# Geological constraints on mesoscale coastal barrier behaviour

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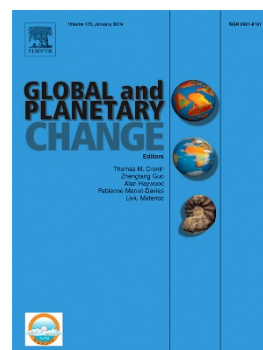Email: jag.cooper@ulster.ac.uk, greena1@ukzn.ac.za, loureiroc@ukzn.ac.za

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ABSTRACT

Highlights

Geological factors are significant controls on mesoscale barrier behaviour

Geological influences on barrier behaviour are identified and organized into a hierarchy of influences.

Initial barrier form significantly influences barrier behaviour and detailed measurement of barrier morphology is an essential prerequisite for any study.

Future research should focus on incorporating important geological influences into modelling efforts.  The few sites with adequate data provide test cases.

Coastal management must acknowledge the qualitative nature of assessments of future change.

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**Abstract**

Barrier/lagoon systems occupy a significant part of the world's coast. They are diverse in size, morphology, geological and oceanographic setting, and morphodynamic behaviour. Understanding the behaviour of barriers at $10^1$ to $10^2$ year and $10^1$ to $10^2$ kilometre scales (mesoscale) is an important scientific and societal goal, not least because of the preponderance of intensive coastal development in a time of global climate change. Such understanding presents significant challenges. Challenges in *describing* mesoscale system behaviour relate largely to the incomplete evidence base of (i) morphological change in system components, (ii) dynamic and internal forcing factors (drivers) and (iii) geological constraints. These shortcomings curtail the development of baseline datasets against which to test models. *Understanding* observed changes and thereby predicting future behavioural patterns demands assumptions and simplifications regarding the linkages between initial state, dynamic drivers, system feedbacks and a multiplicity of geological constraints that are often location-specific.

The record of mesoscale change is improving with the acquisition of long-term morphological datasets. Advances in technology and chronological control mean that geological investigations can now provide decadal to century-scale temporal resolution of morphological change. In addition, exploratory modelling is improving understanding of the influence of various dynamic and geological factors.

Straightforward linking of dynamic forcing and response is seldom able to account for observed mesoscale behaviour. Geological factors exert a significant or even dominant control on barrier behaviour at decadal to century timescales. Whereas these geological controls can be quantified to some extent by detailed investigations of contemporary barrier/lagoon morphology and constituent materials, underlying geology and topography and sediment supply, in all but a few locations, such data are absent. This sets an unavoidable constraint on efforts to quantitatively predict the future behaviour of barrier systems, which are strongly site-specific in terms of their geological setting and morphology. Geological controls exist in a network of interactions that individually and collectively influence mesoscale barrier behaviour. Dominant, first-order controls are:

- Basement slope;
- Basement irregularity and erodibility;
- External sediment supply;
- Orientation; and
- Shoreline lithification (beachrock and aeolianite)

An important intermediate level of geological control is exerted by shoreface morphology. Shorefaces are themselves influenced by underlying geological factors, but they are dynamic at longer timescales than barriers. Geological influences are in most cases unquantified and are usually disregarded when conceptualizing and modelling barrier evolution. Consideration of the geological influences is, however, essential in efforts to predict future behaviour at mesoscale (management) timescales.

Key Words: Barrier, sea-level change, sediment supply, antecedent topography, morphological modelling.

## 1. Introduction

Coastal barrier and barrier-island systems occupy a significant proportion of the world´s coastline. They are chiefly composed of sand, with a significant minority of gravel-dominated barriers concentrated in formerly glaciated areas (Orford et al., 1991). Barrier islands occur on about 10% of the open ocean coast (Stutz and Pilkey, 2011), and, combined with mainland-attached examples, barriers make up about 15% of the world´s ocean shoreline (Davies, 1980). Barriers are also widespread in low-energy, fetch-limited settings of lagoons and bays (Cooper et al., 2007; Pilkey et al., 2009).

In morphodynamic terms, barriers are dynamic, unconsolidated sedimentary systems that respond to various drivers. These drivers may be short-term (e.g. low magnitude/high frequency or modal wave and tide processes), episodic (e.g. wave energy and water level changes during storms (Stone et al., 2004; Houser et al., 2008)), medium term (e.g. the cumulative effect of modal wave and tides; climate oscillations), or longer term (e.g. sea-level change, storminess patterns). The influence of these drivers, however, is mediated by non-dynamic (geological) variables such as the nature of the underlying geology and topography, sediment supply, and the morphology of the barrier/lagoon system itself. These geological controls are difficult to quantify and are often overlooked, ignored or grossly simplified in approaches to understanding or predicting barrier behaviour.

Aside from the importance of barrier-related sediments in the geological record (where they often form petroleum reservoirs), understanding barrier coast behaviour at timescales of decades to centuries is a pressing societal need because of the proximity of human development either on, or adjacent to, barrier systems. In some instances, this development takes advantage of aspects of barrier geomorphology (e.g. navigation through tidal inlets) or is based on proximity to the beach (Pilkey and Cooper, 2014). In many instances, barriers are so intensively human-developed that they are in effect coupled human-natural systems (Lazarus et al. 2015). Barriers, particularly those with extensive dunes, offer a degree of protection against extreme events (Houser et al., 2008), and they respond to changes in dynamic forcing by altering their morphology or material composition.

Understanding decadal/centennial (mesoscale) barrier-lagoon behaviour is a complex 3-D problem in which dynamic factors (their net effect over decadal to century timescales) operate on a changing horizontal plane (sea-level) on materials of a given type within a particular geological framework. *"Longer-term behaviour (years to decades) of the shoreline is the result of hydrodynamic and morphodynamic processes acting over multiple stormy and intervening calm periods during which the advanced or retreated state of the shoreline may be increasingly influenced by sediment supply and geology"* (Hapke et al., 2016 p 42).

While the role of geological factors has long been recognized in long-term (millennial/stratigraphic-level) studies (Belknap and Kraft, 1985; Riggs et al., 1995), only comparatively recently has the importance of this influence been appreciated in mesoscale studies. In many mesoscale studies, incomplete historical records of morphological change taken in conjunction with more complete records of some (but not all) dynamic drivers (e.g. Elias and van der Spek, 2006; Styles et al., 2016) often identify certain morphodynamic relationships and feedbacks. In almost all cases, however, the geological parameters (underlying geology/geomorphology, sediment nature and supply) are unknown and are either unacknowledged, deliberately ignored or assumed to be unimportant. Yet, Hapke et al. (2016, p.43) contend that `... *there are separable patterns of shoreline behaviour that represent response to oceanographic forcing as well as patterns that are not explained by this forcing.*` and Weymer et al. (2015 , p.12) maintain that *"...,an assessment of antecedent geology (i.e., geologic framework) is critical for coastal management and risk assessment ..."*. Such assessments of geological constraints are, however, largely absent in many modelling studies and predictions of future barrier behaviour.

Focusing particularly on the geological influences on mesoscale barrier behaviour, this review begins with a brief description of the essential system components and the diversity in barrier morphology. It briefly outlines current conceptual mesoscale behavioural models. Three main modes of enquiry into mesoscale barrier behaviour (historical, geological and modelling) are described and recent developments related to the understanding of geological controls are reviewed. The influences of these geological factors are discussed individually and collectively and their relevance for scientific understanding of barrier behaviour and for coastal management are outlined.

**2. Common attributes and spatial variability in barrier-lagoon systems**

Many accounts of individual barriers and barrier systems exist and several syntheses have been produced (e.g. Davis, 1994; Leatherman, 1979; Oertel, 1985; Pilkey, 2003; McBride et al., 2013). The transgressive barrier island system diagram of Reinson (1992) is one of the most frequently reproduced and it includes the six main components of an idealized barrier/lagoon system, i.e. mainland; backbarrier lagoon; inlet and inlet deltas; barrier island; barrier platform; and shoreface (Oertel, 1985).

Facies models (Fig. 1) are useful in geological investigations, enabling local variability to be discarded and identifying the key geological constituents to aid in identification of modern and ancient barrier island systems. Despite the generic attributes of the barrier island facies model, individual or regional groups of barrier-lagoon systems (e.g. McBride et al., 1995; Pilkey et al. 1989) show considerable morphological diversity (Fig. 2). Although such variability is regarded as ´´noise´´ from a facies model perspective, it introduces and/or results from variations in dynamics, and geological context that are fundamentally important in terms of how a given barrier/lagoon system functions at decadal to centennial timescales. A barrier whose crest is much higher than the highest wave run-up, for example, will preclude overwash, a process that is of crucial importance in the mesoscale behaviour of many other barrier systems (Leatherman, 1983).

Contemporary barrier-lagoon systems exhibit great morphological diversity that results from large scale climatic, oceanographic and geological influences (Fig. 2). They range in size from the massive Patos/Mirim Lagoon system of southern Brazil with its 600 km-long barrier (Dillenberg and Hesp, 2009) and the 300 km-long Outer Banks barrier island chain off NC (Zaremba et al., 2016)) to the numerous small barriers (often <100 m long) that characterise the rocky coasts of South Africa (Cooper, 2001), eastern Australia (Roy et al., 2001; Sloss et al., 2006) and New England (Duffy et al., 1989) for hundreds of kilometres. Barriers exhibit great diversity in height and width and adjacent lagoon dimensions (Fig 2F). They also vary in composition (gravel/sand), orientation and exposure to wave and tidal processes and occurrence of various extreme wave events (storms, hurricanes,

tsunamis). Orford et al. (1995) consider a primary distinction in terms of historical barrier behaviour to be between drift- and swash-aligned barriers, a variable that combines coastal orientation (often dictated by antecedent geology) with wave climate.

Large-scale distinctions in barrier/lagoon geomorphology can also be made according to the specific coastal setting, with distinctive barrier-lagoon systems in deltaic (Anthony and Blivi, 1999; Stutz and Pilkey 2002), coastal plain (Pilkey, 2003) and rock-bounded settings (Cooper et al., 2012), for example. Climate is a further control, particularly with regard to the backbarrier environment. Arid lagoons in the Persian Gulf (Evans et al., 1973), for example, are in striking contrast to saltmarsh-dominated temperate lagoons, or mangrove-fringed tropical lagoons. Climatic setting also influences barrier dynamics and exposure to storm activity.

Some barrier systems (e.g. Outer Banks, NC, Frisian Islands, Netherlands) have multiple semi-permanent inlets, while others (including very large systems like Patos Lagoon, Brazil and St Lucia Lagoon, South Africa) have single inlets. Barriers in arid or episodic rainfall regions often have ephemeral inlets (McSweeney et al., 2017). Most barriers are sandy, but gravel-dominated systems are particularly common in (but are not confined to) formerly glaciated environments (Carter et al., 1984; Orford et al. 1991; Kirk and Lauder, 2000).

The initial morphology of a barrier system is a key determinant of its mesoscale behaviour. The initial form sets limits on the processes that occur (e.g. overwash, dune building, longshore drift, inlet-associated processes) and influences their magnitude and relative importance. The morphological variation outlined above demonstrates that, beyond the generalizations of the facies model, barrier systems are likely to be strongly site-specific in terms of their mesoscale behaviour. This aspect of geological inheritance is discussed further below.

**3. Barrier behaviour**

Barriers exhibit a range of generalized behaviours essentially involving sediment transfers along- and/or cross-shore, that result in morphological change. These are

most commonly envisaged as simplified conceptual 2- or 3-D models and are outlined below.

## 3.1. Profile models

Conceptual 2-D profile responses of barriers fall broadly into four behavioural categories: rollover; erosion; overstepping; and aggradation/progradation (Fig. 3). In the rollover model, mesoscale barrier behaviour is dominated by overwashing during storms, such that the sediment volume is essentially maintained and the barrier migrates landward (Godfrey and Godfrey, 1973; Hosier and Cleary, 1977; Carter and Orford, 1981, Leatherman, 1983). The rollover response has been widely observed and reported. The rate of migration has been linked to (i) frequency of overwashing storms (Dolan and Godfrey, 1973; Schwartz, 1975; Byrnes and Gingerich, 1987); (ii) barrier volume (Forbes et al., 1991; Priestas and Fagherazzi, 2010); (iii) the gradient of the surface over which the barrier is migrating (Wolinsky and Murray, 2009); and (iv) the rate of sea-level rise. Very fast rates of barrier rollover (30m/year) sustained for several decades were attributed to the small volume of sediment in the low energy barriers in Chesapeake Bay (Cooper, 2013). On low energy barriers the influence of underlying substrate type is particularly evident - periods of barrier stability occur while fronting marsh deposits are eroded, whereupon barrier migration resumes (Fig. 4). High and/or very wide barriers, in contrast, do not overwash and do not exhibit rollover (e.g. Benallack et al., 2016). Barrier migration is also likely to be affected by the depth and volume of the lagoon: there may be insufficient sediment volume in a migrating barrier to fill the backing lagoon in which case the barrier will lose its integrity and will break down.

The erosional response (Fig. 3B) involves the seaward loss of sediment from a barrier during transgression. The Bruun Rule, the best-known parameterization of the erosional response (Carter, 1988) and various profile models based on shoreface retreat, involve simultaneous retreat of the dune, beach, surf zone and shoreface at the same rate, so as to maintain the nearshore profile. The concept of shoreface retreat has assumed a position of pre-eminence in mesoscale barrier evolution and forms the central concept in several investigative models (see below). Aside from various other flaws in the concept and formulation of the Bruun Rule and its derivatives (Cooper

and Pilkey 2004a; Pilkey and Cooper, 2004), the retreat of shorefaces and barriers at the same rate is not widely observed in nature. Rather, shorefaces often retreat at slower rates than adjacent barriers and as they do so they exhibit varying behaviour (Swift et al., 1985). Erosion is the dominant profile response on high barriers that preclude overwash. High dune-topped barriers in southwestern Ireland, for example, show fluctuating shoreline positions due to off-shore and onshore sediment transfers that appear to be linked to storm frequency (Orford et al., 1999). Following a storm surge in 2008, one of these barrier shorelines retreated at ca. 25 m/year, losing sand offshore (Devoy, 2015).

Overstepping (McMaster and Garrison, 1967; Sanders and Kumar, 1975; Rampino and Sanders, 1981, 1982) involves a barrier being drowned in situ, leaving much of its sediment and associated back-barrier sediments on the seabed (Fig 3C). Overstepping requires the reaction time of a barrier to be slow and/or the rate of sea-level rise to be fast, a concept that was initially argued to be unsupportable due to a disconnect between instantaneous responses to storms and the long-term response to sea-level rise (Swift and Moslow, 1982). The process has, however, since been documented at several locations (e.g. Forbes et al., 1991) and been linked to century-scale periods of rapid sea-level rise (meltwater pulses) (Green et al., 2014, Cooper et al., 2016). Often the former barrier is eroded by subsequent shoreface ravinement (Rieu et al., 2005, Storms et al., 2008, Hijma et al., 2010), leaving only the back-barrier sediments, but in other instances (Green et al., 2014; Cooper et al., 2016) the barrier structure itself is preserved. These two scenarios have been termed Sediment Surplus Overstepping (minimal wave reworking and almost complete barrier preservation) and Sediment Deficit Overstepping (barrier moves landward in a sporadic, discontinuous fashion with little possibility of preservation) (Mellet et al., 2012). Favourable conditions for barrier preservation during overstepping include early cementation (e.g. Gardner et al., 2005, 2007; Green et al., 2013a, 2014, 2018), long relaxation times, as in gravel and boulder barriers (e.g. Forbes et al., 1991; Hartstein and Dickinson, 2000), an increase in back-barrier accommodation (linked to a low topographic gradient) (Storms et al. 2008), large sediment volume in the barrier (Orford et al., 1995) and low wave energy (Cooper et al., 2016).

Under conditions of high sediment supply, barrier progradation or aggradation can occur during both falling and rising sea levels (Fig 3D). This can result in development of beachridge plains where a barrier steps seaward through welding of additional sediment (e.g. Green et al., 2013b; Hein et al., 2016), and/or development of high dunes when aeolian reworking of excess sediment is dominant (e.g. Dillenberg et al., 2004). Many sediment-rich barriers exhibit combinations of both aeolian and wave deposits (e.g. Hein et al., 2014).

### 3.2. Planform Models

2-D planform models are particularly well developed for gravel-dominated barriers but less so for sandy barriers. Working essentially in the mesoscale, Carter et al. (1987) presented a conceptual model for gravel barrier planform evolution related to interactions between sediment supply, antecedent topography and sea-level change. A variety of behavioural modes were identified that involve barrier elongation, stretching, cannibalization, breaching and breakdown (Fig. 5). The behaviour was linked to variations in sediment supply, rates of longshore and/or cross-shore sediment transport and sea-level rise. Similar modes of planform behaviour were noted in fetch-limited sand barriers in Chesapeake Bay (Fig. 6) where small island volume causes rapid barrier evolution. The specific role of sea-level rise could be identified by comparing single ridge gravel barriers in swash-aligned settings with varying decadal sea-level rise history (Orford et al., 1995). This demonstrated a clear link between rates of barrier migration and rates of sea-level rise, but even so, the potential influence of the barrier volume (inertia) was acknowledged.

On open ocean sandy barriers dynamic processes lead to periodic opening and closure of inlets, inlet and tidal delta migration, spit progradation, development of recurves and deposition of washover fans that change barrier island planforms. The specifics of their impacts on sandy barrier planform have, however, received less attention than their gravel counterparts. Hayes (1979) identified apparently genetic broadscale links between dynamics (tidal range and wave energy) and barrier planform. The global applicability of this observation has, however, recently been challenged by Mulhern et al. (2017) who found no systematic variation in shape in a global analysis of barrier planform morphometry. Attempting to codify mesoscale planform changes and link

them to dynamic drivers, McBride et al. (1995) identified several types of planform behaviour on the ocean and bay sides of barriers in the Gulf of Mexico. These were divided into simple and complex behaviours (Fig. 7) that involved (1) lateral (alongshore) movement, (2) advance (cross-shore), (3) dynamic equilibrium, (4) retreat (cross-shore). In combination, these produced more complex behaviours involving (5) in-place narrowing, (6) landward rollover, (7) breakup, and (8) rotational instability. The various behavioural modes were conceptually and loosely linked to variations in rates of sea-level rise and sediment supply. An ideal example of the processes involved is provided at the mesoscale by Shanks Island, a fetch-limited barrier island chain in Chesapeake Bay (Cooper, 2013). Here (Fig.8) an initial barrier chain with several inlets experiences landward migration and lateral extension (1994-2006) followed by island widening and flattening (2006-2011) and near-total breakdown by 2013.

## 3.3 3-D barrier-lagoon models

The profile and planform models are acknowledged as simplifications and it has long been known that sedimentary and dynamic relationships exist between the various elements of the barrier-lagoon system (e.g. back-barrier/marsh, tidal prism-tidal inlet, barrier island/tidal delta parts of the system).

In a regional appraisal of mesoscale barrier evolution in Louisiana, McBride and Byrnes (1997) recognized that barriers exhibited changes on both bay and ocean shorelines. They identified 7 'geomorphic response types' (lateral movement, retreat, breakup, advance, landward rollover, rotational instability and dynamic equilibrium). The three-dimensional nature of behaviour was illustrated in examples where growth of one barrier took place at the expense of downdrift barriers that retreated, and others where barrier narrowing was matched by sediment accumulation on the adjacent seabed. Aside from the contemporary morphodynamic linkages that influence this spatially variable barrier behaviour as sediment movement in one location influences adjacent areas, direct geological influences (e.g. subsurface relict delta lobes) were occasionally evident.

FitzGerald et al. (2006; 2008; 2018) presented a conceptual 3D barrier-lagoon behavioural model that links backbarrier intertidal and supratidal marshes, tidal inlets and barrier evolution during rising sea level (Fig 9). In this model, rising sea level drowns marshes and increases the tidal prism. In response, the tidal inlets and ebb deltas enlarge at the expense of barrier island sand volume. Continued growth of the tidal prism under rising sea-level further enlarges the inlets and ebb deltas, to the point that insufficient sediment remains to maintain intervening barriers, at which point the barrier disintegrates and the open ocean shoreline 'jumps' to the former back-barrier shoreline, a mechanism termed 'runaway transgression' in this model. The application of this model to specific locations requires the quantification of barrier and ebb delta volumes, as well as the nature of the stratigraphy of the barriers. As noted by FitzGerald et al. (2018, p 47) "…this is not an easy task because of the large range in the size and sand volume of barriers throughout the world and the fact that barrier lithosomes vary considerably along their length due to changes in width, elevation, and depth."

### 3.4. Discussion: Conceptual barrier behaviour models

Conceptual models of barrier behaviour have existed for several decades. Based on field observations and historical trends, they provide a description of several potential behavioural modes. Over time, however, it has become clear that these models are very much simplifications that incompletely describe actual mesoscale behaviour. Recent research has shown, however, that there are geological constraints on which behavioural mode is applicable in a given place and time. Overstepping, for example appears to be promoted by an increase in back-barrier accommodation (linked to a low topographic gradient) (Storms et al. 2008).

The factors that favour one response over another include: (i) dynamic factors such as wave energy and the rate of sea-level rise; (ii) morphological feedbacks between for example, tidal prism and delta volume; but also (iii) geological factors such as the accommodation space, coastal morphology being transgressed, barrier volume, sediment supply/texture and lithification. In addition, at any given locality factors absent in the conceptual models may be important; aeolian transport and dune

building which is a dominant process on some barriers, does not feature in generic barrier models.

The assumptions inherent in some 2-D profile models in particular are not universally valid. Critical to both rollover and erosion models, for example, is the assumption that the shoreface migrates at similar rates to the barrier. It is, however, known that the shoreface exhibits morphological change at longer timescales than adjacent barriers (Swift et al., 1985). This is, however, spatially variable at the mesoscale. In some locations shoreface retreat does occur at rates comparable to adjacent barrier shoreline retreat (e.g. 5-15 m/yr on barrier island arcs on abandoned Mississippi delta lobes; Penland et al., 1985), but in many others (e.g. North Carolina, Riggs et al., 1995) the process of shoreface retreat is much slower than the adjacent barrier. In some instances, (e.g. German Frisian barrier islands, Flemming and Davis, 1994; Fire Island, NY, Kumar and Sanders, 1975) shoreface retreat does not accompany barrier migration. Instead barriers detach from the shoreface, leaving it drowned, while the surf zone and barrier migrate rapidly landward. The barrier may then form a new shoreface via erosion of underlying strata at its new stabilization point. The former shoreface may remain drowned, or as in the case of the Holland coast (Beets and van der Spek, 2000; Hijma et al., 2010), it may continue to migrate slowly landwards eventually 'catching up' with the surfzone and beach system when the latter stabilizes. The observational evidence therefore points to spatially variable relationships between shoreface and barrier behaviour, (Figure 10) the reasons for which have not been investigated but likely include variations in geological controls (sediment supply, underlying geology) as well as dynamic factors (rate of sea-level rise and wave climate).

## 4. The record of decadal and century scale barrier evolution

A fundamental prerequisite in understanding decadal to century-scale barrier evolution is observational data of changes in morphology and data on related dynamic variables. These can then be compared to seek relationships between behaviour and process and used to test models. Approaches involve historical records and geological investigations either individually or in combination. The nature and availability of data, and particularly their poor temporal spacing has often hampered

the description of mesoscale barrier behaviour. Recent technological advances, however, are improving the situation.

### 4.1. Historical records.

*"Changes in shoreline position tend to synthesize the net effect of coastal variables, thereby providing valuable insight regarding the geomorphic response of a coastal system"*. (McBride et al., 1995, p.146)

The traditional approach to mesoscale barrier change involves analysis of historical data. Analysis of historical records (e.g. maps, nautical charts, air photos, satellite imagery) and repeat field surveys (e.g. of barrier profiles or shoreline position), are standard approaches. List et al. (1997) discuss the methods employed for historical bathymetric data collection, cartographic production, and seafloor change analysis. Often these records pertain to one or a few proxies of barrier position or morphology (high water mark, dune edge, etc) and, contrary to the assertion of McBride et al. (1995) above, each of the myriad of geoindicators records different aspects of coastal behaviour (Carapuço et al. 2016). The temporal record of morphological change is, however, always incomplete and it is necessary to rely on partial records of change and of potential drivers (sea-level change, climate forcing).

The short length of the historical record also impedes efforts to describe mesoscale barrier behaviour. Several European datasets (e.g. Ballarini et al., 2003; Villalobos et al., 2009; Fontolan et al., 2012; Poirier et al., 2017) span several hundred years but these comprise irregular and widely-spaced observations of variable accuracy. In the United States records seldom extend to more than 150 years (e.g. Morton, 2007).

The situation regarding the paucity of data is changing with time as more long-term data sets are compiled. In addition, technological advances (e.g. Light Detection and Ranging (LiDAR), multibeam bathymetry) now permit rapid, large-scale, 3-D repeat surveys to be undertaken (e.g. Raji et al., 2011). The utility of high-resolution LiDAR topographic mapping has been demonstrated in the understanding and storm impacts on barriers (Sallenger et al., 2001; Houser, 2013) and the detailed tracking of barrier

topographic change over decades (White and Wang, 2003; Brock and Purkis, 2009; Lentz et al., 2013).

Historical records of sea-level change and dynamic drivers (wind, waves) are an essential element in attempts to understand observed morphological change. In most cases these records are site-specific and, except for a few long-term records, limited to a few decades. Measured wave records are especially short. The situation is changing with the widening network of operational wave buoys and the advent of global hindcast wind and wave models that demonstrate strong ability to simulate actual wave conditions for several decades past. The Global Ocean wave reanalysis (Reguero et al., 2012) extends back to 1948, for example, while the CERA-20C reanalysis (Buizza et. al., 2018) covers the entire 20$^{th}$ century.

## 4.2. Geological field investigations.

Although traditionally viewed as millennial scale investigations at best, advances in technology in data acquisition and chronological control mean that many geological investigations of barrier/lagoon systems can achieve century to decadal temporal resolution (e.g. Fruergaard et al., 2015; Benallack et al., 2016; Costas et al., 2016). This is useful in understanding barrier behaviour because a much bigger range of sea-level change and environmental conditions was experienced over the Holocene than can be identified by historical investigations on modern coasts. The following examples illustrate the potential of evolving geological techniques to achieve mesoscale resolution.

In the St Lucia lagoon of South Africa, Benallack et al. (2016) and Humphries et al. (2016) used long cores and high-resolution AMS dating, together with high-resolution seismic profiling to identify centennial scale responses of the back-barrier to sea-level forcing and climate oscillations. Using micropalaeontological proxies from the cores, Gomes et al. (2017) documented periods of barrier growth, sealing and storm-wave inundation at the sub-millennial scale. These findings correlated and confirmed findings of Porat and Botha (2009) that employed ground penetrating radar (GPR) and OSL dating to understand the history of the dune barrier.

Zaremba et al. (2016) similarly used ultra-high frequency seismic reflection profiling, vibrocores and AMS dating to study the Holocene evolution of Pamlico Sound at centennial timescales. This was supported by adjoining GPR profiles and cores from the barrier islands (Mallinson et al., 2010). These studies enabled a century-scale analysis of barrier changes associated with the Medieval Climate Anomaly, followed by inlet closures and barrier consolidation since 500 cal BP.

Clarke et al. (2014) used grain size analysis from a small back-barrier system in California to infer decadal cycles of barrier-inlet breaching and closure. These were further linked to climatic drivers at the decadal scale using a combination of wavelet analyses coupled to very-high resolution dating using anthropogenic radionuclides.

Improvements in dating techniques (Van Heteren et al., 2000; Preusser and Schreurs, 2011) mean that changes in geological studies can now be documented at century scale that provide insights into shoreline translation rates associated with barrier overstepping, for example, that are not observable in historic records of barrier change. Since the inception of OSL dating of clastic sediments in 1985 (Rink and Lopez, 2010) several studies have employed the technique to establish decadal to century scale records of barrier behaviour. Studies on prograded barriers in particular have been able to assess the frequency and impact of extreme wave events on overall progradation rates (Rink and Lopez, 2010; Tamura 2012) and to link historic change to millennial scale evolution (Oliver et al., 2017). Mellett et al. (2011) resolved the timing of formation and subsequent overstepping of a gravel barrier in the English Channel using high-resolution seismic profiling and coring and were able to resolve formation and breaching dates at century timescales. High-resolution bathymetric and seismic studies of the drowned barrier systems of the SE African shelf revealed extensive barrier and back-barrier systems that were preserved by an early Holocene meltwater pulse (Green et al., 2013a; Salzmann et al., 2013; Green et al., 2014). Pretorius et al. (2016) used ultra-high resolution seismic data and cores from the back barrier of one of these systems to unravel stepped changes in Holocene sea level. Alternating rollover and overstepping of the barrier was attributed to centennial-scale alterations in sea level. De Falco et al. (2015) documented a drowned barrier and back barrier system in the northern Adriatic. They concluded that barrier evolved

over a time period of 1 ka and the time between formation and drowning of barriers was in the centennial timescale.

In addition to the mesoscale record of barrier change that can be deduced from geological studies, a range of traditional and emerging technologies enables the framework geology of barrier islands and their surroundings to be investigated (Weymer et al. 2015).

## 5. Statistical and investigative modelling approaches

Modelling approaches to barrier-lagoon behaviour at the scales of decades to centuries have traditionally aimed at understanding process-response relationships. As discussed above, those models can only be tested against incomplete records of dynamic forcing, partial records of morphological response and near absence of data on underlying geological control. A variety of approaches have been applied over the past two decades, including statistical, morphological-behaviour and process-based models, to investigate the range and direction of behaviour or the relationship between various process-response variables. Nonetheless, investigative models can be used to better understand barrier behaviour.

Statistical or data-driven approaches to large-scale coastal behaviour of barrier systems are typically based on the analysis of morphological datasets collected during lengthy and coherent monitoring programs. The statistical techniques employed rely solely on the mathematical analysis of records of morphological change, without invoking detailed treatment of the physical processes (Reeve and Karaunarathan, 2009). A wide range, from simple to advanced statistical techniques, have been applied to coastal morphological datasets (Kroon et al., 2008) to understand mesoscale behaviour. Empirical orthogonal function (EOF) decomposition is perhaps the most commonly used technique to identify decadal patterns of barrier behaviour (Wijnberg and Terwindt, 1995; Hapke et al., 2016). While EOF and other statistical techniques have proved useful for understanding past behaviour (Kroon et al., 2008), there is limited application of data-driven models to forecasting coastal change (Reeve et al., 2016). Recently, however, probabilistic data-driven approaches based on Bayesian Networks (BN) have been used to predict long-term shoreline change on

barrier islands, given their ability to assimilate large observational datasets of coastal change and integrate them with boundary and forcing variables. Plant et al. (2016), building on the work of Gutierrez et al. (2011, 2015) developed a long-term predictive model for dune-height, shoreline change rate, and shoreline position on barrier islands, demonstrating that inclusion of a dune-height constraint improved the shoreline-change prediction.

Morphological-behaviour models, also termed exploratory (Murray, 2003) or reduced complexity models (Murray, 2007), aimed at simulating large-scale coastal morphological behaviour and stratigraphic evolution of barrier systems in response to changes in sea-level and sediment volume have proliferated since the 1990s (FitzGerald et al., 2008). From the outset, the morphological-behaviour modelling approaches to barriers varied significantly, ranging from numerical implementation of empirical geometric relationships, to parameterized mathematical-physics models (de Vriend, 1991), and adopting different methods for aggregating coastal features and processes into sub-systems (Cowell et al., 2003). Without necessarily implying increasing degrees of model complexity, Lorenzo-Trueba and Ashton (2014) subdivided barrier morphological-behaviour evolution modelling approaches as morphokinematic, relaxed morphokinematic and morphodynamic (Fig. 11). Common to all approaches is sediment mass conservation (Wolinsky and Murray, 2009) and barrier schematization based on an idealized cross-shore configuration (discretized into relevant spatial components that normally include the shoreface, barrier and lagoon).

Morphokinematic models simulate long-term barrier evolution as simple translation driven by sea-level change, disregarding the processes that lead to morphological change (e.g. overwash), while considering geometrical shapes based on equilibrium concepts (Lorenzo-Trueba and Ashton, 2014). As such, morphokinematic models of barrier evolution tend to rely on assumptions such as the generalized Bruun rule of Dean and Maurmeyer (1983), where the entire barrier system maintains its form while migrating landward with sea-level rise (Fitzgerald et al., 2008; Lorenzo-Trueba and Ashton, 2014). The Shoreface Translation Model (STM) of Cowell et al. (1992, 1995) encapsulates this approach, with morphological evolutionary modes ranging from barrier translation (i.e. roll over) to encroachment, determined fundamentally by

the steepness of the pre-existing substrate. The role of geological inheritance in barrier evolution is partly incorporated in STM via the substrate slope, although the substrate can also be freely reworked given its parameterization as unconsolidated sediment (Cowell et al., 1995). The assumptions regarding shoreface profile shape in such approaches have been identified as a fundamental weakness (Cooper and Pilkey, 2004a; Pilkey and Cooper, 2006).

Building on the morphological-behaviour concepts and sediment conservation rules proposed by Cowell et al. (1995) in STM, Stolper et al. (2005) developed the Geomorphic Model of Barrier, Estuarine, and Shoreface Translations (GEOMBEST). By handling the substrate as distinct (user defined) stratigraphic units with variable sediment composition and erodibility, as well as incorporating a depth-dependent response rate, GEOMBEST implementation allows relaxation of the assumption of equilibrium profile configuration and can simulate the influence of complex geological inheritance in barrier morphological evolution (Stolper et al. 2005; Moore et al., 2010). Disequilibrium becomes a fundamental aspect of this modelling approach (FitzGerald et al., 2008), leading to its classification as relaxed morphokinematics (Lorenzo-Trueba and Ashton, 2014). Given GEOMBEST's flexible approach and implementation, it has been increasingly used to investigate the coupled long-term evolution of barrier-lagoon systems, providing new insights into barrier disintegration (Moore et al., 2014), interactions between backbarrier deposition, substrate slope and underlying stratigraphy (Brenner et al., 2015), and the influence of backbarrier marshes on barrier island evolution (Walters et al., 2014).

Morphological-behaviour models that focus on sediment fluxes, explicitly simulating the principal erosional and depositional processes and/or feedbacks that drive long-term barrier island evolution are defined as morphodynamic (Lorenzo-Trueba and Ashton, 2014). Morphodynamic models vary in complexity and time scales. On the longer, geological scale, the stratigraphic process-response BARSIM model (Storms et al., 2002; Storms, 2003) considers barrier evolution as event-driven, simulating different depositional patterns for storms and intervening fair-weather conditions. Also at the millennial-scale, Masetti et al. (2008) proposed the Barrier Island Translation (BIT) morphodynamic model which uses simplified equations to simulate barrier evolution due to wave-driven sediment diffusion in the inner shelf and

sediment reworking on the shoreface, sediment overwash on the barrier during energetic events and lagoonal deposition in the backbarrier. More recently, Lorenzo-Trueba and Ashton (2014) introduced a morphodynamic morphological-behaviour model that focuses separately on the active shoreface (treated as a single linear unit) and the barrier-backbarrier domain. The centennial scale evolution of the barrier system is driven by shoreface fluxes, passive flooding during sea-level rise and overwash fluxes, with the morphodynamic model being able to simulate complex barrier behaviours, including rollover, drowning and discontinuous retreat.

On decadal scales, morphological changes in barrier islands are frequently conceptualized using sediment budget approaches, which analyse the sediment balance and transfer pathways of the relevant constituent landforms of the coastal system (French et al., 2016a). Developed using a combination of physics-based and empirical approximations, sediment budget approaches can be included in the morphodynamic morphological-behaviour suite of models, given their geometric simplification of barrier system configuration and numerical treatment of a restricted number of processes. Recent examples include the profile model of Rosati et al. (2010), which simulates decadal barrier migration over compressible substrates to investigate the impact of sediment compaction in barrier evolution; the sediment balance model of Aagaard and Sorensen (2013), which integrates longshore and cross-shore sediment transport to determine long-term evolution of a barrier system; and the profile response model of Larson et al. (2016), which focuses on sediment exchanges driven by dune erosion and overwash, aeolian transport and bar-berm coupling. These models generally concentrate on the intertidal to subaerial domain, where long-term observations are available for calibration.

Based on detailed hydrodynamic fluid motions and physics of sediment transport, 2D and 3D process-based numerical models have been widely used in the coastal and marine engineering community (Fagherazzi and Overeem, 2007). Improvements have been made with established process-based models to widen their spatial and temporal range of applicability, including improved morphodynamic upscaling with the morphological acceleration factor implemented in Delf3D (Lesser et al., 2004; Roelvink, 2006; Ranasinghe et al, 2011), or coupling diverse model suites (e.g ROMS, SWAN, XBeach) for regional scale simulations (Warner et al., 2008, 2010;

Barnard et al., 2014). However, non-linearity, internal dynamics, free and forced dynamic responses to stochastic conditions are not adequately captured by models that simulate flows and sediment transport processes at high-resolution and very short time-steps. This limits the use of process-based models for addressing mesoscale evolution of barrier-lagoon systems (Moore et al., 2010; Carrasco et al., 2016; Ruggiero et al., 2016), irrespective of whether meaningful schematization has been undertaken of input conditions (Cayocca, 2001).

Recent efforts have been made to couple diverse model types to create integrated modelling frameworks that address decadal to centennial-scale evolution of whole stretches of coast (French et al., 2016b; van Maanen et al., 2016). The CoSMOs-COAST modular model of Vitousek et al. (2017) is a recent example of this hybrid approach, combining historical data assimilation with process-based models of cross-shore and longshore sediment transport to simulate long-term shoreline position along sandy barriers.

## 6. Geological influences on mesoscale barrier behaviour

The geological influence on barrier behaviour in millennial scale stratigraphic studies is well established (e.g. Riggs et al., 1995; Schwab et al., 2000) but, until recently, this has been less clear in investigations of mesoscale barrier behaviour. Investigations using historical, geological and modelling approaches, and taking advantage of advances in chronological control and spatial measurement, now reveal that a variety of geological factors do influence barrier morphology and behaviour at the mesoscale (e.g. Honeycutt and Krantz, 2003; Lentz and Hapke, 2011; Houser, 2013; FitzGerald, 2015).

These can be visualized in a systematic view of the barrier/lagoon environment (Fig. 12). Barrier/lagoons are open systems that involve inputs of energy (via dynamic variables such as waves, tides, and wind) and sediment (a geological variable), which can be positive or negative. Within the system boundary (which is set by the surrounding geological framework), a particular barrier morphology develops whose subsequent behaviour is then influenced by a variety of geological controls. Thus, mesoscale barrier/lagoon behaviour is influenced both by inherited geological factors

that control the initial barrier morphology and geological factors that influence ongoing changes.

Many of these elements (particularly relating to surface morphology) are readily quantifiable using available and widely employed techniques (airborne LiDAR, multibeam bathymetry), but others (chiefly relating to sub-surface geology) require approaches that are common in geological/stratigraphic studies but which are only occasionally applied in studies of mesoscale barrier/lagoon behaviour (e.g. Costas et al., 2006). Increased recognition of the resolution available in contemporary geological investigations such as those described above, is likely to lead to more frequent application of those techniques in mesoscale studies.

Several potentially important geological parameters are interrelated and consequently a tentative hierarchy is here proposed (Fig. 13). This identifies the primary geological controls as the basement characteristics (slope, topography and erodibility), shoreface morphology and sediment supply. Lithification is also a locally important primary control, particularly in the tropics where beachrock and aeolianite formation occurs in barriers (Cooper, 1991).

These primary controls influence secondary geological controls such as barrier and lagoon extent and orientation, barrier volume and morphology (especially height and the extent to which overwash is possible), barrier planform morphology (swash- or drift-aligned), the tidal prism and thereby the size and abundance of tidal inlets. Dealing with them separately is a somewhat artificial exercise, however, by reference to examples, the role of the primary controls and the network of linkages to subordinate levels of geological and dynamic control are outlined below.

## 6.1. Basement slope

Many studies have shown a relationship between basement slope and rates and patterns of barrier migration. Geological investigations (e.g. Belknap and Kraft, 1985) have shown that the antecedent slope controls the relative accommodation space available for a migrating barrier and largely influences whether in-place drowning, rollover, erosion or accretion occurs. Schwab et al. (2000) found that barrier islands

resting on a steeper transgressive ravinement surface migrated landward at a faster rate than those on flatter surfaces. The palaeo-slope on which contemporary barrier islands rest, also influences contemporary wave dynamics on the barrier shoreface. Steeper palaeo-slopes were found to produce thinner shoreface accumulations due to differential changes in wave refraction (Riggs et al., 1995). Roy et al. (1994) found a critical retention threshold at an antecedent gradient of 1°; slopes steeper than this promoted the offshore loss of sandy sediment. On flatter slopes, sandy sediment was moved onshore into the littoral zone where it became accessible to the barrier shoreface. This relationship is likely enhanced in regressive barrier systems where local progradation of the barrier front may cause steepening of the shoreface and net seaward sediment loss from the shoreface over time.

Salzmann et al. (2013) and Green et al. (2018) highlighted the role of antecedent slope in the preservation and response of barriers to mesoscale sea-level rise. Steeper slopes provided a limited accommodation that caused barriers to aggrade during sea-level stillstands. However, the steeper slopes also focused shoreface erosion more effectively as sea-levels subsequently rose, with a greater amount of erosion per unit of time (e.g. Cattaneo and Steel, 2003).

Hapke et al. (2016) showed that the long-term shoreline change pattern alongshore was influenced by variations in slope of the beach (Lentz et al., 2013), sediment availability and bathymetric features on the inner continental shelf (Hapke et al., 2010; Schwab et al., 2000, 2013). They were able to statistically demonstrate the influence of processes constrained by framework geology on barrier island evolution at the mesoscale.

Brenner et al. (2015) examined the role of antecedent topography on barrier evolution on Metompkin Island, Virginia. In a hindcast study of subaerial barrier modification with rising sea levels, they considered a wide back barrier the most important variable to affect the island migration trajectory (i.e. roll over, in place drowning or erosion). Rather than the straightforward basement slope, they found that the back-barrier width modulated the slope relationship as it dampened the migration rates due to sediment scavenging from a sandy back-barrier and associated changes in back-barrier width. This points to the antecedent substrate type and back-barrier antecedent

conditions as perhaps the most important control on barrier response to sea-level rise (Moore et al., 2010).

The application of several investigative models (Murray, 2003) has greatly advanced the understanding of underlying slope control on barrier evolution as well as some of the interactions and feedbacks. These investigative approaches evolved from early applications of Bruun Rule-type profile responses on an infinitely erodible and homogenous coastal plain (Cowell et al., 1995) through variations that allowed the effect of a heterogenous underlying geology to be investigated (Stolper et al., 2005 Valvo et al., 2006; Hapke et al., 2010; Moore et al., 2010). Similarly, modelling of shoreline planform evolution (Wolinksy et al., 2015; Valvo et al., 2006) has allowed the role of underlying lithology of varying composition to be assessed.

Most conceptual diagrams of basal slope over which a barrier is transgressing depict it as a continuously sloping surface (e.g. Cowell and Kinsella, 2018). While the slope of the area that has already been transgressed (i.e. seaward of the barrier) can readily be assessed, the area landward of the contemporary barrier cannot be regarded as a straightforward continuation of that slope (see below). It has yet to be transgressed and subject to the processes of wave ravinement that produced the basal surface to seaward. Its geology and topography will influence how that surface evolves with ongoing transgression.

## 6.2. Basement Topography and erodibility: Headlands, cliffs, depressions and topographic highs

When resistant basement material is present in the surface being transgressed, irregularities (topographic highs and lows) significantly influence the morphology and behaviour of barriers (Demarest and Leatherman, 1985; Wolinsky and Murray, 2009) and backbarriers via control on accommodation space (Storms et al. 2008; Koster et al., 2017) (Fig 1B). Indeed, according to Beets and van der Spek (2000, p.8) *"The size of the back-barrier basin, which is a function of the slope of the pre-transgressional surface, and the rate of RSL rise are the main factors defining the accommodation space"*. Headlands act both as anchor points and sources of sediment for barriers. With slowly rising or stationary sea levels, they help fix the position of

barriers (Orford et al., 2002) and subsequent shoreline evolution may lead to development of swash- or drift-aligned planforms.

An extreme example of bedrock influence on barrier behaviour is evident in the barrier islands of the Outer Hebrides of Scotland (Cooper et al., 2012). Here, a 70 km-long chain of sandy barriers rests on a broadly planar surface of Precambrian gneiss. The bedrock surface dips seaward at between 0.001° and 0.002° from +30 m to -100 m MSL. Glacial modification of the bedrock surface has created depressions of various sizes (Dawson et al., 2013). Modern sandy barriers migrate landwards over the bedrock surface by overwash and aeolian deflation and their planform is much influenced by bedrock topography (Fig 13). Two main types of barrier island morphology exist within the chain. In bedrock depressions (Figure 13B) the barrier island has a shoreface and is backed by a lagoon with sufficient tidal prism to maintain an inlet and associated ebb- and flood-deltas. In areas of high bedrock topography, (Figure 13A) the barrier island lacks a shoreface and the impounded back-barrier water body lacks tidal inlets due to the limited basin size. As the barriers migrate across the essentially unerodible bedrock surface they encounter areas of low and high backing topography that determines which morphology is adopted by the barrier island. In this setting, bedrock topography is the primary determinant of barrier response to environmental change.

Barrier sediment may be sourced from erosion of the underlying substrate (e.g. Belknap and Kraft, 1985; Riggs et al., 1995). The profusion of fossil shark teeth in barrier sediments of North Carolina (Pilkey et al., 2004), and Pleistocene mammal bones on the Lagoa dos Patos barrier in Brazil (Lopes and Buchmann, 2011), testify to a portion of barrier sediment being derived from erosion of underlying sediments. The nature of the erodible material also influences the texture of the derived sediment. Where underlying palaeo-valleys are transgressed and a headland is exposed on the shoreface, coarser sediment may be liberated from the headland than from intervening valleys (e.g. Belknap and Kraft, 1985). ``*The lithology of the underlying units exerts a primary control on the distribution, texture, and composition of surficial sediments, as well as inner-shelf bathymetry*`` Thieler et al. (2001, p 958). Murray and Moore (2018) explicitly considered the influence of erodible seabed material on shoreface and barrier morphology under rising sea-level. In model studies they showed how the

influence can be quantified according to the relative proportions of fine and coarse-grained sediment yielded by erosion as the shoreface erodes into former back-barrier sediments. There are, however, few quantified field reports of the nature of the *actual* material being eroded through such erosion.

The rate of sea-level rise can also influence the degree to which underlying geology affects barrier evolution. In a comparative study of gravel barriers experiencing different rates of sea-level rise Carter et al. (1989, p.221) showed that "*In Ireland* [slow sea-level rise], *barrier-lagoon form is controlled by local basement expression, particularly through the emergence of headlands …. [while]… the Nova Scotian examples [fast sea-level rise] are associated with rapidly moving erosional fronts, with local basement control relegated to a subordinate role at the expense of rapid changes in sediment supply*"

## 6.3. External sediment supply

"*Barrier island response to changing conditions is likely to be complex and variable, and will be determined, in part, by the rate of sand supply*" (Brenner et al., 2015, p. 334)

Sediment is supplied to barriers from diverse sources that largely reflect the environmental setting (Fenster et al., 2016; Ruggiero et al., 2016). The rate of sediment supply is difficult to quantify (mainly because of temporal and spatial variability: it can also be strongly episodic) and often historical data are absent. Although sediment budgets have long been applied in studies of mesoscale barrier behaviour (e.g. Pierce, 1969; Kana, 1995) there are significant uncertainties regarding volumes, sources and supply rates.

The shelf and shoreface are perhaps the most common sources of barrier sand (Schwab et al., 2013), but fluvial sources dominate on deltaic and high-relief coastlines (Cooper, 1990), while cliff erosion is prevalent on paraglacial gravel barriers (Orford et al., 1991). The rate and nature of sediment supply to barriers not only influence their overall morphology (Fig. 2) but are also key constraints on their mesoscale evolution (Fig. 12). Former sediment supply conditions during barrier

initiation or stabilization may differ markedly from contemporary conditions. Ferreira et al. (2016) distinguished four stages of barrier development for the Ria Formosa barrier in Portugal as sediment accumulated. Stage 1 involved low elevation barriers dominated by overwash that maintained or widened the barrier. Stage 2 involved aeolian transport and vegetation expansion and reducing overwash frequency. Stages 3 and 4 correspond to development and expansion of the foredune, respectively. Barrier volume increased significantly from stages 1 to 3, with a negative sediment balance and barrier narrowing leading to reduced volumes in stage 4. The different stages can be seen in contemporary barriers of the Ria Formosa, and their evolution is not necessarily sequential, as it depends on the accommodation space provided by the topographic configuration of the system, inlet dynamics, sediment availability and (latterly) human interference.

In longshore drift-dominated barriers, continued sediment supply is necessary to sustain barrier integrity as evidenced by the dramatic effects of groyne and jetty construction on downdrift systems (e.g. Wijnberg, 2002). The influence of changing sediment supply is well illustrated in gravel barrier planform models (Fig. 5) where a reduction in supply can prompt reorganization of the barrier leading to stretching, cannibalization, cell development and ultimate breakdown (Carter et al., 1987), processes that can be reversed with a fresh influx of sediment. Murray and Moore (2018) show how convergences and divergences of longshore drift sediment delivery cause barriers or sections of barriers to advance or retreat, respectively, under sea-level rise.

Episodic sediment supply to barriers is exemplified by river floods (Cooper, 2002) which may cause initial barrier erosion followed by rapid progradation as flood-derived sediment is reworked landward under wave action (Cooper, 1990). The reverse effect is well illustrated by damming of rivers in the US West coast which cut the sediment supply and led to barrier retreat (Warrick et al., 2014). Storms are often linked to loss of sediment from barriers or to overwashing depending on the circumstances (Sallenger, 2000; Donnelly et al., 2001), however, Fruergaard et al. (2013) showed that extreme storms can also access sources of sediment on the seabed leading to progradation and formation of new islands. In the example they documented in southern Denmark, an entirely new chain of barrier islands formed in

the North Sea following an influx of marine-derived sediment after a severe Medieval storm.

The sediment supply strongly influences coastal dynamics on barriers (Fenster et al., 2016). It is also a key determinant of barrier volume, and this in turn, exerts further controls on barrier behaviour (Jennings et al., 1998). Barrier inertia (Orford et al., 1995; 2002) is a determinant of how rapidly a barrier can be reorganised in response to external forcing and it is a function of sediment volume as measured by barrier cross-sectional area.

Not only the total barrier volume but its morphology, is important. This is seen most readily in whether a barrier is low enough to permit overwash and thereby roll landwards. However, even relatively small variations in dune crest height (Houser, 2012, 2013), or foreshore morphology (Matias et al, 2014) have been shown to modulate overwash vulnerability and barrier migration. Miselis and McNinch (2006) found that nearshore sediment thickness was a strong determinant of barrier shoreline stability.

Large-volume barriers exist on many coasts including southern Brazil (Dillenberg and Hesp, 2009) and SE Africa (Cooper and Pilkey, 2002; Benallack et al., 2016). Most of these barriers are too wide (7 km in Brazil) or high (80-100 m in Africa) to permit overwash. Consequently, they do not migrate, although sediment may accumulate on them or pass across them via aeolian activity. Conversely, small-volume barriers can evolve very quickly. Sustained shoreline recession rates of 20 to 30 m per year were noted on low volume barriers in Chesapeake Bay (Cooper, 2013) and the Mississippi Delta (Penland et al., 1985).

Temporal changes in sediment supply can be manifest in sandy barrier morphodynamics at timescale ranging from instantaneous in the case of river floods (e.g. Cooper, 1993) to decadal and centennial in longshore-drift-dominated systems.

**6.4.    Coastal orientation/aspect**

The coastal orientation and aspect are often inherited factors determined by the geological surface on which contemporary coastal systems are developed. They are influenced by long-term geological processes related to tectonics, glaciation and long-term weathering patterns. The inherited coastal orientation, in turn influences the degree of exposure to wave and current action and the extent to which barriers are subject to longshore or cross-shore processes. On barrier/lagoon coasts with many headlands, cross-shore effects tend to dominate, whereas on coastal plans, longshore drift predominates. Wijnberg (2002) showed how coastline orientation influenced exposure to the prevailing offshore wave climate and exerted significant influence on decadal scale barrier behaviour. Orientation is also a key influence on reworking of lagoon barrier margins (McBride et al., 1995; Ashton et al., 2009).

**6.5. Shoreline lithification (beachrock/aeolianite formation)**

Lithification of barrier sediments as beachrock and aeolianite is particularly prevalent in the tropics and subtropics (Davies, 1980; Vousdoukas et al., 2007), but is also increasingly recognised in temperate latitudes (e.g. Cooper et al., 2017). It is a locally important primary-level control on barrier behaviour (Cooper, 1991). Cementation (usually by carbonate mineral precipitation between the beach/dune grains) can take place rapidly, and certainly occurs at decadal/century timescales (Vousdoukas et al., 2007; Mauz et al., 2015). Cementation in barriers has the immediate effects of removing sediment from the active littoral budget, reducing porosity and creating resistant geological elements (headlands and platforms) that exert a direct geological influence on subsequent barrier behaviour (Cooper, 1991; May et al., 2012). The cemented material itself then undergoes breakdown under wave action (e.g. Cooper and Green 2016) and its preservation potential depends on the rate of submergence and its resistance to wave-induced erosion. Even when submerged, continued erosion of overstepped cemented barriers can occur through direct wave action and storm-return flows (Pretorius et al., 2018).

Multibeam bathymetry has revealed spectacular and widespread occurrences of beachrock and aeolianite-cemented shorelines in the Gulf of Mexico (Jarrett et al. 2005; Gardner et al., 2005, 2007), the southwest Indian Ocean (Green et al., 2018; Salzmann et al., 2013) and the Mediterranean Sea (de Falco et al., 2015), where they

preferentially preserve former shorelines through their resistance to erosion during subsequent sea-level rise.

## 6.6. Shoreface morphology

Although many shorefaces are mobile and to that extent, dynamic features, the timescales of significant morphological change on the shoreface are typically much longer than those on adjacent barriers (Swift et al., 1985; Ruggiero et al., 2005), rendering them geological controls at the decadal to century timescale. Shoreface morphology is an important geological influence on mesoscale shoreline behaviour (Riggs et al., 1995; Wijnberg, 2002). Indeed, Cowell and Kinsella (2018) argue that shoreface processes are a fundamental control on barrier form and behaviour. Shoreface morphology is itself strongly controlled by the underlying geology (Riggs et al., 1995; Thieler et al., 1995) and sediment supply and is therefore an intermediate level geological control on barrier behaviour (Fig. 13).

Riggs et al. (1995) showed that underlying geology created six different shoreface morphologies along the North Carolina coast, the primary distinction being between shorefaces underlain by relict headlands (interfluves) or incised valleys. They noted (p.213) that "stratigraphically-controlled bathymetric features on the inner shelf modify waves and currents and thereby affect patterns of sediment erosion, transport, and deposition on the adjacent shoreface." Working at decadal timescales, Wijnberg (2002) showed shoreline behaviour along the Holland coast was strongly influenced by adjacent shoreface morphology, particularly the occurrence of shoreface-connected ridges (SCRs). These quasi-stationary features have also been linked to the development of long-term coastal concavities, for example on Fire Island, NY (Safak et al., 2017).

## 7. The role of initial barrier morphology

The geological factors outlined above, in combination with the prevailing dynamic regime, create barrier islands of varying morphology. In any study of geomorphological change, the initial morphology is a key determinant of the direction and rate of future travel. This is most immediately evident during storms when the

differential responses of barriers can readily be linked to pre-existing morphology (Kahn and Roberts, 1982; Sallenger, 2000; Matias et al., 2008; Masselink and van Heteren, 2014), but pre-existing morphology also influences the nature of longer term geomorphic feedbacks on barrier systems (Houser, 2012, 2013). To this extent, the geomorphic form of any barrier is an important constraint in its future behaviour (Houser et al., 2017). The diversity of barrier forms outlined above thus implies a multiplicity of mesoscale behaviours.

Several studies have demonstrated complex links between initial barrier morphology and decadal scale evolution. The following two case studies serve to illustrate.

Houser et al. (2008) studied the morphology and mesoscale behaviour of Santa Rosa Island, FL. The island exhibited systematic variation in dune crest elevation at several length scales. Analysis showed that these correlated with transverse ridges on the inner shelf, backbarrier cuspate features and historic rates of shoreline change. The work demonstrated that the inner shelf ridges influenced the elevation of dunes on the barrier island through their impact on wave refraction and focusing. This variation in dune crest height in turn caused alongshore variation between sectors that experienced offshore sand loss (high dunes) and those that experienced overwash (low areas) during storms. The post-storm recovery reinforced this spatial difference with low, overwashed areas close to the water table, experiencing lower rates of subsequent dune growth. In contrast, high dune areas that had lost sand to the adjacent shoreface, regained it and rebuilt high dunes in the post-storm period. The historical rates of shoreline change strongly correlated with island width and foredune height. The linkages between these morphological features led Houser et al. (2008, p.238) to conclude not only that foredune morphology profoundly affected barrier response to storms, but also that "the height and extent of foredune development and the presence and relative location of the backbarrier dunes are "geologically" controlled and reinforced during successive storms"

Mesoscale changes on a stretch of the NW French coast show a strong link between shoreface morphology, seabed sediment supply and barrier behaviour (Anthony, 2013), demonstrating again the importance of the immediately antecedent barrier and nearshore morphology on barrier behaviour. In the study area, a series of wide, dune-

topped barriers are fronted by a topographically irregular but low gradient shoreface that contains a set of large-scale tidal sand bars and ridges elongated parallel to the shore. These form a nearshore depocentre where sediment from the North Sea accumulates. Episodic welding of these tidal sandbars to the barrier cause the beach to widen, creating a backshore sand flat on which embryo- and then foredunes develop at a timescale of several decades. Bar welding and dune growth is associated with wave dissipation offshore on the submerged section of the welded sandbar. Additional sediment is delivered to the barriers by the welding of smaller shoreface features including sandwaves and subaqueous dunes, all of which are driven by storm activity.

Unsurprisingly, the historic patterns of shoreline change show marked alongshore variability. Some areas are retreating at >8m/year while others have prograded at up to 2m/yr. The differences in shoreline behaviour are linked to the relationship between nearshore sandbars and the barriers and the way in which this relationship is mediated by storms. Areas of beach progradation and active foredune growth occur where sand banks welded onshore under the influence of storms. The onset of erosion in areas that were historically progradational are attributed to interactions between offshore banks, storms, longshore sand transport and possible current gyres generated by a projecting rocky headland. Amongst other processes, lowering of the bar crest, and increased onshore wave energy leads to shoreline erosion. Anthony (2013) remarked on the spatial variability in storm barometric pressure, wind velocity, set–up and tidal stage that, coupled with the marked variability in barrier-nearshore morphology, rendered the response to storms, spatially variable and entirely unpredictable.

Although these case studies come from vastly different barrier settings, both clearly demonstrate (i) the morphological links between shoreface and barrier morphology *and* behaviour, (ii) the different temporal scales of morphological change on barrier and shoreface, (iii) the complexity of barrier response to storms and (iv) marked spatial variability in mesoscale barrier behaviour and rates of change. In both instances, any effort to predict future barrier behaviour would require a detailed initial assessment of the barrier and nearshore morphology.

**8. Discussion**

Following a long period during which the dominant research theme in mesoscale barrier behaviour was focused on linkages between dynamics and response (morphodynamics), appreciation of the important influence of geological inheritance has increased in the past two decades. This appreciation has built upon and extended insights from early stratigraphic studies that had millennial scale resolution. It is, however, now clear that geological inheritance also significantly influences barrier behaviour at decadal/centennial scales. This influence is asserted directly and indirectly through:

(a) barrier morphology at the beginning of the period of investigation ($t_0$);
(b) underlying attributes of the surface upon and/or over which the barrier is evolving ($t_1$-$t_x$); and
(c) sediment supply which can be an internal or external geological influence.

Recognition of the role of geological inheritance has been derived in part from traditional, historical scale investigations that are now benefitting from enhanced temporal databases of morphological change and potential drivers. In addition, traditional geological methods (stratigraphy and coring) that could formerly only achieve millennial scale temporal resolution are now yielding centennial and even decadal scale insights into barrier behaviour. Since these often come from the Holocene record, they allow the role of the underlying geology to be inferred. They also cover a wider variety of sea-level scenarios and environmental settings than are observable at the present. Improved investigative modelling is enabling potential geological controls on mesoscale barrier evolution to be studied and compared to findings from historical and geological investigations. In combination, the many historical, geological or modelling studies demonstrate the often critical influence of geological factors in moderating or steering barrier behaviour. Added to this is the documentation of many diverse barrier types around the world, whose morphology is clearly a primary determinant of their behaviour (high, dune-topped barriers do not overwash, for example).

Recent developments in the understanding of mesoscale behaviour and the extent to which they are influenced by geological controls (e.g. shoreface-barrier decoupling; and the influence of the often irregular surface being transgressed), indicate that some of our conceptual and analytical models are oversimplified, incomplete or erroneous. Shoreface translation is far from ubiquitous and the role of underlying topography is far greater than supposed.

With acknowledgement of the role of geological factors, comes the challenge of incorporating them into future studies, firstly to aid the interpretation of past mesoscale behaviour and secondly to predict future response to climate and sea-level change in particular. Measurement and quantification of geological controls has long been possible with geophysical methods, both marine and terrestrial. The more recent advent and increased application of multibeam bathymetry and LiDAR technology enables quantification of contemporary morphology at resolutions that were previously inconceivable. This helps quantify the contemporary morphology as a starting point for consideration of future mesoscale behaviour. Studies such as those discussed above in Lake St Lucia, South Africa and the Pamlico Sound, NC demonstrate the utility of geological investigations to yield century- and even decade-scale resolution. However, adequate quantification of contemporary morphology (barrier topography, nearshore and lagoon bathymetry) and underlying geological control (bedrock morphology, type, sediment volume, thickness, type etc) to fully constrain models of future shoreline behaviour (i.e. to define the geological controls) exists in only a few barrier lagoon systems. Notable examples include Fire Island, NY, which has been the focus of detailed USGS investigation (Schwab et al. 2017) and Galveston island, TX (Wernette et al., 2018), where historical data augmented with new barrier investigations enabled a rare quantification of the linkage between antecedent geology and contemporary form. In the Netherlands, an abundance of subsurface data enabled construction of a 3D assessment of Holocene base level rise in two tributaries of the Rhine-Meuse system (Koster et al., 2017). Such locations offer an opportunity to assess the role of some geological factors, but their limited diversity means that other parameters cannot yet be studied, other than by modelling.

Of key importance to coastal management is the desire to predict future barrier position and status under various scenarios. This is traditionally undertaken by

morphodynamic modelling that takes little account of geological inheritance. While this was dismissed as an essentially millennial scale influence or local 'noise', we now know that geological inheritance potentially exerts control on hydrodynamics themselves and both the long- and/or short-term responses to hydrodynamic forcing. As noted by Wijnberg (2002 p. 227) *"... detailed comparison of alongshore variation in environmental variables along the Holland coast with the observed marked regional differences in decadal nearshore morphologic behaviour reveals that neither offshore hydrodynamic parameters nor grain size are discriminating factors"*. In a similar vein, Lorenzo-Trueba and Ashton (2014, p.779) state that ``*barrier response can be particularly sensitive to the sea-level rise rate and back-barrier lagoon slope. Overall, our findings contrast with previous research which has primarily associated complex barrier behaviour with changes in external forcing such as sea-level rise rate, sediment supply, or back-barrier geometry*``.

Much progress has been made in understanding the role of geological parameters in barrier behaviour. However, there remains a disconnect between this understanding and the operational area of coastal management and modelling in support of this goal. Geological influences are routinely overlooked. Modelling approaches (e.g. Zhang et al. 2010, 2012; Jimenez and Sanchez-Arcilla, 2004; van Maanen et al., 2015) that seek to apply deterministic, process-based models to predict coastal behaviour in the absence of an appreciation of geological control hold little potential to improve understanding of or predict barrier-lagoon behaviour. As noted by Valvo et al. (2006, p. 12) ``*quantitatively accurate modelling of sediment-poor coastlines will remain an elusive goal for the foreseeable future"*. Efforts to link such models and create ever more complex models (e.g. Van Maanen et al., 2015) are simply exercises in modelling rather than attempts to understand system behaviour; they hold no prospect for improving predictions of decadal scale behaviour and contribute only a false sense of confidence to coastal managers. Future research should focus on incorporating important geological influences into modelling efforts. The few sites described above for which adequate data exist provide ready yardsticks against which new models may be compared.

Sensitivity to initial conditions is known to be a critical issue in modelling and yet, modelling efforts often lack adequate description of initial conditions. Knowing the

starting conditions for any modelling exercise is known to be critical, and parameters such as the depth to bedrock, the vertical and lateral variations in sediment character (that are temporally variable) are either totally unknown, or at best, incompletely described or parameterized in modelling studies. Several studies have demonstrated complex links between initial barrier morphology and decadal scale evolution. These serve to illustrate the critical importance of initial barrier state in any future forecasting of mesoscale behaviour. These geological parameters might be capable of measurement by, for example, use of a dense grid of high-resolution geophysical investigations, but they are not currently given serious consideration in most applied studies. Geological data at adequate resolution to assess its influence is unfortunately lacking, nor is it given serious consideration in most shoreline prediction efforts. Furthermore, the quantification of sediment supply in the mesoscale remains an issue because of the variability of sources, temporal variability in supply, variations in source and sink areas within a barrier system, and the difficulty in measuring sediment supply (Cooper and Pilkey, 2004b).

Quantification of the geological framework is essential to understanding decadal to century scale evolution of barrier-lagoon coasts and should be a basic requirement of investigations of future shoreline behaviour. Tools exist to undertake the necessary investigations and the evolution of new mapping technologies (e.g. Pavlis and Mason, 2017) emphasize the potential to incorporate geological parameters into models of mesoscale behaviour of barrier/lagoon systems. The geological framework and morphology of barriers is strongly site-specific and simulating their future mesoscale evolution requires that it be measured. While morphological behaviour models have provided insights into barrier behaviour and have enhanced our understanding of interactions that are difficult to observe or quantify, they rely on simplifications (e.g. sediment mass conservation or barrier cross-section schematization) that preclude their use as quantitative predictive tools in the real world. As a consequence, the prediction of future barrier behaviour will necessarily remain in the qualitative domain. The apparent high-resolution and accuracy claimed by morphodynamic modelling studies is not real. Neither can morphological behaviour models deliver quantitative predictions. They do, however, allow qualitative assessment of future barrier condition. Coastal managers must be reconciled to the need to base decisions on such qualitative projections.

**Figure Captions**

Figure 1. A. Unconstrained barrier island facies model (after Reinson, 1992); B. Barrier island facies model showing geological influences and resulting morphological variations.

Figure 2. Barriers exist in many diverse settings and exhibit vastly different morphology and dimensions. These both derive from a combination of dynamics and geological influences, and impart key constraints on future barrier behaviour. Various sizes of barriers are depicted here. Note the variation in scale. A. Pamlico-Albemarle system, USA, a multiple inlet system with small barrier volumes; B. Lagoa dos Patos, Brazil, a single inlet system with a wide and low barrier; C. St Lucia lagoon, South Africa, a single inlet system with a very high barrier; D. Ria Formosa, Portugal, a multiple inlet system; E. Frisian Islands, Netherlands and Germany, a multiple inlet system with generally prograding/aggrading barriers). F. comparative cross-sections at a common scale show the contrasts in morphology and setting of these systems (arrows mark the barrier position). The Outer Banks, Patos Lagoon and Frisian Island systems are in low gradient, coastal plain settings with wide continental shelves. The St Lucia and Ria Formosa systems are on steep bedrock coasts fronted by narrow continental shelves.

Figure 3. Profile models of barrier response: A. Rollover; B. Erosion/Bruun Rule; C. Overstepping; D. Progradation/aggradation (Adapted from Mellet et al., 2013)

Figure 4. Chesapeake Bay fetch-limited barrier profile evolution. The barrier migrates over a backing marsh which is exposed on the foreshore. During exposure of the marsh the barrier detaches from the shoreface and continues to migrate across the marsh surface until it is beyond effective wave reach. Erosion of the exposed marsh continues until it is removed and the barrier and shoreface are again united. (After Cooper, 2013)

Figure 5. Gravel barrier planform behaviour model. (A) An initial prograding barrier/spit is supplied with sediment from alongshore. (B) External sediment supply is reduced and sediment begins to be eroded from the updrift end of the barrier (cannibalization). Deposition of eroded material leads to development of littoral cells

as the barrier strives for equilibrium with incident waves. (C) Cell development and continued sediment starvation cause the barrier to breach (After Carter et al., 1987).

Figure 6. Rapid morphological evolution of a fetch-limited barrier on the western shores of Virginia. The barrier evolution follows the model of gravel barrier planform development in Figure 5. A. Initial barrier morphology (1994). B. Sediment influx generates an alongshore elongation of the barrier across a coastal re-entrant (2005). C. Sediment starvation leads to cell development (2007). D. The barrier stretches and breaches (2008).

Figure 7. Generalized 8-mode geomorphic response-type model for Gulf of Mexico sand and barriers (inspired by McBride et al. 1995). Arrows depict shoreline direction of change and resulting planform changes. Upper panels represent time t0, while lower panels represent future time t1. Primary response modes are: lateral (alongshore) movement; advance (cross-shore); retreat (cross-shore); dynamic equilibrium (cross-shore stability). These, in combination, lead to more complex modes: in-place narrowing; landward rollover; break up; and rotation. Barrier A is accreting at one end and eroding on the other. Lateral variations in cross-shore behaviour are causing the island to rotate counter clockwise. Sediment supply from lateral erosion favours accretion at one end and erosion at the other. Barrier B is exhibiting landward rollover accompanied by some lateral movement. Overall, the sediment volume of the barrier is maintained. In Barrier C lateral movement and bayside and oceanside erosion cause the barrier to break up and disintegrate.

Figure 8. 19-year time series of images of Shanks Island, VA in Chesapeake Bay. An initial barrier island chain is gradually broken up as the islands lose volume, in the absence of an ongoing sediment supply. The island chain is progressively eroded and converted into a series of subtidal shoals.

Figure 9. 3-D model of barrier/lagoon evolution under sea-level rise. An initially stable system is progressively affected by rising sea level. In this model, back-barrier marshes are unable to accrete at the same rates as sea-level rise. The tidal prism thus increases, and the inlet and tidal delta volumes increase at the expense of the barrier

islands.  Ultimately, the barrier islands decay and the sediment from both islands and deltas is reworked landward   (FitzGerald et al. 2006).

Figure 10.   Shoreface-barrier linkages: shoreface retreat modes.   A.   Barrier and shoreface retreat at equal rates (keep-up). B. Shoreface retreat slower than barrier migration (give-up); C.  shoreface 'catch-up'.

Figure 11.   Conceptual schematization of the different morphological-behaviour model approaches; a) STM morphokinematic model (adapted from Cowell et al., 1995); b) GEOMBEST+ relaxed morphokinematic model (adapted from Walters et al., 2014); c) BARSIM morphodynamic model (adapted from Storms et al., 2008).

Figure 12. System view of barrier island system showing linkages between energy and sediment inputs, initial state and geological constraints, and response conditioned by geological constraints.

Figure 13. Hierarchy of geological controls on mesoscale barrier behaviour.   First order controls are inherited geological controls independent of dynamics.   These influence second order controls (morphological parameters) of barriers.   An intermediate level of geological control is exerted by the shoreface, which, although dynamic, tends to evolve at longer timescales than adjacent barriers, thus rendering the shoreface a geological control.

Figure 14.  Hebrides barrier islands, western Scotland.  These barrier/lagoon systems, developed on resistant bedrock are and end-member in terms of the influence of underlying geology on barrier morphology and behaviour and provide a graphic illustration of bedrock control.  Barrier planform morphology is clearly influenced by bedrock outcrop throughout the barrier island chain, creating, for example, swash-aligned barrier sections between headlands and cuspate shoreline features or tombolos in the lee of offshore outcrops.  Two distinctive morphological types are present, depending on the elevation of the bedrock over which the barrier is migrating.  In topographically high areas (A), barriers enclose small, perched lagoons with insufficient tidal influence to create inlets.  In areas of low bedrock elevation, back-barrier basins are larger and tidal circulation creates inlets and associated deltas (B).

The primary determinant of future barrier morphology is the bedrock morphology over which it migrates.

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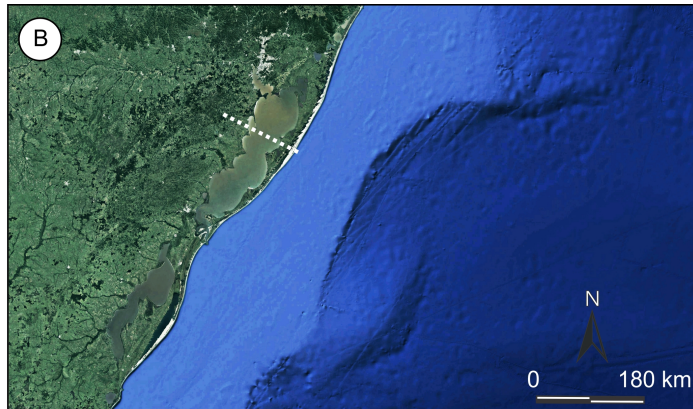Wijnberg, K.M. 2002. Environmental controls on decadal morphologic behaviour of the Holland coast. Marine Geology 189, 227-247.

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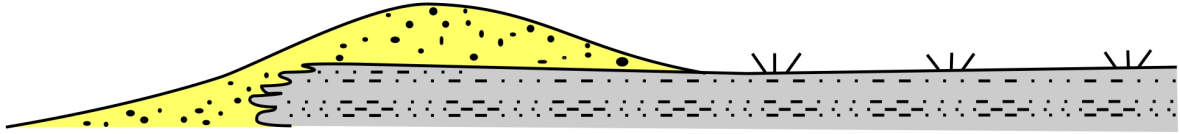
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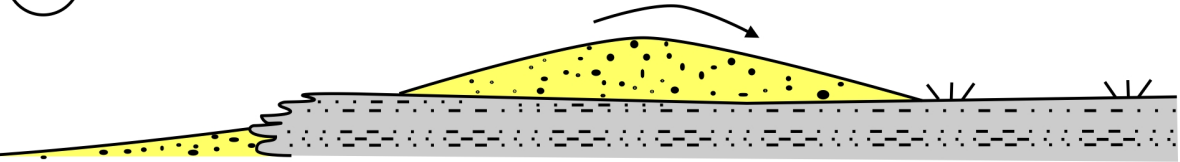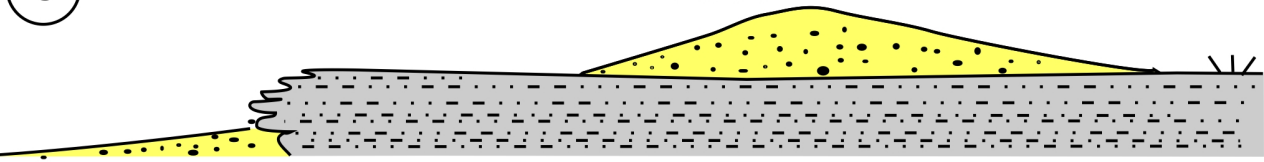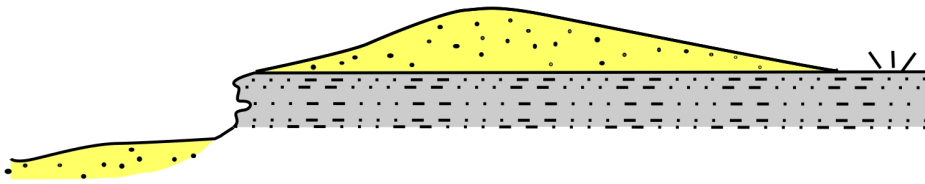
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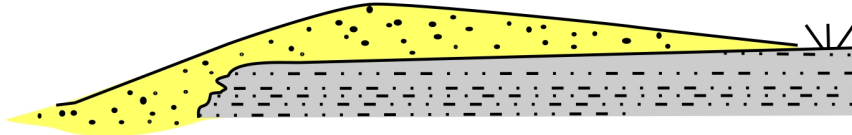
Washover fan

Marsh

Tidal flat

Marsh

Fluvial inlet

Tidal flat

Marsh

Flood tide delta

Tidal inlet

Ebb tide delta

Dunes

Beach

Shoreface

Bedrock

**Bottom diagram labels:**

Rocky headland

Lagoon

Rocky outcrop

Ephemeral inlet

Rocky outcrop

Low dunes/overwash

Washover fan

Marsh

Tidal flat

Flood tide delta

Tidal inlet

Ebb tide delta

Marsh

Fluvial inlet

Tidal flat

Marsh

Rocky outcrop

Shoreface

Bedrock

High dune/no washover

To landward →

Outer Banks (Low gradient, sediment)

Patos Lagoa (Low gradient, sediment)

Lake St Lucia (High gradient, bedrock)

The Algarve (High gradient, bedrock)

Frisian Islands (Low gradient, sediment)

Elevation

0    50 km

Barrier complex

Barrier crest

Back-barrier beach

Barrier shore

Back-barrier

MSL

Shoreface

Bedrock substrate

Barrier/Barrier Island

Washover

Back-barrier inlet/lagoon

Legend:
- Sand
- Gravel
- Mud
- Mixed

(A) Seaward — Landward

MSL 2

MSL 2

New shoreline

Complete reworking of barrier deposits offshore

Barrier retreat through rollover

(B) Seaward — Landward

MSL 2

MSL 1

Complete reworking

Bedrock substrate

Shoreface

(C) Seaward — Landward

MSL 2

MSL 1

New shoreline

Back-barrier beach and inlet/laggon deposits preserved offshore

Barrier retreat through overstepping

(D) Seaward — Landward

Aggradation

Aggradation

Progradation

Bedrock substrate

A

B

C

Static

D

E

(A)

Recent
progradation

Sediment transport

(B)

Erosion
Cell 1
Deposition
E
D
Cell 1

(C)

Breach
D  D
D
E  E
E
D
E
D
Cell 1
Cell 2
Cell
3
Cell 4

........ Old beach
ridge

——— New beach
ridge

– – – Cell
divide

——→ Transport
direction

D  Deposition

E  Erosion

A — 500 m

Time 1

A

Washover

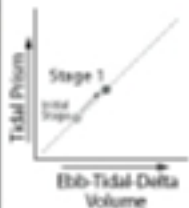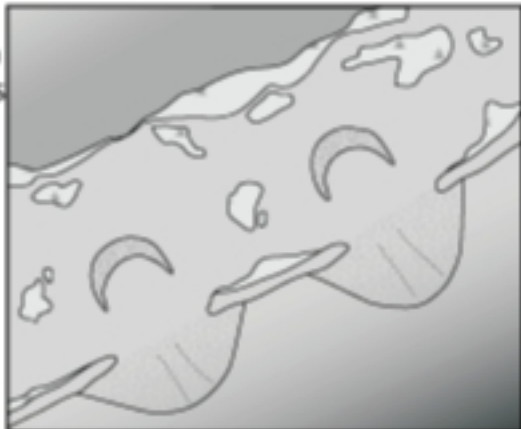Upland

Dune

Inlet

B

Washover

Dune

Dune

Estuary

Inlet

C

Beach

Time 2

Washover

Upland

Dune

Washover

Dune

Dune

500 m

04/1994     Image U.

11/2006     Image U.S. Ge

06/2011     Image © 2018 Commo
Image USDA Farm
Image U.S. Geol

10/2013
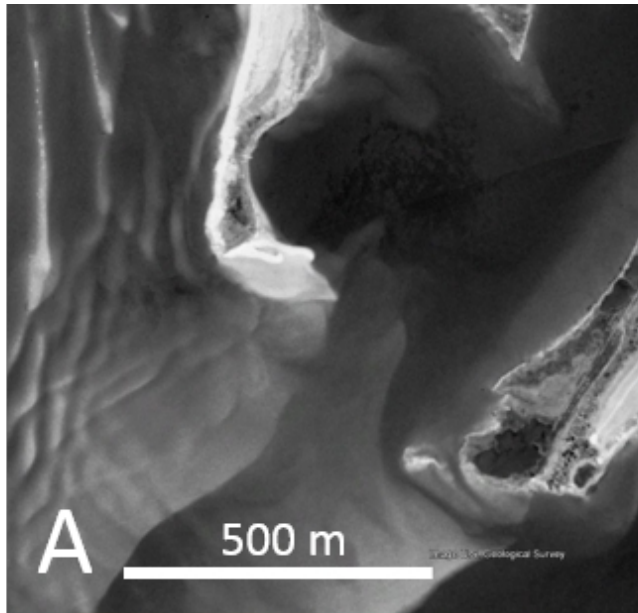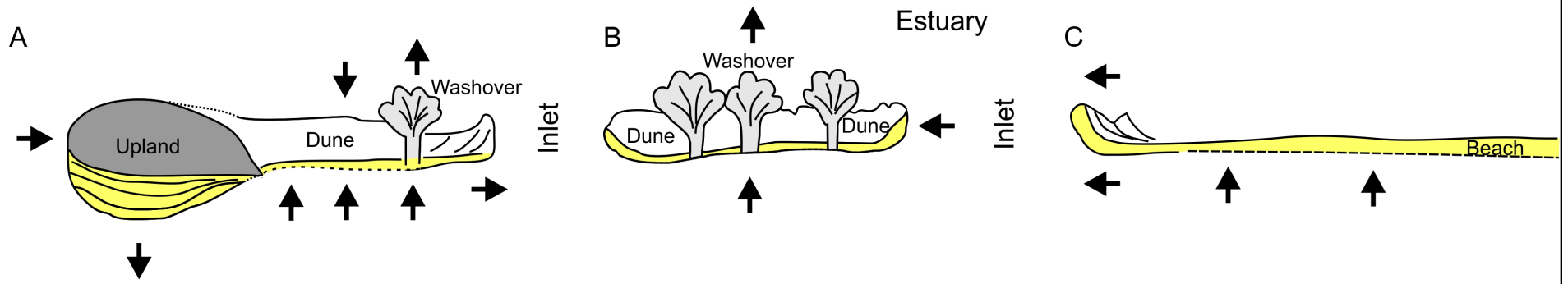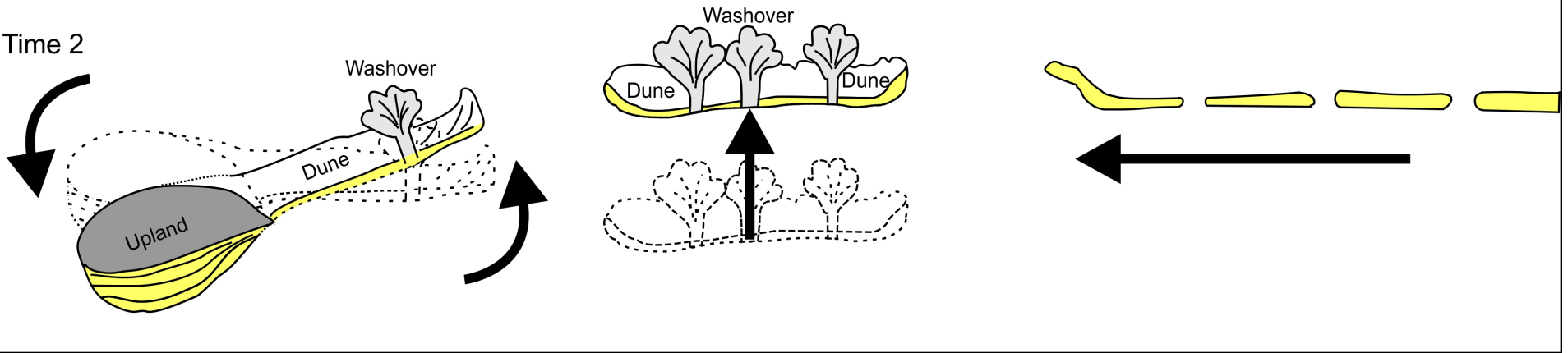
Initial Condition:
**Stable Barrier**

Tidal Prism

Initial Stage

Ebb-Tidal-Delta Volume
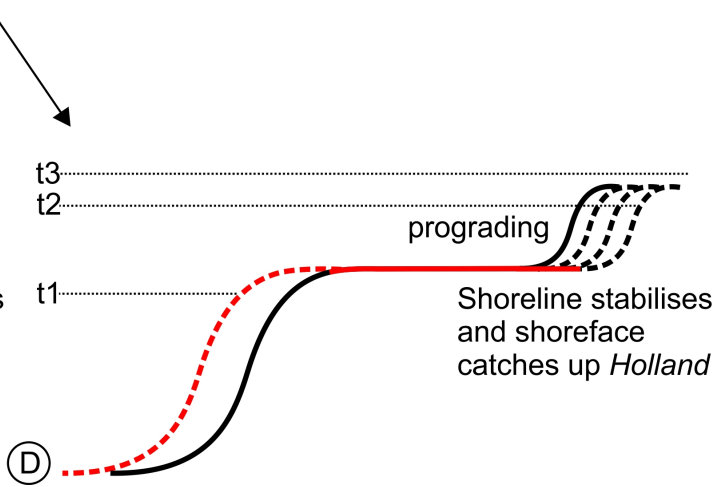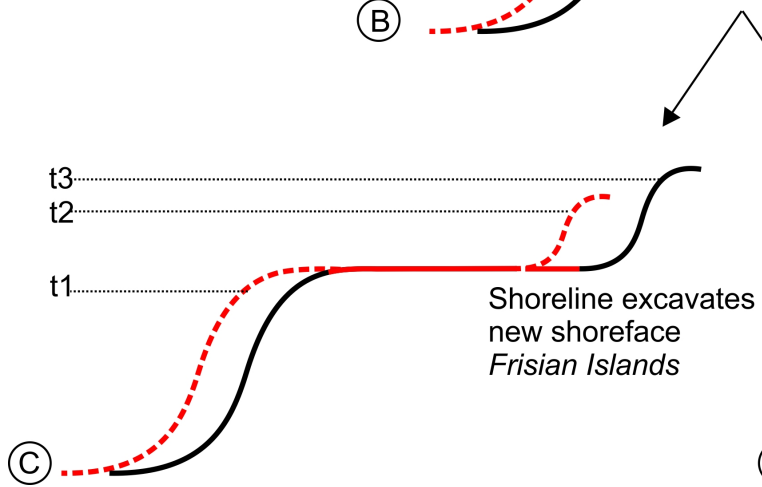
Stage 1:
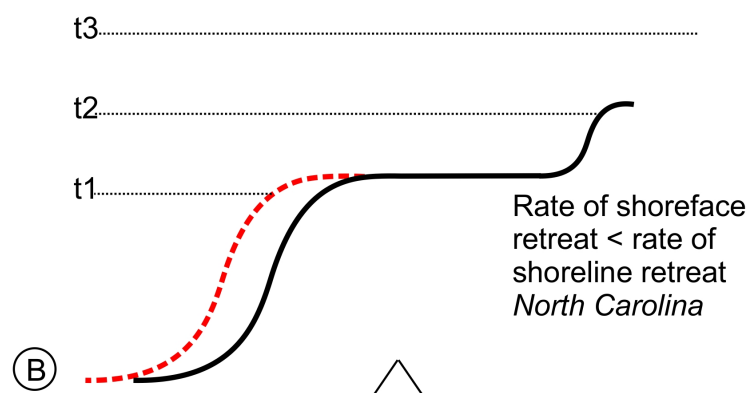**Marsh Decline**

Tidal Prism

Stage 1

Initial Stage
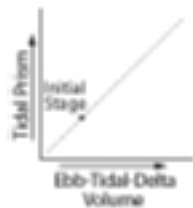
Ebb-Tidal-Delta Volume

Stage 2:
**Fringing Marsh & Marsh Islands**

Tidal Prism

Stage 2

Stage 1

Initial Stage

Ebb-Tidal-Delta Volume
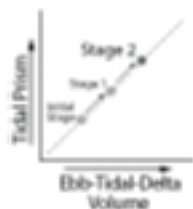
Stage 3:
**Runaway Transgression**

Tidal Prism

Stage 3

Stage 2

Stage 1

Initial Stage

Ebb-Tidal-Delta Volume

**A** — Rate of shoreface retreat = rate of shoreline retreat *Lousiana*

**B** — Rate of shoreface retreat < rate of shoreline retreat *North Carolina*

**C** — Shoreline excavates new shoreface *Frisian Islands*

**D** — Shoreline stabilises and shoreface catches up *Holland*; prograding

**a)**

Estuary ←——————→ Barrier ←——→ Shoreface ←————————————→

Inner-shelf ←————————————————————————————→

equilibrium profile

Substrate

**b)**

Backbarrier (bay & marsh) ←————————————————→ Barrier ←——→ Shoreface ←————————————→

Marsh

Bay

Substrate

**c)**

Mainland ←——→ Backbarrier ←——→ Barrier ←——→ Shoreface ←——→ Shelf ←————————————————→

reworking zone

washover deposition

tidal deposition

no deposition

deposition curve coarse sediment

deposition curve fine sediment

erosion

accretion

# Input

**Mesoscale dynamic drivers**

- storms,
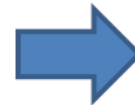- sea-level,
- cumulative microscale processes

**Sediment supply**
(+ve / -ve)

# Receiving system parameters (Geological inheritance)

Size/tidal prism
Barrier volume
Barrier height
Barrier sediment texture
Lagoon size (width/depth)
Lagoon sedimentation rates
Basement slope
Basement topography
Basement erodibility
Drift/swash-aligned
Shelf/shoreface morphology

# Barrier response

- Rollover
- Overstepping
- Erosion
- Breakdown
- Elongation
- Inlet open/closure
- Aggradation/progradation

**Orientation**

Shelf width

**Basement characteristics**

Slope

Irregularity

Erodibility

Barrier orientation

*Planform*

*Drift/swash alignment*

Lagoon orientation and dimensions

*Inlet configuration*

**Shoreface morphology**

**Sediment supply**

Barrier volume

*Stability Inertia*

Barrier grain size

Elevation of barrier

**Lithification**