

Mechanism for retreating barriers to autogenically form periodic deposits on continental shelves

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ABSTRACT

Relict barrier deposits preserved on the shelf seabed from barrier transgression are common features of passive, sandy margins, with multiple deposits occasionally found evenly spaced several to tens of kilometers apart. The formation of these deposits has typically been ascribed to allogenic overstepping processes, most commonly to episodes of rapid sea-level rise, although changes in topography or external sediment supply have also been invoked. Here, we present a mechanism whereby autogenic feedbacks between shoreface dynamics and the landward overwash of sediments can form regularly spaced shelf deposits even with constantly rising sea level. A simple morphodynamic model of barrier transgression exhibits a mode of periodic retreat whereby alternating episodes of translation and aggradation arise from internal dynamics, generating low-relief cross-shore deposits of barrier sediment with kilometer-scale spacing that increases for more gradual shelf slopes. Modeled barriers develop autogenic partial overstepping on shelf slopes with gradients between 1 and 3 m/km and for rates of sea-level rise between 1 and 18 mm/yr. Deposits produced by the model correlate with field observations of overstepped barriers from around the world, sharing an inverse relationship between shelf slope and spacing (wavelength). This result suggests that discrete remnant barrier deposits may not be exclusively indicative of changes in external forcing and that currently stable barrier islands may be susceptible to rapid behavioral transitions.

INTRODUCTION

During marine transgression, landward-migrating barrier islands occasionally produce remnant deposits of shoreface/back-barrier sediments. These sedimentary deposits are typically thought to record changes in allogenic forcing, such as variations in the rate of sea-level rise or sediment supply (Rampino and Sanders, 1980; Mellett et al., 2012; De Falco et al., 2015). Remnant barrier deposits also provide a window into the past response of transgressive coastal systems to the historically unprecedented rates of sea-level rise projected for the coming centuries (Donoghue, 2011; Cooper et al., 2016). This past response informs future economic and social risks, as human utilization of developed barrier systems typically does not consider the multidecadal- to century-scale processes driving their evolution (McNamara and Lazarus, 2018).

Commonly, it is assumed that barrier islands migrate landward exclusively as a function of external forcing (Swift, 1975), a paradigm that ignores potential complexities that can arise from internal dynamics. In other sedimentary systems, recent research has emphasized the role of autogenic behaviors, where internal processes drive changes in deposition (Hajek and Straub, 2017). Such autogenic behaviors are common in coastal marine systems, including deltas (Li et al., 2016; Kim et al., 2014) and sand spits (Ashton et al., 2016). Landward-migrating barriers are no exception, and internally driven periodic retreat—described as alternating migration and aggradation—has been modeled using a simple morphodynamic framework (Lorenzo-Trueba and Ashton, 2014).

Here, we examined how episodic barrier retreat can occur, where autogenic abandonment of the lower shoreface produces a

cyclically repeating pattern of deposition and erosion on the shelf seabed. To understand the controls on shelf deposit spacing (wavelength) and volume, we used a simple numerical model to quantify the rates of sea-level rise and shelf slopes amenable to periodic barrier retreat and compared modeled seabed patterns to morphologically similar features observed at field sites. Ultimately, we sought to determine if periodic retreat could occur commonly on passive margins, elucidating previously unknown risks to modern barriers.

BACKGROUND

Remnant cross-shore depositional and erosional surfaces are observed on passive margins around the world (Table 1; Item DR1 in the GSA Data Repository¹). The spacing of such deposits is variable, but it typically scales in kilometers in the cross-shore direction, while thickness is on the order of several meters (Fig. 1). Formation of these deposits has been associated with former barriers that have been completely or partly drowned—overstepped—by episodes of rapid sea-level rise (e.g., Mellett et al., 2012). For example, Locker et al. (1996) correlated closely spaced relict shoreline structures on the South Florida shelf with high-magnitude, century-scale fluctuations in rate of sea-level rise during late Pleistocene to early Holocene glacial meltwater pulses. The upper surfaces of deposits may also be reworked into submarine dunes or sand waves due to ongoing or previous alteration by waves and currents (Locker et al., 2003).

Cattaneo and Steel (2003) suggested that shelf slope may play a critical role in the formation of remnant deposits, particularly as low-gradient shelves require only small changes in sea level to cause relatively large horizontal barrier

¹GSA Data Repository item 2019088, Item DR1 (field site profiles), Items DR2–DR4 (animations of barrier periodic retreat on 1 m/km slope, 2 m/km slope, and 3 m/km slope), and Item DR5 (model sensitivity to input parameters), is available online at <http://www.geosociety.org/datarepository/2019/>, or on request from editing@geosociety.org.

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TABLE 1. FIELD SITES

Location	Number of oscillations	Wavelength, λ (km)	Estimated volume (m ³ /m)	Shelf slope (m/km)	Sea-level rise rate (mm/yr)	Time frame (k.y.)
Long Island ¹	1	5	<1800–3000	2	≤5	7–8
Sardinia ²	3	0.3	200–10,000	5–7	10–15	7.5–9.5
Florida ³	1–2	6–11	<3000–1,2000	1	~3	3–8
Hastings ⁴	2	2	2700–18,000	3	~0.3–3.6	8.3–9.5
New Jersey ⁵	2	8–17	12,000–72,000	1	~14	11.4–12.8
S. Africa ⁶	≥4	0.01–1	850–2975	≥5	~2.9	5.5–11.7

Note: Locations: 1—Rampino and Sanders (1980); 2—De Falco et al. (2015); 3—Locker et al. (2003); 4—Mellett et al. (2012); 5—Nordfjord et al. (2009); 6—Pretorius et al. (2016).

movement. This could lead to deposits becoming thinner and more widely spaced. While Cataneo and Steel did not specifically describe periodic deposits, Locker et al. (2003) noted that the thickness of regularly spaced Holocene seabed deposits across the West Florida shelf is inversely proportional to shelf gradient. Other sets of relatively regularly spaced remnant barrier deposits have been identified at locations along the coasts of North America, Europe, and Africa (Table 1; Fig. 1).

MORPHODYNAMIC MODEL

Our cross-shore morphodynamic model of barrier island evolution produces periodic retreat under constant forcing from shelf slope and rate of sea-level rise, expressed as a cyclical alternation between episodes of migration and aggradation. These cycles generate regularly spaced remnant deposits that appear similar to deposits observed in nature. Developed using a reduced complexity framework, the model focuses on feedbacks among sea-level rise, shoreface dynamics, and overwash during

barrier transgression based upon a simplified barrier geometry that can be described by the barrier height above sea level and three moving boundaries: the shoreface toe, the ocean shoreline, and the back-barrier shoreline (Lorenzo-Trueba and Ashton, 2014). Overwash translates the barrier shorelines landward with sea-level rise, and shoreface dynamics move both the shoreface toe and shoreline as the shoreface dynamically adjusts toward a steady-state shape (see Appendix for model inputs). Additionally, the vertical position of the shoreface toe is constrained to the so-called shoreface “depth of closure,” a fixed elevation below sea level where sediment exchange between the shoreface and the shelf is assumed to be negligible (Ortiz and Ashton, 2016).

In addition to periodic retreat, the model also captures drowning and constant rollover behaviors (Lorenzo-Trueba and Ashton, 2014). In constant rollover, fluxes of sediment at the shoreface and overwash fluxes are balanced such that the barrier maintains its shape, migrating at a constant rate equal to the rate of sea-level

rise over the shelf slope. Drowning occurs in two different manners, with the barrier losing either its entire height or width. This behavior could hypothetically produce remnant barrier deposits through complete overstepping, but for this study, we focused on deposits that appear relatively evenly spaced and/or have low relief, suggesting partial overstepping from deposition of the lower shoreface.

Periodicity arises in the model framework specifically from a temporal lag between shoreface dynamics and overwash, whereby the barrier oscillates around a dynamic equilibrium state in which all three moving boundaries would retreat parallel to the trajectory of the shelf itself (Items DR2–DR4 in the Data Repository). In a cycle beginning with a migratory phase, overwash initially outpaces fluxes of sediment at the shoreface, resulting in barrier thinning as the island shorelines retreat at a faster rate than the shoreface toe (Fig. 2A). However, fluxes of sediment from the lower shoreface to the barrier grow as the shoreface flattens and the toe excavates or ravines the shelf. Eventually, the rapidly migrating barrier experiences a decrease in back-barrier accommodation as it moves into shallower water, starting to slow and widen (Fig. 2B). When the barrier exceeds a critical width, overwash is no longer able to reach the back-barrier lagoon, and the barrier undergoes aggradation (Fig. 2C). For a relatively short period of time, sediment continues to move onshore, resulting in additional widening. Once the shoreface has responded, however, the barrier shoreline slowly erodes and steepens (Fig. 2D). The majority of a periodic cycle is spent in this aggradational phase, with sediment moving from the shoreline to the shoreface toe. Finally, increasing sea level and gradual shoreline erosion thin the barrier so that overwash can again reach the back-barrier lagoon, reinitiating the periodic cycle. Immediately following aggradation, a portion of the barrier below the elevation of the shoreface toe becomes stranded on the shelf as an isolated body, similar to the remnant deposits observed in natural systems (Fig. 1; Item DR1). We note that the mass of the barrier in our model is conserved during periodic retreat, such that the cross-sectional volume of deposition is compensated by corresponding erosion of the seabed during migration, reflecting an oscillation around dynamic equilibrium.

RESULTS

The modeled wavelengths of remnant deposits produced by periodic retreat are inversely related to shelf slope, decreasing from a maximum of ~15 km at 1–3 m/km shelf slopes to approaching the subkilometer scale at shelf slopes greater than 6 m/km (Fig. 3). This inverse trend is also apparent for field sites, with measured wavelengths decaying rapidly with increasing slope. Although the number of field

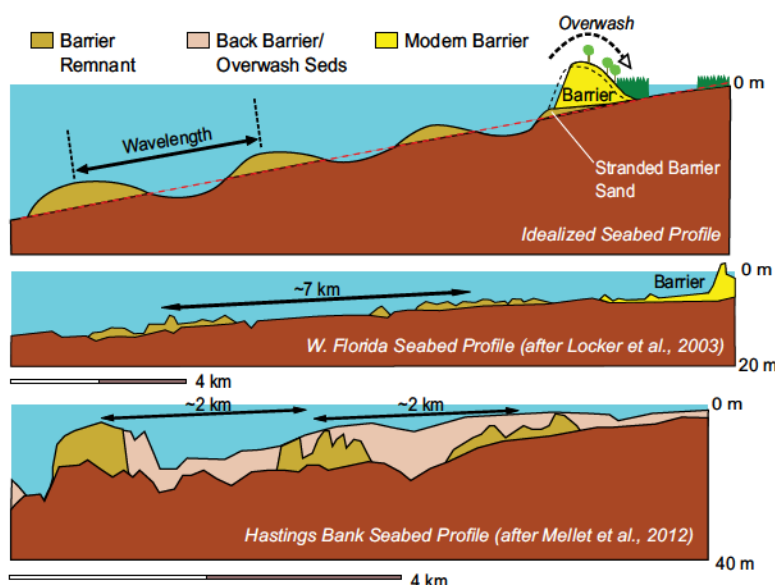


Figure 1. Top Panel: Idealized transgressive barrier sequence with alternating remnant sand bodies and erosional ravinement surfaces. Middle Panel: West-to-east profile through Sand Key, West Florida, after Locker et al. (2003). Bottom Panel: South-to-north profile of Hastings Bank, after Mellett et al. (2012). Additional field site profiles are included in Item DR1 (see text footnote 1).

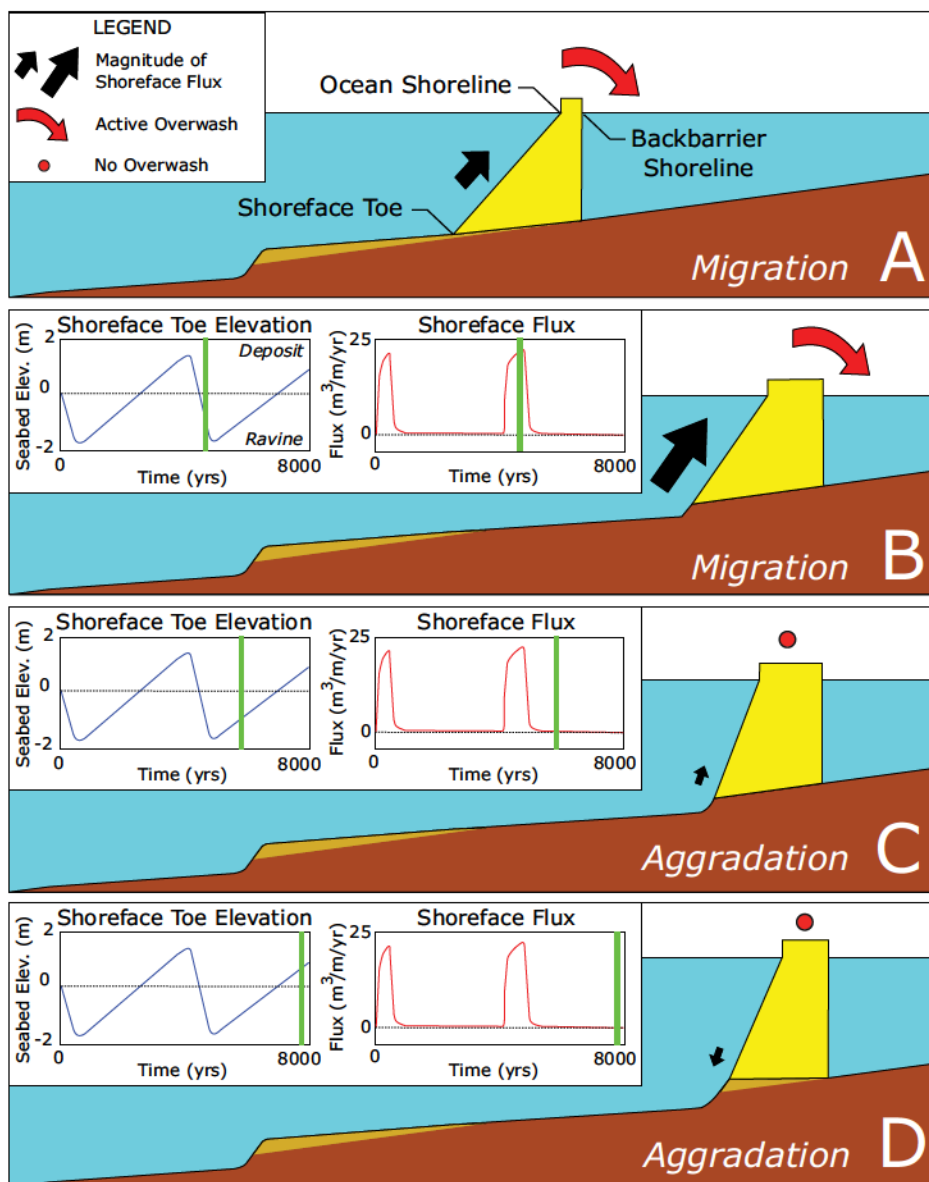


Figure 2. Model output depicting cycle of periodic retreat. Remnant deposit is left on seabed as barrier migrates (A,B) following a previous aggradational episode, culminating in erosion of shelf and return to aggradation (C,D). Size of black arrow indicates magnitude of fluxes at shoreface. Red arrow indicates active migration through overwash, while red circle indicates aggradation (no overwash). Inset elevation of shoreface toe is relative to shelf seabed.

sites is small, and in some cases only a few oscillations can be measured, the general agreement with the model trend strongly suggests periodic deposition follows the paradigm of deposit spacing described by Cattaneo and Steel (2003) and observed by Locker et al. (2003).

Similar to the inverse relationship between wavelength and slope, the greatest cross-sectional volumes of remnant deposits occur on shelf slopes of 1–3 m/km and quickly decrease at slopes of 5+ m/km, suggesting that shallowly to moderately sloping shelves provide the ideal conditions for producing periodic deposits (Fig. 3). Significant volumes are modeled at rates of sea-level rise up to 18 mm/yr for slopes approaching 3 m/km. Beyond this rate, and at

higher slopes, constant rollover and drowning dominate the barrier behavioral response, resulting in negligible deposition, or conversely, complete overstepping.

DISCUSSION

Although we employed a simple morphological model, it captures patterns of deposition found on shelf seabeds around the world. In particular, modeled deposit wavelengths and volumes compare similarly with the dimensions of seabed features apparent at gently sloping shelf sites, including Long Island, Florida, and New Jersey (Table 1). This apparent match between model results and field observations suggests that internally driven

periodicity plausibly explains the behavior of a variety of transgressional barriers throughout the Holocene.

However, while the wavelengths observed in nature for steeper shelves compare favorably with the model, deposit volume is inconsistent, particularly for South Africa and Sardinia. Observations for deposits on slopes in excess of 4 m/km are up to two orders of magnitude larger than predicted by our model, which constrains volumes to ~500 m³/m or less. The most likely explanation is that volume accumulation is subject to additional processes that are not accounted for in the current framework, including variable sedimentology.

Our investigation did not explore all the conditions where periodicity is possible, but as autogenic influence is demonstrable with up to 18 mm/yr of sea-level rise, we suggest that internal dynamics are a key driver of barrier evolution in nature. Consequently, periodic retreat behavior likely poses a previously unknown risk for modern barriers. As the aggradational phase accounts for the longest portion of the periodic retreat cycle, barriers thought to be stable could undergo abrupt changes in behavioral state, reverting to rapid migration.

Fundamentally, our results demonstrate a novel retreat behavior that offers a nonexclusive alternative to current interpretation of relict barrier deposits. While some repetitive deposits can probably be accounted for by modulation of allogenic forcing (e.g., Locker et al., 1996), we show that periodicity can arise readily from internal barrier dynamics. Future work with this model framework could also incorporate variable stratigraphy and back-barrier processes to explore the structure and variety of deposits that can be generated by internal dynamics. For example, Forbes et al. (1991) described a gravel barrier in Atlantic Canada in which the lower and upper portions of the barrier superstructure became separated, partly due to rapid sea-level rise and a reduction in sediment supply. The upper portion of the barrier, owing to its reduced volume, migrated rapidly landward across a sand/mud back-barrier platform, while the lower portion remained stranded offshore. In the context of periodic deposition, a comparable outcome could hypothetically occur during the transition from aggradation to migration, conceivably producing a deposit similar to Long Island, where back-barrier sediments are extensively preserved in the landward direction (Rampino and Sanders, 1980).

CONCLUSIONS

By modeling remnant deposits produced by internally driven periodic retreat, we demonstrated an inverse relationship between shelf gradient and deposit spacing, which is also observed at field sites. Additionally, the volumes of individual deposits at field sites with shelf

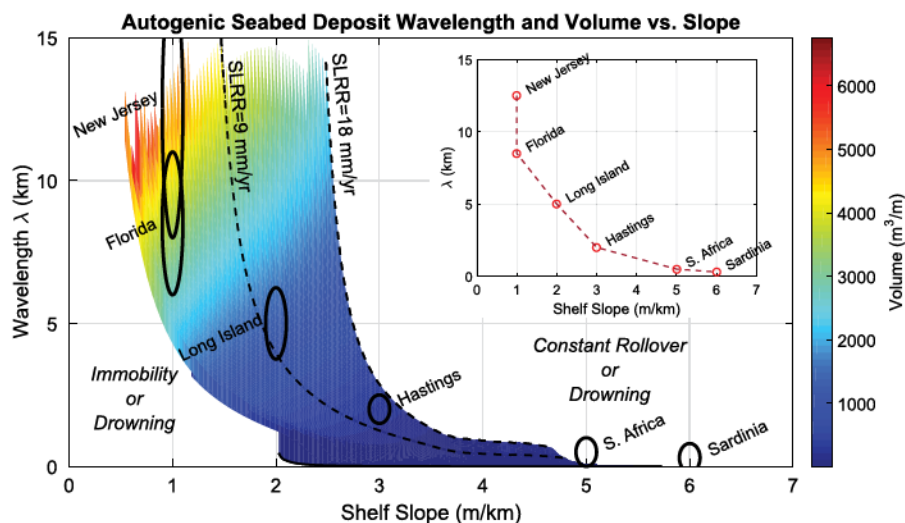


Figure 3. Modeled remnant seabed deposit wavelength (spacing) and volume produced by barrier undergoing periodic retreat overlain with field site interpretations. Results are shown for constant sea-level rise rates (SLRRs) from 0.01 to 18 mm/yr and a run time of 20 k.y. (see Appendix for input parameters; see Item DR5 [see footnote 1] for additional input sensitivity analysis).

slopes of 1–3 m/km match those produced by the model, implying that autogenic periodicity occurring under constant external forcing plausibly explains the behavior of some Holocene

barriers. Projecting into the future, this suggests that the long-term retreat of modern barriers may deviate significantly from current conceptual models, posing unknown risks.

APPENDIX

APPENDIX TABLE 1. MODEL INPUT PARAMETERS

Parameter	Symbol	Inputs (Figure 2)	Inputs (Figure 3)
Slope (m/km)	β	1	0–6*
Shoreface toe depth (m)	D_t	15	15
Equilibrium width (m)	W_e	800	800
Equilibrium height (m)	H_e	2	2
Equilibrium shoreface slope	α_e	0.02	0.02
Maximum overwash (m³/m/yr)	$Q_{OW,max}$	100	100
Maximum deficit volume (m³/m/yr)	$V_{d,max}$	$0.5 \cdot H_e \cdot W_e$	$0.5 \cdot H_e \cdot W_e$
Shoreface response (m³/m/yr)	K	2000	2000
Sea-level rise rate (mm/yr)	z	3	0.01–18*

*Denotes a range of tested values.

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