Letter

An integrated hypothesis for regional patterns of shoreline change along the Northern North Carolina Outer Banks, USA

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A B S T R A C T

Combining analyses of plan-view shoreline change and shoreline curvature with existing nearshore geologic and bathymetric data and the results of a recent theoretical, large-scale shoreline-evolution model that couples geologic framework to alongshore sediment transport, we propose an integrated explanation for persistent patterns of shoreline change observed on the northern Outer Banks of North Carolina, USA. Concentrated sources of coarse-grained sediment, derived from relict fluvial stratigraphy or densely grouped relict inlet channels excavated from the shoreface, may both enable persistence of nearshore bathymetric anomalies and control multi-km-scale undulations in shoreline curvature, which in turn affect gradients in wave-driven alongshore sediment transport that drive long-term shoreline change.

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1. Introduction and motivation

The sandy barrier-island system of the North Carolina Outer Banks (Fig. 1) is an area of intensive study for those trying to understand why shorelines accrete in some places and erode in others—a fundamental question in coastal research, and one of immediate importance to oceanside communities where developed property overlaps the littoral zone. A wealth of literature exists on the underlying geologic framework of the Outer Banks, derived from core stratigraphy, sediment grab-samples, seismic profiles, and side-scan sonar (Moslow and Heron, 1994; Riggs et al., 1995,1996; Boss et al., 2002; McNinch, 2004; Mallinson et al., 2005; Browder and McNinch, 2006; Culver et al., 2006; Miselis and McNinch, 2006; Corbett et al., 2007; Culver et al., 2007; Culver et al., 2008; Mallinson et al., 2010a,b). Topographic data are as abundant: the North Carolina Division of Coastal Management offers an online catalog of historical shoreline measurements dating back to 1849 (NC DCM, http://dcm2.enr.state.nc.us/Maps/chdownload.htm); topographic and shoreline-position changes have been extracted from recent and historical aerial photography (e.g., Moore, 2000; Smith et al., 2008); and airborne lidar and vehicle-mounted GPS instruments have yielded a decade of high-precision records of shoreline position and change (Stockdon et al., 2002; List et al., 2006; Schupp et al., 2006; Lazarus and Murray, 2007).

The Outer Banks and surrounding coastal region have also motivated theoretical models of coastal morphodynamic phenomena, including the organization and persistence of large-scale nearshore bedforms (Murray and Thieler, 2004; Coco et al., 2007a,b), the evolution of cuspate and cape-dominated shorelines (Ashton et al., 2001; Ashton and Murray, 2006a,b), regional-scale shoreline response to storm patterns (Slott et al., 2006), and the influence of heterogeneous shoreface lithology on plan-view shoreline shape (Valvo et al., 2006). Though the gap between characterizing and explaining large-scale shoreline behavior is narrowing (e.g. Falqués and Calvete, 2005; Lazarus and Murray, 2007; List and Ashton, 2007; Brodie and McNinch, 2009; Lazarus et al., in press), open questions abound. The dynamics of how geologic heterogeneity in the nearshore affects shoreline change onshore, for example, are still poorly understood. Drawing on extant field data and theory, we offer a dynamical hypothesis for how the effects of three morphological elements—relict fluvial deposits, nearshore bedforms, and plan-view shoreline curvature—may interact across a range of spatial and temporal scales to shape observed regional patterns of shoreline change along the Outer Banks. Our intention is not to supplant or counter other hypotheses regarding the continuing evolution of the Outer Banks, but to demonstrate how seemingly disparate pieces of the nearshore puzzle may fit together here and perhaps extend to other localities.
(e.g. Honeycutt and Krantz, 2003; Houser et al., 2008; Hapke et al., 2010).

2. Regional setting

2.1. Geologic framework

A network of Pleistocene paleo-fluvial channels extends across the coastal-plain province between southeastern Virginia and Cape Hatteras, North Carolina (Riggs et al., 1995, 1996; Thieler et al., 2001; Boss et al., 2002; Schwartz and Birkemeier, 2004; Mallinson et al., 2005; Miselis and McNinch, 2006). The paleo-channels, which truncate the Quaternary strata that comprise the regional shoreface, backfilled with Pleistocene and Holocene sediments when rising sea level inundated the coastal floodplain following Wisconsin-age low stands (Moslow and Heron, 1994; Riggs et al., 1995). The paleo-channels substrate includes bedded sequences of muddy estuarine sediments, fine to medium sands, and lenses of fluvially-rounded gravel that outcrop in the shoreface (Boss et al., 2002; McNinch, 2004; Mallinson et al., 2005; Miselis and McNinch, 2006). The paleo-channels, which truncate the Quaternary strata that comprise the regional shoreface, backfilled with Pleistocene and Holocene sediments when rising sea level inundated the coastal floodplain following Wisconsin-age low stands (Moslow and Heron, 1994; Riggs et al., 1995). The paleo-channel substrate includes bedded sequences of muddy estuarine sediments, fine to medium sands, and lenses of fluvially-rounded gravel that outcrop in the shoreface (Boss et al., 2002; McNinch, 2004; Mallinson et al., 2005; Miselis and McNinch, 2006; Mallinson et al., 2010a,b). In some areas, coarse sands and gravels define cross-sectional fluvial channels up to several km wide (McNinch, 2004; Mallinson et al., 2005), but also mark abundant relict inlet incisions on the order of $10^2$ m wide (Rice et al., 1998; McNinch, 2004; Mallinson et al., 2005; Browder and McNinch, 2006; Culver et al., 2008).

As many as four major branches of the paleo-Roanoke/Albemarle fluvial system (Riggs et al., 1995; Boss et al., 2002) intersect the modern lower shoreface offshore of Duck, Kitty Hawk, Kill Devil Hills, and Nags Head, North Carolina, north of Oregon Inlet. Bathymetric surveys proximal to the surf zone between Kitty Hawk and Nags Head identify several paleo-channels $>500$ m wide and a large paleo-channel $~6–8$ km wide at Kitty Hawk (McNinch, 2004; Browder and McNinch, 2006; Miselis and McNinch, 2006); the Kitty Hawk paleo-channel complex has been mapped beneath Albemarle Sound on the back-barrier side of the island (Mallinson et al., 2005). On the beaches near the USACE Field Research Facility at Duck, swash-sorted patches of pea-sized, fluvially-rounded gravel clasts are ubiquitous; sedimentological analysis of the anomalous beach material suggests that a source of fluvial sediment has outcropped on the nearby shoreface in recent time (Caliari, 1994; Rice et al., 1998; Miselis and McNinch, 2006), even if no obvious channel exists there at present.

Broad fields of nearshore, shore-oblique, unconsolidated sandbars sitting atop a gravel layer that outcrops in the troughs, each bar typically 200–1000 m wide and $1$ km long, appear to coincide with the expression of paleo-channels in the shoreface and persist over multiannual time scales (McNinch, 2004; Browder and McNinch, 2006; Miselis and McNinch, 2006). These nearshore bar fields also spatially correlate with onshore hotspots of shoreline variability and, in some places, zones of long-term (decadal scale) erosion (List et al., 2006; Schupp et al., 2006). New measurement techniques that simultaneously record foreshore beach topography and the proximal wave field (which...
can be inverted for a proxy of swash-zone bathymetry), show how the bar fields set up highly localized alongshore gradients in wave energy that affect shoreline behavior, particularly during large wave events (McNinch, 2007; Brodie and McNinch, 2009). Cross-shore sediment transport during storms can cause large but transient excursions in shoreline position that amount to no net change on the time scale of days to weeks (List and Farris, 1999), even where nearshore bedforms are present (Brodie and McNinch, 2009; K. Brodie, pers. comm.). The relationship between these gravel-bedded nearshore bedforms and zones of cumulative erosion raises questions regarding the roles that shoreface composition and larger-scale alongshore sediment-transport gradients might play in these hotspot dynamics.

2.2. Sediment transport

Over multi-annual time scales and multi-km spatial scales, gradients in wave-forced alongshore sediment flux may drive cumulative shoreline change (Ashton et al., 2001; Ashton and Murray, 2006a,b; Lazarus and Murray, 2007; Lazarus et al., in press). Modeling of large-scale sandy-coastline evolution has shown that flux of sediment alongshore, which is a function of the relative angle between shoreline orientation and incident waves, is maximized when the relative angle between incident deep-water waves and the shoreline is ~45° (Falqués, 2003; Ashton and Murray, 2006a). Given a plan-view bump in a sandy shoreline, deep-water waves with relative incident angles greater than ~45° set up a convergence of alongshore sediment at the convex-seaward crest of the bump (not necessarily a directional convergence, but a flux convergence), causing the bump to accrete and plan-view shoreline curvature to exaggerate. Oppositely, when the deep-water incident wave climate is dominated by low-angle waves (relative angles <~45°), the resulting transport gradient across a sandy bump causes the bump to erode and sediment is distributed laterally, tending to maintain a shoreline that is relatively straight in plan-view (Ashton and Murray, 2006a).

Numerical model results and recent analyses of shoreline change along the Outer Banks have suggested that even subtle large-scale curvature is enough for corresponding gradients in alongshore sediment transport to be effective (Valvo et al., 2006; Lazarus and Murray, 2007). Along the North Carolina seaboard north of Oregon Inlet, over the last decade and at large spatial scales, convex-seaward promontories appear to have eroded landward while concave-seaward embayments have tended to accrete; shoreline curvature and shoreline-position change are thus negatively correlated at those scales, consistent with the smoothing effects of alongshore-transport gradients that result from a low-angle wave climate (Lazarus and Murray, 2007). But despite the tendency for the prevailing wave climate to smooth the northern Outer Banks coastline over long time scales (Ashton and Murray, 2006b), the large-scale curvatures have not diffused away (Fig. 2), as we might expect if wave-driven gradients alone were forcing shoreline change. So why do these plan-view bumps in the shoreline persist? Their longevity may relate to geologic heterogeneities in the shoreface substrate, like those the paleo-channels introduce.

2.3. Where sediment transport meets geologic framework

An exploratory model by Valvo et al. (2006) suggests a mechanism for the dynamic coupled relationship between large-scale (~km) shoreline curvature, underlying geologic framework, and long-term...

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**Fig. 2.** Plots of (A) northern Outer Banks plan-view shoreline position (north at left); (B) 1996 (black) and 2005 (red) plan-view shoreline curvature; (C) difference in shoreline curvature 1996–2005 shown in (B); and (D) difference in plan-view shoreline position from 1996–2005. Calculations in (B), (C), and (D) are processed with a 5 km Gaussian-type filter after Lazarus and Murray (2007). Shaded portions mark the composite, approximate alongshore extents of relict-channel evidence reported by Rice et al. (1998), Boss et al. (2002), and Browder and McNinch (2006). Stippling denotes alongshore reaches of shore-oblique bar systems documented by Schupp et al. (2006).
(>> year) shoreline change. Shoreface lithology in the model is divided into two types: coarser-grained, and finer-grained, with a weathering-rate algorithm to convert the respective rock types into mobile sediment. A predominantly low-angle incident wave climate interacts with local plan-view shoreline orientation to drive gradients in alongshore sediment flux, diffusing mobile sediment alongshore (Ashton and Murray, 2006a) and mantling the model shoreface with a layer of sediment whose thickness varies alongshore. Not all weathered material in the model becomes mobile sediment—only sediment coarse enough to stay in the nearshore system remains in the domain. In a natural high-energy surf zone, sand and gravel entrained by breaking waves may get redistributed on the shoreface but its displacement does not constitute a net volumetric change. By contrast, fine sediment, once suspended in a high-energy environment, will tend to remain in the water column, and is therefore treated in the model as a volumetric loss.

The model predicts that on a generally eroding coastline, subtle plan-view embayments will develop where a greater proportion of the mobile sediment created by shoreface weathering is too fine to stay in the nearshore system, creating subtle promontories where the proportion of fine grains is smaller. The amplitude of the plan-view undulations (the cross-shore offset between the promontories and adjacent embayments), and the associated curvatures, reaches a steady state when gradients in alongshore transport redistribute sediment from promontories to embayments as rapidly as fine sediment is lost from the embayments (Valvo et al., 2006). The steady-state amplitude of these shoreline undulations depends on the wave climate, represented by an effective diffusivity that expresses how rapidly sediment tends to be redistributed. The higher the percentage of low-angle waves constituting the incident wave climate, the higher the effective diffusivity; a shoreline being smoothed out by a low-angle wave climate can also be described as having a positive effective diffusivity (Ashton and Murray, 2006b). Fluctuations in effective diffusivity in this scheme will produce fluctuations about the long-term steady-state amplitude of offset, in which periods when erosion is accentuated along the promontories alternate with periods when the embayments erode more rapidly (Valvo et al., 2006).

Extending the implications of this model to the Outer Banks, we might expect areas of convex-seaward curvature to spatially correspond with a greater percentage of relatively coarse underlying material, such as in the vicinity of paleo-channels or relict sandy inlets (Figs. 2 and 3). We might also expect zones of shoreline onshore of paleo-channels to be erosional hotspots for some number of years (while the intervening embayments are hotspots at other times), persisting for durations related to those of fluctuations in the wave climate and to diffusional time scales. The diffusional time scale in this case is proportional to the squared alongshore length scales of the coarse-grained areas and the finer-grained interfluves. During times in which the channel-related promontories are eroding relatively rapidly, as seems to have been the case recently (Figs. 2 and 3), gravel deposits will tend to be exposed.

Fig. 3. Plots of (A) plan-view shoreline position near Kitty Hawk and Kill Devil Hills, (B) plan-view shoreline curvature from 1996 (black) and 2005 (red), (C) difference in plan-view shoreline position between 1996 and 2005, as shown in Fig. 2. Schematics (D) and (E) show the bedform complex that dominates the shoreface bathymetry there (D), and a cross-section of the underlying paleo-channel (E). Plots are registered to the same alongshore scale. Both schematics after McNinch (2004, Figs. 8 and 13).
3. Our hypothesis

3.1. Integrating the pieces

We suggest that the over-arching linkage between paleo-channels, gravel outcrops and bar fields, and long-term patterns of shoreline change is the relationship between shoreline curvature and gradients in alongshore sediment transport (Fig. 3). If multi-kilometer-scale areas of curvature in the shoreline spatially correspond with concentrations of relict fluvial sand and gravel in the shoreface, we hypothesize that the greater availability of coarse paleo-channel substrate holds the large-scale curvature of the shoreline in place through interactions with patterns of alongshore sediment flux, allowing broad areas of positive curvature (and fields of gravel-associated nearshore bedforms) to persist despite a wave climate that tends to focus erosion at such promontories. Large-scale shoreline curvature could thus set up gradients in net wave-driven alongshore sediment transport that will tend to affect net shoreline change over long time and large spatial scales (Lazarus et al., in press), even as complex hydrodynamic interactions across the nearshore bedforms force highly variable but transient shoreline-change patterns. Such consideration of spatial and temporal scales is central to differentiating among the transport processes that affect shoreline change. Over multi-km spatial scales, the small-scale and rapidly changing shoreline patterns filter out, laying bare the patterns of long-term, large-scale shoreline change (Lazarus and Murray, 2007; Lazarus et al., in press).

3.2. Possible implications

Existing geological observations are broadly consistent with our hypothesis, but tests of agreement are still inconclusive, especially where spatially extended, long-term data records are needed but limited. As high-resolution bathymetric surveys, reliable geological mapping of the shoreface, and long-term bathymetric-change measurements of the upper shoreface and surf zone become available for greater extents of the North Carolina coastline and elsewhere, those repeated measurements can help test our hypothesis more rigorously and calibrate model predictions of large-scale shoreline evolution. But supposing the hypothesized framework/process relationship we propose is reasonably true, we can extend an intriguing line of inference. In the Valvo et al. (2006) modeling, the fluctuations in the wave climate were stochastic; recent wave-buoy observations, however, indicate a systematic shift in wave climates along the southeastern U.S. coastline, as tropical-storm-generated waves have become larger (Komar and Allan, 2008). Given the directions from which these waves tend to come—nearly shore-normal to the overall coastline orientation, according to hindcasts from NOAA WIS buoys off the Carolina coast (D. McNamara, pers. comm.)—this climate-change-related shift corresponds to an increase in the effective diffusivity (the tendency to smooth plan-view perturbations) along the northern Outer Banks coastline. Our posited connections between shoreline lithological variations, subtype alongshore undulations, and large-scale patterns of shoreline change would, by extension, hold that promontories will continue to experience enhanced erosion relative to the intervening embayments as long as the apparent trend toward increased hurricane intensity continues (Komar and Allan, 2008).

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