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- Bayhead deltas stabilize at tributary junctions during transgression
- Inherited topography impacts the nature of subsequent transgressions
- Smaller deltas retreat at slower rates within flooded valley networks

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Where do coastlines stabilize following rapid retreat?

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Abstract We present a numerical model that shows that the transgressing upper shoreline of wave-dominated estuaries (bayhead deltas), which commonly contain populous urban and industrial centers, stabilizes, and their rate of retreat decreases at tributary junctions. The decreased rate of retreat across a tributary junction is caused by a decrease in the total accommodation, while sediment supply remains conserved. Our model predicts that bayhead deltas from smaller systems will be located closer to tributary confluences than their larger counterparts. An examination of the modern bayhead deltas in Albemarle Sound, U.S. Atlantic Coast, reveals that bayhead deltas from smaller tributaries are located closer to tributary confluences than bayhead deltas associated with larger tributaries, supporting our model prediction. Our results highlight the importance of antecedent topography created during falling sea-levels on shaping the nature of transgression during the ensuing sea-level rise. In particular, tributary junctions act as pinning points during transgression.

1. Introduction

Many estuaries contain stratigraphic records of episodic shoreline retreat of bayhead deltas, central basins, and barrier island complexes [e.g., *Amorosi et al*., 2005; *Anderson et al*., 2010]. By comparing the stratigraphic record to sea-level and climate change records, those periods of rapid retreat have been tied to increases in the rate of sea-level rise (SLR), changes in climate, and autocyclic mechanisms such as delta lobe avulsion and the flooding of relict topography. The timing of the subsequent decrease in the rate of transgression however is largely ignored or assumed to be driven by relaxation of the same forcing mechanism that initiated rapid transgression. Our understanding of what factors control where coastlines stabilize following the periods of rapid retreat is limited. Broadening our focus on the mechanisms governing coastline stabilization after transgression is important for coastal planners trying to develop proper mitigation strategies for projected increases in the rate of SLR. Most current models of coastal change in response to SLR simply flood existing topography [e.g., *Anthoff et al*., 2006], ignoring impacts from associated changes in sediment accommodation, accumulation, and redistribution as well as shoreline erosion. Thus, they provide only limited insights into where the shorelines may stabilize following rapid retreat. Generating more physically based shoreline change models is an important goal for improving predictions of coastline response to future SLR; however, to be useful, those models need to be parameterized correctly.

Most modern estuaries were created by the drowning of dendritic fluvial networks that formed across the shelf and coastal plain as sea-level fell during the last glacial-eustatic cycle [*Swift et al*., 1980; *Belknap and Kraft*, 1985; *Nordfjord et al*., 2005; *Simms et al*., 2006; *Maselli and Trincardi*, 2013]. In wave-dominated systems, these estuaries commonly have a tripartite architecture composed of a bayhead delta, central basin, and barrier-bar mouth complex [*Dalrymple et al*., 1992](Figure 1). Bayhead deltas and their associated floodplains (hereafter referred to as "bayhead deltas") link watersheds with estuaries (Figure 1) and serve as storage sites for terrestrial materials eroded from the landscape [*White et al*., 2002] and pollutants discharged into rivers [*Hanson et al*., 1993]. Bayhead deltas also serve as biogeochemical processors of nutrients, carbon, and particulate matter [*Noe and Hupp*, 2009] and host a high diversity of aquatic and terrestrial plant and animal species [*Pringle et al*., 2000]. Major industrial and urban centers are built on bayhead deltas, including the Port of Houston, Texas; San Jose, California; Tokyo, Japan; St. Petersburg, Russia; and Melbourne, Australia. Growth of coastal urban centers has threatened the ecological function of these important coastal systems [*Nichols et al*., 1986]. Bayhead deltas are further threatened by the installation of dams that reduce sediment supply [*Jaffe et al*., 2007]. This isolation from important sediment source areas, coupled with their low elevation, makes bayhead deltas vulnerable to SLR and their ability to maintain present areal extents questionable.

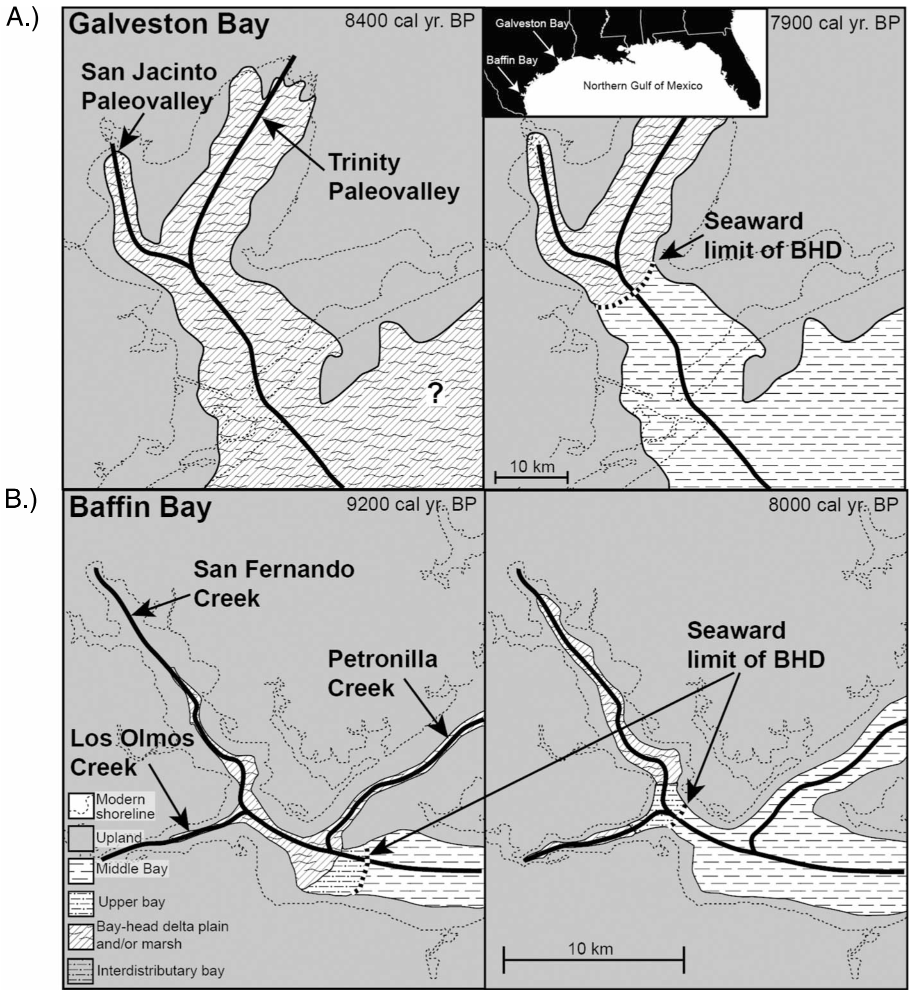

Figure 1. Paleogeographic reconstructions of the (a) Trinity and (b) Baffin Bay flooded river valley systems before and after the 8.2 ka climate and sea-level event [from *Rodriguez et al.*, 2010].

While documenting the late Pleistocene/Holocene history of rapid coastline retreats within the estuaries of the Gulf of Mexico, we noticed that the estuarine shorelines of bayhead deltas commonly stabilized at the confluence of tributary junctions of the flooded river valleys [*Anderson and Rodriguez*, 2008](Figure 1). As relative sea-level rose, bayhead deltas migrated landward through dendritic drainage networks of the lower coastal plain and encountered well-constrained changes in river morphology upstream. Changes in valley morphology and relative sea-level primarily controlled accommodation. Accommodation and sedimentation are the main factors that drive shoreline change. In this paper, we develop a model that examines the behavior of bayhead delta shorelines as they cross tributary junctions during a transgression. Our model takes into account predictable changes in the width and gradient of river valleys, which are important drivers of accommodation during inundation.

2. Background

Valley dimensions in coastal plains are largely controlled by upstream variables, dominantly drainage basin size [*Mattheus and Rodriguez*, 2011; *May et al.*, 2013]. Valley width generally decreases upstream, and empirical studies have shown that width varies largely as a function of stream discharge, rock type, sediment flux, and base-level changes [*Leopold and Miller*, 1956; *Martin et al.*, 2011]. The width of valleys commonly decreases abruptly upstream of tributary junctions because the discharge decreases sharply as the stream order decreases. In addition, the sum of the tributaries' sediment flux should be approximately equal to the sediment flux of the trunk valley located down gradient. Because of those well-defined relationships, the number of bayhead deltas increase, and the size of bayhead deltas decrease as the estuarine shoreline moves landward through a valley and past a tributary junction.

In general, the stream and valley slopes increase updip. In *Horton's* [1945] classic paper on stream orders, he showed that lower order streams (smaller tributaries) in Pennsylvania have higher slopes, which he labeled the "law of stream slopes." That law applies to different river settings and was also verified in arid New Mexico by *Leopold and Miller* [1956] and humid northern California by *Snyder et al.* [2000]. Both studies showed a significant negative relationship between stream size and slope. Thus, as the bayhead deltas transgress into flooded tributaries, they encounter steeper gradients. Those steeper gradients should result in a decrease of accommodation across tributary junctions.

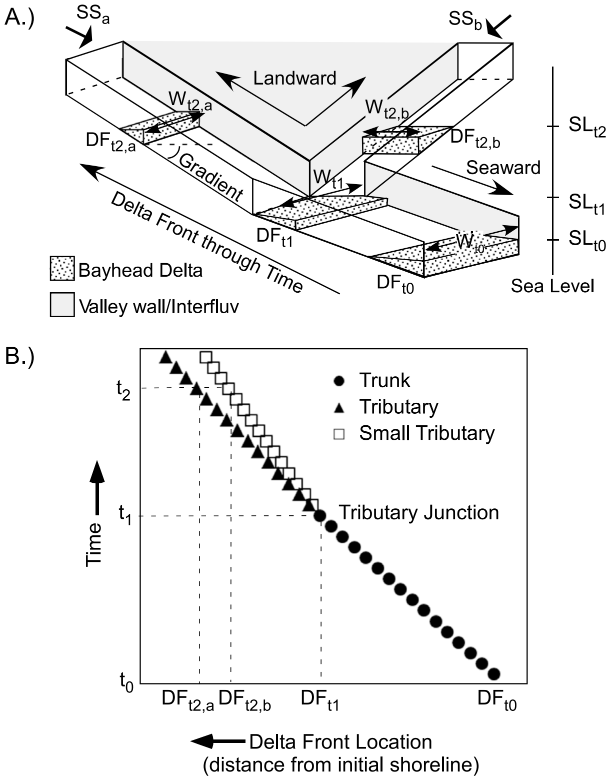

Figure 2. (a) Numerical model parameterization and (b) results illustrating the importance of tributary junctions in coastal evolution.

3. Methods

To evaluate the behavior of bayhead-delta retreat at tributary junctions, we built a simple numerical model based on the interactions between sediment accommodation and sedimentation (Figure 2a). Accommodation is created through time due to SLR inundating the valley, and that space is filled due to sedimentation within the delta. We assumed that only sediment transported by the stream supplies the delta, the delta is confined by the valley walls within the estuary, and the width of the delta is equal to the width of the flooded valley. In addition, as the delta moves landward, we assumed that waves erode down to the base of the delta front but leave the underlying surface unmodified, and the model ignores sedimentation in the central basin and any corresponding variations in depth of the sediment-water interface.

The horizontal distance a delta front (DF; length) moves is a function of the interplay between accommodation (*A*; volume) created and accommodation filled by sediment supplied (SS; volume). This can schematically be written as

$$\mathrm{DF} \;= f(A\text{–}\mathrm{SS}) \tag{1}$$

A is dependent on the amount of SLR, the width of the valley (*W*), and the inundation length (IL) due to SLR, all in units of length:

$$A = \mathrm{SLR} \;*\; W \;*\; \mathrm{IL} \tag{2}$$

IL is a function of the gradient (*G*) of the floodplain that is inundated during SLR. Using the standard equation for gradient (Δ elevation/Δ distance), the IL is solved for any SLR using

$$\mathrm{IL} = \mathrm{SLR}/G \tag{3}$$

Placing equations (2) and (3) into equation (1) results in

$$\mathrm{DF} = f\{[\mathrm{SLR} \;*\; W \;*\; (\mathrm{SLR}/G)] \;-\; \mathrm{SS}\} \tag{4}$$

In order to balance the units, because DF is in the units of length and A and SS are in the units of volume, the right-hand side of the equation must be divided by the cross-sectional area in which the delta front moves across, defined by the product of SLR and W:

$$\mathrm{DF} = \{[\mathrm{SLR} * W * (\mathrm{SLR}/G)] - \mathrm{SS}\}/(W * \mathrm{SLR}) = (\mathrm{SLR}/G) - [\mathrm{SS}/(W * \mathrm{SLR})] \tag{5}$$

Using equation (5), we simulated inundation of a river valley across a tributary junction by keeping the rate of SLR constant and incorporating updip changes in valley width, sediment supply, and gradient (Figure 2). The width of a valley has been shown to be an exponential function of drainage basin area [*Snyder et al.*, 2000; *Mattheus and Rodriguez*, 2011; *Phillips*, 2011]:

$$W = k * {A_d}^b \tag{6}$$

where k is a constant for the drainage basin, A_d is the drainage basin area in units of length square, and b is a constant generally found to vary between 0.3 and 0.5 for the systems of the U.S. Gulf Coast and Atlantic coastal plains [*Mattheus and Rodriguez*, 2011; *Phillips*, 2011]. Following equation (6), as the delta front moves through the trunk valley of width W and crosses a tributary junction, the valley generally undergoes a stepwise narrowing upstream as A_d is partitioned.

Sediment supply is conserved across the tributary junction such that

$$\mathrm{SS} = \mathrm{SS}_a + \mathrm{SS}_b \tag{7}$$

The stream gradient will increase with decreasing stream order and drainage basin size [*Horton*, 1945; *Snyder et al.*, 2000]. The gradient of a stream can be expressed as a function of the drainage area in the form:

$$G = K_s * {A_d}^\theta \tag{8}$$

in which K_s and θ are constants derived for the fluvial drainage basin [*Snyder et al.*, 2000]. In our model, we used this expression to control the gradient. The constants K_s and θ used in our analysis (0.129 and -0.388, respectively) were based on solving an exponential equation that fit the drainage basin areas and stream gradients given for the rivers of the northern Gulf of Mexico and U.S. mid-Atlantic coastal plain [*Mattheus and Rodriguez*, 2011]. Other constants could be used and probably change with underlying geology and drainage basin size [*Snyder et al.*, 2000]. At tributary junctions, the stream order and drainage basin size of the tributaries undergo a step decrease. Thus, it follows that similar to valley width, the gradient of the streams being flooded will also undergo a step increase in the upstream direction at tributary junctions.

4. Results

Our model predicts that the rate of retreat decreases at the tributary junction (Figure 2b). In addition, the model predicts that bayhead deltas within smaller flooded-river-valley estuaries (e.g., DF_b) will retreat at slower rates than larger systems (e.g., DF_a). Decelerated retreat is largely due to the increasing gradients of the river valleys across tributary junctions. The smaller tributary systems have higher gradients than their associated trunk valleys. This results in an abrupt decrease in accommodation when a tributary junction is inundated, while at the same time, sediment supply is conserved. As the estuarine shoreline moves landward through a valley, bayhead deltas decrease in size across tributary junctions and the sediment accommodation/sediment supply ratio decreases. Furthermore, the rate of landward retreat decreases as transgression continues across subsequent tributary junctions (Figure 2b).

5. Discussion and Conclusions

To test our model, we examined the present distribution of bayhead deltas within Albemarle Sound on the Atlantic Coast of the U.S. Our model predicts that the bayhead deltas of larger rivers will have retreated farther up their flooded river valleys than smaller systems due to the changes in valley gradient. To test that prediction, we measured the distances of modern bayhead deltas from tributary junctions and compared those distances to the width of the flooded tributary river valleys at their confluence, using width as a proxy for drainage-basin size (Figure 3). Even when ignoring the changes that have occurred in the rate of relative

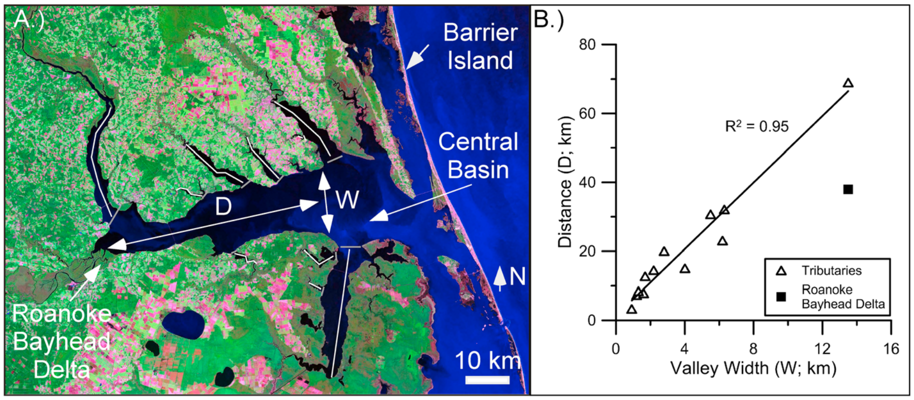

Figure 3. (a) Aerial photograph of the Abemarle Sound region of North Carolina, USA, showing the parameterization used to test the predictions of our model (image courtesy of the U.S. Geological Survey). (b) Plot of the distance of bayhead deltas from tributary junctions versus width of the flooded tributary valley at its confluence measured as shown in Figure 3a using Google Earth.

SLR through the last transgression and changes in sediment supply that may have occurred over this time period, a strong correlation ($R^2 = 0.95$; Figure 3) is found for the Albemarle Sound region when removing the Roanoke Delta. Although the Roanoke Delta is in a present state of retreat [*Riggs and Ames*, 2003], it could be an outlier due to an earlier predam phase of rapid progradation. Regardless, the relationship shown in Figure 3 supports the predictions of our model that smaller coastal plain bayhead deltas retreat at slower rates than their larger counterparts.

Our model is applicable to coastal plain wave-dominated estuaries. Although those estuaries are common along many modern and ancient margins, estuaries that formed in valleys that incised into bedrock or have morphologies controlled by tectonics likely do not fit our model as well as the simple case considered here. Taking into account, some additional important observations about the geometries of valleys at tributary confluences positively reinforce our model. For example, *Nordfjord et al*. [2005] noted that tributary valleys have a more V-shaped profile, and trunk valleys have a more flat-bottomed profile. The differences in shape between the tributary and trunk systems would further decrease the accommodation across the tributary junction leading to even slower rates of retreat within tributary systems. Nevertheless, our model does highlight the importance of valley morphology on the creation of sediment accommodation and its intrinsic influence on the behavior of transgressing bayhead deltas.

This numerical model builds on passive coastal inundation models by including changes in sediment accommodation and sedimentation in projecting shoreline positions. By including well-defined geomorphologic changes such as changing gradients and valley widths that exist across tributary junctions in the model, we predict nonlinear rates of delta front transgression under the conditions of constant SLR. The coastal inundation models that predict shoreline position under different SLR scenarios without consideration of sedimentation and accommodation should have the highest uncertainty at bayhead deltas near tributary junctions. These models are likely to overestimate the magnitude of transgression or might miss the possibility of regression despite continued SLR.

Our model may also help to explain the noticeable differences in the character of bayhead deltaic deposits at tributary junctions such as the coarser grain sizes found seaward of tributary junctions [*Nordfjord et al*., 2006]. These depositional changes may reflect the changes brought about by sediment redistribution rates that operate as a function of the time in which the physical processes such as waves and tides have to rework sediments at the delta front. They also may reflect the changes in exposure to waves and tides brought about by a more protected location within smaller tributary valleys. Another implication of this research is that it quantifies the importance of underlying geology (in this case, the valley dimensions carved during the preceding sea-level fall) in controlling the character of the ensuing transgression [e.g., *Belknap and Kraft*, 1985]. Our model highlights how ignoring autogenic forcing mechanisms may lead to large errors when trying to predict coastline movement due to SLR. Thus, reconstructing paleogeography increases the accuracy of characterizing both past and future coastal change.

Acknowledgments

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