THE ROLE OF COASTAL SEDIMENT SINKS IN MODIFYING LONGSHORE SAND FLUXES: EXAMPLES FROM THE COASTS OF SOUTHERN BRAZIL AND THE MID-ATLANTIC USA

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Abstract: Coastal change fundamentally occurs in response to changes in the balance between accommodation creation and filling, the latter in part reflecting longshore sediment fluxes. In Santa Catarina (southern Brazil), growth of the Jurerê Strandplain trapped 50–110 x 10^6 m^3 of sand, effectively halting longshore transport for 3000 years; re-initiation of headland bypassing in the last 1000 years allowed for formation of the downdrift Daniela Spit. In northern Virginia (U.S. East Coast), elongation of the Assateague Island spit-end during just the last 100 years has sequestered a similar volume of sand (~45 x 10^6 m^3), reducing longshore transport fluxes by at least 25%, and contributing to the erosion and/or landward migration of adjacent, downdrift barrier islands. These findings demonstrate the potential for longshore sediment trapping through natural growth of updrift sediment sinks to control long-term and large-scale downdrift coastal behavior.

Introduction

Coastal morphology is fundamentally controlled by the balance between accommodation creation (relative sea-level change) and filling (Curray 1964), the latter associated with both natural (*i.e.*, climate, tectonics) and human-induced changes in coastal sedimentation across decadal to geologic timescales. Along wave-dominated coasts, long- and cross- shore transport rates may be modified by artificial shoreline hardening or inlet stabilization (FitzGerald and Pendleton 2002; Hapke et al. 2013) or natural growth or erosion of updrift sediment reservoirs (*e.g.*, Field and Duane 1976; Anthony 1995; Park and Wells 2007). The resulting variability in sediment fluxes has the potential control state changes between growth (progradation, aggradation, elongation), erosion, and retrogradation (landward migration) of downdrift coastal systems, and their overall stability in the face of sea-level rise.

Here, we use sedimentologic, stratigraphic, and geochronologic data from coastal depositional systems in each Ilha de Santa Catarina (Santa Catarina state, southern Brazil) and the central Delmarva Peninsula (Virginia, mid-Atlantic USA) to explore the magnitude and timescales of updrift accretionary processes in controlling longshore sediment fluxes and attendant downdrift changes in coastal morphology over multi-decadal to multi-millennial timescales.

Study Sites

This study focuses on two sandy coastal systems formed and modified primarily through wave-dominated longshore-transport processes (Fig. 1). Both are located >100 km from major rivers, and their sediment fluxes are therefore predominantly controlled by delivery from updrift sources and exchanges with the shoreface.

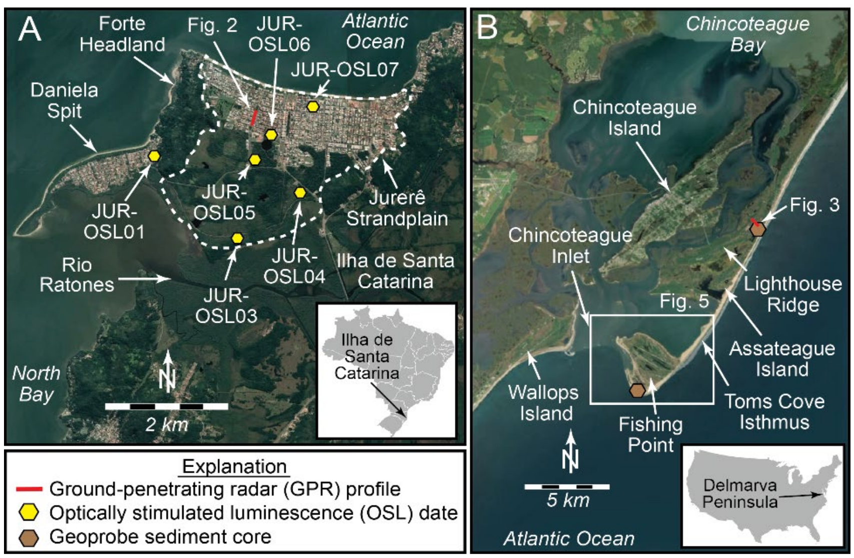

Fig. 1. Study sites and data sources. (a) Jurerê Strandplain and Daniela Spit (northwest Ilha de Santa Catarina, Brazil). (b) Assateague, Chincoteague, and Wallops islands, and the Assateague Island spit-end (Fishing Point) (northern Virginia, USA).

Jurerê Strandplain and Daniela Spit, northwest Santa Catarina Island, Brazil

Jurerê and Daniela are located in central Santa Catarina State (Fig. 1a), a region composed of re-entrants, bays, and strandplains separated by granitic bedrock headlands and characterized by a relatively narrow, discontinuous coastal plain bordered by crystalline bedrock of the Serra Geral to the west (Dominguez 2009). This microtidal (mean range: 0.7 m; Truccolo et al. 2004) coast has experienced a sea-level fall of 2–4 m during the last 5–6 kyr (Angulo et al. 2006).

The 7.5 km^2 Jurerê Strandplain built into an embayment located in northwest Ilha de Santa Catarina as a 2.6 km-wide series of beach and foredune ridges (Fig. 1a). To its west lies the Daniela Spit, which extends 2.8 km to the southwest from the Forte headland (Fig. 1a). This section of coast is largely protected from both prevailing east and southeast swells, and dominant storm-driven waves approaching from the south with an average period of 12 sec and significant height of 2 m(Araújo et al. 2003). The Santa Catarina coast experiences net northerly longshore transport, which is locally modified by wave refraction and sediment bypassing around bedrock headlands (Vieira da Silva et al. 2016). Along Jurerê Beach, transport is to the west, reflecting net westerly tidal currents and the oblique, eastern wave approach (Barletta 2008; Vieira da Silva et al. 2016). Sand introduced to the northern Ilha de Santa Catarina littoral cell from the island's eastern coast through headland bypassing and dune overpassing is transferred to Jurerê from the east at an average annual rate of 850 m^3/yr by net westerly tidal currents and the oblique, eastern wave approach (Vieira da Silva et al. 2016). At the western margin of Jurerê, sediment from the beach and inner shelf is transported around the Forte Headland at a rate of *ca.* 6000 m^3/yr, with 5000 m^3/yr of sand traveling along the beach and nearshore (to 8 m depth) of Daniela Spit and deposited at and beyond (SW) of the spit terminus (Vieira da Silva et al. 2016).

Southern Assateague Island, USA

Located along the >200 km wide coastal plain of the mid-Atlantic U.S. East Coast, the Delmarva Peninsula is composed of deposits from at least five successive Pleistocene sea-level highstands (Oertel et al. 2008; Krantz et al. 2016). This coast has experienced sea-level rise since the Last Glacial Maximum, accelerating in the last century from *ca.* 1.0 to 4–5 mm/yr ((Boon and Mitchell 2015). Sediment is introduced to the >200 km long modern chain of barrier islands and headland-attached beaches fronting the Delmarva Peninsula largely from erosion of pre-Holocene headland and shoreface deposits (Kraft 1971; Toscano and York 1992). It is transported predominantly to the south at rates of 0.46–1.6 x 10^5 m^3/yr, largely by intense northeast storms (Fenster and McBride 2015).

At 58 km, the mixed-energy, wave-dominated Assateague Island is the longest barrier island along the Delmarva Peninsula (Fig. 1b). It experiences semi-diurnal tides with a mean tidal range of 0.64–0.66 m and mean long-term wave heights of 1.1–1.2 m (Seminack and McBride 2015). At its southern end, Assateague Island has grown southward through >6 km of spit extension since at least the mid-1800s (Field and Duane 1976), forming Fishing Point (also called "Toms Cove Hook") (Fig. 1b). Although currently growing into 8–10 m deep water, earlier spit extension was modified by growth atop two bathymetric highs, which were responsible for the morphology of the narrow isthmus connecting Fishing Point to Assateague Island (Fig. 1b) (Krantz et al. 2016).

Methods

Ground-penetrating radar (GPR) data was collected using either a GSSI SIR-3000 with a 200 MHz shielded antenna (Santa Catarina) or a MALA Geosciences X3M with a 250 MHz shielded antenna (Virginia), and post-processed (site-specific filtering, migration, and variable gain control) and time-depth converted (radar velocity: 7 cm/ns) using RadExplorer. These units produced reflection data to between 5 and 10 m below the ground surface, depending on the depth of the brackish ground-water table. In southern Assateague, GPR data were ground-truthed with two direct-push cores (>15 m long) collected using a Geoprobe Model 66DT. These were split, photographed, described for texture (as compared to standards), mineralogy, and color, and sampled for select grain-size analysis.

Geochronology is provided from optically stimulated luminescence (OSL) dating (Jurerê, Daniela; Fig. 1a) and georeferenced historical maps and aerial and satellite imagery (Assateague). OSL samples were collected by hand augering 70 cm below the ground surface and inserting a 100 cm opaque PVC tube into the auger hole flush with the ground surface. Tubes were extracted and the bottom 30 cm removed, capped, and sealed under an opaque cover to ensure minimal sunlight exposure. Samples were analyzed at the East Carolina U. Dept. of Physics. Doses from quartz samples were obtained following the single-aliquot regenerative-dose procedure of Murray and Wintle (2000) and Wintle and Murray (2006). Uranium, thorium, and potassium contents were measured with high-resolution gamma spectrometry in the Radiation Physics Laboratory at Oklahoma State U. The dose rate was calculated with standard procedures as outlined by Rhodes (2011).

Finally, we use OSL and historical-shoreline chronologies to map changes in the areas of each Jurerê and Fishing Point between a given paleo-shoreline, and the oldest mappable foredune ridge or the northern end of Toms Cove Isthmus, respectively. For Jurerê, we assume that preserved dated foredune ridges are shoreline-continuous features formed contemporaneous with that given ridge.

Results

Jurerê Strandplain is composed of a *ca.* 7 m thick package of northerly- (seaward-) dipping (3–4º) radar reflections (Fig. 2) capped by dozens of shore-parallel, 1–2 m high aeolian foredune ridges, interpreted as former shoreline positions. Ridges are well preserved in the southern ~2 km of Jurerê as part of the Instituto Carijós Nature Preserve, but have largely been flattened along the northern 800 m by development. Shallow (< 2 m) hand auger cores collected through each Jurerê and Daniela indicate that both are composed of mature, quartz-dominated, well-sorted, very fine- to fine- grained sand. OSL analyses indicate that Jurerê Strandplain built between 4 and 1 ka, whereas Daniela Spit is significantly younger (only *ca.* 100 years at its northern end) (Table 1). The OSL date for Daniela is anomalously young, as historical maps from at least the mid-1700s indicate the presence of a spit-like feature in the region of modern Daniela (Bellin 1764); this spit has continued to grow throughout the last century (Diehl 1997).

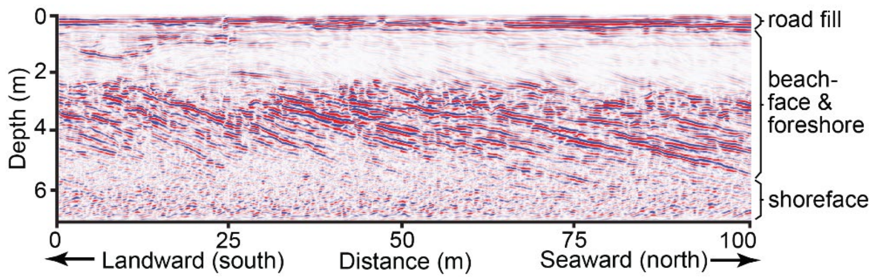

Fig. 2. Processed ground-penetrating radar profile from central Jurerê Strandplain.

Table 1. Results of optically stimulated luminescence (OSL) analyses from Jurerê and Daniela.

	Radionuclide concentrations			**Water content, %**	**Total dose, Gy**	**Dose Rate, Gy/ka**	**Age, years**
Sample	**U, ppm**	**Th, ppm**	**K, %**				
JUR OSL 01	0.29 ± 0.04	1.07 ± 0.10	0.26 ± 0.03	0.26 ± 0.05	0.0523 ± 0.003	0.479 ± 0.026	108 ± 8
JUR OSL 03	0.54 ± 0.05	1.15 ± 0.16	0.11 ± 0.02	0.16 ± 0.05	1.714 ± 0.065	0.437 ± 0.022	3920 ± 250
JUR OSL 04	0.21 ± 0.03	0.53 ± 0.07	0.05 ± 0.03	0.15 ± 0.05	0.855 ± 0.027	0.284 ± 0.022	3010 ± 250
JUR OSL 05	0.14 ± 0.03	0.52 ± 0.14	0.08 ± 0.02	0.15 ± 0.05	0.621 ± 0.021	0.301 ± 0.017	2060 ± 140
JUR OSL 06	0.28 ± 0.03	0.78 ± 0.14	0.23 ± 0.02	0.10 ± 0.05	0.585 ± 0.021	0.478 ± 0.022	1223 ± 71
JUR OSL 07	0.16 ± 0.03	0.70 ± 0.13	0.11 ± 0.02	0.17 ± 0.05	0.339 ± 0.011	0.328 ± 0.018	1033 ± 66

The beach and foredune ridges of southern Assateague Island are significantly younger than those of Jurerê and Daniela. Assateague grew to the south in front of the then open-ocean-exposed Chincoteague Island starting in the 16th century (Goettle 1981). By the early 1800s, the Assateague Island shoreline was positioned east of southern Chincoteague, forming Lighthouse Ridge (Fig. 1b), the most prominent and highest-elevation foredune ridge on Assateague. Progradation and elongation of the spit since then has extended Assateague another *ca.* 6.5 km to the south through growth of Toms Cove Isthmus and Fishing Point. Ground-penetrating radar reveals that the internal structure of the southern Assateague Island beach and foredune ridges is characterized by sigmoid-oblique reflections dipping seaward (southeast to south) at *ca.* 3–4° (interpreted as foreshore and beachface reflections) downlapping onto more shallowly (0.5–1.9°) seaward-dipping reflections interpreted as shoreface deposits (Fig. 3). Occasional strong, relatively shallow (2–4°), laterally continuous reflections are evidence of beach flattening associated with storm erosion, and correlate with steep (~6°) scarps in overcapping aeolian dunes, which are otherwise characterized by semi-chaotic landward and seaward dipping reflections. These erosional units are often accompanied by with thin (0.5 m), overlying sections of westward-dipping beds interpreted as landward-migrating bars associated with post-storm beach re-growth.

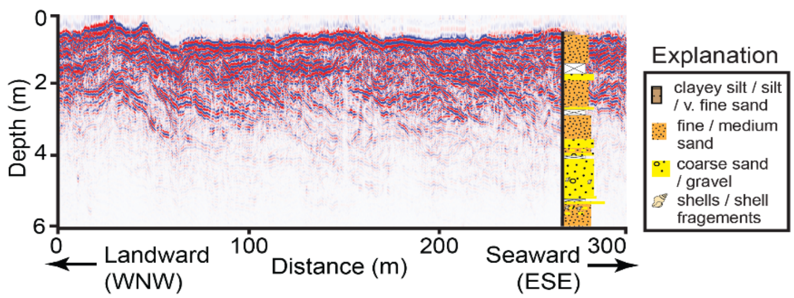

Fig. 3. Processed GPR profile and Geoprobe core log from east of Lighthouse Ridge, Assateague I.

Sediment cores collected reveal that regressive deposits are composed of very fine to fine sand at the base generally coarsening upward to fine to coarse sand. Decimeter-scale beds of immature (abundant mica and rock fragments) coarse to very coarse sand with occasional pebbles and shell fragments are found throughout the upper 4 m. The overall coarsening-upward regressive sequence at Fishing Point begins at 7.5 m below mean sea level. This is deeper than that estimated by Halsey (1978) from northern Fishing Point (~5 m), suggesting that Fishing Point has been gradually building into deeper water. Given an average elevation of Fishing Point of *ca.* 0.5 m (Ciarletta et al. in review), we estimate a regressive deposit thickness of 7 m.

Discussion

Longshore Sand Trapping at Jurerê Strandplain and Fishing Point

Progradational sand deposits at Jurerê Strandplain, Daniela Spit, and Fishing Point are *ca.* 7, 3, and 8 m in thickness, respectively, corresponding to total deposit volumes of *ca.* 65 x 10^6, 3.6 x 10^6, and 44 x 10^6 m^3 (Table 2).

Table 2. Comparison of sediment fluxes associated with Jurerê, Daniela, and Fishing Point.

Site	Area, x10^6 m^2	Estimated total sand volume, x10^7 m^3	Period of growth	Modern longshore sediment input flux rate, x10^4 m^3/yr	Avg. sand flux during growth period, x10^4 m^3/yr
Jurerê Strandplain	7.5	5.3–11	*ca.* 4000–900 yr ago	0.085	1.5–3.5
Daniela Spit	1.2	0.36	*ca.* 900 yr ago – present	0.5–0.6	0.36
Fishing Point	6.2	4.35	1908 CE – present	16–110	26

Jurerê Strandplain initiated progradation around 4 ka and built seaward during the following *ca.* 3000 years at an average rate of 0.82 m/yr. Assuming a strandplain thickness of 7 m, this corresponds to a net sand flux of 1.5 x 10^4 m^3/yr, with an apparent, though uncertain, acceleration in the final several hundred years (Fig. 4). Calculated sand fluxes are minimum estimates based on limited GPR data without ground-truthing nor sampling below the depth of radar penetration. It is possible that strandplain deposits extend to depths similar to those found at the nearby Pinheira Strandplain (*ca.* 15 m; Hein et al. 2015); in this case fluxes would be as high as 3.5 x 10^4 m^3/yr (Table 2).

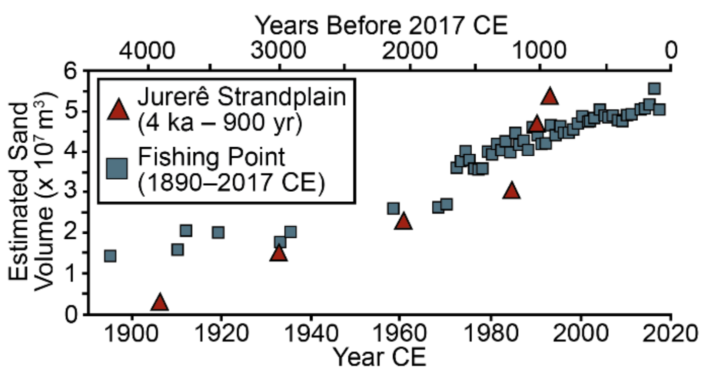

Fig. 4. Volumetric growth of Jurerê and Fishing Point over the last 4000 and 100 years, respectively.

Subaerial growth of Fishing Point began sometime after the mid-1850s, although formation of the recurved spit end, and associated coast-perpendicular ridge development, did not begin until the early 20th century. Between 1908 and the present, Fishing Point prograded nearly 2.5 km through the onshore welding of sand bars and the wind-driven growth of at least twenty distinguishable foredune ridges

(Fig. 5). Mean, long-term southerly progradation was *ca.* 24 m/yr, accelerating to 42 m/yr since the 1980s (Ciarletta et al. in review). However, because of sand loss from western Fishing Point, notably that starting in 2006 associated with rapid widening of Chincoteague Inlet, the overall volume of Fishing Point has increased roughly linearly through time at a 100-year average rate of *ca.* 26 x 10^4 m^3/yr (Fig. 4). This represents a volumetric growth rate of an order-of magnitude larger than that at Jurerê, corresponding to a modern longshore transport rate several orders of magnitude higher at Assateague Island (Table 2).

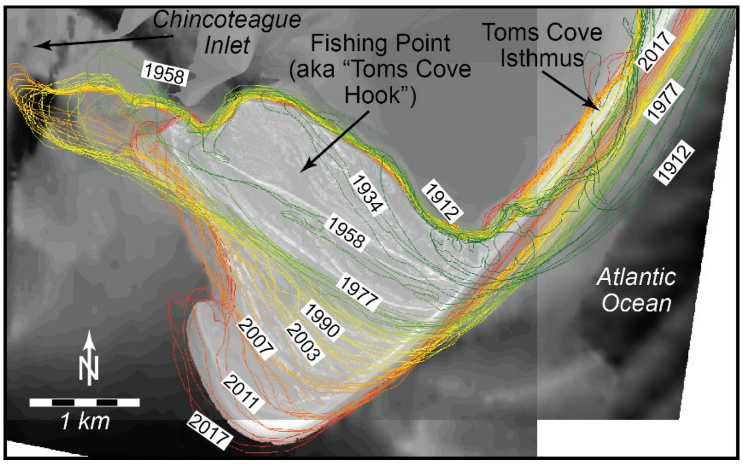

Fig. 5. Historical shoreline positions of Fishing Point (Assateague Island), 1912–2017. Data overlain on 2016 Lidar-based digital elevation model from the US Geological Survey.

Downdrift Impacts of Coastal Sediment Sinks

The growth of each the Jurerê Strandplain and Fishing Point was responsible for significant changes in downdrift coastal morphology. In northwest Ilha de Santa Catarina, the gradual filling of the Jurerê Embayment with at least 53 x 10^6 m^3 of fine to medium sand during a period of late Holocene sea-level fall created a longshore sediment sink that lasted for thousands of years. Sand fluxes to Jurerê were 2.5–5 times the modern rate of headland bypassing around Forte Headland, likely reducing longshore transport rates beyond Jurerê to near zero. However, progradation of the shoreline to a position nearly flush with bounding headlands around 1 ka allowed for accelerated transport around the headland and either initiation or acceleration of growth of the 2.8 km long, 100–700 m wide Daniela Spit (Fig. 6). Assuming that growth of Daniela began soon after Jurerê had grown to its modern configuration (*ca.* 1 ka), growth of this spit would have required an estimated 3600 m^3/yr of sediment, a flux equal to ~75 % of the modern longshore sand transport rate to Daniela (5000 m^3/yr; Vieira da Silva et al. 2016).

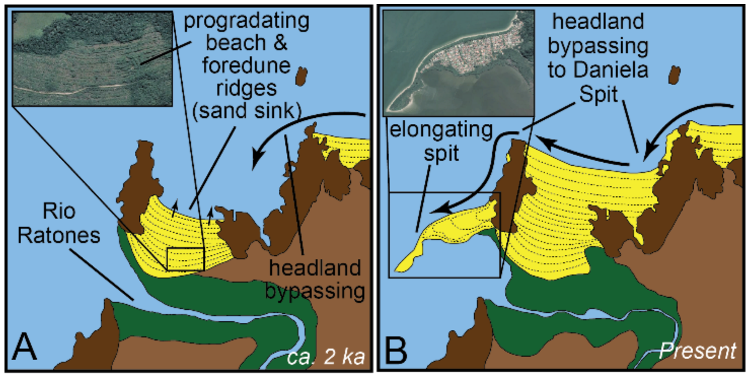

Fig. 6. Sand trapping associated with the filling of the Jurerê embayment through growth of beach and foredune ridges, starving the longshore sediment system (a). As Jurerê prograded toward the mouth of the embayment, sand could again bypass Forte headland, allowing for the formation of Daniela Spit (b).

Along southern Assateague Island, Fishing Point has grown southward by >6 km since the late 1890s, accumulating an estimated 45 x 10^6 m^3 of fine to coarse sand at a rate (2.6 x 10^5 m^3/yr) comparable to widely varying estimates of longshore transport at southern Assateague Island (1.6–11 x 10^5 m^3/yr; Finkelstein 1983; Headland et al. 1987). Even at the upper-end estimate, the growth of subaerial Fishing Point alone sequesters *ca.* 25 % of all sand reaching southern Assateague Island annually through longshore transport. Combined with the gradual southern migration of the downdrift wave shadow and associated longshore transport gradients due to elongation of Assateague Island (Jones 2016), this process starves the downdrift coast of sand, and has long been attributed to the rapid migration of the four barrier islands south of Assateague (Rice and Leatherman 1983). In fact, the growth of Assateague and Chincoteague islands over the last ~1000 years accounted for the development of a combined ~30 km^2 of progradational beach and foredune ridges. Assuming similar sediment thicknesses to those observed at Fishing Point (7 m), the < 1000-year-old parts of these barriers impound—in subaerial reservoirs alone—an estimated volume of sand (~200 x 10^6 m^3) greater than that stored in subaerial portions of all barrier islands south of Assateague, combined (~150 x 10^6 m^3) (Fig. 7); Fishing Point, formed in just the last 100 years, accounts for 20 % of this volume. This has contributed, at least in part, to the erosion (narrowing) and/or landward migration of these islands at a system-wide rate of ~5 m/yr during that time (Deaton et al. 2017).

Conclusions

Here, we present case studies from each southern Brazil and the U.S. East Coast of the growth of updrift sediment sinks in modifying longshore downdrift sediment fluxes in wave-dominated coastal systems (Table 2). Growth of the Jurerê Strandplain into a 7.5 km^2 basin sequestered ≥ 53 x 10^6 m^3 of fine to medium sand during a period of late Holocene sea-level fall, likely trapping all sand bypassed around the adjacent headland from updrift sources, and effectively starving the downdrift coast of all longshore-derived sand for 3000 years. Progradation of the shoreline towards the mouth of the embayment allowed for renewed or accelerated transport around the downdrift headland and growth of the headland-attached Daniela Spit in the last 1000 years. During this same 1000-year period, delivery of sand alongshore at a rate at least 250 times that experienced by Jurerê allowed for elongation of Assateague Island and growth of beach-ridge plains on Assateague and Chincoteague islands. This process sequestered a volume of sand greater than that comprising the 11 barrier islands south of there, combined. In particular, during just the last 100 years Fishing Point incorporated nearly as much sand as is found in all of Jurerê Strandplain, starving the downdrift island chain and contributing, at least in part, to the erosion and/or retrogradation of these islands. These findings demonstrate the potential for longshore sediment trapping through natural growth of updrift sediment sinks to control long-term and large-scale downdrift coastal behavior, and the importance of longshore sand bypassing in the balance between accommodation creation and filling.

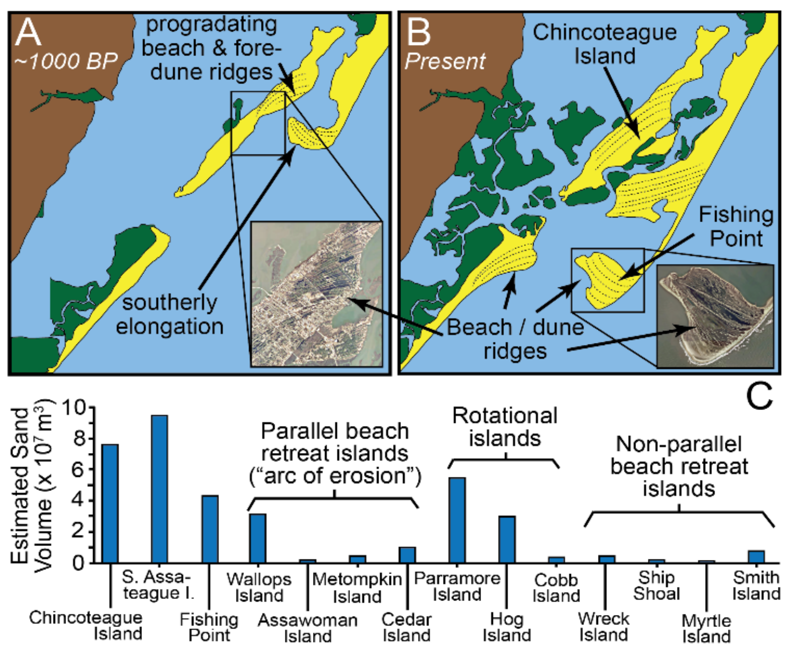

Fig. 7. The progradation and elongation of Chincoteague and Assateague islands from *ca.* 1000 years ago (a) to present (b), resulted in the trapping of sand in subaerial portions of the these islands equivalent to the volume of the entire southern Virginia barrier-island chain (c), estimated from barrier areas combined with (commonly sparse) sediment core data from Rice et al. (1976), Gayes (1983), Finkelstein and Ferland (1987), Byrnes (1988), Oertel et al. (1989), and Raff et al. (2018).

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