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Insights into barrier-island stability derived from transgressive/regressive state changes of Parramore Island, Virginia

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ABSTRACT

Barrier islands and their associated backbarrier ecosystems front much of the U.S. Atlantic and Gulf coasts, yet threshold conditions associated with their relative stability (i.e., state changes between progradation, erosion, and landward migration) in the face of sea-level rise remain poorly understood. The barrier islands along Virginia's Eastern Shore are among the largest undeveloped barrier systems in the U.S., providing an ideal natural laboratory to explore the sensitivity of barrier islands to environmental change. Details about the developmental history of Parramore Island, one of the longest (12 km) and widest (1.0–1.9 km) of these islands, provide insight into the timescales and processes of barrier-island formation and evolution along this mixed-energy coast. Synthesis of new stratigraphic (vibra-, auger, and direct-push cores), geospatial (historical maps, aerial imagery, t-sheets, LiDAR), and chronologic (optically stimulated luminescence, radiocarbon) analyses reveals that Parramore has alternated between periods of landward migration/erosion and seaward progradation during the past several thousand years. New chronology from backbarrier and barrier-island facies reveals that Parramore Island has existed in some form for nearly 5000 years. Following a period of rapid overwash-driven retrogradation, and coinciding with a period of slow relative sea-level rise (~1 mm/ yr), Parramore stabilized ~1000 years ago in partial response to pinning by and sediment delivery from erosion of a Pleistocene-aged antecedent high. Following pinning, Parramore built seaward through development of successive progradational beach and dune ridges. Morphological and historical evidence suggests that these processes were interrupted by inlet formation—possibly associated with an interval of enhanced storminess—at least three times during this period. Following inlet closure in the early 1800s, island progradation was rapid, with Parramore Island reaching its maximum width ca. 150 years ago. It has since switched states again, undergoing accelerating erosion (~12 m/ yr since 1980). The relative youth of Parramore Island is in contrast to many East Coast barrier islands, which generally reached their present positions about 3500–2000 years ago. Moreover, these results demonstrate that the apparent robustness and stability of Parramore are ephemeral features of an island that has undergone multiple state changes within the last 1000 years. Finally, they refine current knowledge of the roles of antecedent topography, sediment delivery rates, storms, and sea-level rise in barrier-island stability and resilience to future climate change.

1. Introduction

Barrier islands front approximately 5000 km of the U.S. Atlantic and Gulf coasts (Davis and FitzGerald, 2004), with the 405 islands within this region comprising 24% of the total global barrier-island shoreline length (Stutz and Pilkey, 2011). Globally, barrier islands, and their backbarrier marshes and tidal flats, provide key ecosystem services (Barbier et al., 2011), protect mainland coasts from large storm events (Otvos, 2012), and are hosts to economically important communities and infrastructure (Brander et al., 2006). Barrier islands are typically composed of a shoreface and barrier platform, beach and adjacent foredune, beach and dune ridges, inlets and tidal deltas, lagoon, marsh, and mainland coast (Oertel et al., 1992; Davis and FitzGerald, 2004); these components are together referred to as a “barrier system”.

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In response to the high degree of dynamism observed along barrier islands, including undergoing sub-decadal periods of erosion, growth, migration, and rotation, recent studies have attempted to approach these systems holistically—from the shoreface to the backbarrier marshes and lagoons—to fully understand the mechanisms responsible for observed changes (e.g., Brenner et al., 2015; Deaton et al., 2017; Lorenzo-Trueba and Mariotti, 2017). Over millennial time scales, the effects of climate change and relative sea-level rise (RSLR) are the dominant cause of landward barrier-island migration (Wolinsky and Murray, 2009; Moore et al., 2010; Brenner et al., 2015). Several additional factors play significant roles in the rate of shoreline retreat and barrier-island migration by influencing the balance between accommodation creation (generally due to RSLR) and infilling (due to net sediment inputs). Among these are increased storminess and human development (e.g., Rogers et al., 2015); antecedent topography and inland slope (e.g., Wolinsky and Murray, 2009; Lorenzo-Trueba and Ashton, 2014; Ashton and Lorenzo-Trueba, 2018); and substrate erodibility, slope, and sediment fluxes (e.g., Moore et al., 2010). Walters et al. (2014) and Brenner et al. (2015) together demonstrate the roles that underlying substrate, barrier width, backbarrier deposition rates, and the presence/absence of marsh can have on barrier-island migration rates with respect to RSLR. They establish that backbarrier deposition, which fills newly developed accommodation space, is crucial to maintaining a subaerial barrier island. Similarly, Lorenzo-Trueba and Mariotti (2017) show that an essential component of barrier-island resilience to RSLR is a steady supply of fine sediment to the backbarrier from overwash processes. Similar barrier-backbarrier couplings form the foundation of the “runaway transgression” model (FitzGerald et al., 2008, 2018), which suggests that a reduction in sediment supply (or an increased rate of RSLR) can cause the drowning of backbarrier marshes and lead to an increase in backbarrier tidal prism and inlet ebb-tidal-delta volumes and attendant erosion and thinning of adjacent barrier islands. In this conceptual model, increased frequency of overwash of beach/shoreface sediment to the backbarrier drives the collapse of barrier-island dunes, leading to eventual breaching and inundation as the island narrows, and fostering accelerated landward migration.

Despite the new insights into the interactions between barrier islands and backbarrier environments that have emerged from conceptual and numerical models, field investigations treating these as coupled systems have been rare. Furthermore, the threshold rates of RSLR, storminess, and cross- and long-shore sediment delivery rates required for barrier-island state changes between transgressive/destructive and regressive/constructive phases remain unknown.

This study investigates the forces responsible for morphologic and sedimentologic change along the Virginia Barrier Islands (VBI) through an examination of the formation and evolutionary history of centrally located Parramore Island. Specifically, it focuses on past barrier-backbarrier system couplings for Parramore Island and how they are preserved in the present topography and stratigraphy. Analysis of the history of change along Parramore Island serves to place the evolution of the VBI alongside regional relative sea-level (RSL) changes. Furthermore, the exploration of morphologic transitions of Parramore Island over the past 1000–2000 years provides insight into the processes responsible for the formation of mixed-energy and progradational barrier islands, with implications for the stability of other barrier-island systems and associated infrastructure and natural resources.

2. Regional setting

2.1. Coastal and physical setting

Parramore Island is approximately 12 km long and 2 km wide and is located within The Nature Conservancy's Virginia Coast Reserve, along the southern Delmarva coast (Fig. 1a). Parramore is characterized by complex shore-normal to shore-parallel dune ridges to the north and a series of semi-shore-parallel dune ridges and swales in the north-central part of the island. These ridges include the ~3 km long, > 7 m high, 60–120 m wide “Italian Ridge”, the highest feature along the VBI (McBride et al., 2015). Along the southern 8 km of the island, there are a series of low, segmented ridges and swales (including larger, named features such as Little Beach, South Little Beach, and Revels Island; see Fig. 1b, c), marsh, tidal channels, and circular, sandy, vegetated, isolated dunes (i.e., “pimples”, sensu Hayden et al., 1995). The entire island is fronted by a narrow beach and shore-parallel foredune ridge.

Parramore Island fronts the mainland of the Virginia Eastern Shore, the 100 km long, 5–15 km wide, southern-most portion of the Delmarva Peninsula. This feature originally formed as a spit that prograded progressively southward (Oertel and Overman, 2004) during a series of former Pleistocene sea-level highstands, filling former lowstand channels of the Susquehanna River (Oertel and Foyle, 1995; Foyle and Oertel, 1997). These lowstand paleochannels, likely dating to 600–120 ka, today act as stabilizing locations for tidal inlets along the VBI (Krantz et al., 2016), including the 14.5 m deep Wachapreague Inlet and 18 m deep Quinby Inlet that bound Parramore Island to the north and south, respectively. Between these inlets are barrier islands composed primarily of unconsolidated sand, silt, and clay, and backed by saltmarshes (predominantly low marsh) and open-water lagoons.

Tides along the VBI are semi-diurnal with a mean tidal range of 1.23 m, and a mean spring range of 1.37 m (Fenster and McBride, 2015). The mean wave height is ~0.95 m, based on a record covering 2012 to 2015 (Fenster and McBride, 2015). Dominant winds are from the north (associated with northeast extratropical storms), leading to net southerly nearshore current and wave directions, and thus net southerly longshore sediment transport (Finkelstein and Ferland, 1987; Fenster et al., 2016).

The Virginia coast experiences both hurricanes and intense northeast storms, although the latter are recognized to be the primary agent of geomorphic change (Hayden and Hayden, 2003). Hayden (2003) documents a gradual increase in the frequency of cyclone impacts along the VBI between 1885 and 2002, with notable periods of reduced storminess in the 1940s and 1970/80s; these changes are reflected in system-wide, decadal-scale shoreline-change rates, which gradually track storm-impact frequencies (Fenster et al., 2017).

2.2. Holocene sea-level history

Initial barrier-island formation along the Virginia coast coincided with a gradual deceleration in RSLR during the middle to late Holocene (Newman and Rusnak, 1965; Finkelstein and Ferland, 1987; Van de Plassche, 1990; Engelhart et al., 2009). Available RSL curves from this region are based on widely-spaced data dominated by marine- and terrestrial-limiting points, with few index points (Engelhart and Horton, 2012). These local records indicate that RSLR along the Virginia coast slowed from a time-averaged rate of 1.6–1.7 mm/ yr to ca. 1.0 mm/ yr around 1500 years ago (Fig. 2). It has since undergone significant acceleration due to local subsidence and glacial isostatic adjustment (Boon et al., 2010), reaching approximately 5 mm/yr in the last 50 years (Boon and Mitchell, 2015). Higher-resolution curves available from North Carolina reveal that RSLR accelerated to ca. 1.3 mm/ yr between 1000 and 450 years ago in response to the Medieval Climate Anomaly, followed by a deceleration to ~1.0 mm/ yr until the end of the 19th century (Kemp et al., 2011).

2.3. Barrier-system morphology

Despite long-term exposure to similar RSL changes, tidal range, storm impacts, and overall wave climate, the VBI are highly diverse with respect to their morphologies and shoreline-change trends. The barrier chain is categorized into three morphological groups on the basis of shoreline-retreat rates and orientation (Fig. 1a): 1) a northern set of landward-migrating barrier islands retreating parallel to the mainland shore along what is often referred to as the “Arc of Erosion”