DROWNED FOREDUNE RIDGES AS EVIDENCE OF PRE-HISTORICAL BARRIER-ISLAND STATE CHANGES BETWEEN MIGRATION AND PROGRADATION

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Abstract: The processes driving barrier-island state changes between erosion/migration and growth/progradation are poorly understood. Stratigraphic and chronologic data are used to infer past state changes of Cedar Island, VA, USA. These data indicate that Cedar Island formed seaward of its present position approximately 5000–6000 years ago. Following a period of net landward migration, the north-central section of the island was breached prior to *ca.* 450 years ago. During this time, an extensive flood tidal delta was deposited in the backbarrier. After inlet closure, the island migrated landward atop these flood delta deposits, and aggraded, eventually entering a phase of net progradation. From 1852 to present the island has eroded and migrated landward ~1 km. The modern barrier is located stratigraphically above a shallow antecedent high (-5.5 m MSL). The state changes and antecedent geology observed here are discussed and used to infer potential future sediment sources to the island.

Introduction

Projected accelerations in sea-level rise and changes in storm frequency and intensity will likely alter barrier-island morphology and shoreline behavior. To predict and constrain future responses, recent efforts have sought to investigate the past responses of barrier islands to changes in sea level, storminess, and sediment fluxes. In particular, both field stratigraphic (*e.g.,* Raff et al. 2018) and numerical modeling (*e.g*., Duran Vinent and Moore 2015) studies have explored the processes which control changes between islands characterized by high-relief, overwash-resilient morphologies and low-relief, overwash-prone morphologies. A prime example of a low-relief barrier island is Cedar Island, Virginia (USA), which currently is actively overwashing and migrating landward at a rate of ~7 m/yr (Deaton et al. 2017).

Here, we document evidence from the stratigraphic record, including remnants of a drowned foredune ridge, which demonstrates that Cedar Island has undergone multiple state changes over the last *ca.* 450 years. We explore the drivers of this change and present a conceptual evolutionary model of barrier state changes. Additionally, we discuss potential future sediment sources to this and similar barrier systems.

Study Site

Cedar Island is an undeveloped, ~12 km long, 250 m wide, mixed-energy barrier island (Figure 1) that has undergone a series of historic breaches (Hanley and McBride 2011) and accelerating landward migration. These have together resulted in the loss through burial and/or erosion of approximately 10 km^2 of backbarrier marsh during the last 150 years (Deaton et al. 2017).

Fig. 1. (a) Study area regional map, (b) field data locations, and (c) drone photo of southern Cedar Island (credit: D. Gong)

Methods

We use a suite of over 20 vibra-, auger, and direct-push sediment cores (up to 12 m deep) to characterize the stratigraphy and document the pre-historic evolution of Cedar Island. Sediment cores were split, photographed, described for texture, mineralogy, and color (using a Munsell Soil Color Chart), and sampled for select radiocarbon-dating analyses.

Accelerator mass spectrometer radiocarbon analyses of samples were performed at the National Ocean Sciences Accelerator Mass Spectrometry Facility (Woods Hole, MA, USA). Radiocarbon ages were calibrated using OxCal 4.2 (Bronk Ramsey, 2009) which includes a reservoir correction (Table 1). Terrestrial samples (peat roots) were calibrated with the Intcal13 calibration curve (Reimer et al. 2013). Marine samples (all mollusks) were calibrated using the Marine13 curve (Reimer et al. 2013), corrected to a ΔR of 54 ± 74 years (average of northern and southern VBI values from Rick et al. [2012]).

Table 1. Radiocarbon age estimates from the Cedar Island, VA barrier-backbarrier system.

Core ID (NOSAMS ID)	**Sample Depth** (m MSL*)	**Dated Material**	**δ13C** (‰VPDB)	**Reported Age** (yrs BP)	**Cal. 2-σ Age** (yrs BP)
CEDG 03 D10 (OS-137434)	-11.42 – -11.43	wood fragment	-28.3	5,340 ± 35	6120 ± 132.5
CEDV 02 (OS-134780)	-5.89 – -5.94	*Crassostrea virginica* shell	0.05	3,350 ± 20	3130 ± 208.5
CEDV 03 (OS-134783)	-5.58 – -5.59	wood fragment	-23.22	4,650 ± 25	5407 ± 76.5
CEDV 12 (OS-134781)	-8.35 – -8.37	Terebrid shell	2.58	2,840 ± 15	2527 ± 186
CEDV 24 (OS-134785)	-1.76 – -1.78	saltwater peat	-13.95	320 ± 15	386 ± 73

* Meters below mean sea level

A sample for optically stimulated luminescence analyses was collected by insertion of 30 cm opaque PVC tubes into walls of a hand-dug pit 63.5 cm below the ground surface (Table 2). K-feldspar from the sample was prepared under dark-room conditions using standard coarse-grain procedures by R. Dewitt at the East Carolina University Department of Physics. The measurement procedure was based on the single aliquot regenerative-dose (SAR) procedure described by Murray and Wintle (2000) and Wintle and Murray (2006), adapted for feldspars. 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).

Results and Discussion

Geochronology and Stratigraphic Interpretations

Pleistocene upland and coastal sediments

The base of the stratigraphic sequence consists of a Pleistocene-age unit that ranges in depth across the backbarrier, with the shallowest deposits (approx. -4 m below mean sea level) found adjacent to the modern upland and underlying the modern barrier (Figure 2). The sedimentary texture of these deposits is heterogeneous, containing mixed fine gravel, fine to medium sand, and stiff silty clays. Along the northernmost stratigraphic transect, this unit is relatively shallow, directly underlying the modern barrier island (Figure 3).

Holocene backbarrier muds and sands

Holocene backbarrier deposits directly overlie the basal Pleistocene unit and range in thickness from 4–5 m to nearly 8 m. A thin layer (5–30 cm) of organic-rich mud (gyttja) occasionally comprises the base of the Holocene unit and dates from *ca.* 5000 to 6000 years ago. Muddier Holocene deposits associated with tidal flats and lagoons are found in the central backbarrier, while clean, medium sand—interpreted as flood tidal delta and washover deposits—is found proximal to the southern and north-central sections of the island (Figure 2). Flood tidal delta deposits on the southern cross-section of the island are part of the modern and historically stable Wachapreague Inlet, which is anchored in an ancient Pleistocene paleo-channel (Morton and Donaldson 1973). Additional flood tidal delta deposits are visible in the oblique aerial images of southern Cedar (Figure 1) and are the result of multiple historical (*ca.* 1956 to 1962, 1993 to 1997, and 1998 to 2007 CE) breaches along the island (Hanley and McBride 2011). Additionally, a large washover apron is visible, the result of overwash-driven barrier rollover (see Hanley and McBride 2011; Deaton et al. 2017).

Holocene barrier-island and shoreface sands

Modern barrier and shoreface sands are 3–6 m thick. Along north-central Cedar Island, the deepest sections of the barrier island consist of silty sand with occasional shell hash, interpreted as pre-historical inlet fill (Figures 3 and 4). This interpretation is consistent with detailed stratigraphic analyses of historical breaches which occurred elsewhere on Cedar Island and resulted in multiple inlet channel-fill sequences along the barrier island (Hanley and McBride 2011).

Table 2. OSL age estimate from the Cedar Island, VA (USA) barrier-backbarrier system.

	CED OSL 01
Depth from surface (cm)	63.5
K-feldspar grain (µm)	150-250
Aliquots measured (number)	25
Aliquots used for age (number)	23
Overdispersion (%)	3.6
U (ppm)	0.70 ± 0.05
Th (ppm)	2.10 ± 0.13
K (%)	0.96 ± 0.03
Water content (%)	22 ± 5
Dose (Gy)	0.505 ± 0.017
Dose rate (Gy/ka)	1.736 ± 0.085
Uncorrected age (a*)	291 ± 18
G-factor	3.6%/decade
Corrected age (a*)	**376 ± 34**

* where a is calendar years relative to 2016

Barrier-Island Formation and State Changes

Pre-historical island state change from retrogradation to progradation

The initial formation of Virginia's Eastern Shore barrier islands was coincident with a deceleration in relative sea-level rise to 1.6–1.7 mm/yr during the mid-to-late Holocene (Raff et al. [2018] and references therein). At Cedar Island, initial backbarrier deposition of fine sands and mud overlying coarser and stiffer pre-Holocene clayey-sands and gravels occurred *ca.* 5000–6000 years ago (Figure 2). Much of the stratigraphic record has been eliminated by reworking during transgression. Prior to ca. 450 years ago, proto-Cedar Island underwent a period of net landward migration and inlet breaching prior to *ca.* 450 years ago (Figure 5). Stratigraphic data indicate an inlet channel throat once occupied the present position of the modern north-central barrier. Both the inlet fill and relict flood tidal delta deposits indicate the barrier previously was located seaward of its present position during the pre-historical breach. While the tidal prism of the inlet is unknown, the inlet was active long enough to develop an extensive flood tidal delta (~300 m shore-perpendicular width).

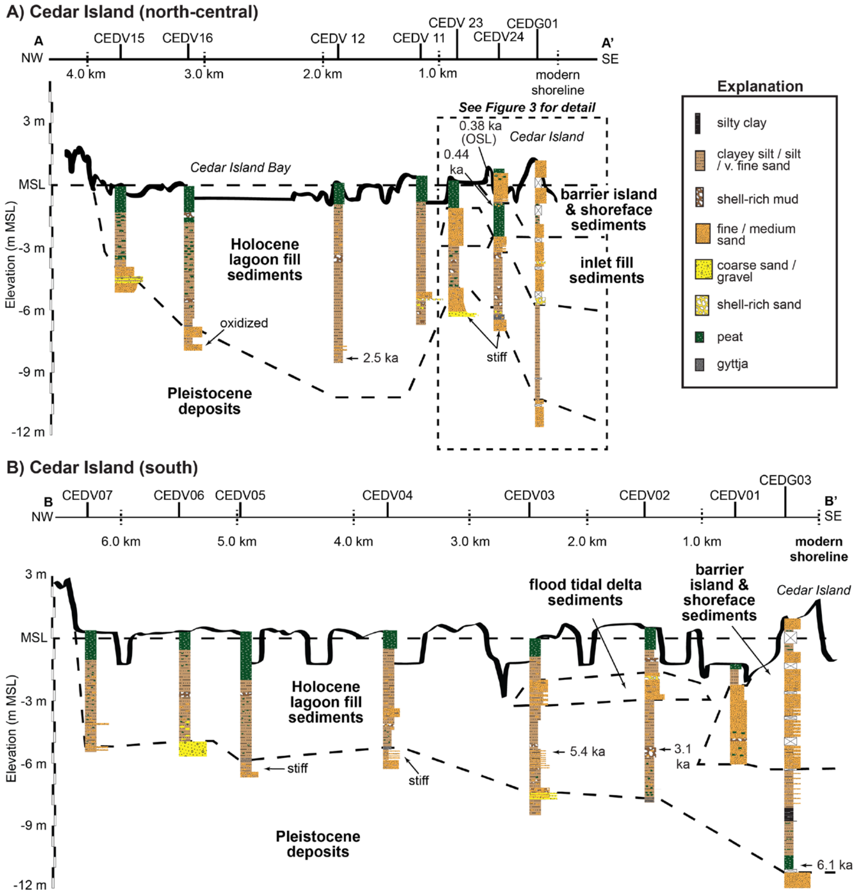

Fig. 2. Stratigraphic cross section of (a) north-central and (b) southern Cedar Island. Note the variation in the topography of the Pleistocene-Holocene unconformity between the two transects. See Figure 3 for detailed stratigraphy of the north-central island.

The north-central inlet closed and filled prior to *ca.* 450 years ago, after which a saltmarsh formed over the relict flood tidal delta, eventually forming a 0.5–1.5 m thick peat. Together, the flood tidal delta and marsh deposits provided a platform over which the barrier island migrated and eventually aggraded.

Washover fans and the presence of a relict foredune ridge (Snead's Beach) indicate the landward most position of the retrograding barrier was ~800 m landward of the modern barrier shoreline.

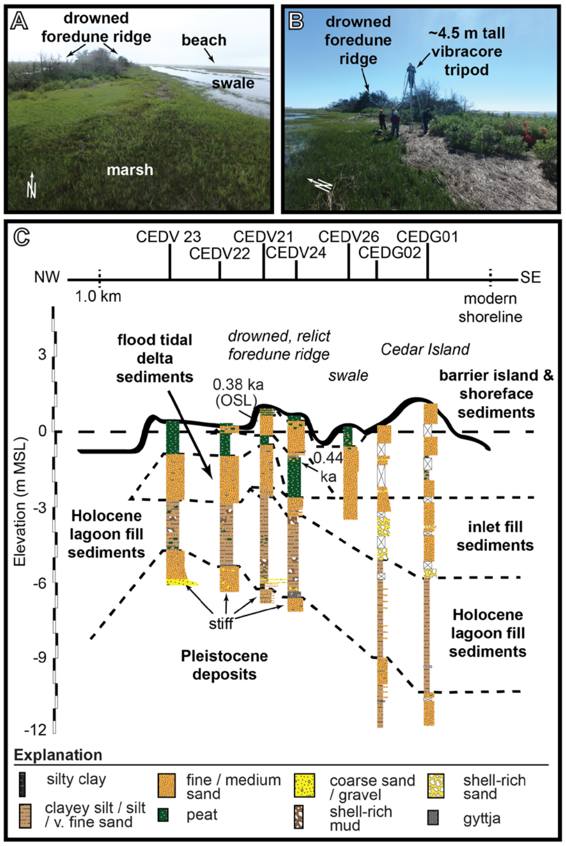

Fig. 3. (a and b) North-central Cedar Island, where a relict foredune ridge provides evidence of an island state change between migration and progradation. Photos taken by the authors. (c) Detailed stratigraphic cross-section highlighting the modern barrier island and a relict foredune ridge.

The island-proximal washover and flood tidal delta deposits along the northern section of the island are located landward of a relict foredune ridge (age: 1640 ± 34 years CE; height: ~2 m below mean sea level), indicating that, beginning *ca.* 400 years ago, Cedar Island underwent a state change from low-relief, migration-dominance to net progradational, during which it developed higher relief and greater width than in its previous state. A broad swale and at least one additional relict beach and foredune ridge set existed seaward of Snead's Beach in 1852 (U.S. Coast Survey 1852). During this period, the island reached its maximum width. While the precise maximum island width is indeterminable, Cedar Island was 1 km wider than present in 1852 (~170 years ago; Nebel et al. 2012).

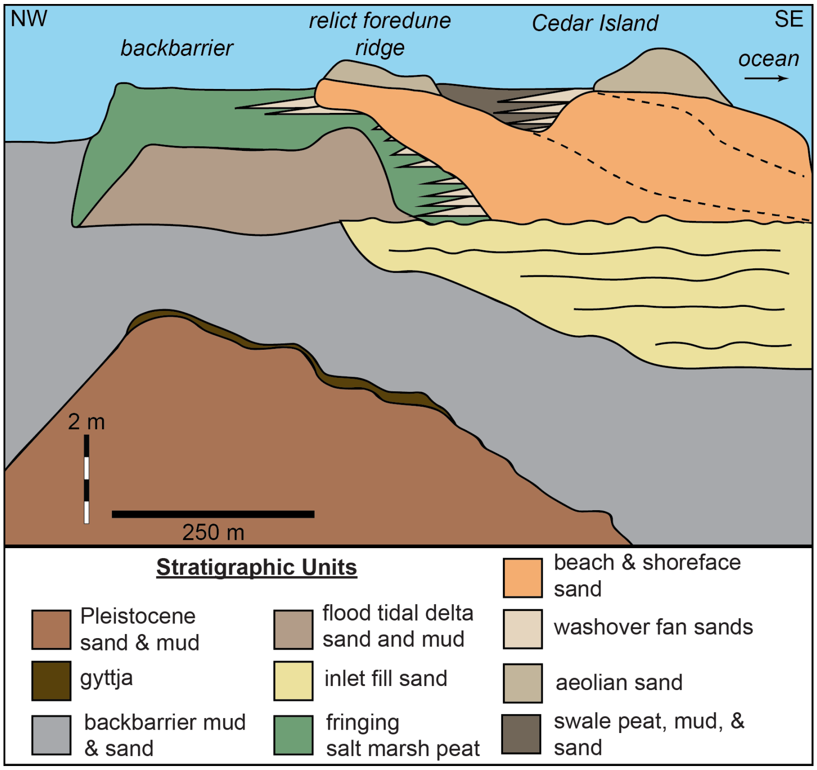

Fig. 4. Interpreted stratigraphic cross-section across northern Cedar Island, where an inlet fill sequence and flood tidal delta underly relict progradational features of the barrier island. Today, the barrier island is experiencing overwash-driven landward migration.

Historical and modern erosion and retreat

During the historical period (*ca.* 1852 to present), Cedar Island underwent another state change, becoming erosion-dominated and transitioning towards eventual island disintegration. Simultaneously, low-relief sections of the island drowned, and marsh encroached into swales between relict and modern foredunes. Historical shoreline positions highlight a phase of island narrowing and erosion (*ca.* 1852 to 1960), with an eventual phase of retrogradation (*ca.* 1960) (Gaunt 1991). Landward island migration resulted in the loss of 10 km^2 of marsh to burial or shoreface erosion (Deaton et al. 2017).

Modern and Future Sediment Fluxes: Insights from Past Changes

The Virginia coast currently experiences among the highest rates of relative sea-level rise on the U.S. Atlantic Coast (~5 mm/yr; Boon and Mitchell 2015). Projected rates of accelerated sea-level rise (Chuch et al. 2013) and the potential for increased storm frequency and intensity (Lin et al. 2012) may further destabilize the barrier islands along this sediment-starved coast. New stratigraphic data from this study constrains a range of likely future sediment sources along this coast.

Antecedent sediment sources and slopes

Antecedent slopes and topographic highs can provide nucleation points for barrier island formation (Hayes 1994) and may also provide a local offshore sediment source (Simms et al. 2006) and deposits accessible for excavation through island breaching and inlet formation (Raff et al. 2018). The presence of such topographic highs may therefore allow barrier islands, such as those fronting Virginia's Eastern Shore, to stabilize and shift from landward migration/erosion to progradation, primarily during periods of ephemeral island breaching in which tidal processes excavate sediment from shallow Pleistocene deposits (Raff et al. 2018). Stratigraphic data from this study indicate the presence of a shallow topographic high underlying modern Cedar Island, proximal enough to the surface to enable future excavation, or to have provided a past sediment source.

Additionally, the relatively steep gradient (0.7 % slope) and shallow depth of the antecedent high likely controlled backbarrier accommodation during landward island migration. Backbarrier slope can control the long-term rate of barrier-island retreat (Wolinksy and Murray 2009), but the response can be complex and depend on range of factors such as backbarrier deposition rates, backbarrier width, and substrate sediment type (Brenner et al. 2015). The presence of steep antecedent gradients and sand-rich Pleistocene substrates are expected to slow barrier migration (Brenner et al. 2015), but at Cedar Island the presence of these antecedent deposits may have contributed to forcing the island into a phase of progradation, rather than simply slowed migration. Such complex state changes are at present not captured in cross-shore barrier morphokinematic models because of an underlying assumption of constant barrier-island geometry (Ashton and Lorenzo-Trueba 2018). This thus presents an opportunity for further model refinement to capture these multi-centennial dynamics observed in the field.

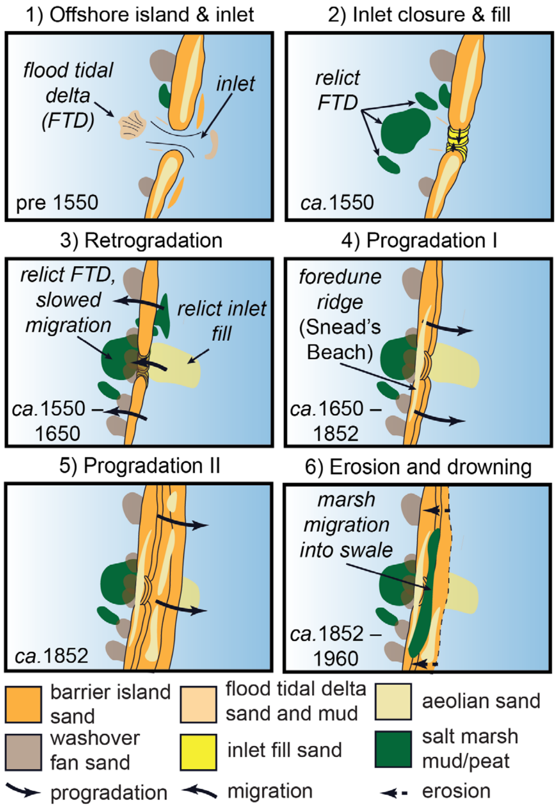

Fig. 5. Conceptual evolutionary model of north-central Cedar Island, VA, during the late Holocene.

Future change along Cedar Island may be controlled by the relative differences in substrate slope between the southern and north-central sections of the island. Along north-central Cedar, an underlying sand-rich antecedent high may provide a future sediment source as the island erodes and migrates. After this sediment reservoir is depleted, however, the island and shoreface will transgress over thick (8+ m) mud-rich Holocene backbarrier deposits and a more gently seaward-sloping Pleistocene substrate. Southern Cedar already is transgressing over similarly thick Holocene muddy backbarrier deposits and gentler Pleistocene substrate slope, suggesting a future island-wide shift to more rapid migration.

Flood tidal delta deposits

Through the development of flood tidal deltas at ephemeral or newly formed tidal inlets, sediment is removed from the longshore transport system and transferred to the backbarrier lagoon, thus presenting an important barrier-island sediment sink (*e.g.*, Morton and Donaldson 1973). Given sufficient sediment supply, the formation and longshore migration of tidal inlets, and the attendant development of flood tidal deltas, can contribute to barrier aggradation and stability (Simms et al. 2006). In contrast, inlet migration can also drive barrier-island transgression: flood tidal deltas grow volumetrically at rates 1.5 times the longshore sediment flux, thus starving the adjacent beach and shoreface of sediment and forcing net landward movement of a barrier island (Nienhuis and Ashton 2016).

Flood tidal development along north-central Cedar Island prior to *ca.* 450 years ago transported sand at least 300 m landward of the then-active inlet channel throat. Similarly, flood tidal delta deposits associated with the ephemeral inlet open between *ca*. 1998 and 2007 along southern Cedar Island extend upwards of 400 to 600 m landward of the relict inlet channel throat (Hanley 2015). While contributing to net landward movement of the barrier through sediment transport into the backbarrier, the flood tidal delta sands overlying marsh deposits also decreased accommodation, allowing for aggradation and slowed migration of the barrier. In this way, relict flood tidal delta deposits may act similarly to fringing backbarrier marshes which ultimately reduce barrier-island migration rates (Walters et al. 2014).

Conclusions

The state changes of Cedar Island documented in this study provide a model for multiple pre-historical and historical transitions from barrier retrogradation to progradation, and, finally, to renewed transgression and rapid landward migration (rollover). In particular, we document the effects of a Pleistocene-age antecedent high on backbarrier accommodation during mid-to-late Holocene transgression. Furthermore, we demonstrate that a relict flood tidal delta likely acted to reduce backbarrier accommodation and may have resulted in a period of barrier aggradation, followed by a period of progradation. Historical evidence from this and previous studies demonstrates more recent erosion of the island shoreline followed by wholesale barrier rollover. As Cedar Island continues to migrate landward, the growth of flood tidal deltas associated with new inlet breaches—such as those which occurred on multiple occasions during the last *ca*. 50 years—will provide an important mechanism for the import of sand to the backbarrier, thereby acting as an alongshore sediment sink and starving downdrift islands.

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References

Ashton, A. D., and Lorenzo-Trueba, J. (2018). “Morphodynamics of barrier response to sea-level rise,” in L. J. Moore & A. B. Murray (Eds.), “Barrier Dynamics and Response to Climate Change,” Springer International Publishing, 395 p.

Boon, J. D., and Mitchell, M. (2015). “Nonlinear change in sea level observed at North American tide stations,” *Journal of Coastal Research*, 316(6), 1295–1305.

Brenner, O. T., Moore, L. J., and Murray, A. B. (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, 334–350.

Bronk Ramsey, C. (2009). “Bayesian analysis of radiocarbon dates,” *Radiocarbon*, 51(1), 337–360.

Church, J. A. et al. (2013). “Sea level change,” in Stocker, T. F., Qin, D., Plattner, G.-K., et al. (Eds.), “Climate Change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change”, Cambridge University Press, Cambridge, 1137–1216.

Deaton, C., Hein, C., Kirwan, M. (2017). “Barrier island migration dominates ecogeomorphic feedbacks and drives salt marsh loss along the Virginia Atlantic Coast, USA,” *Geology,* 45(2), 123–126.

Duran Vinent, O., Moore, L. (2015). “Barrier island bistability induced by biophysical interactions,” *Nature Climate Change*, 5, 158–162.

Gaunt, C.H., (1991). “Recent evolution and potential causal mechanisms of Cedar Island, Virginia, 1852–1986,” *Proceedings of the Specialty Conference on Quantitative Approaches to Coastal Sediment Processes*, ASCE, 2335–2349.

Hanley, J., McBride, R. (2011). “Repetitive breaching on Cedar Island, Virginia, USA: History, geomorphology, and deposits,” *Proceedings of the Coastal Sediments 2011*, World Scientific Press, 149–162.

Hanley, J. (2015). “Stratigraphic architecture, morphodynamics, and evolution of breaches along Cedar Island, VA: A low-profile, washover-dominated, transgressive barrier island”, Ph.D. Dissertation, pp. 377.

Hayes, M. O. (1994). “The Georgia Bight barrier system,” in R. A. Davis (Ed.), “Geology of Holocene Barrier Island Systems,” Springer, 233–304.

Lin, N., Emanuel, K., Oppenheimer, M., and Vanmarcke, E. (2012). “Physically based assessment of hurricane surge threat under climate change,” *Nature Climate Change*, 2(6), 462–467.

Morton, R. A., and Donaldson, A. C. (1973). “Sediment distribution and evolution of tidal deltas along a tide-dominated shoreline, Wachapreague, Virginia,” *Sedimentary Geology*, 10(4), 285–299.

Nebel, S. H., Trembanis, A. C., and Barber, D. C. (2012). “Shoreline Analysis and Barrier Island Dynamics: Decadal Scale Patterns from Cedar Island, Virginia,” *Journal of Coastal Research*, 280(2), 332–341.

Nienhuis, J. H., and Ashton, A. D. (2016). “Mechanics and rates of tidal inlet migration: Modeling and application to natural examples,” *Journal of Geophysical Research: Earth Surface*, 2118–2139.

Murray, A. S., and Wintle, A. G. (2000). “Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol,” *Radiation Measurements*, 32(1), 57–73.

Raff, J., Shawler, J., Ciarletta, D., Hein, E., Lorenzo-Trueba, J., Hein, C. (2018). “Insights into barrier-island stability derived from transgressive/regressive state changes of Parramore Island, Virginia,” *Marine Geology*, 403, 1–19.

Reimer, P.J. et al. (2013). “IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 Years cal BP,” *Radiocarbon*, 55(4), 1869–1887.

Rhodes, E. J. (2011). “Optically stimulated luminescence dating of sediments over the past 200,000 years.” *Annual Rev. Earth Planetary Sci.,* 39, 461–488.

Rick, T. C., Henkes, G. A., Lowery, D. L., Colman, S. M., and Culleton, B. J. (2012). “Marine radiocarbon reservoir corrections (ΔR) for Chesapeake Bay and the Middle Atlantic Coast of North America,” *Quaternary Research*, 77(1), 205–210.

Simms, A. R., Anderson, J. B., and Blum, M. (2006). “Barrier-island aggradation via inlet migration: Mustang Island, Texas,” *Sedimentary Geology*, 187, 105–125.

U.S. Coast Survey (1852). Sea Coast of Virginia, Accomac County, from Gargathy to Wachaprigue Inlet

Walters, D., Moore, L. J., Duran Vinent, O., Fagherazzi, S., and Mariotti, G. (2014). “Interactions between barrier islands and backbarrier marshes affect island system response to sea level rise: Insights from a coupled model,” *Journal of Geophysical Research: Earth Surface*, 119(9), 2013–2031.

Wintle, A. G., and Murray, A. S. (2006). “A review of quartz optically stimulated luminescence characteristics and their relevance in single-aliquot regeneration dating protocols,” *Radiation Measurements*, 41(4), 369–391.