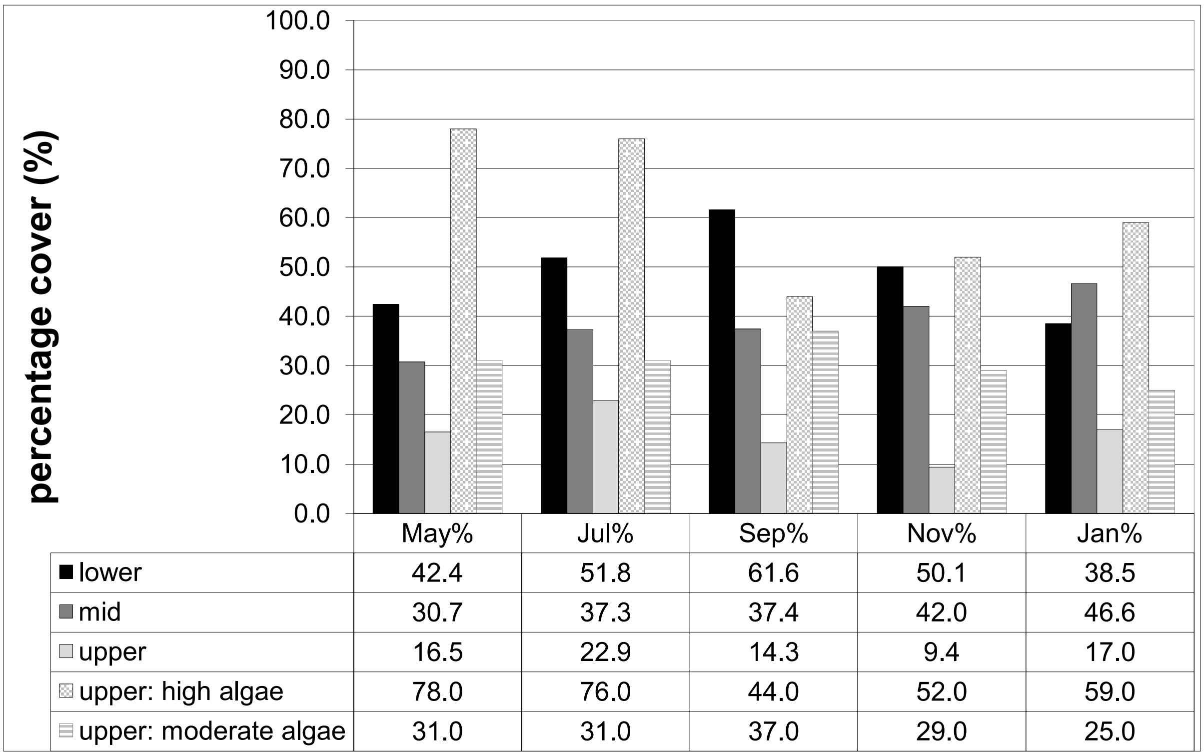
In some predominantly rocky settings, such as on highly embayed coasts, beach morphology may be more a function of the longshore dimensions of the embayments in which they are formed rather than solely the platform elevation and width (Bowman et al., 2009). For example, in Niue in the South Pacific Ocean the beaches sit at the rear of wide shore platforms at intertidal elevations, but are ephemeral, disappearing during tropical cyclones, and during non-storm periods only the low intertidal parts of the profile can form. Their morphology is therefore limited by the accommodation space. That is, in addition to being vertically geologically constrained, their high intertidal and supratidal profile cannot form due to the presence of vertical cliffs which limit lateral accommodation space.

3.2. Temporal variation in sediment coverage

On geologically controlled beaches, there is a paucity of empirical data on spatial and temporal changes compared to studies of unconstrained beaches (Fox and Davis, 1978; Davidson-Arnott and Law, 1996; Masselink et al., 2016). Yet, the limited observations show that there can be dramatic temporal changes in sediment coverage and thickness over the geological substrate. For example, during the extreme 2013–14 winter storms in SW England, large quantities of sand moved offshore (Masselink et al., 2016), revealing the underlying rocky substrate. Such behaviour can also occur on a regular basis over seasonal time-scales, such as on a beach overlying a calcarenite limestone platform near Perth, WA, where in winter, the sub-horizontal platform can be exposed, and then recovered with sediment during summer (Doucette, 2009). An example is shown in Figure 3 of Yanchep, WA, which also undergoes dramatic seasonal changes in sediment coverage and thickness (Gallop et al., 2013). There have been few studies comparing rates of erosion and accretion of geologically controlled compared to unconstrained beaches. Muñoz-Pérez and Medina (2010) found that the accretion rate was much faster on an unconstrained, sandy beach profile, compared to a profile geologically-constrained by a rock reef (1.01 m^3 day^{-1} compared to 0.33 m^3 day^{-1}) in Cadiz, SW Spain. The relatively slower rates of recovery of geologically controlled beaches may relate partly to the ability of sediment to be transported above the seaward terminus of the rock/coral substrate and onto the beach. In microtidal environments this seaward edge can range in shape from a gently sloping ramp to vertical cliff (Kennedy, 2015, 2016), and when steep it can prevent onshore sediment movement during calm conditions (Trenhaile, 2004). Bosserelle et al. (2011) reported that the presence of a sand ramp fronting a rock reef was crucial to allow sediment to overtop the reef onto the beach. This can increase the time it takes for beaches on platforms/reefs with abrupt seaward terminuses to recover after erosive events and periods, as very specific and relatively infrequent hydrodynamic conditions that combine moderately energetic constructive waves and larger tidal ranges are required for subtidal sediments to be entrained and transported onshore.

Figure 3. *Example of large differences in seasonal sediment accumulation at Yanchep, Western Australia, where the beach is fronted by calcarenite limestone reef. (a) is the winter (eroded) state; and (b) the summer (accreted) state. (Photos: C. Bosserelle). Volume changes of up to 1.13 m^3/m between summer and winter have been measured here, leading to a total seasonal change of up to 93,970 m^3 over this 600 m long beach (Gallop et al., 2013).*

On some types of geologically controlled beaches, such as those on seaward sloping platforms, a reduced capacity for sediment storage (Trenhaile, 2004) may allow only the development of a thin, veneer beach in months with more quiescent wave conditions, which can be easily eroded in winter to expose the platform. For example, in South Wales, UK, calmer, more southerly and shorter-fetch summer winds and waves transport sand onto the shore platforms, which are then typically removed during winter storms where longer-fetch south westerly waves dominate (Naylor et al., 2016). This trend is most evident in the lower intertidal zone where sand accumulation is highest (Figure 4). Nine months of bi-monthly cross-shore monitoring of sand percentage cover (as the accumulations are very thin, typically less than 1–2 cm thick) data were collected from 26 systematically randomly placed 1 m^2 quadrats across the intertidal zone (Figure 4). Sand accumulations varied across this platform where the presence of sand was strongly modulated by: (1) shore position (with the upper intertidal zone having considerably less sand accumulation than lower down the shore); (2) surface morphology, as more sand accumulated in depressions; and (3) biology, where macroalgae helped retain sediment (Figure 4). It is important to note that these seasonal modulations of sand allow the polychaete worm, *Sabellaria alveolata*, to establish large communities on these shore platforms, as the species requires the presence of sand to grow the tubes which provide their habitat and a hard substratum on which to affix themselves to establish their colonies (Naylor and Viles, 2000).



	May%	Jul%	Sep%	Nov%	Jan%
■ lower	42.4	51.8	61.6	50.1	38.5
■ mid	30.7	37.3	37.4	42.0	46.6
□ upper	16.5	22.9	14.3	9.4	17.0
▨ upper: high algae	78.0	76.0	44.0	52.0	59.0
▤ upper: moderate algae	31.0	31.0	37.0	29.0	25.0

Figure 4. *Spatial and temporal variations in the percentage cover of ephemeral sand accumulations on a rocky shore platform in South Wales, UK over a 9-month period between May 1999 and January 2000. (Source: data adapted from Naylor (2001)).*

3.3. Geologically controlled reduction in wave exposure

On any given beach, the amount of incident wave energy that reaches the shore (wave exposure) and it’s alongshore variability is integral to the beach morphology and behaviour. Geological features can have a significant influence on the wave exposure of a beach, where features such as headlands can result in wave shadowing in their lee (Daly et al., 2014), which creates an alongshore gradient in wave energy and concurrent variations in the beach morphology and behaviour (Castelle and Coco, 2012; McCarroll et al., 2014). In addition, other wave dissipation processes such as wave breaking and bottom friction can also be amplified on geologically controlled beaches. For example, besides the relatively shallow nature of some engineered rock structures and rock/ coral reefs that induce wave breaking due to depth limitation (Frihy et al., 2004; Gallop et al., 2012), the roughness of rocks and reefs can increase wave dissipation through bottom friction (Rey et al., 2004; Ford et al., 2013; Ruiz de Alegria-Arzaburu et al., 2013), theree reducing wave exposure and beach erosion (Dickinson, 1999; Frihy et al., 2004). On Kaanapali Beach, Maui, for example, the shallow (<1 m deep) fringing coral reef promotes beach stability by reducing rates of longshore sediment transport and increasing wave dissipation (Eversole and Fletcher, 2003). At Yucatan Peninsula (SE Mexico), the landfall of category 4 hurricane Wilma in 2005 caused widespread erosion of an unconstrained beach at Cancun, while 25 km south a geologically controlled beach with a fringing coral reef accreted due to wave and current dampening in the lee of the reef (Mariño-Tapia et al., 2014; Mulcahy et al., 2016). It is also important to consider that the nearshore submarine geology can also influence shoaling processes and ultimately local beach morphodynamics (Gómez-Pujol et al., 2019), similar to the reefs and submerged engineering structures described previously. For example, the presence of paleo-channel/ sub-marine canyons (Jacob et al., 2009) can result in alongshore gradients in wave energy through impacts on wave refraction and dissipation and can also lead to rip currents (Long and Özkan-Haller, 2005).

Significant amounts of wave energy may still propagate through submerged coastal structures such as reefs, due to low-frequency fluctuations, and if resonant conditions occur (Karunarathna and Tanimoto, 1995). These low-frequency oscillations can occur due to nonlinearities in the short wave field, and include bound and free long waves (Karunarathna and Tanimoto, 1995; Payo and Muñoz-Perez, 2013). Moreover, measurements indicate that the energy spectrum on coral reef flats is dominated by infragravity frequencies (Young, 1989; Brander et al., 2004; Winter et al., 2017), and reef topography can lead to excitation of resonant modes (Péquignet et al., 2009), such as by wave groups (Gallop et al., 2012). In addition, on beaches resting on platforms, the frequency of waves is altered as they propagate across the platforms, with wave breaking filtering out gravity waves and increasing infragravity wave height (Beetham and Kench, 2011; Ogawa et al., 2012). Thus, while submerged rock substrates supporting beaches can dissipate waves, significant amounts of wave energy can still impact the shoreline during particular topographic and forcing conditions. It was demonstrated by Winter et al. (2017) that cross-shore standing water elevation patterns can be generated by infragravity waves, even in environments with highly irregular alongshore bathymetry such as coral reefs; and refraction of infragravity waves by nearshore reefs can also propagate in opposite alongshore direction causing a local standing wave pattern.

3.4. Geologically controlled rip currents

Rip currents are commonplace on wave-dominated beaches and play a key role in sediment transport, surf zone circulation, and beach morphodynamics (Wright and Short, 1984; Gallop et al., 2018). There are three broad categories of rip currents, all of which can be present on geologically controlled beaches. As outlined in the recent review by Castelle et al. (2016), the first two categories: (1) *hydrodynamically controlled rip currents* (flash rips and shear instability rips); and (2) *bathymetrically controlled rip currents* (channel rips and focused rips) are found on wave-dominated beaches with and without geological controls. Although geological controls can influence the spacing, dimensions and behaviour of these rip currents (Holman et al., 2006; Bryan et al., 2009; Gallop et al., 2011c; Castelle and Coco, 2012), they are not explored further here as their presence is not fundamentally dependent on geological controls. On the other hand, the presence of rip currents in the third category: (3) *boundary controlled rip currents*, is dependent on geological formations such as headlands (or engineered structures such as breakwaters that mimic these) that exert lateral controls on surf zone circulation (Alvarez-Ellacuria et al., 2009; Castelle et al., 2016). The two key types of boundary controlled rips are *shadow rips* and *deflection rips*, and they tend to be relatively permanent features. Shadow rips can form on beaches where an obstacle such as a headland, shadows (protects) part of the beach from obliquely-incident waves, resulting in an alongshore gradient in incident wave energy and driving an offshore-flowing jet (rip current) against the boundary (Pattiaratchi et al., 2009; McCarroll et al., 2014). Deflection rips are formed when oblique waves drive strong alongshore currents that deflect seaward when reaching an obstacle such as a headland (Castelle and Coco, 2013; Scott et al., 2016).

Geological controls from rock or coral reefs and shore platforms can also result in current jets in cross-shore through to longshore directions, with rapid shifts between longshore to rip-dominated beach circulation dependent on wave direction and tidal stage (Horta et al., 2018). For example, rock and coral reefs (or breakwaters) exert an important control on wave breaking, which results in gradients in water level due to wave set-up and radiation stress, contributing to “piling” of water in the lee of a reef due to impeded return flow (Dean et al., 1997). This drives the development of longshore and rip currents (Dean et al., 1997; Gallop et al., 2011a; Gallop et al., 2011c; Taebi et al., 2011; Gallop et al., 2015a), which during storm events can both: (a) exacerbate erosion in areas where sediment is taken from; and (b) ultimately reduce erosion in areas where sediment transported by the current is deposited as a sand bar which then promotes wave breaking (Gallop et al., 2012).

On embayed beaches, embayment-cellular rips can also occur (Castelle et al., 2016), where a rigid boundary (e.g., headlands) can dominate the circulation of the embayment (Short and Masselink, 1999). These *embayment-cellular rips* are often topographically controlled and occur along headlands at one or both ends of an embayment depending on the boundary geological controls, waves and beach curvature (Castelle and Coco, 2012), or may also occur at the centre of larger embayed beaches (Short, 2007). Cellular circulation on embayed beaches is particularly relevant during storms, as it can drive the development of large, erosional rip current systems called *mega-rips* (Short, 1985, 2007; Loureiro et al., 2012a). Mega-rips is a broad term describing large (>1 km), strong rip currents flows that extend far beyond the surf zone that can play an important role in surf zone morphology and circulation even during post-storm low energy conditions (Short, 1985; McCarroll et al., 2014). Cellular rip current flows in embayed beaches tend to scale positively with increasing wave height and decreasing embayment size (Short and Masselink, 1999). Megarips can cause severe surf zone and beach and dune erosion during storms (Short and Hesp, 1982), particularly when the mega-rip and feeder channels persist over successive storms promoting continued erosion and hindering beach recovery (Loureiro et al., 2012a)

3.5. Beach rotation

Due to the inherent alongshore compartmentalisation and exposure to temporal and spatially variable wave conditions, beach rotation is a common phenomenon on geologically controlled beaches (Gallop et al., 2013; Habel et al., 2016; Trenhaile, 2016). Beach rotation can be defined as the alternating morphological response of opposite sections of an embayed beach, driven by cross-shore and/or longshore morphodynamic processes or their interaction, coupling the beach and nearshore in response to changes in hydrodynamic forcing (Loureiro and Ferreira, 2020). Beach rotation occurs mainly through alongshore and/or cross-shore non-uniform sediment transport due to variation in wave direction and/or gradients in wave energy (Harley et al., 2011; Harley et al., 2015), but can also be driven by cellular circulation mechanisms (Loureiro et al., 2012b). While beach rotation is an embayment-wide morphological response on geologically constrained beaches, the precise mechanisms and drivers of beach rotation are often characterized by interacting and complementary morphodynamic processes (Muñoz-Pérez et al., 2001; Harley et al., 2015; Blossier et al., 2017). Loureiro and Ferreira (2020) distinguish beach rotation as: (1) an alongshore coherent response to reversals in wave direction, when sediment transported alongshore accumulates against a geological boundary (e.g. headland, reef, engineered structure), while the opposing section erodes and thus the beach appears to rotate, usually around a pivotal point or transition zone (Antonio Henrique da Fontoura et al., 2002); (2) the result of combined cross-shore and longshore morphological response to variability in wave forcing, as detailed in Harley et al. (2015); and (3) beach rotation as the planform expression of changes in nearshore morphological dynamics and cellular circulation.

Beach rotation occurs at single or combined timescales that range from short-term, often as a response to individual storms (Ojeda and Guillén, 2008; Bryan et al., 2013), to long-term rotation driven by interannual to decadal climate-forced changes in wave climate (Ranasinghe et al., 2004). In the medium-term (months to a year), beach rotation is associated mainly with seasonal changes in incident wave characteristics (Turki et al., 2013; Habel et al., 2016), which can be particularly pronounced in regions that experience a bi-directional wave climate. This distinction between mechanisms and timescales does not necessarily mean that beach rotation at any given beach takes place always in the same timescale or through exact the same morphodynamic mechanisms (Loureiro and Ferreira, 2020). Overlapping or interacting timescales and processes are frequently observed, particularly in cases where quick rotation towards one end of the embayment is driven by storm events, while the rotation in the reverse direction takes place as slower, posts-storm recovery, often lagging the changes in hydrodynamic forcing (Ranasinghe et al., 2004).

On beaches that experience variable cross-shore geological control, mainly due to the differences in the alongshore configuration of rock outcrops, seasonal beach rotation can occur in response to non-uniform oscillation of the cross-shore beach profile (Muñoz-Pérez et al., 2001). Alongshore variability in nearshore reef configuration also contributes to rotational responses of geologically controlled beaches, particularly when seasonal infilling of the nearshore area between the reef and the beach inhibits alongshore sediment transport, resulting in downdrift erosion. Conversely, when this sediment is eroded due to winter storms, sediment can then nourish the downdrift beach such as evidenced at Yanchep Lagoon, Western Australia (Gallop et al., 2013).

Beach rotation can lead to changes in shoreline position in the order of tens of meters (Short and Trembanis, 2004), but in most cases sediment is assumed to remain within the embayment, implying no net changes in the overall sediment budget. While this assumption is valid for most cases and geologically controlled beaches are closed sediment system cells or compartments, the accumulation of sediment towards one end of an embayment combined with headland sediment bypassing can lead to significant sediment losses. In such cases beach rotation becomes a fundamental mechanism for sediment connectivity, contributing to a shift of geologically controlled beaches from closed to leaky compartments (Thom et al., 2018).

4. Models of geological control

Beach-state classifications and conceptual models provide a framework for understanding the beach environment by distinguishing beaches through the morphology of the depositional landforms and coupled morphodynamic processes (Wright and Short, 1984; Wright et al., 1985). In the sections below, we consider existing models and classifications for beaches with longshore and cross-shore geological control of beach morphodynamics, and build on these to systematise new conceptual models for geologically controlled beaches. For a more detailed analysis of accommodation space and first order geological controls for beaches/barriers see Cooper et al. (2018).

4.1. Longshore geological control

Many geologically controlled beaches are defined as embayed as they are bound laterally by physical boundaries such rocky headlands and platforms (Hsu and Evans, 1989). The length, spacing, planform and morphology of embayed beaches is significantly impacted by this pre-existing bedrock which provides the accommodation space (Short and Masselink, 1999; Cooper et al., 2018), so geological boundaries are a primary control on the morphodynamics of embayed beaches. The headlands on embayed beaches have diverse morphology, and may be symmetrical or asymmetrical in terms of their length, width, and orientation to the shoreline/wave approach (McCarroll et al., 2016; Fellowes et al., 2019). Embayed beach dimensions and headland length have an important influence on the level of geological control on the sediment budget and alongshore connectivity. Larger headlands promote sediment retention within the compartment while leaking or ‘bypassing’ of sediment is more likely for smaller headlands, especially combined with large waves coming from an oblique angle (George et al., 2019). This can result in embayed beaches being defined as ‘closed’ if sediment is retained within the compartment, or ‘leaky’ if it can bypass headlands by littoral drift and be lost from the compartment (Thom, 1989; Thom et al., 2018).

In addition to providing the initial setting and accommodation space for a beach to form, the headlands of embayed beaches are also a fundamental driver of beach morphodynamics. This occurs through various processes, including wave shadowing which creates an alongshore wave energy gradient (discussed in Section 3.3), alongside geologically-induced wave refraction and dissipation (Loureiro et al., 2012a). As discussed in Section 3.4, headlands and the associated wave shadowing can result in the formation of boundary controlled rip currents (shadow rips and deflection rips) (Castelle et al., 2016), and, moreover, the embayment dimensions can also result in cellular circulation and the developed of mega-rips (Loureiro et al., 2012a). The length and orientation of headlands has an important influence on the afore-described processes, for example affecting the extent of wave shadowing and hence alongshore wave energy gradients, which dictate alongshore changes in morphodynamic beach state, surf zone width and rip channel dimensions (McCarroll et al., 2016). Whether or not headlands are symmetric is also important in terms of beach storm response, for example at the embayed Bondi Beach in Australia McCarroll et al. (2016) found that symmetrical headlands resulted in mega-rip formation at each headland, while asymmetric headlands may prevent this. In this case, the more protected end of the beach may remain in a low energy morphodynamic state such as low tide terrace, while the more exposed zone transitioned to a higher beach state such as from transverse bar and rip to a complex double bar, with a mega rip at the exposed headland (McCarroll et al., 2016). Thus, the morphology of headlands, particularly their length and orientation, is integral for defining the beach setting, whether the beach is a closed or leaky compartment, and the beach morphodynamics.

The recognition of the fundamental role of geological control has led to a progression of parametric equations to classify embayed beach planform and morphology. Hsu et al. (1989) developed the embayed beach planform ratio (based on the ratio of indentation of the embayment to width between headlands (R_o), which can only be applied to embayed beaches with a parabolic shape (Klein and Menezes, 2001). Short and Masselink (1999) developed the non-dimensional embayment scaling factor ($\acute{\delta}$) which is calculated by:

$$\acute{\delta} = {S_l}^2/100R_0H_b \qquad \text{Eq. (1)}$$

where S_l is the embayment length (combining length of headland and beach width) and H_b is breaker wave height. $\acute{\delta}$ is used to classify between the three key surf zone circulation patterns on embayed beaches as cellular ($\acute{\delta} < 8$), transitional ($\acute{\delta} = 8 - 19$), and normal ($\acute{\delta} > 19$). Castelle and Coco (2012) built on this to explore in more detail the degree of headland impact on beach circulation by considering the ratio between embayment length (L), surf zone slope (β) and breaking wave height:

$$\delta = \frac{L\gamma_b\beta}{H_s} \qquad \text{Eq. (2)}$$

where γ_b is the breaking parameter and H_s is significant wave height. Fellowes et al. (2019) later developed a new approach not requiring *in situ* data, as it could be applied through open-source imagery, which classified the degree of embaymentisation through the embayment morphometric parameter (γ_e) calculated as:

$$\gamma_e = a/\sqrt{A_e} \qquad \text{Eq. (3)}$$

Where *a* is indentation of the embayment from the seaward end of the headland to landward back-beach limit, and A_e is the embayment area within these limits. The degree of embaymentisation (γ_e) is an indicator of the level of alongshore geological control on beach morphodynamics. Fellowes et al. (2019) applied γ_e to 168 swell-dominated embayed beaches from 6 global regions, and using k-means clustering identified 4 classes of embayed beach, with γ_e increasing with the degree of headland influence and impact on beach wave exposure. The classes ranged from 1 to 4, with Class 1 being the least embayed, through to Class 4 which is the most embayed. These classes are represented in Figure 5a.

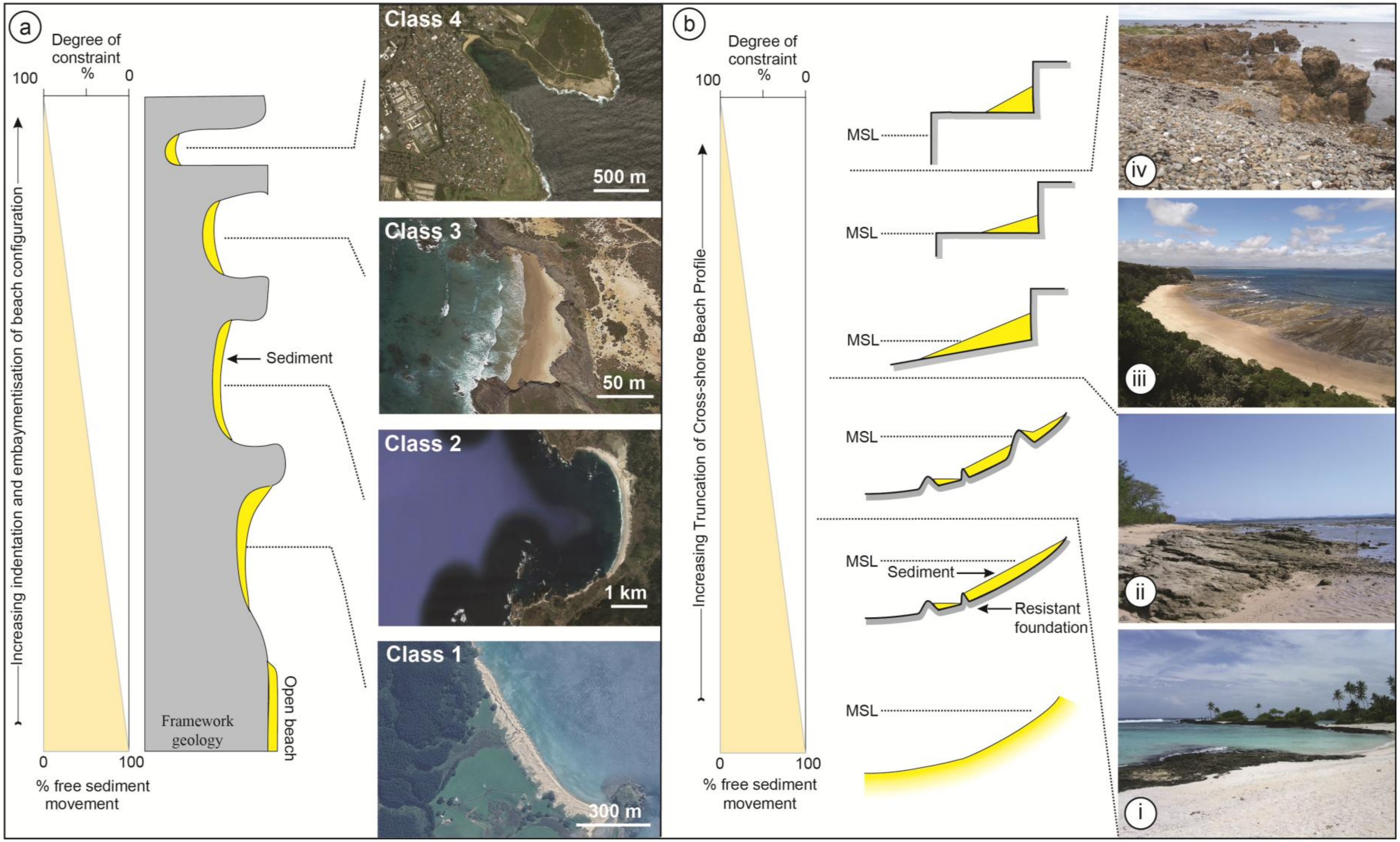

a
Degree of constraint %
100
0
Increasing indentation and embaymentisation of beach configuration
0
100
% free sediment movement
Sediment
Framework geology
Open beach
Class 4
500 m
Class 3
50 m
Class 2
1 km
Class 1
300 m
b
Degree of constraint %
100
0
Increasing Truncation of Cross-shore Beach Profile
0
100
% free sediment movement
MSL
MSL
MSL
MSL
MSL
Sediment
Resistant foundation
MSL
iv
iii
ii
i

Figure 5. *Conceptual models of geological control on contemporary beach morphodynamics. The longshore model (left - a) is based on Fellowes et al. (2019) and considers the degree to which the indentation of an embayment constrains the nearshore circulation and planform response. Examples from the four classes of embayed beaches along this continuum are provided of Class 1— Mataora, Coromandel Peninsula, New Zealand; Class 2— Carnota, Galicia, Spain; Class 3— Pedra da Bica, Alentejo, Portugal; and Class 4— Malabar, NSW, Australia. The cross-shore model (right - b) shows the continuum between a classic unconstrained profile (bottom) to relict beaches with strong cross-shore geological control (top). This model is based on the degree to which bedrock (or other relatively hard substrate such as coral reef) truncates the dynamic equilibrium profile of the beach. Examples of beaches along this continuum are provided; (i) shows a beach in Samoa with waves breaking on the seaward reef create and basaltic beach rock outcropping on the mid beach face; (ii) shows a beach in Fiji fronted by a fringing coral reef with beach rock cementation of the intertidal profile; (iii) is a beach overlying intertidal shore platform in Victoria, SE Australia; and (iv) shows a mixed sand and gravel beach at the rear or contemporary shore platforms in Wellington, New Zealand, fronting vegetated uplifted relict systems,(Photos: D.M. Kennedy).*

4.2. Cross-shore geological control

In addition to the longshore geology, the addition of cross-shore geological controls completes setting the 3D accommodation space where beaches can accumulate. Cross-shore geological control on beaches can occur in a variety of forms, from thick and semi-permanent deposits atop of hard substrates; through thin, ephemeral veneers over shore platforms (Trenhaile, 2004; Jackson et al., 2005; Doucette, 2009; Gallop et al., 2013; Marsters and Kennedy, 2014; Trenhaile, 2016). There have been several attempts to classify levels of geological control on cross-shore beach profiles. Short (2006) suggested that in addition to wave/tide-dominated and wave-modified beaches, there is also a distinct type that is influenced by intertidal rock flats and fringing coral reefs present in Australia. Jackson and Cooper (2009) later introduced a conceptual model of levels of beach geological control based on beaches on the Outer Ards Peninsula in Northern Ireland, ranging from *unconstrained*, through to *semi*- and *highly-constrained*, depending on how much the beach volume and profile mobility are affected by geology intruding into the natural beach profile. There remains a need therefore for a universal classification system for the cross-shore geological control of beaches. Therefore, here we propose a new conceptual model of levels of geological control on beach morphodynamics, based on the degree of profile truncation.

The model we present in Figure 5b builds on the original model proposed by Jackson and Cooper (2009) and includes two extremes of beaches relative to the level of cross-shore geological control on beach profile activity. One end of the spectrum is occupied by unconstrained beaches with no cross-shore geological control (Jackson and Cooper, 2009), and which have a profile with free sediment movement from the wave base to the upper (landward) limit of storm-wave influence (Short and Jackson, 2013). In such cases, beach morphology is only a function of interactions between the nature of sediments, sediment supply and the hydrodynamic environment (Wright and Thom, 1977; Short and Jackson, 2013). At the other end of the spectrum, the geomorphological evolution of relict geologically controlled beaches has removed them from the contemporary littoral zone, so that they are now above the normal reach of waves and tides (Figure 5, example iv). In between these two extremes, there are varying degrees of geological control. Such beaches actively respond to marine processes but they are not able to completely form a dynamic equilibrium profile as sediment supply is limited and rock outcrops at the surface. That is, their cross-shore profile is interrupted by a relatively hard substrate at some position on the shoreface, i.e., between the landward limit of wave run-up and wave base (Cowell et al., 1999).

Geologically controlled beaches, can be found close to MSL on shore platforms, often at the cliff-platform junction such as along the Great Ocean Road in SE Australia (Kennedy and Milkins, 2015), Niue in the South Pacific Ocean (Marsters and Kennedy, 2014) or SE China (Chen et al., 2011) Such beaches correspond to the examples iii and iv in Figure 5. Here, most of the beach volume is found in the intertidal zone (Paris et al., 2011), yet they are still geologically controlled as the lower part of the intertidal profile is occupied by resistant shore platforms rather than loose sediment. At the opposite end of the spectrum, are beaches where only the uppermost part of the profile is present, with bedrock or a similar immovable substrate occupying the lower portions of the profile (Figure 5b, example iv) This part of the beach will only be active during high magnitude storm events, but can still evidence typical beach processes as longshore sediment grading (Green et al., 2016).

It is important to note that development of beaches in coral reef seas does not necessarily occur directly on a reef surface; it can be separated from the reef crest by a lagoon (Kennedy and Woodroffe, 2002) (e.g., Figure 5b, example i). The depth and width of the lagoon and its hydrodynamic environment will then determine the degree of geological control. For example, in the shallow lagoons of the Maldives (Kench and Brander, 2006; Kench et al., 2006), Lord Howe Island, Australia (Kennedy, 2003), Cancun, Mexico (Mulcahy et al., 2016) and Samoa (Figure 5b, example i), the wave base is located offshore on the surrounding reef rim, with active sediment movement occurring across the entire reef system. In deeper atoll lagoons, such as Kapingamarangi Atoll, Federated States of

Micronesia, the beach profile is not constrained and extends as an entirely sandy surface down to wave base (McKee et al., 1959).

At the extreme end of cross-shore geological control is when rocky outcrops are found only on the lowest parts of the beach profile (termed *semi-constrained* by Jackson and Cooper (2009). Such examples are found worldwide, such as in Portugal (Loureiro et al., 2012b) and Ireland (Jackson et al., 2005), where bedrock has been lowered below the intertidal zone or resistant lithology is present in the subtidal zone that can resist erosive marine forces (Figure 5b, example ii). The southern coast of south Western Australia (WA) is an example where rocky outcrops that are initially shore attached progressively deepen and move further offshore as the coast becomes embayed. In such settings the degree of sediment movement is directly influenced by the degree of truncation to the beach profile (Gallop et al., 2011b; Gallop et al., 2012, 2013). In some cases, the geologically controlled nature of the beaches may only be observable with detailed inshore surveying. For example, in Victoria, SE Australia, sandy beaches may be relatively sediment-rich in the swash zone under normal conditions but at greater depths where waves shoal, bedrock dominates the profile (Figure 6). In this respect, while the upper parts of the beach reflect a classic beach-bar system, the entire profile would have cross-shore geological control during storm conditions when wave base is located on the rocky outcrops. The rocky and sandy sections also have largely identical slopes, and the sandy beach profile is not concave as would be expected based on the equilibrium beach profile theory (Bruun, 1954; Dean, 1977, 1991), suggesting that the sandy beach has inherited its shape from the pre-existing rocky surface. Such systems have received scant attention in the literature.

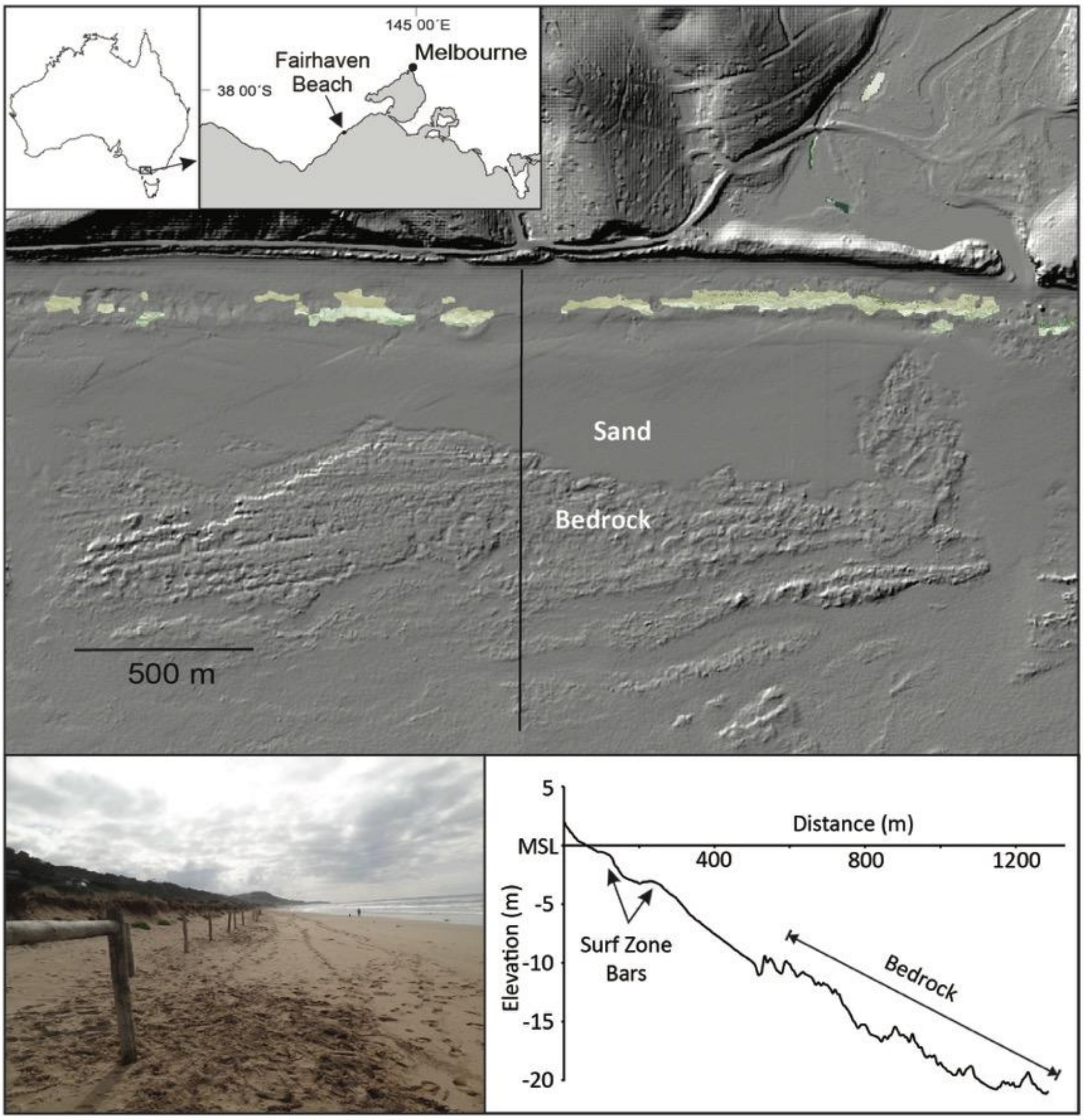


Figure 6. *Bathymetric LiDAR of the nearshore of Fairhaven Beach, Victoria, SE Australia. The toe of the sandy beach extends only to 10 m water depth, after which there is bare rock down to the wave base. The presence of cross-shore geological control is not obvious when observing only the subaerial beach face (photo: D.M. Kennedy).*

5. Management of geologically controlled beaches

In addition to the many services provided by beaches themselves, these coastal systems also provide an important form of natural protection from the impacts of waves and sea level rise to coastal communities, infrastructure and habitats which lie behind. As shown by the review above, our knowledge of geologically controlled beach morphodynamics and therefore how to manage them, is limited. There are few case studies on the management of beach sediment erosion on geologically controlled beaches. Those that exist tend to apply techniques that do not consider the complexity and variety of geologically controlled beach systems. For example, artificial reefs and offshore breakwaters have been put forward as mechanisms for controlling cross-shore beach erosion (Dean and Dalrymple, 2001), while perpendicular structures such as groins or artificial headlands are used with the aim of controlling longshore erosion and promote a stable beach planform (Silvester and Hsu, 1997). While such engineering techniques seem conceptually robust, they are based on a narrow consideration of the long-term apparent stability of geologically controlled beaches. They fail to consider the vast majority of characteristic morphodynamic responses of geologically controlled beaches that we highlight in this paper, such as alongshore non-uniformity in storm response, rip circulation and beach rotation. Because the morphodynamics of geologically controlled beaches are much more complex than assumed by existing beach engineering concepts, achieving a dynamic equilibrium with geological control is unfeasible with coastal engineering solutions that focus on one specific aspect (i.e., cross shore erosion or planform equilibrium) and disregard the complex cross and longshore morphodynamics.

Beach nourishment, reprofiling and redistribution are other possible methods to assist these beach systems provide continued coastal flood and erosion risk alleviation benefits to society. Some suggestions for applying these techniques to geologically controlled beaches are made here. First, when considering beach nourishment, it is important to distinguish between the apparent loss of nourished sediment due to beach rotation or the *actual loss* of sediment due to headland bypassing (i.e. leaky systems), which is likely to increase in nourished geologically controlled beaches. The adjustment of a nourished beach profile when there are cross-shore geological constraints is also likely to depart from theoretical models of cross-shore sediment redistribution used in coastal engineering (Muñoz-Perez et al., 2020). Scaling up to a local sediment cell, there is scant understanding of and limited modelling tools to predict the rates of sediment transport from geologically controlled beaches to other coastal systems, or between these beaches (Naylor et al., 2016). For example, a geologically controlled beach might be an important supply of sediment to a nearby spit (as in Westward Ho!, North Devon, UK), but we have limited understanding of the process and of how much geologically controlled beach material serves as a key source of sediment to an economically and socially valuable beach spit. Moreover, it is largely unclear how to account for spatial variations in geological controls to quantify beach nourishment volumes and costs, and how to include the effect of this variation on the beach morphodynamics and hence nourishment performance and longevity (Muñoz-Perez et al., 2020).

Management implications of sea level rise for geologically controlled beaches can also consider the changes in accommodation space by higher sea levels and the fact that geologically controlled beaches cannot retreat landwards according to a Brunn rule style (Bon de Sousa et al., 2018), as many are backed by rocky cliffs or seawalls/promenades on developed coasts. This will lead to “coastal squeeze” (Pontee, 2013) and potential modification of the beach profile steepness and morphodynamics, such as the potential for erosion of the beach via faster rates of longshore or cross-shore transport of material. For example, Brayne (2016) showed that in North Devon the alongshore difference in platform elevation can be used as a proxy for sea level rise impacts, showing that as sea level rises, wave energy delivery to beaches at the cliff-platform junction will increase causing the beaches to be steeper and higher.

Recent storm events have demonstrated that sandy beaches can be eroded so significantly during storm events that the underlying bedrock is exposed (see Section 3.2). This means that beaches can oscillate between behaving as an unconstrained sandy beach, and geologically controlled beach. Beach recovery will occur during the geologically controlled phase, which as discussed in this review, is a state for which we largely lack data-driven methods and models to apply to beach restoration. In addition to ecological and coastal defence implications, this also has economic implications, as these beaches are often highly important for coastal tourism, and thus local economies (e.g. Bon de Sousa et al., 2018). Conceptual and empirical models that can explain the shifts in beach type and their recovery (or oscillation between beach types) and response to sea level rise, storminess and changes in wave climate as well as sediment supply, are thus an important need.

Addressing this gap in our scientific knowledge of these systems and to develop improved tools for coastal risk management of these beach systems is thus critical to support geologically controlled beach management strategies and for evaluating their exposure to to climate change risks. Of key importance for now, is for coastal geomorphologists, coastal engineers and coastal managers to clearly communicate what geologically controlled sandy beaches are and how they differ from well-studied and modelled, unconstrained sandy beaches. Crucially, it is important to articulate what this means for modelling and managing these systems, specifically to (1) highlight the poor applicability of the majority of existing morphodynamic parameterisations and models; and (2) advise managers on how best to assess, predict and manage geologically controlled beaches.

5. Conclusions

Geologically controlled beaches are a distinct beach type, and have their own unique morphodynamic processes that make them behave differently to unconstrained beaches. This review focused on bringing together the various naming conventions and studies of what geologically controlled beaches are, and focused on the morphology and morphodynamics of those composed of sand. In addition to sediment supply, key factors that determine where geologically controlled beaches form are determined by basement geology, both in terms of longshore accommodation, such as in the form of coastal embayments with lateral headlands; and in the cross-shore dimension, particularly if there is a rock platform, whose elevation and gradient also are important factors for determining if a beach can accumulate. Geologically controlled beaches can have striking variations in sediment coverage, where at times the underlying geology could be totally exposed with little beach sediment or only a thin veneer, through to relatively deep beaches that may have little interaction with the underlying bedrock. Many geologically controlled beaches are embayed within headlands, thus wave shadowing by headlands, sometimes enhanced by wave breaking and dissipation in areas of exposed rock or coral substrates, can result in strong alongshore gradients in wave energy which result in corresponding variations in beach morphology, morphodynamics and storm responses. Geologically controlled rip currents such as shadow rips and deflection rips are important features on embayed beaches, and cellular circulation and mega-rips can also occur. Finally, beach rotation is also an important process on many geologically controlled beaches as a result of the combined cross-shore and longshore gradients in wave energy and resulting beach morphological responses. To encompass the above processes, we present longshore and cross-shore models of geological beach control. In the longshore dimension, our model ranges from low geological control in the form of relatively shallow embayed beaches, through to highly embayed beaches, as indentation and embaymentisation have an important influence on the morphodynamic processes and determine if the beach sediment budget is closed or leaky. The cross-shore model is based on the degree of geological constraint on cross-shore sediment transport, from beaches with no cross-shore geological control through to relict geologically controlled beaches that are above the contemporary littoral zone. Further study is identified as a research priority to more clearly define why and how the morphodynamics of geologically controlled beaches differ from unconstrained beach systems. This knowledge is critical for revising sediment transport equations and morphodynamic models of beach evolution. Such data and process understanding are crucial to assist coastal managers in effective management of geologically controlled beach systems both now and under an uncertain future climate.

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