Geometric Constraints on Long-Term Barrier Migration: From Simple to Surprising

A. Brad Murray and Laura J. Moore

Abstract Considerations of mass conservation, sediment budgets, and geometry lead to insights regarding how barriers respond to sea-level rise. We begin with relatively simple insights, which facilitate more surprising conclusions as more complicated cases are considered. The simplest case assumes: (1) a constant depth beyond which sediment transport is negligible; (2) a lack of gradients in net long-term alongshore sediment flux that add or remove sediment; (3) shoreface erosion into a substrate that produces sediment which is all sufficiently coarse to remain in the nearshore system; and (4) a spatially uniform slope across which a barrier migrates (i.e., the substrate slope). In this case, the migration trajectory for the barrier shorelines—the ratio between the rates of sea-level rise and landward transgression—parallels the average slope of the barrier and shoreface profile (the surface over which active sediment transport occurs). In the next simplest case, substrates composed partly of fine sediment (which is lost to the nearshore system when the substrate is eroded) cause a reduction of the slope of the migration trajectory, because more landward migration is required for each increment of sea-level rise in this case. Gradients in net alongshore sediment transport also cause adjustments to the migration trajectory (although the adjustment depends on the rate of relative sea-level rise). Analysis shows that even with a gradient in net alongshore sediment transport, in the long term, barrier geometry adjusts until the trajectory parallels the (spatially uniform) slope of the substrate. When a barrier is eroding into material that was deposited in back-barrier bay or marsh environments, surprising results come from considerations of geometry and conservation of mass. In this case, the effects of substrate slope on barrier migration trajectory become indirect and time-lagged. In addition, depending on the relative compositions of marsh and bay deposits, feedbacks tend to either produce a stable bay/marsh width and barrier geometry, or a runaway widening or narrowing of the back-barrier environment.

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When substrate slope (or alongshore-transport gradients or substrate composition) varies as the barrier migrates landward, numerical investigation is required to determine how the migration trajectory varies with time.

Keywords Generalized Bruun Rule • Barrier migration • Substrate slope • Shoreface depth • Equilibrium profile • Overwash • Geometry • Barrier evolution • Shoreline erosion • Numerical modeling • Analytical modeling • Conservation of mass • Barrier response to sea-level rise • Barrier migration trajectory • Back-barrier depth

1 Introduction

We focus in this chapter on narrow barriers that are migrating landward, and the response of these "transgressive" barriers to sea-level rise. We take a long-term view, addressing timescales that are long compared to both the return period of strong storms (i.e., decades to centuries), and possible shifts between alternate "high" and "low" stable states triggered by stochastic storm sequences (Duran Vinent and Moore 2015; Moore et al. this volume). The resulting analyses, arising from the constraints imposed by geometry and the conservation of mass, apply generically, to a range of barrier types, including those composed of sand and those composed of gravel (which we refer to collectively as "coarse" sediment).

Although barriers responding to sea-level rise move vertically as well as horizontally, first consider the horizontal component of barrier migration separately (which could occur in nature where relative sea level is steady, driven by an ongoing loss of sediment). Prolonged shoreline erosion leads to horizontal barrier migration: The shoreline moves landward where storm-driven overwash and/or gradients in wave-driven alongshore sediment transport remove sediment from the beach and shallow seabed (in and near the surf zone; for background information, please see Preface of this volume). When a barrier becomes sufficiently narrow, overwash deposition can extend to the landward edge of the barrier, tending to maintain a minimum barrier width related to the cross-shore extent of the largest overwash events (Leatherman 1979). Thus, in the long term, the open-ocean shoreline and the landward bay-facing shoreline (i.e., landward edge) of a migrating barrier will tend to move landward at the same rate.

Understanding the vertical component of barrier migration in response to sea-level rise requires consideration of sediment transport during storms. Although extreme storms in which water levels "inundate" a barrier can remove sediment (Sallenger 2000; Sallenger et al. 2007), less extreme storm events, which produce "overwash," deposit sediment on the barrier. On balance, in the long term, transgressive barriers can gain elevation as the result of these storm effects. (In addition, sandy barriers can gain elevation through eolian dune growth between overwash events, and the sediment making up the dunes is then redistributed during overwash events; e.g., Donnelly et al. 2006.) In the absence of relative sea-level rise (RSLR), the elevation of a transgressive barrier will tend to approach a maximum, related to the maximum elevation to which storm waves can move sediment (tide level plus storm surge plus wave set up plus wave run up; Sallenger 2000; Stockdon et al. 2006). Although dune growth can add elevation, dunes are transient features (e.g., Houser et al. this volume; Moore et al. this volume).

If sea level is rising, the processes affecting barrier elevation change, but only slightly. Rising sea level tends to decrease barrier elevation relative to sea level, therefore increasing the frequency of overwash events and overwash deposition rates. Therefore, a negative feedback arises, in which the rate of overwash deposition increases as the RSLR increases. In the long term, this feedback tends to produce a steady state in which the elevation of the barrier increases at the same rate that sea level rises. In this case, relative to sea level (a moving frame of reference), barrier elevation remains constant, at approximately the maximum elevation to which storm waves can move sediment (much as would occur in the absence of RSLR).

For a transgressive barrier that is translating both horizontally and vertically, migration occurs along a slope equal to the ratio of the RSLR rate and the landward migration rate; both the shoreline and the landward edge of the barrier migrate along lines parallel to this slope (Fig. 1). Here, we will address what determines this migration "trajectory"—i.e., how much landward movement (including shoreline erosion) occurs for each increment of RSLR. In Sects. 2 and 3, we introduce background material and provide an intuitive explanation of a broadly applied framework (stemming originally from Bruun 1962) for analyzing how shoreline erosion relates to sea-level rise. Our analysis applies this framework to barrier migration trajectories (an exercise inspired originally by the results of the Shoreface Translation Model; Roy et al. 1994; Cowell et al. 1995). We start with the simplest set of assumptions in Sects. 2 and 3, to review how considerations of mass conservation and the tendency for barrier geometry to remain constant lead to basic insights about the factors that determine how barrier migration changes over time—including the tendency for the trajectory to approach a steady state (Roy et al. 1994; Wolinsky and Murray 2009; Moore et al. 2010). We then consider cases in which the simplifying assumptions are relaxed, leading to further insights, which become progressively more surprising as further complexities are considered. We sequentially introduce factors that influence barrier migration trajectory, and how it evolves over the long term, including: in Sect. 4, the composition of the "substrate" over which the barrier migrates; in Sect. 5, "external" losses or gains of sediment (e.g., from gradients in alongshore transport, or in some cases from onshore sediment flux from a shallow continental shelf; e.g., Cowell and Kinsela this volume); and, in Sect. 6, the cross-shore extent of back-barrier environments such as marshes or shallow bays, and the thickness and composition of the resulting deposits. In this contribution, we also present graphical illustrations of how trajectories evolve (as introduced by Moore et al. 2010), under the assumption that some or all of these factors remain constant. Finally, in Sect. 7, we introduce the need for numerical analyses to address barrier evolution in more complicated, realistic situations.

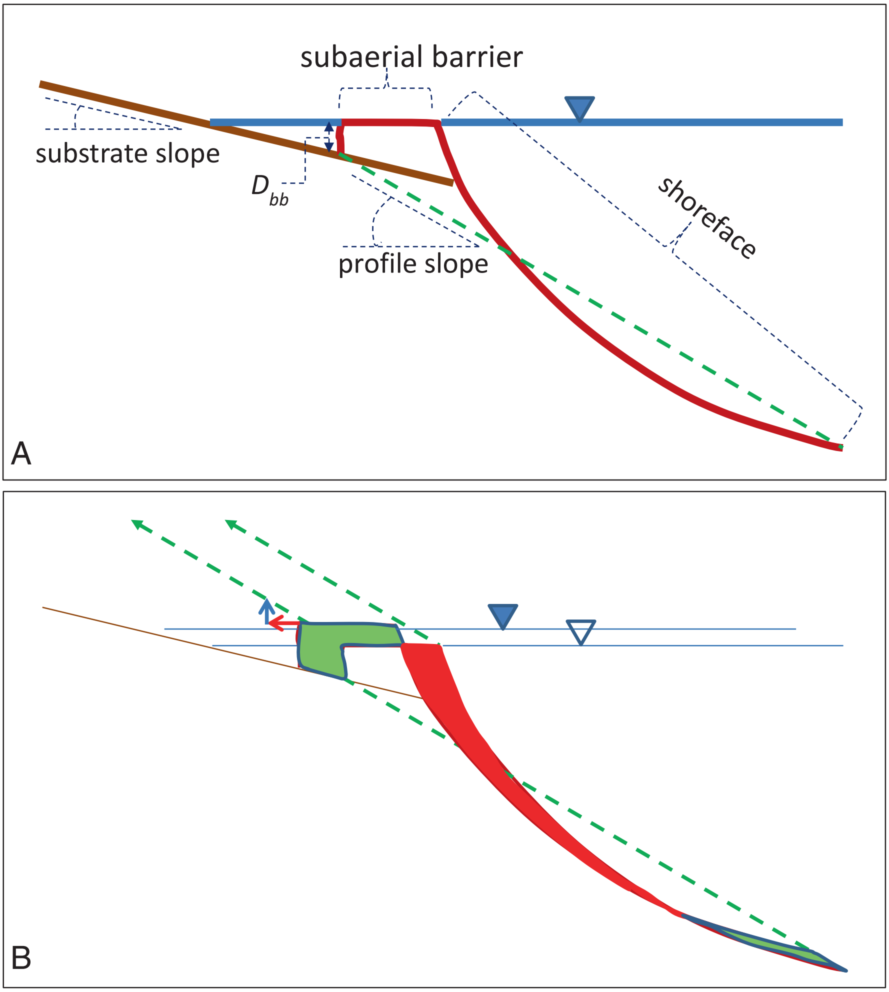

Fig. 1 A transgressive barrier, migrating upward and landward in response to relative sea level rise (RSLR). (**a**) Schematic diagram showing the subaerial barrier and shoreface extents, the substrate and average barrier profile slopes, and the back-barrier depth, D_{bb}. The green dotted line shows the average slope of the active barrier profile. Blue triangle indicates sea level. (**b**) Shows the profile at two different times, before and after the amount of RSLR indicated by the blue horizontal lines and triangles (open triangle indicates sea level at the earlier time). Red area indicates where sediment was made available through shoreface erosion, and the green area shows where deposition occurred. The red arrow shows the amount of horizontal translation—barrier retreat, *R*—while the solid blue arrow shows the amount of vertical translation, which together define the migration trajectory, along which points on the profile (e.g., the seaward and landward barrier shorelines and shoreface toe) migrate, as shown by the dotted green arrows. Note the vertical exaggeration in this (and subsequent) figures; the cross-shore scale is kilometers, while the vertical scale is tens of meters. (Graphical interpretation of the barrier migration trajectory after Moore et al. 2010)

2 Background

2.1 Cross-shore Shoreface-Barrier Profile

The visible, subaerial portion of a barrier is part of a larger system; it is intimately connected to the nearshore seabed. Wave processes tend, in the long term, to create a characteristic equilibrium cross-shore shoreface profile (extending down to the depth below which waves move little sediment, which is a fuzzy, time-dependent boundary; Preface, this volume; and e.g., Hallermeier 1981; Stive and de Vriend 1995; Ortiz and Ashton 2016). Considered in isolation, nearshore waves tend to sweep coarse sediment toward shore (e.g., Fredsøe and Deigaard 1992), creating a pile of sediment, with gentle slopes extending along the nearshore seabed (Fig. 1) upward to approximately the long-term limit of wave influence—i.e., the top of the barrier (excluding aeolian dune-building processes). The local slopes of the sediment surface tend to adjust, in the long term, to be sufficiently steep to prevent further net onshore sediment transport. These "equilibrium slopes" depend on the strength of wave influence locally (as well as the grain size of the sediment), so that the local equilibrium slopes tend to decrease as the depth increases with distance offshore (e.g., Dean 1977, 1991; Fredsøe and Deigaard 1992). Thus, the equilibrium shoreface profile composed of these equilibrium slopes tends to exhibit a concave-upward shape (Fig. 1). (This heuristic description of the shoreface profile neglects surf zone currents, and the storm-driven temporal fluctuations in the shape of the landward-most portions of the profile; e.g., Lee et al. 1988.)

The subaerial barrier, shaped by storm-driven overwash (and possibly aeolian processes), with a maximum elevation related to the height above sea level to which storm waves can reach, can be thought of as the top portion of the surface of active sediment transport. In what follows, the term "barrier profile" includes both the shoreface and subaerial barrier components of the equilibrium profile (except where otherwise specified). This barrier profile extends from the seaward toe of the shoreface (at the shoreface depth) to the long-term landward extent of overwash deposition (at the bay depth immediately behind the barrier, the back-barrier depth; Fig. 1a).

2.2 Landward Profile Translation and Sediment Excavation

Losses of sediment from the beach, dunes, and surf zone, either from storm-driven overwash or gradients in alongshore sediment transport, can drive prolonged shoreline erosion. This erosion tends to propagate across the entire shoreface, through reductions of the shoreface slopes, which allow waves to sweep sediment onshore (please see the Preface, this volume). Because the tendency for waves to sweep sand onshore extends to the toe of the shoreface over long timescales, the oceanward portion of the barrier profile (the shoreface, beach, and dunes) tends to move landward in unison with the shoreline. Assuming the storm/wave climate remains approximately constant, and the erosion is sufficiently gradual, the shape of the profile remains approximately constant (maintaining near equilibrium slopes). Each increment of landward translation of the beach, dunes, and shoreface, *R*, liberates a quantity of sediment (a volume of sediment per unit alongshore length, or an area in cross-shore profile; Fig. 2a). This quantity is equal to $R * H$ (Bruun 1962), where *H* is the height of the barrier profile (Fig. 2a). This relationship does not depend on the shape of the barrier profile. To understand the lack of dependence on shape, consider first the limiting case of a rectangular shoreface, for which the eroded area is clearly $R * H$ (Fig. 2a). If that area is sliced into thin horizontal slabs, those slabs can be slid horizontally by different amounts to reproduce the area between any shoreface shape and its landward-translated equivalent (Fig. 2b). In other words, as long as the shape remains constant over time, the eroded area = $R * H$. If the material underlying the shoreface—the "substrate"—isn't already mobile sediment, then as erosion exposes that material, physical, chemical, and biological processes tend to weather it into its component pieces (i.e., sand, silt, clay), converting it into transportable sediment. What the substrate is composed of affects the migration trajectory (as we discuss in Sect. 4), but for now we ignore this complication.

If erosion of the profile is associated with a migrating barrier, then some of the sediment made available by beach, dune, and shoreface erosion is used to move the barrier landward (Fig. 1b). Thus, the effective height, H_{eff}, of the barrier profile—the height of the part of the profile that contributes new sediment to the nearshore system as the barrier migrates—is the difference between back-barrier depth and shoreface depth (Fig. 2c, d).

2.3 Response to Sea-Level Rise: Qualitative Concept

RSLR induces horizontal and vertical shifts in the entire barrier profile through increases in the rate of overwash events and overwash deposition on the barrier (as well as the inlet-related processes that move sediment from the front to the back of a barrier). This removes sediment from the beach and upper shoreface, causing the shoreline and shoreface to translate landward (please see the Preface, this volume). Overwash deposition tends to raise the elevation of the barrier at a rate equal to the rate of RSLR (over timescales longer than the characteristic overwash return interval). In addition, the shoreface portion of the profile moves upward at that same rate (as the tendency for waves to sweep sediment toward shore tends to maintain an equilibrium profile). To understand this point, consider that the equilibrium slopes that define the shoreface profile are a function of depth relative to sea level. Therefore, starting at the shoreline and moving offshore, the sequence of equilibrium slopes are always the same—independent of the absolute elevation of sea level (relative to some datum). In the limit of high rates of RSLR, the lower parts of the shoreface may not adjust to changing sea level rapidly enough to keep up. Cowell and Kinsela (this volume) and Ashton and Lorenzo-Trueba (this volume) consider this case, although we neglect it in this chapter.

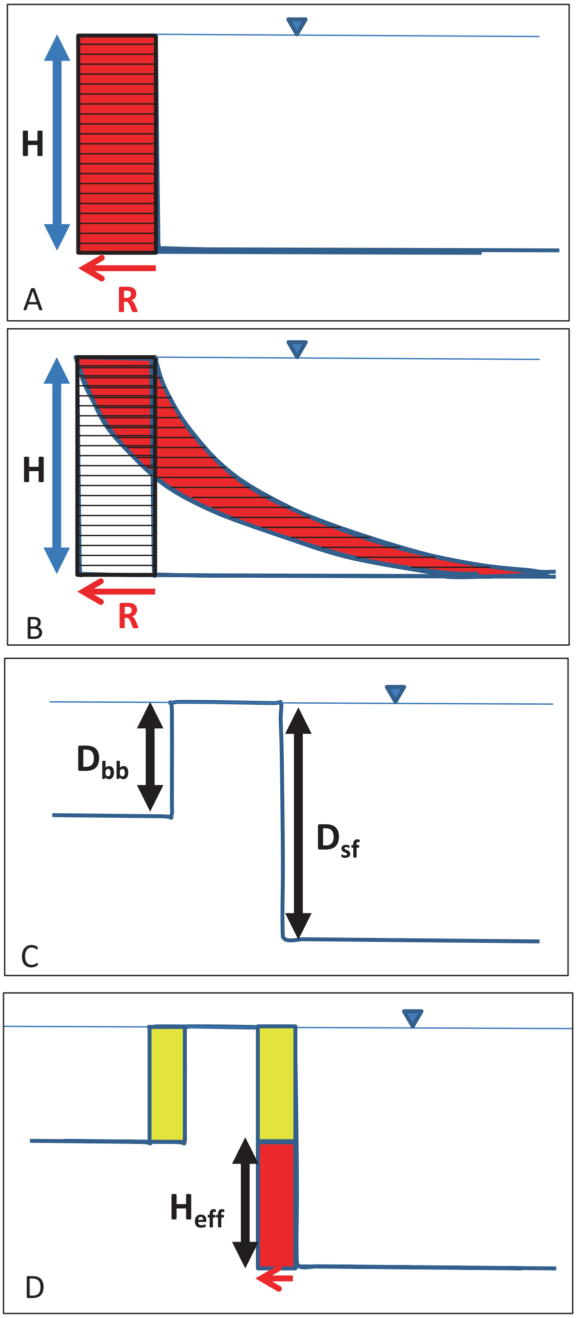

Fig. 2 Sediment produced by landward barrier translation. (**a**) For a hypothetical rectangular shoreface (e.g., the limiting case of a concave shoreface with very high concavity), the area (volume/unit alongshore distance) eroded equals $R * H$. (**b**) This eroded area is independent of the shape of the shoreface (concave shoreface profile shown here), as long as the shape remains constant; sliding the slabs composing the eroded area for the rectilinear profile horizontally by different amounts reproduces the eroded area for the concave profile. (**c**) A hypothetical rectilinear barrier profile, showing the shoreface and back-barrier depths, D_{sf} and D_{bb}. (**d**) Because area eroded above the elevation of (sea level—D_{bb}) equals the area deposited above (sea level—D_{bb}), the net sediment produced by landward translation equals $R * (D_{sf} - D_{bb})$, or $R * H_{eff}$, where H_{eff} is the effective height of the barrier profile ($D_{sf} - D_{bb}$)

In other words, relative to the reference point of the shoreline, which is moving upward and landward with RSLR, both the subaerial and subaqueous portions of the barrier profile will tend to retain a constant shape. (In one exception to this tendency to retain a constant shape, the depth of the water into which overwash is deposited at the landward edge of the barrier profile, D_{bb} (Fig. 2b) will tend to change as sea-level rises, as we discuss in the next section.) In the analytic/geometric framework we are assuming, we consider in the next three sections, how the distance that the barrier profile moves landward for a given amount of RSLR—which defines the migration trajectory—is determined by a balance between the amount of coarse sediment (sand and/or gravel) needed to raise the elevation of the barrier profile where deposition occurs (chiefly the subaerial portion of the profile) and the amount of coarse sediment available from erosion of the seaward portion of the barrier profile (with the possible addition of sources or sinks from outside the cross-shore profile, as discussed below).

3 Simplest Migration Scenario: Generalized Bruun Rule for Barriers, and Long-Term Consequences

3.1 Assumptions

The simplest scenario for barrier migration involves several assumptions: (1) the depth of the shoreface—the depth to which erosion occurs as the shoreface moves landward—remains constant (an assumption relaxed in Cowell and Kinsela this volume); (2) all sediment produced by shoreface erosion is sufficiently coarse to remain in the high-energy nearshore system (relaxed in Sect. 4); (3) sediment is conserved within the cross-shore profile, with no net sources or sinks from outside the profile (i.e., there are no gradients in net alongshore sediment transport, as in Sect. 5, or cross-shore fluxes from the continental shelf, as in Cowell and Kinsela, and Ashton and Lorenzo-Trueba this volume); (4) deposition in the back-barrier bay is negligible (relaxed in Sect. 6); and (5) the slope of the substrate over which the barrier progressively migrates is spatially uniform (relaxed in Sects. 6 and 7).

3.2 Generalized Bruun Rule for Barriers

To derive the ratio between an increment of RSLR(S) and the associated landward migration (R), we first consider the vertical and horizontal movements separately, in a sequence of thought experiments. As described in Sect. 2.2, if the barrier profile only shifts landward (by R), this produces an amount of sediment equal to $R * H_{\mathrm{eff}}$. Conversely, if the barrier profile is just elevated by an amount, S, this requires an amount of sediment equal to $S * L$, where L is the horizontal length of the profile

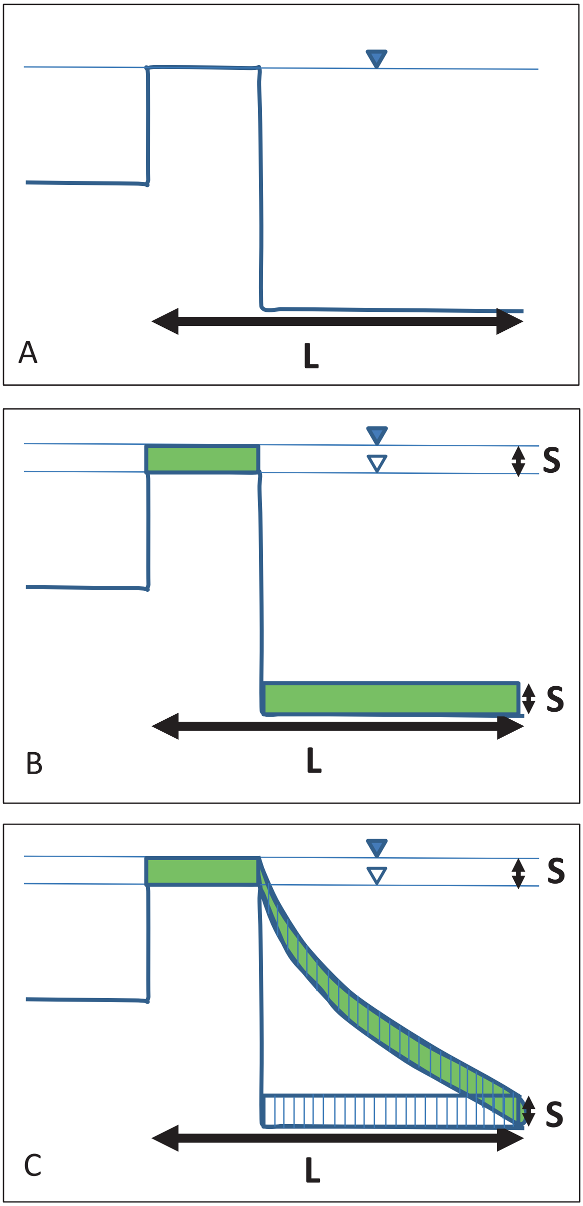

Fig. 3 Sediment required for vertical barrier translation. (**a**) The length of the profile, *L*, includes the lengths of the shoreface and the subaerial barrier. (**b**) Raising the profile requires *L* * *S*, where *S* is the amount of SLR (depicted by difference between the lines denoted by the blue triangles; the open triangle shows the earlier sea level). (**c**) This sediment area (volume/unit alongshore distance) is independent of profile shape, as long as the shape remains constant (see Fig. 2 caption)

(including subaerial and subaqueous portions; Fig. 3a, b). As in the case of the considerations of shoreface erosion in Sect. 2.2, this result is clear for a profile with a rectangular shoreface, but it also applies to profiles of any shape, as long as the shape remains constant; Fig. 3c. In addition, this analysis applies to a snapshot in time, during which H_{eff} and L can be considered constant. Over time, these variables can change, as we discuss in Sect. 3.2. Now, if the barrier profile is first shifted

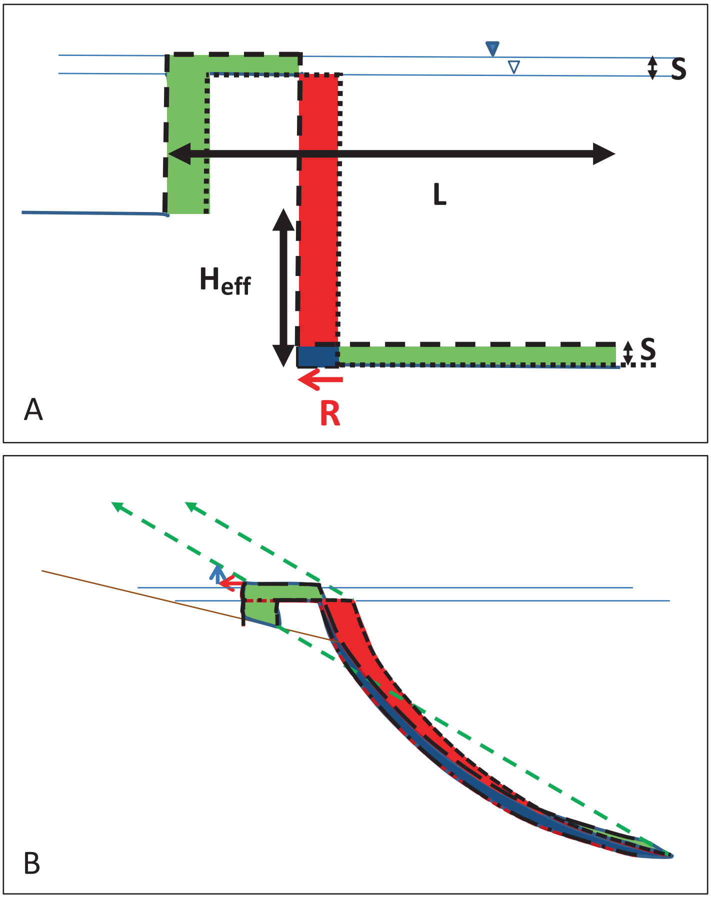

Fig. 4 Combining horizontal and vertical barrier translations, as a barrier responds to RSLR. (**a**) Neglecting sources/sinks of sediment from outside the cross-shore profile, the net area (volume/unit alongshore distance) of sediment eroded, shown in red, must equal the net area deposited, shown in green. The net area eroded equals ($R * H_{eff}$, minus the area of the blue rectangle in the corner), while the net area deposited equals ($L * S$ minus the area of the blue rectangle in the corner). Equating these quantities, the blue rectangle in the corner drops out, and therefore $R * H_{eff} = L * S$, or $S/R = H_{eff}/L$. (**b**) The same analysis applies to a less simplified geometry, although the blue area that does not contribute to the net eroded area or the net deposited area has a different shape

horizontally, and then the resulting sediment derived from shoreface erosion is used to raise the profile vertically, $R * H_{\text{eff}} = S * L$, or, rearranging:

$$R = S * \left(L / H_{\text{eff}} \right) \tag{1}$$

In this last thought experiment, we applied the horizontal and vertical components of the profile migration sequentially—but how might the answer (Eq. 1) be different for the more realistic case in which both horizontal and vertical components occur simultaneously? Figure 4a, which uses a schematic rectangular shoreface for clarity, shows that, *relative to the sequential-motion thought experiment*, there is an area not subjected to net erosion in the combined-motion thought experiment. The deficit in net erosion in the combined-motion thought experiment is indicated by the dark rectangle in the bottom corner of the shoreface in Fig. 4a. Similarly, relative to the sequential experiment, an area in the combined-motion experiment is not subjected to net deposition (the same rectangle in the bottom corner of the shoreface). However, the deficit in erosion (relative to the sequential-motion experiment) is equal to the deficit in deposition (relative to the sequential experiment). Thus, these deficits cancel out, leaving the result of the sequential-motion thought experiment—Eq. 1—intact. Figure 4b demonstrates graphically that this result also holds for a less-schematized profile geometry.

In Eq. 1, L/H_{eff} is the inverse of the average slope of the barrier profile. L is typically on the order of kilometers, H_{eff} is typically on the order of 10s of meters, and L/H_{eff} typically ranges from a few hundred to a thousand (e.g., Moore et al. 2010; Lorenzo-Trueba and Ashton 2014). Because L/H_{eff} is a large number, a small amount of RSLR and associated cross-shore sediment fluxes can cause a relatively large amount of barrier migration, including shoreline erosion.

Bruun (1962) originally derived an expression similar to Eq. 1, but applied it only to the shoreface—i.e., involving the average slope of the shoreface, rather than the entire barrier profile. The concepts of constant geometry and conservation of mass introduced by Bruun can be extended to include either beach-backing cliffs or overwash plains and barriers (e.g., Dean and Maumeyer 1983; Davidson-Arnott 2005; Wolinsky and Murray 2009; Rosati et al. 2013), which is more appropriate than the original Bruun Rule when considering timescales that are sufficiently long for cliff erosion or overwash to occur. Equation (1) is the generalization specific to barrier coasts (e.g., Wolinsky and Murray 2009).

3.3 Long-Term Consequences

Equation 1 defines the slope of the migration trajectory: $S/R = H_{eff}/L$ (Fig. 5a). However, this trajectory only applies to a snapshot in barrier evolution, because as the barrier migrates along the trajectory, H_{eff} will tend to change. To see how this occurs, first consider Fig. 5a, which illustrates that as the barrier profile migrates, the shoreface toe, the shoreline, and the subaerial landward edge of the barrier all migrate along parallel trajectories. However, if the slope of these trajectories is steeper than the slope of the (spatially uniform) substrate the barrier is migrating across, the depth of the water behind the barrier (D_{bb}) will increase over time, as Fig. 5b shows. This increase in the back-barrier depth decreases H_{eff}, which, in turn, leads to a shallowing of the average slope of the barrier profile. Thus, over time, the slope of the migration trajectory decreases (Fig. 5b)—and the trajectory slope must continue to decrease as long as it remains steeper than the substrate slope. As the

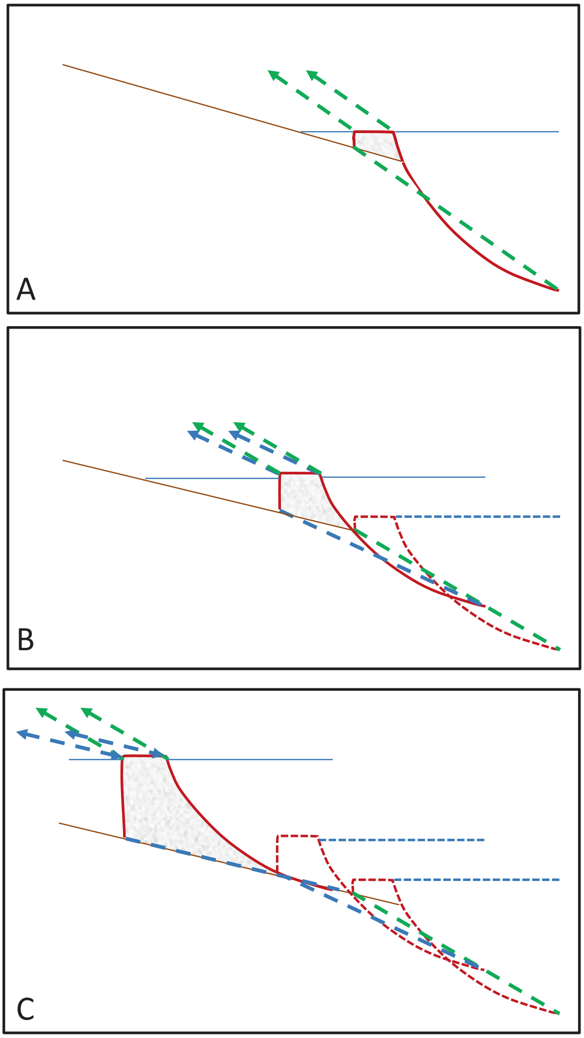

Fig. 5 Long-term adjustments to the barrier geometry—barrier volume, back-barrier depth, and average profile slope—as a barrier migrates across a constant-slope substrate. (**a**) The average profile slope (green dashed line) and barrier migration trajectory (shown for both the seaward and landward edges of the barrier; green dashed lines with arrows) parallel each other. Note that the slope of the migration trajectory is steeper than the slope of the substrate in this hypothetical initial geometry. (**b**) At a later time, the back-barrier depth has increased, which decreases the average profile slope (blue dashed line) and migration-trajectory slope (blue dashed lines with arrows). (**c**) Eventually, the migration-trajectory slope approaches the substrate slope, producing a steady state back-barrier depth and migration trajectory slope. (After Wolinsky and Murray 2009; Moore et al. 2010)

trajectory slope approaches the substrate slope, the rate of change of H_{eff}, and therefore the rate of change of the trajectory slope, decreases (holding RSLR rate constant). In this way, the trajectory slope asymptotically approaches the substrate slope (Fig. 5c) (Moore et al. 2010). (In this case, it is the slope of the substrate evaluated at the landward edge of the barrier that controls the evolution of the barrier migration trajectory. In contrast, in Sect. 6, where we consider back-barrier deposition and spatially varying substrate slope, both the substrate slope at the landward edge of back-barrier deposition and at the point of intersection with the shoreface control the barrier migration trajectory. When the substrate slope is spatially uniform, of course, all three of these slopes are the same.)

Once the trajectory slope converges to the substrate slope, the geometry of the barrier ceases to change with time (Wolinsky and Murray 2009; Moore et al. 2010). The asymptotic approach to steady state occurs over a timescale that depends on the rate of RSLR; Wolinsky and Murray (2009) show analytically that the adjustment requires a sufficient amount of RSLR—an amount that is commensurate with the height of the profile (H_{eff}). The configuration in which the barrier migration trajectory equals the substrate slope, and the geometry of the barrier (relative to the moving reference of sea level) is in steady state, represents a dynamically stable equilibrium; perturbing the migration-trajectory slope (or the substrate slope) triggers a negative feedback that tends to bring the system back to the steady state (as in the thought experiment above).

With the simplifying assumptions in this scenario, the geometry of the barrier approaches the configuration often depicted in textbooks: a large body of sand, perched on top of the underlying substrate (Fig. 5c; Roy et al. 1994). In this configuration, the barrier "rolls" across the substrate as sea level rises, as sand moves from the seaward to the landward portions of the profile (via overwash or barrier bypassing through inlets, and associated onshore sediment flux on the shoreface; e.g., Leatherman 1979; Rodriguez et al. this volume; Preface, this volume). However, this configuration is only an end member possibility; as we will see in Sect. 5, barriers will commonly evolve toward a state in which part of the shoreface is incised into the underlying substrate (e.g., Fig. 5a, b), so that each increment of landward translation tends to excavate new sediment that is added to the nearshore system (e.g., with incision being driven by a divergence in net alongshore sediment flux; Sect. 5).

4 The Effect of Shoreface Composition on Barrier Response to RSLR

We have so far assumed that all of the new sediment added from shoreface erosion is available to the island system as the profile moves upward and landward. However, prolonged landward translation will ultimately expose the underlying substrate on the shoreface; the tendency of waves to sweep sediment toward shore, interacting with shoreface slopes, creates gradients in cross-shore sediment fluxes on the shoreface (Preface, this volume) that can uncover the underlying substrate. Once exposed, the substrate (if lithified) weathers into transportable sediment (via physical, biological, and chemical weathering processes). If all of the resulting substrate-derived sediment is sufficiently coarse, relative to the energy conditions of the coast in question (i.e., sand and/or gravel), it will remain in the nearshore system. In this case, each increment of landward translation, R, produces an amount of sediment equal to $R * H_{eff}$, as assumed in deriving Eq. 1. However, some substrates consist, at least partly, of material that weathers into finer sediment (i.e., silt and clay, weathering out from a muddy back-barrier deposit, or lithified rock with a mudstone or shale component, or mud from former deltaic deposits). In this case, the fine fraction of the sediment produced by shoreface erosion is lost from the nearshore system (advecting and or/diffusing into some lower-energy environment). In this case, each increment of landward translation produces a reduced amount of sediment available for deposition as the barrier-shoreface profile migrates.

We can quantify this effect and incorporate it into the framework of Eq. 1 (Wolinsky and Murray 2009): The amount of coarse sediment produced by an increment of landward translation is equal to $(R * H_{eff}) * F$, where F is the fraction of the sediment produced by shoreface erosion that is coarse enough to remain in the nearshore system (the "coarse fraction," ranging from 0 to 1). Here, F is an average of the coarse fraction over H_{eff} (Fig. 2b). Figure 5a illustrates that the portion of the shoreface spanned by H_{eff} will in general include both mobile sand and outcrop of the underlying substrate (i.e., the "transgressive ravinement surface" in stratigraphic terminology).

The portion of the shoreface consisting of outcropping substrate is the result of the previous migration history of a barrier (Brenner et al. 2015). In addition, the composition of the substrate depends on the history of deposition in the back-barrier environment as well as the migration history of the barrier (Brenner et al. 2015), as we discuss in Sect. 6. However, in this section, for simplicity we take the average composition of the shoreface (over H_{eff}) to be an extrinsic constraint.

Taking F as an input, we can calculate how much landward translation is needed to meet the demands of raising the profile; $(R * H_{eff}) * F = S * L$, or, rearranging:

$$R = S^* \left(L / H_{eff} \right)^* \left(1 / F \right) \tag{2}$$

Then, relative to results of Eq. 1, the slope of the barrier migration trajectory is reduced if $F < 1$:

$$S / R = \left(H_{eff} / L \right)^* F \tag{3}$$

A thought experiment analogous to that in Sect. 3.2 leads to the conclusion that even if $F < 1$, given a sufficient amount of RSLR, the barrier profile will tend to adjust qualitatively as it does when $F = 1$, toward a state in which the migration trajectory parallels the slope of the substrate (with the same barrier volume that would occur if $F = 1$; Fig. 5c).

5 The Effect of Sediment Losses (or Gains) on Barrier Response to RSLR

The trajectory is also modified when the sediment supply/loss rate, from sources other than shoreface erosion, is not 0. For example, in most shoreline locations, gradients in net alongshore sediment transport cause either a net gain (when the rate of sediment transport into a shoreline segment is greater than the rate at which sediment is transported out; a convergence of net sediment flux) or a net loss (when the rate of sediment transport into a shoreline segment is lower than the rate at which sediment is transported out; a divergence of net sediment flux). (Note that "convergence" and "divergence" do not necessarily imply a directional convergence or divergence; the net flux can be moving in the same direction on either end of a shoreline segment, but with different magnitudes.)

A divergence of net alongshore sediment transport induces landward translation of the barrier profile (please see Sect. 2.2; the Preface, this volume; and Roy et al. 1994). This additional component of horizontal translation is in addition to the landward motion associated with RSLR (e.g., Moore et al. 2010) and equates to a reduction in the slope of the migration trajectory (Fig. 6). This shallowing of the migration-trajectory slope alters the geometry that a barrier tends to develop in the long term (compared to the case without net sediment loss). For example, imagine starting with a barrier that consists entirely of mobile sediment, perched on top of the substrate. In the absence of a net sediment loss, this geometry is a stable steady state, in which the migration-trajectory slope parallels the substrate slope (e.g., Fig. 6a, blue arrow), as outlined in Sect. 3. However, adding a sediment loss increases shoreline and shoreface erosion—i.e., increasing the landward translation of the barrier profile that occurs during each increment of RSLR. This increased landward translation reduces the slope of the migration trajectory, so that it is lower than that of the substrate (Fig. 6a, red arrow). As a result, over time, the back-barrier depth (D_{bb}) will decrease, and the toe of the shoreface will become incised into the substrate as the barrier profile moves landward (Fig. 6c, purple arrow). Because the elevation of the shoreface toe (relative to sea level) remains constant, while the elevation of the landward end of the barrier profile relative to sea level increases (corresponding to the decrease in back-barrier depth), the average slope of the barrier profile increases over time. Therefore, as the barrier evolves from this hypothetical initial state, the trajectory slope will steepen (Fig. 6, green and purple arrows). As long as the slope of the migration trajectory is lower than the substrate slope, the back-barrier depth will continue to decrease and a greater proportion of the shoreface will erode into the substrate as the barrier profile migrates. As in Sect. 3, these changes in profile geometry (barrier volume, D_{bb}) will, again, ultimately cause the trajectory slope to approach the slope of the substrate (Fig. 6c).

However, in the case of a net sediment loss, the steady-state geometry that produces a migration trajectory parallel to the substrate slope features a shoreface that partly erodes the substrate as it moves landward. In fact, steady state is only possible when enough of the shoreface is eroding into the substrate to produce new sediment (as distinguished from the mobile sediment already atop the substrate; Fig. 6) at a rate equal to the rate at which sediment is being lost. For a given average barrier profile slope, the vertical extent of the shoreface that needs to be actively eroding into the substrate depends on the substrate composition (through its effect on the average shoreface sediment composition F) and on the rate at which sediment is being lost (e.g., how large the gradient in net alongshore sediment transport is).

In the case of a net sediment gain—either from a convergence of net alongshore sediment transport (Moore et al. 2010), or from onshore sediment flux from a shallow continental shelf (Cowell and Kinsela this volume)—the added component of horizontal translation is in the seaward direction (as the sediment gain in the beach and upper shoreface decreases shoreline erosion, and the rest of the profile responds;

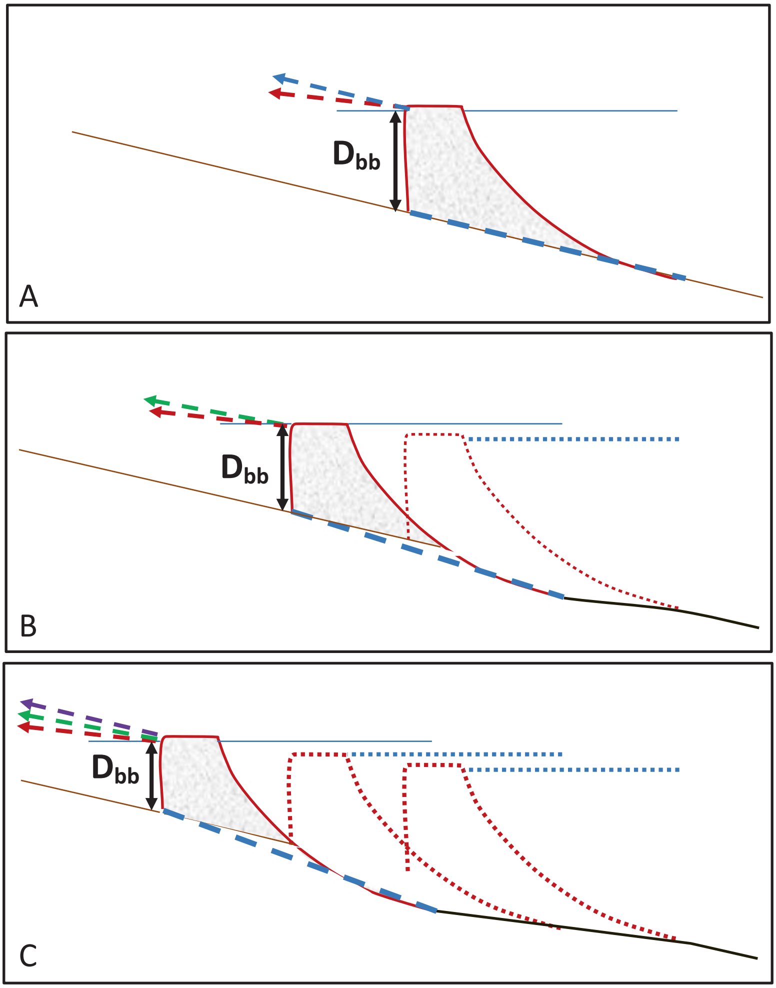

Fig. 6 Long-term adjustments to the barrier geometry and migration trajectory when sediment is being lost from the cross-shore profile (e.g. when there is a gradient in net alongshore sediment transport). (**a**) In a hypothetical initial condition the average slope of the barrier profile (blue dashed line) equals the slope of the substrate (brown line). However, because of the negative sediment budget the slope of the migration trajectory (red dashed line with arrow) will be lower than the average profile slope (which otherwise sets the migration trajectory slope). (**b**) Consequently, the back-barrier depth decreases over time, and the average profile slope increases (blue dashed line), tending to increase the slope of the migration trajectory (green arrow, relative to the red arrow that shows the migration trajectory in (**a**)). Note that the toe of the shoreface becomes incised into the substrate, so that shoreface erosion tends to bring new sediment into the nearshore system. (**c**) At a later time the slope of the migration trajectory (purple dashed line with arrow) has approached the slope of the substrate, so that the back-barrier depth and migration trajectory have approached steady state. Note that this steady state is reached when the profile is incised into the substrate far enough for the landward to retreat feed new sediment into the nearshore system at a rate that equals the rate at which sediment is lost from the cross-shore profile (e.g. the divergence of the net alongshore sediment flux)

please see Sect. 2.2 and the Preface, this volume). This tends to increase the slope of the migration trajectory. (We do not consider in this chapter the case in which sediment is added rapidly enough to cause shoreline progradation, and a widening barrier, which Cowell and Kinsela this volume and Moore et al. this volume examine).

In Sects. 3 and 4, the slope of the barrier migration trajectory was a kinematic result, independent of the RSLR rate (because both horizontal and vertical translation rates are proportional to RSLR). However, when sediment losses or gains are considered, the trajectory slope does depend on RSLR rate. More precisely, it depends on the relative magnitudes of RSLR rate and the rate of horizontal translation induced by the sediment loss or gain. By definition, the migration-trajectory slope is the ratio of the rate of vertical translation (equal to RSLR rate) and the rate of horizontal translation. In the case of a sediment loss or gain, the horizontal translation rate results from two independent contributions: RSLR causes horizontal translation with a rate proportional to RSLR rate (Eq. 3); and a sediment loss/gain causes horizontal translation at a rate that depends on the rate of sediment loss or gain (which is in general independent of RSLR rate). For example, consider the case of a divergence in net alongshore sediment flux, Q_s. The sediment loss rate, dQ_s/dx (where x is the alongshore coordinate), must equal the rate at which coarse sediment is produced, which is $F * H_{eff}$ multiplied by the horizontal translation rate arising from the sediment loss. Therefore, rearranging this equation, the contribution to the horizontal translation rate equals $(1/F) * (1/H_{eff}) * (dQ_s/dx)$.

How much the slope of the migration trajectory is altered by a sediment loss or gain, relative to the effect produced by RSLR alone (Eq. 3), depends on the relative magnitudes of the horizontal translation rates related to RSLR and to dQ_s/dx. When RSLR rate is relatively low, so that the rate of landward retreat related to RSLR (Eq. 3) is small compared to the rate of horizontal translation related to the external sediment loss or gain rate, then the trajectory is strongly affected by the loss or gain—and vice versa. We can quantify this within the analytical framework by adding the two components of horizontal translation together, where the sediment gain/loss term represents a gradient in net alongshore sediment transport (and where we have treated the increments of landward retreat, RSLR, and time as differentials, *dR, dS, and dt*):

$$dR = dS * (1/F) * (L/H_{\text{eff}}) + (1/F) * (1/H_{\text{eff}}) * (dQ_s/dx) * dt. \tag{4}$$

Or, rearranging:

$$dS/dR = (H_{\text{eff}}/L) * F * \left[1 - (1/dR) * (1/F) * (1/H_{\text{eff}}) * (dQ_s/dx) * dt\right]. \tag{5}$$

Then, substituting dS/(RSLR rate) for dt makes clear that the trajectory depends on the balance between RSLR rate and the magnitude of the gradient in net alongshore sediment transport:

$$dS/dR = \left(H_{\text{eff}}/L\right)*F *\left[1-\left(1/F\right)*\left(1/H_{\text{eff}}\right)*\left(dQ_{s}/dx\right)*\left(dS/dR\right)*\left(1/\text{RSLR rate}\right)\right] \tag{6}$$

Even though (6) is not an explicit equation for the trajectory (because *dS/dR* appears on both sides), it does show that the trajectory slope: (1) reduces to the pure RSLR response either when RSLR rate is very high or the gradient in net alongshore sediment transport is very small (so that the second term in the brackets approaches 0); and (2) will approach 0 (pure horizontal translation) either when RSLR rate is very low or the gradient in net alongshore sediment transport is very high (so that the second term in the brackets approaches 1).

6 The Effect of Back-Barrier Deposition, Deposit Thickness, and Composition

6.1 Coupling Between Back-Barrier Deposition and Barrier Migration Trajectory

In this section, we consider the case in which deposition occurs in the environments landward of a barrier, typically marshes and/or shallow bays (elaborating on the results from Brenner et al. 2015). Where such deposition occurs, a barrier moves across these deposits as it migrates landward. In this case, the substrate cropping out on the shoreface will consist at least partly of back-barrier deposits (Fig. 7a), which typically have $F < 1$. We will assume that back-barrier deposition keeps up with RSLR (e.g., Marani et al. 2007; Mariotti and Fagherazzi 2010); that sediment is supplied to the back-barrier environment (from rivers and/or the coastal ocean) at a rate that is sufficient to fill the accommodation space as fast as it is created by RSLR.

In this case, the influence of the substrate slope on the barrier migration trajectory is different than in the cases considered so far. In Sects. 3–5, the relationship between the slope of the migration trajectory and the slope of the substrate at the landward edge of the barrier profile (Fig. 4) determines whether the depth of the water into which the barrier migrates increases or decreases as the barrier migrates landward. Changes in this back-barrier depth, then, equate to changes in H_{eff} and therefore to changes in the barrier migration trajectory. However, when back-barrier deposition occurs, and keeps up with RSLR, then the depth of water into which the barrier migrates remains constant (defined by the steady-state depth of the marsh or bay, relative to sea level), and therefore, H_{eff} remains constant in time and is not influenced by the substrate slope.

Even in the case of back-barrier deposition, substrate slope influences the barrier migration trajectory. In this case, however, the influence is modulated by the effect of the thickness of the back-barrier deposit (Brenner et al. 2015). To understand this modulated influence, we pose a thought experiment: Consider a case in which the

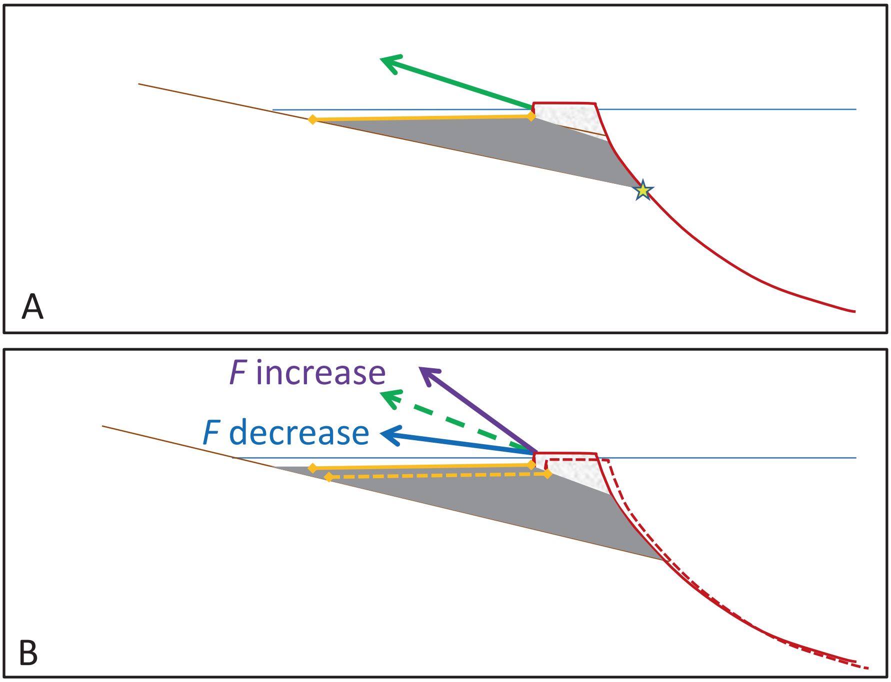

Fig. 7 Barrier migration trajectory (green arrow) depends on the thickness of the back-barrier deposit. (**a**) The migration trajectory, influenced by the composition of the back-barrier deposit (gray) and the thickness of that deposit on the shoreface, is steeper than the substrate slope in this hypothetical condition. Yellow line shows the width of the back-barrier deposition at this snapshot, and the star shows where the contact between the substrate and the back-barrier deposit (i.e. the substrate slope beneath the back-barrier deposit) intersects the shoreface. (**b**) The effects of a thicker back-barrier deposit where it outcrops on the shoreface (i.e. a wider back-barrier environment, for a constant substrate slope) depends on whether the back-barrier deposit is coarser than the underlying substrate (purple arrow) or finer than the underlying substrate (blue arrow). The green dashed line shows the initial trajectory. Dashed yellow line and dashed barrier-shoreface profile show the back-barrier width and barrier profile location in the snapshot shown in (**a**). The solid yellow line depicts the width of the back-barrier in (**a**), at the elevation of the top of the back-barrier deposit in the snapshot shown in (**b**) (i.e. it is the dashed yellow line translated along the barrier migration trajectory), showing that the back-barrier in the snapshot shown in (**a**) is narrower than the back-barrier in the snapshot shown in (**b**). (After Brenner et al. 2015)

substrate slope is lower than the slope of the current barrier migration trajectory (Fig. 7a). In this case, the cross-shore width of the back-barrier environment increases with time (Fig. 7b). With the assumption (for now) that the substrate slope is spatially uniform, widening of the back-barrier environment corresponds to a thickening of the back-barrier deposit where it outcrops on the shoreface (Fig. 7b). Therefore, a low substrate slope, relative to the slope of the barrier migration trajectory, means that the proportion of the shoreface consisting of back-barrier deposits increases over time.

The proportion of the shoreface composed of back-barrier deposits, combined with the composition of the back-barrier deposit, affects the average shoreface composition, *F* (Sect. 4). Thus, the thickness of the back-barrier deposit, which depends in part on the barrier migration trajectory, in turn, affects barrier trajectory (Sect. 4); a coupling between the thickness of the back-barrier deposit and the barrier migration trajectory. The long-term consequences of this coupling depend on the composition of the back-barrier deposit relative to the composition of the underlying substrate (Brenner et al. 2015).

6.2 Negative Feedback

If the back-barrier deposit weathers into sediment consisting of a smaller proportion of coarse material (hereafter referred to as "less coarse") than the underlying substrate, then thickening the outcrop of the back-barrier deposit on the shoreface decreases the coarse sediment fraction liberated by shoreface erosion (*F*), and therefore decreases the slope of the migration trajectory (Fig. 7b, blue arrow). The decreased slope of the trajectory then decreases the rate at which the back-barrier environment widens and therefore the rate at which the deposit thickens. As long as the slope of the barrier migration trajectory is greater than the substrate slope, the widening and thickening continue, and the slope of the migration trajectory continues to decrease. As the slope of the barrier migration trajectory approaches the substrate slope, back-barrier widening slows to a halt (Brenner et al. 2015).

In a parallel thought experiment, consider the situation in which the back-barrier deposit is less coarse than the underlying substrate, as above, but initially the substrate slope is steeper than the slope of the barrier migration trajectory. In this case, the back-barrier environment narrows and the thickness of the back-barrier deposit on the shoreface decreases over time. The resulting increase in the coarse fraction of sediment liberated by shoreface erosion (*F*) will steepen the barrier migration trajectory. Ultimately, the outcrop of the back-barrier deposit on the shoreface will become sufficiently thin for the slope of the barrier migration trajectory to approach the substrate slope.

These considerations reveal that if the back-barrier deposit is less coarse than the underlying substrate, the barrier/back-barrier system will tend to approach a dynamic equilibrium defined by: (1) a barrier migrating along a trajectory parallel to the substrate slope (as in Sects. 3–5), (2) a steady-state thickness of the back-barrier deposit on the shoreface; and (3) a steady-state back-barrier width, determined by a combination of the substrate slope and the composition of the back-barrier deposit relative to the composition of the underlying substrate. This dynamic equilibrium state is stable (as was the case in Sects. 3–5); if the thickness of the back-barrier deposit on the shoreface is perturbed from the equilibrium value, the barrier migration-trajectory slope will be perturbed as well, and a negative feedback will tend to return the system to the equilibrium (as in the thought experiments above; Brenner et al. 2015).

6.3 Positive Feedback

Now, consider the case in which the back-barrier deposit is *coarser than* the underlying substrate. A steady-state configuration is still theoretically possible; some value of the thickness of the back-barrier deposit on the shoreface will produce a barrier migration-trajectory slope equal to the substrate slope. However, in this case the equilibrium is unstable. Starting from this equilibrium condition, If the back-barrier deposit thickness on the shoreface is perturbed so that it is slightly thicker than the equilibrium value, the slope of the barrier migration trajectory will become steeper than the substrate slope, so that the proportion of the shoreface consisting of back-barrier deposit increases. Then, the average shoreface composition becomes increasingly coarse. This increase in F causes the barrier trajectory to steepen (Fig. 7b), which increases the difference between the migration-trajectory slope and the substrate slope. Thus, the back-barrier will continue to widen, at an ever-increasing rate (Brenner et al. 2015).

Conversely, if the back-barrier deposit thickness on the shoreface is perturbed so that it is slightly lower than the equilibrium value, the barrier-trajectory slope will be less steep than the substrate slope, leading to narrowing the back-barrier environment, further decreasing the thickness of the back-barrier deposit and leading to ever more rapid back-barrier narrowing, in a runaway feedback (Brenner et al. 2015). This positive feedback, which pushes the barrier/back-barrier system away from the equilibrium state, will not operate indefinitely. In the case of narrowing, the barrier would ultimately become welded to the mainland.

In the case of runaway widening, ultimately the back-barrier deposit will extend to the base of the shoreface. If this happens, the migration trajectory becomes disconnected from the substrate slope entirely. However, before runaway widening goes too far in any actual barrier landscape, the assumptions we make in this section are likely to break down. As the back-barrier environment widens, RSLR creates accommodation space at an increasing rate. In many actual barrier landscapes, the rate of sediment input from rivers, tidal inlets, and overwash is finite, preventing back-barrier deposition from keeping up with RSLR indefinitely.

Where back-barrier deposits are predominantly muddy, as is common in marshes and shallow bays, the negative feedback in Sect. 6.2 will be more likely to occur than the positive feedback in Sect. 6.3. The positive feedback, which requires back-barrier deposits to be coarser than the underlying substrate, is probably relevant for fewer actual barrier landscapes. However, some bay environments, with high-energy waves or tidal currents, can feature a high proportion of sand, and some substrates can consist of material that weathers into predominantly fine sediment, so that the positive feedback is possible.

6.4 Timescalesof Migration-Trajectory Adjustments

When back-barrier deposition is occurring, it is the thickness of the back-barrier deposit where it outcrops on the shoreface that needs to adjust to produce the equilibrium state. As an examination of Fig. 7 demonstrates, changes in this thickness arise directly from the difference between the slope of the contact between the back-barrier deposit and the overlying sandy barrier (which is a record of the slope of the barrier migration trajectory through time) and the slope of the substrate, where these slopes intersect the shoreface. If these two slopes are not equal, adjustments to the migration trajectory related to changes in thickness of the back-barrier deposit on the shoreface occur with no delay. However, starting from a hypothetical initial condition in which back-barrier deposits are absent, developing a back-barrier deposit with a sufficient thickness for the slope of the barrier migration trajectory to equal the substrate slope (i.e., dynamic equilibrium) would take time. Developing the equilibrium thickness would require an amount of RSLR commensurate with the equilibrium thickness. Therefore, the characteristic time to come to approach equilibrium would scale with this thickness divided by RSLR rate.

A different timescale arises if the slope of the substrate varies in space, so that the slope of the substrate under the back-barrier deposit is different where it intersects the shoreface than it is at the landward edge of the back-barrier deposit (Fig. 8a). As discussed in Sect. 6.1, assuming back-barrier deposition keeps up with sea-level rise, the slope of the substrate at the landward edge of the back-barrier deposit, in relation to the slope of the migration trajectory, determines the rate of change of the back-barrier width. However, the slope of the migration trajectory is only coupled directly to the slope of the substrate where it intersects the shoreface. The slope of the substrate at the landward edge of the back-barrier deposit (at a snapshot in time as an island migrates) will not affect the barrier migration trajectory until much later—until the barrier has migrated landward (and upward) far enough for the point on the substrate slope corresponding to the former landward edge of back-barrier deposition to crop out on the shoreface (Fig. 8b,c). In other words, the barrier migration trajectory will not begin to adjust to a change in the substrate slope (at the landward edge of back-barrier deposition) until after a time that scales with the width of the back-barrier environment divided by the horizontal translation rate ($dR/dt = dS * (1/F) * (L/H_{eff})$).

To examine barrier evolution when substrate slope is highly variable, as occurs in many actual barrier systems (e.g., Moore et al. 2010), requires numerical modeling, which we discuss in the next section.

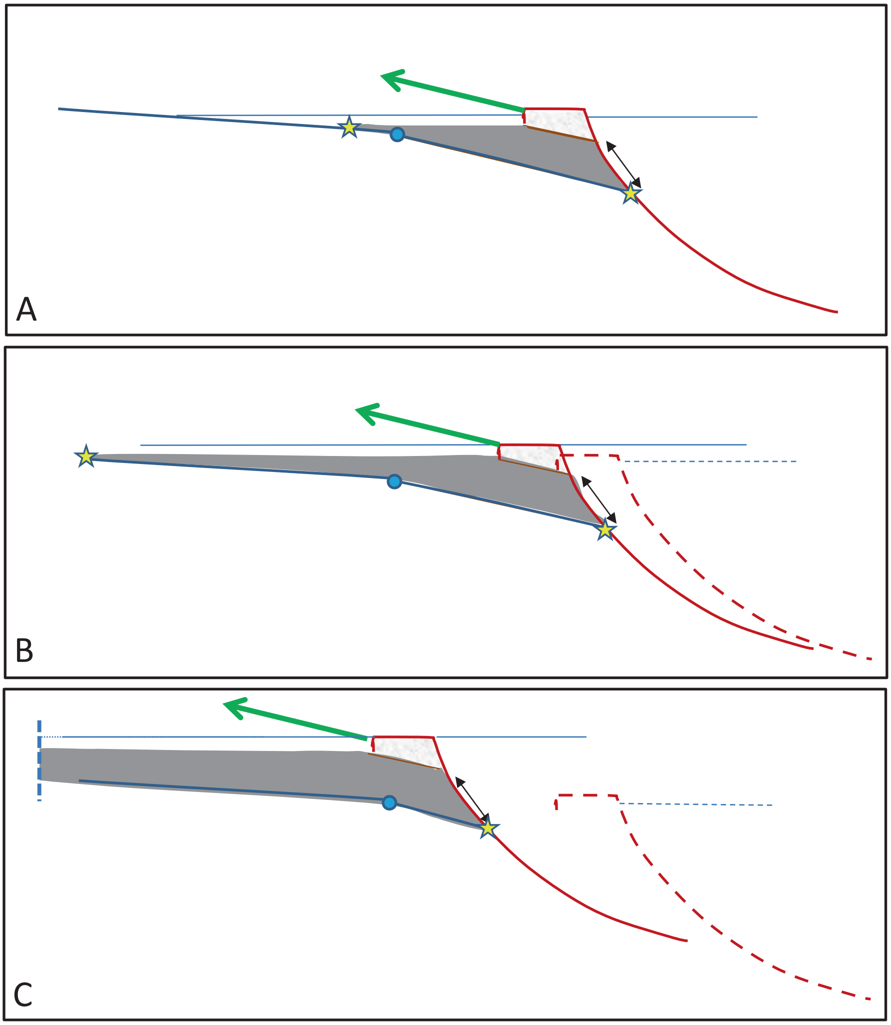

Fig. 8 Time-lagged adjustment of migration trajectory to substrate slope changes. (**a**) In this thought experiment, the migration trajectory is adjusted to the substrate slope where it intersects the shoreface. However, the substrate slope is not uniform; it becomes lower at the location near the current mainland shoreline, highlighted by the blue circle. Yellow stars show the substrate slope at the locations of the landward edge of the back-barrier deposit and at the intersection with the shoreface. (**b**) At a later time, the location of the change in substrate slope (blue circle) is in the middle of the back-barrier environment, and the back-barrier environment is widening. However, the thickness of the back-barrier deposit where it outcrops on the shoreface has not yet changed, so the barrier trajectory has not yet been affected. Dotted lines show the initial profile and sea level. (**c**) At a time shortly before the location of the change in substrate slope (blue circle) outcrops on the shoreface, after which the thickness of the back-barrier deposit on the shoreface will increase, and the barrier migration trajectory will respond. If the composition of the back-barrier deposit is less coarse then the substrate, then the migration trajectory will ultimately adjust to be parallel to the new substrate slope

7 Toward the Real World: Numerical Modeling

The scenarios considered above involve three key assumptions (either implicitly or explicitly): (1) that the slope of the substrate is uniform in space, and therefore constant in time as the barrier migrates across it (with the exception of Sect. 6.4); (2) that the composition of the substrate underlying the barrier (Sects. 3–5) or the back-barrier deposits (Sect. 6) is spatially constant; and (3) that depth of the seaward toe of the shoreface remains constant. These assumptions simplify the analyses, clarifying the basic insights about barrier behavior to be gleaned from considering idealized geometry and conservation of mass. However, these assumptions are not likely to apply strictly in any actual coastline setting, and considering barrier response to RSLR in a more realistic way is also beneficial. Relaxing these assumptions requires numerical modeling.

Numerical modeling of long-term barrier response to sea-level change, driven primarily by the constraints of geometry and conservation of mass as described above, started with the Shoreface Translation Model (Roy et al. 1994; Cowell et al. 1995). The BARSIM model (Storms et al. 2002; Storms 2003) features an analytical representation of a decrease in the response timescale of the shoreface with depth, representing long-term lower shoreface sediment fluxes (e.g., Stive and De Vriend 1995), leading to changes in the effective depth of the shoreface toe as a function of migration rate (e.g., Cowell and Kinsela this volume). Ashton and Lorenzo-Trueba have recently introduced a numerical model including shoreface dynamics—sediment fluxes on the shoreface as a function of the shoreface slope—and the consequent time lags between the responses of the subaerial and subaqueous portion of the barrier profile (Lorenzo-Trueba and Ashton 2014; Ashton and Lorenzo-Trueba this volume).

A complementary model, GEOMBEST (Stolper et al. 2005; Moore et al. 2010), which also treats variations in shoreface response rates with depth and variations in substrate characteristics, has proven useful especially for exploring barrier migration as influenced by variations in substrate slope, substrate erodibility, and substrate composition. In GEOMBEST, the substrate is represented as distinct strata (e.g., Fig. 9) that in general have different compositions and erodibilities (maximum erosion rates), which can be represented as realistically as can be justified based on available sediment-core data and geophysical data. The erosion-rate limitation can lead to a change in the geometry of the shoreface as a function of migration rate. In addition, resolving distinct strata allows the composition of the shoreface, averaged over the strata outcropping on the shoreface, to change as the migration trajectory brings the shoreface into contact with different units. GEOMBEST experiments based on actual barriers can be used to explore the conditions under which variations in substrate composition and slope prevent the approach to equilibrium described in Sects. 3–6—i.e., preventing the slope of the barrier migration trajectory from adjusting to the slope of the substrate (Fig. 10; Moore et al. 2010; Brenner et al. 2015).

Other insights from GEOMBEST experiments include how barrier geometry (e.g., back-barrier depth and barrier sand volume) and landward migration rates of

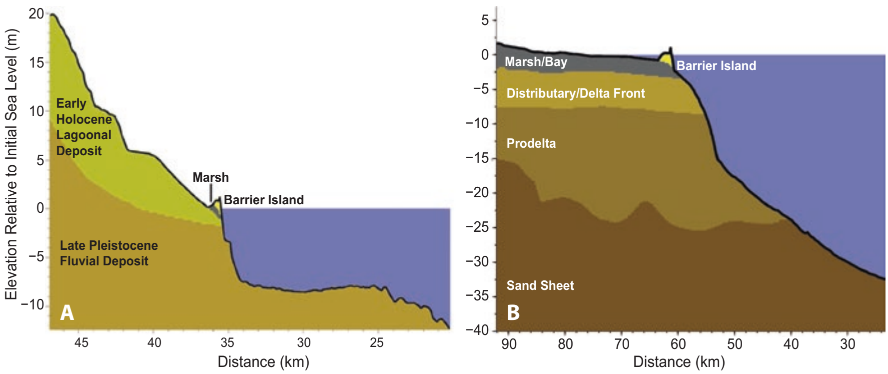

Fig. 9 GEOMBEST initial conditions, representing generalized stratigraphic units and substrate/island morphologies, based on best-available sediment-core, geophysical, topographic and bathymetric data, for (**a**) Northern Metompkin, Island, Virginia and (**b**) North Chandeleur Island, Louisiana. Reprinted from Brenner et al. (2015) and Moore et al. (2014), respectively, with permission from Elsevier

particular barrier chains are likely to change, in response to scenarios of increased rates of RSLR (e.g., Moore et al. 2010)—and under what conditions barriers may cease to persist in the long term (e.g., Moore et al. 2014), leading to barrier drowning or "overstepping" (e.g., Mellett and Plater this volume). In particular, barriers in deltaic environments face multiple challenges. The substrate composition tends to be dominated by fine material, and RSLR rates tend to be high. In addition, on abandoned delta lobes where sediment supply rates are low, back-barrier deposition will ultimately not be able to keep up with RSLR, so that back-barrier depths increase over time (contrary to the assumption in Sect. 6). The Chandeleur Islands off of southeast coast of Louisiana provide a striking example of barrier evolution in such an environment (e.g., Penland et al. 1985; McBride et al. 1992; Fearnley et al. 2009), highlighting the important role of substrate sediment composition and changes in back-barrier width and depth in determining island response to sea-level rise (Moore et al. 2014). The example of the Chandeleurs also highlights that spatial (and temporal) changes in substrate composition, as well as changes in back-barrier width—which can't be addressed with the analytical approaches outlined in previous chapters—can play key roles in barrier evolution.

8 Discussion

Though we have focused in this chapter on cross-shore variability, substrate slope and composition, as well as back-barrier depth, can vary significantly and abruptly alongshore (e.g., Brenner et al. 2015). In addition, although the sediment supply/loss from outside the cross-shore profile (Sect. 5) can encompass the effects of gradients in net alongshore sediment transport, the features that give rise to such

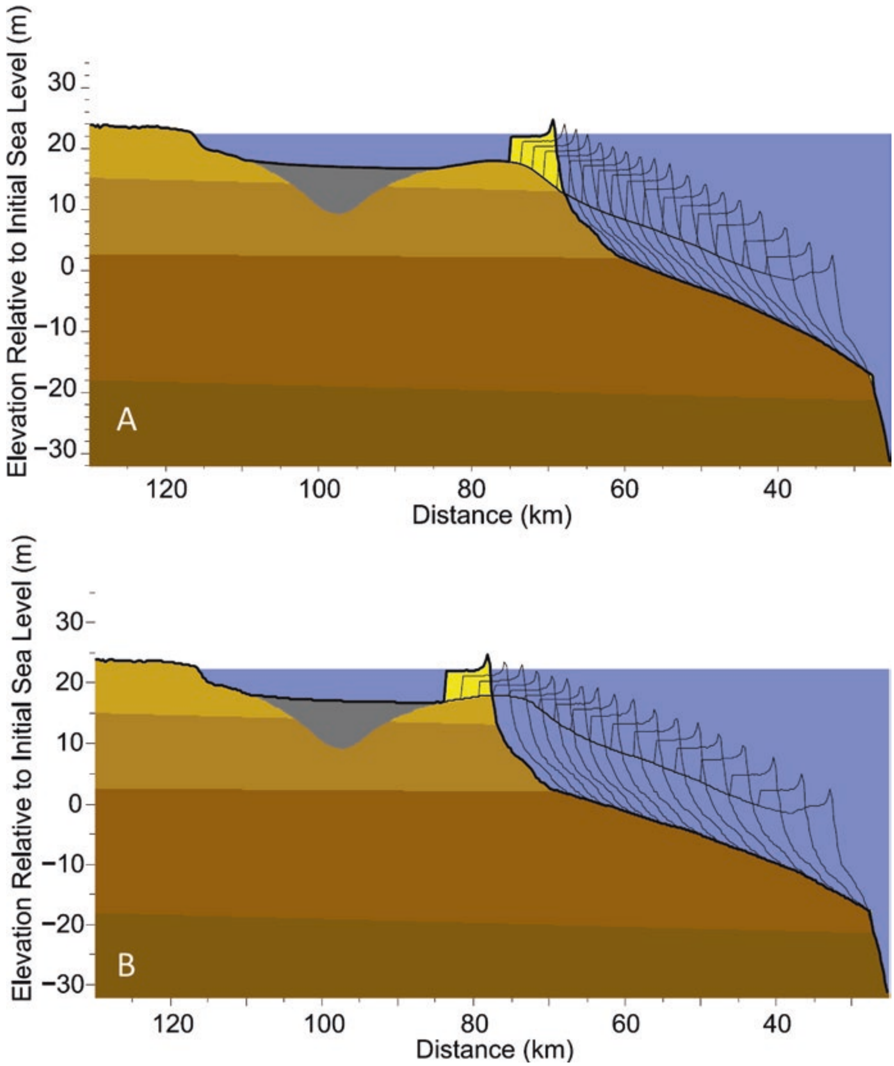

Fig. 10 (**a**) The final time step in an 8500-year GEOMBEST simulation of a generalized stretch of barrier along the Outer Banks, NC. Each trace represents a 500-year time increment and the modern barrier island appears in yellow. The initial surface is shown as a thin black line above the bold black line, which represents the modern shelf surface. The line of traces shows the migration trajectory the barrier has been following, which is approximately parallel to the substrate it has been traversing across. (**b**) The final time step in an 8500-year simulation for the same barrier under different conditions (i.e., a greater rate of sediment loss from gradients in alongshore sediment transport), which result in the barrier migrating farther landward by the end of the simulation than in (**a**). In this case, the traces show a shallowing of the migration trajectory but the migration trajectory, as shown by the several last traces, is not in equilibrium with the substrate slope landward of the barrier at the end of the simulation. From Moore et al. (2010)

gradients can vary significantly alongshore leading to alongshore variations in the sediment/loss rate. For example, coastline curvature can vary significantly even along an approximately straight shoreline (e.g., Lazarus et al. 2011), and the proximity to tidal inlets and effects of wave-shadowing by promontories tend to be localized (e.g., Barkwith et al. 2014). If the factors driving cross-shore barrier migration vary alongshore, consequent alongshore variations in migration rates will feed back upon the evolution of plan-view coastline shape, which partly drives cross-shore migration. Thus, to fully address coastline and barrier evolution, models focusing primarily on cross-shore processes/profiles need to be coupled to models addressing alongshore-extended domains.

However, despite the potential effect of alongshore variations in driving factors on cross-shore migration rates, gradients in net alongshore sediment transport tend to smooth most coastlines and therefore to homogenize shoreline-change rates (Valvo et al. 2006)—and migration trajectories—alongshore. We can consider the variables in the cross-shore focused analysis presented here to represent alongshore averages (i.e., substrate composition, substrate slope, sediment gain/loss rate, and back-barrier deposit composition; e.g., Cowell et al. 2003; Moore et al. 2010). Therefore, the main insights from the simplified scenarios considered in Sects. 3–6 likely apply to actual coastlines broadly, as tendencies guiding long-term barrier evolution. In particular, if RSLR is sufficiently gradual and substrate composition and slope sufficiently uniform, we can expect that after an amount of RSLR commensurate with the height of the profile (Wolinsky and Murray 2009), the geometry of the cross-shore profile will tend to adjust in a way that leads the migration trajectory to become approximately parallel to the slope of the substrate. If the slope of the substrate is approximately spatially uniform, then this slope corresponds to the slope of the landscape the barrier is migrating across, in the very long term. This tendency means that the slope of the landscape ultimately dictates the rate at which the shoreline (and barrier) moves landward as sea level rises. From a geological perspective, this result seems intuitive—if sea level rises far enough, how could the slope of the landscape not determine future coastline positions in the very long term? However, this intuitive, long-term result can seem to be at odds with shorter-term predictions based on the analytical framework of the generalized Bruun rule (e.g., Wolinsky and Murray 2009). The analysis recapitulated here shows how the very long-term intuition is consistent with the analytical framework (e.g., Figs. 5 and 6, and Eqs. 3 and 6).

Thought experiments analogous to those presented here lead to complementary insights for coastline types other than barriers. For example, if the substrate (i.e., landscape) slope is steeper than the slope of the shoreface, and sea level is rising, a cliffed coastline results (Wolinsky and Murray 2009). In addition, after sea level has risen far enough (commensurate with the height of the profile), the height of the cliff will adjust toward a steady-state value—a value that produces a migration trajectory parallel to the landscape (Eq. 6, where H_{eff} represents the height of the shoreface plus the cliff height). Thus, whether a barrier or rocky coastline develops depends on the slope of the landscape (averaged over a sufficient scale). Early numerical experiments using the Shoreface Translation Model (Roy et al. 1994) imply these conclusions, which are verified and explained by analytical modeling (Wolinsky and Murray 2009) and graphical/geometric framework presented here. Additionally, if back-barrier narrowing leads to a barrier welding to the mainland (Sect. 6.3), the cross-shore extent of overwash deposition will become limited by the space available (rather than maintaining a constant value related to the strength of the largest characteristic storms, as we have assumed in the rest of the chapter). As long as the shoreline migration-trajectory slope differs from the substrate slope, the cross-shore extent of overwash deposition will change over time. Consequently, the effective length of the profile, and therefore the migration trajectory, will change over time. In this case, thought experiments analogous to those presented here demonstrate that the migration trajectory will ultimately adjust to parallel the substrate slope, as in the previous cases.

In Sects. 3–6, we presented theoretical analyses, meant to explore the tendencies for long-term barrier evolution that geometry and conservation of mass impose. Although these tendencies will never be exactly manifest on actual barriers, which are also affected by spatial/temporal variations in substrate slope and composition (as well as other factors discussed in Sect. 6 and 7), the relevance of these long-term tendencies could be tested by strategic comparison with large-scale stratigraphic evidence. For example, if in the long term a barrier migration trajectory adjusts to approximately parallel the substrate slope, the condition of the substrate over which the barrier has migrated should depend on the sediment budget (averaged over the long term): If the sediment budget is balanced (i.e., no net sediment gain or loss from outside the cross-shore profile), the substrate should (on average) neither be eroded by the passage of the barrier or covered with barrier-related sediments (Fig. 5c, extrapolated further in time). If a net sediment loss exists (e.g., from a gradient in net alongshore sediment transport), the substrate should exhibit an erosion surface—a "transgressive ravinement surface" (Fig. 6C)—and if a net sediment gain exists (e.g., from a gradient in net alongshore sediment transport or onshore sediment flux from a shallow continental shelf), a sheet of shoreface sediment should remain on top of the substrate as the barrier migrates past.

The long-term analysis we have focused on, which involves a constant time-averaged profile shape, excludes dynamics that drive important variations in barrier-profile shape and barrier response to climate change on human timescales, including cycles of dune destruction (during major overwash or inundation events) and dune growth (e.g., Houser et al. this volume)—as well as associated longer-term shifts between high- and low-island states related to recently illuminated barrier bistability (Vinent Duran and Moore 2015). In addition, we have neglected the effects of human development and management practices on barriers (e.g., McNamara and Werner 2008; McNamara and Lazarus this volume), which can prevent or change the cross-shore sediment fluxes that drive barrier evolution in our analyses. For example, coastal development and dune maintenance can curtail overwash fluxes and overwash deposition, which can lead to barrier narrowing and ultimately, potentially, drowning (e.g., McNamara and Werner 2008; Magliocca et al. 2011; Lorenzo-Trueba and Ashton 2014; Rogers et al. 2015).

9 Conclusions

Under conditions in which the shape of a cross-shore barrier profile (including the subaerial and subaquesous portions) tends to remain approximately constant, conservation of mass constrains how barriers migrate in response to relative sea-level rise. The factors determining the rate of landward barrier migration, relative to the rate of relative sea-level rise (RSLR), can be understood intuitively as well as expressed analytically. A framework for analyzing this "barrier migration trajectory" (the generalized "Bruun Rule") can be extended to include the effects of: (1) variable composition of the substrate over which a barrier migrates; (2) a loss or gain of sediment from alongshore or the continental shelf; and (3) sediment deposition in back-barrier environments. This analytical framework can be used to address how barrier migration trajectories, and the geometry of barrier systems, tend to evolve over time. The slope of the barrier migration trajectory (i.e., the rate of RSLR divided by the rate of landward migration) tends, in most cases, to approach the slope of the substrate (either evaluated at the landward edge of the barrier, or in the case of back-barrier deposition, at the edge of the back-barrier deposit, if not spatially uniform) over time. If the substrate slope is spatially uniform, a dynamic equilibrium results in which the barrier and back-barrier geometries remain constant, relative to the frame of reference of sea level. The characteristics of the steady-state geometry depend on the sediment loss rate, and on the composition of back-barrier deposits. When substrate slope, substrate composition, or sediment gain/loss rates vary in space and/or time, the steady state is never attained and numerical investigations are needed to address how the constraints of geometry and the conservation of mass influence barrier evolution.

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References

Ashton AD, Lorenzo-Trueba J (2018) Morphodynamics of barrier response to sea-level rise. In: Moore LJ, Murray AB (eds) Barrier dynamics and response to changing climate. Springer, New York

Barkwith A, Thomas CW, Limber PW, Ellis MA, Murray AB (2014) Coastal vulnerability of a pinned, soft-cliff coastline. Part I, assessing the natural sensitivity to wave climate. Earth Surf Dyn 2:295–308

Brenner OT, Moore LJ, Murray AB (2015) The complex influences of back-barrier deposition, substrate slope and underlying stratigraphy in barrier island response to sea-level rise: insights from the Virginia Barrier Islands, Mid-Atlantic Bight, U.S.A. Geomorphology 246:340–350. https://doi.org/10.1016/j.geomorph.2015.06.014

Bruun P (1962) Sea-level rise as a cause of shore erosion. J Waterw Harb Div 88(1):117–132

Cowell PJ, Kinsela MA (2018) Shoreface controls on barrier evolution and shoreline change. In: Moore LJ, Murray AB (eds) Barrier dynamics and response to changing climate. Springer, New York

Cowell PJ, Roy PS, Jones RA (1995) Simulation of large-scale coastal change using a morphological behaviour model. Mar Geol 126(1–4):45–61

Cowell PJ, Stive MJ, Niedoroda AW, de Vriend HJ, Swift DJ, Kaminsky GM, Capobianco M (2003) The coastal-tract (part 1): a conceptual approach to aggregated modeling of low-order coastal change. J Coast Res 19(4):812–827

Davidson-Arnott RG (2005) Conceptual model of the effects of sea level rise on sandy coasts. J Coast Res 21(6):1166–1172

Dean RG (1977) Equilibrium beach profiles: US Atlantic and Gulf coasts. Department of Civil Engineering and College of Marine Studies, University of Delaware

Dean RG (1991) Equilibrium beach profiles: characteristics and applications. J Coast Res 7(1):53–84

Dean RG, Maurmeyer EM (1983) Models for beach profile response. In: Komar PD (ed) CRC handbook of coastal processes and erosion. CRC Press, Boca Raton, pp 151–165

Donnelly C, Kraus N, Larson M (2006) State of knowledge on measurement and modeling of coastal overwash. J Coast Res 224:965–991

Duran Vinent O, Moore LJ (2015) Barrier island bistability induced by biophysical interactions. Nat Clim Chang 5(2):158–162

Fearnley S, Miner MD, Kulp M, Bohling C, Penland S (2009) Hurricane impact and recovery shoreline change analysis of the Chandeleur Islands, Louisiana, USA: 1855–2005. Geo-Mar Lett 29:455–466

Fredsøe J, Deigaard R (1992) Mechanics of coastal sediment transport, vol 3. World Scientific, Singapore

Hallermeier RJ (1981) A profile zonation for seasonal sand beaches from wave climate. Coast Eng 4:253–277

Houser C, Barrineau P, Hammond B, Saari B, Rentschler E, Trimble S, Wernette P, Weymer B, Young S (2018) Role of the foredune in controlling barrier island response to sea level rise. In: Moore LJ, Murray AB (eds) Barrier dynamics and response to changing climate. Springer, New York

Lazarus E, Ashton A, Murray AB, Tebbens S, Burroughs S (2011) Cumulative versus transient shoreline change: dependencies on temporal and spatial scale. J Geophys Res Earth Surf 116(F2):2156–2202. https://doi.org/10.1029/2010JF001835

Leatherman SP (1979) Migration of Assateague Island, Maryland, by inlet and overwash processes. Geology 7(2):104–107

Lee GH, Nicholls RJ, Birkemeier WA (1988) Storm-driven variability of the beach-nearshore profile at Duck, North Carolina, USA, 1981–1991. Mar Geol 148(3):163–177

Lorenzo-Trueba J, Ashton AD (2014) Rollover, drowning, and discontinuous retreat: distinct modes of barrier response to sea-level rise arising from a simple morphodynamic model. J Geophys Res Earth Surf 119(4):779–801

Magliocca NR, McNamara D, Murray AB (2011) Long-term, large-scale effects of artificial dune construction along a barrier island coastline. J Coast Res 27:918–930

Marani M, D'Alpaos A, Lanzoni S, Carniello L, Rinaldo A (2007) Biologically-controlled multiple equilibria of tidal landforms and the fate of the Venice lagoon. Geophys Res Lett 34:L11402. https://doi.org/10.1029/2007GL030178

Mariotti G., Fagherazzi S (2010) A numerical model for the coupled long-term evolution of salt marshes and tidal flats. J Geophys Res Earth 115(F1)

McBride RA et al (1992) Analysis of barrier shoreline change in Louisiana from 1853 to 1939. In: Williams SJ et al (eds) Miscellaneous 1-2150-A. U.S. Geological Survey, Reston

McNamara DE, Lazarus ED (2018) Barrier islands as coupled human–landscape systems. In: Moore LJ, Murray AB (eds) Barrier dynamics and response to changing climate. Springer, New York

McNamara, D. E., Werner, B. T. (2008). Coupled barrier island–resort model: 1. Emergent instabilities induced by strong human-landscape interactions. J Geophys Res Earth 113(F1).

Mellett CL, Plater AJ (2018) Drowned barriers as archives of coastal-response to sea-level rise. In: Moore LJ, Murray AB (eds) Barrier dynamics and response to changing climate. Springer, New York
Moore LJ, List JH, Williams SJ, Stolper D (2010) Complexities in barrier island response to sea level rise: insights from numerical model experiments, North Carolina Outer Banks. J Geophys Res Earth 115(F3)
Moore LJ, Patsch K, List JH, Williams SJ (2014) The potential for sea-level-rise-induced barrier island loss: insights from the Chandeleur Islands, Louisiana, USA. Mar Geol 355:244–259
Moore LJ, Goldstein EB, Vinent OD, Walters D, Kirwan M, Rebecca L, Murray AB, Ruggiero P (2018) The role of ecomorphodynamic feedbacks and landscape couplings in influencing the response of barriers to changing climate. In: Moore LJ, Murray AB (eds) Barrier dynamics and response to changing climate. Springer, New York
Ortiz AC, Ashton AD (2016) Exploring shoreface dynamics and a mechanistic explanation for a morphodynamic depth of closure. J Geophys Res Earth Surf 121(2):442–464
Penland S, Sutter JR, Boyd R (1985) Barrier island arcs along abandoned Mississippi River deltas. Mar Geol 63:197–233
Rodriguez AB, Yu W, Theuerkauf EJ (2018) Abrupt increase in washover deposition along a transgressive barrier island during the late 19th century acceleration in sea-level rise. In: Moore LJ, Murray AB (eds) Barrier dynamics and response to changing climate. Springer, New York
Rogers LJ, Moore LJ, Goldstein EB, Hein CJ, Lorenzo-Trueba J, Ashton AD (2015) Anthropogenic controls on overwash deposition: evidence and consequences. J Geophys Res Earth 120(12):2609–2624
Rosati JD, Dean RG, Walton TL (2013) The modified Bruun Rule extended for landward transport. Mar Geol 340:71–81
Roy PS, Cowell PJ, Ferland MA, Thom BG (1994) Wave-dominated coasts. In: Carter RWG, Woodroffe CD (eds) Coastal evolution: late quaternary shoreline morphodynamics. Cambridge University Press, Cambridge, pp 121–186
Sallenger AH Jr (2000) Storm impact scale for barrier islands. J Coast Res 16(3):890–895
Sallenger A, Wright CW, Lillycrop J (2007) Coastal-change impacts during Hurricane Katrina: an overview. In: Kraus N, Rosati JD (eds) Coastal sediments '07: proceedings of the sixth international symposium on coastal engineering and science of coastal sediment processes. American Society for Civil Engineers, Reston, pp 888–896
Stive MJ, De Vriend HJ (1995) Modelling shoreface profile evolution. Mar Geol 126(1–4):235–248
Stockdon HF, Holman RA, Howd PA, Sallenger AH (2006) Empirical parameterization of setup, swash, and runup. Coast Eng 53(7):573–588
Stolper D, List JH, Thieler ER (2005) Simulating the evolution of coastal morphology and stratigraphy with a new morphological-behaviour model (GEOMBEST). Mar Geol 218(1–4):17–36
Storms JE (2003) Event-based stratigraphic simulation of wave-dominated shallow-marine environments. Mar Geol 199(1–2):83–100
Storms JE, Weltje GJ, Van Dijke JJ, Geel CR, Kroonenberg SB (2002) Process-response modeling of wave-dominated coastal systems: simulating evolution and stratigraphy on geological timescales. J Sediment Res 72(2):226–239
Valvo LM, Murray AB, Ashton A (2006) How does underlying geology affect coastline change? An initial modeling investigation. J Geophys Res Earth Surf 111(F2):F02025
Wolinsky MA, Murray AB (2009) A unifying framework for shoreline migration: 2. Application to wave-dominated coasts. J Geophys Res Earth Surf 114(F01009). doi:https://doi.org/10.1029/2007JF000856