

HOLOCENE BENTHIC FORAMINIFERAL ASSEMBLAGES OF TIDAL-INLET
DEPOSITS ALONG CEDAR ISLAND, VA, USA: INSIGHTS INTO STORM
IMPACTS, BREACH DYNAMICS, AND INLET EVOLUTION

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A Thesis submitted in partial fulfillment of the requirements for the degree of Master of
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DEDICATION

This thesis is dedicated to my incredible husband Joel and delightful daughter Charlotte.

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ABSTRACT

HOLOCENE BENTHIC FORAMINIFERAL ASSEMBLAGES OF TIDAL-INLET DEPOSITS ALONG CEDAR ISLAND, VA, USA: INSIGHTS INTO STORM IMPACTS, BREACH DYNAMICS, AND INLET EVOLUTION

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Cedar Island, VA is a low-profile, mixed energy, rapidly transgressing, barrier island that has breached and formed an ephemeral inlet (Cedar Island Inlet) at least three times in the past sixty years. Historical charts, air photos, satellite imagery, and geomorphic features indicate that Cedar Island Inlet was open from 1956-1962, 1992-1997, and 1998-2007 and was wave-dominated. Nonetheless, the sedimentary record of Cedar Island Inlet, including benthic foraminiferal deposits offers unique insights beyond the current known scope of Cedar Island Inlet activity.

Benthic foraminiferal analyses of three sediment vibracores, from the final 1998-2007 Cedar Island Inlet position, reveal detailed information about inlet dynamics and lifecycle evolution. Four foraminiferal biofacies were identified through cluster analysis and compared with similar studies performed along the U.S. Atlantic coast to determine the depositional environment(s) associated with each biofacies. Accordingly, four depositional environments including inlet channel floor, flood-tidal delta/inlet fill, high

energy inlet fill, and washover/beach/aeolian were identified. *Elphidium excavatum* dominates environments low in organics, with sandy substrates, and a range of marine salinities like those found associated with Cedar Island Inlet. Accordingly, *Elphidium excavatum* dominates each of the biofacies and comprises 54-100% of all non-barren samples. The inlet channel floor assemblage is characterized by low abundances, and the largest proportions of a secondary species, *Haynesina germanica*. Flood-tidal delta/inlet fill contains an abundant, heterogeneous mixture of shelf and estuarine species including *Buccella frigida*, *Ammonia parkinsoniana*, *Haynesina germanica*, and the only agglutinated species, *Trochammina inflata*. The high energy inlet fill biofacies is characterized by low abundances and low diversity and contains predominately shelf species including *Elphidium gunteri*. Washover/beach/aeolian biofacies also exhibit low abundances and low diversity and contain shelf species including *Buccella frigida*, and *Elphidium mexicanum*, as well as euryhaline species, *Ammonia parkinsoniana*. A fifth depositional environment, which includes all barren samples, was identified as a quiescent estuary.

The stratigraphic positions of the foraminiferal biofacies within the cores revealed a previously undiscovered inlet fill/flood tidal delta deposit which may be attributed to the earliest inlet (1956-1962) or an inlet prior to the known scope of Cedar Island Inlet activity (i.e., 1956). Additionally, foraminiferal biofacies distribution and newly obtained historical and satellite imagery reveal that, contrary to previous Cedar Island Inlet lifecycle models, the wave-dominated tidal-inlet does not follow a prescribed lifecycle where the inlet opens, migrates in the direction of net longshore transport, rotates

counterclockwise, and closes. Instead, each of the last three Cedar Island Inlet lifecycles has exhibited a different rotational mode of the wave-dominated inlet lifecycle model including clockwise rotation (1956-1962 inlet), no rotation (1992-1997 inlet), and counterclockwise rotation (1998-2007 inlet). Each Cedar Island Inlet experienced a unique lifecycle where the degree of migration and rotation was determined by differing tidal prisms, accommodation space availability, and flood-tidal delta morphologies.

INTRODUCTION

Statement of Purpose

Barrier island systems are characterized by the presence of six coastal sedimentary environments including: (1) mainland, (2) backbarrier lagoon, (3) tidal inlets and their associated flood and ebb-tidal deltas (4) barrier island, (5) barrier platform, and (6) shoreface (Oertel, 1985). The barrier island component is defined as a subaerial body of unconsolidated sand or gravel that is bounded by inlets and flanked by the shoreface and backbarrier lagoon or estuary (Komar, 1976; Oertel, 1985). Many barrier islands are currently undergoing erosional thinning and increased island breaching because of reduced supply, rising sea level, and increased storm duration and intensity (Greenwood and Keay, 1979; Davis and Fitzgerald, 2004; Emanuel, 2005; Nebel et al., 2013; Seminack and McBride, 2015). Island breaching can occur through retrogradation of islands thinned by erosion, large incising storm waves, or elevated bay water levels (storm surge), which excavate a channel (Pierce, 1970; Kraus, 2003; Richardson and McBride, 2011). Barrier island breaches remain active for short periods (weeks, months) and are closed by longshore sediment transport (Kraus et al., 2002; Buynevich and Donnelly, 2006; Seminack and McBride, 2015). However, if a breach captures sufficient tidal prism from neighboring inlets, a new tidal inlet will be established and remain active for long periods (years, decades, etc.) (Kraus et al., 2002; Seminack and McBride, 2015).

Frequent breaching occurs on Cedar Island, Virginia in response to storm impacts. Over the past 60 years, three ephemeral inlets formed approximately 3.5 km north of Wachapreague Inlet (Moyer, 2007; Richardson and McBride, 2011; Nebel et al., 2013; Hanley, 2015). Cedar Island Inlet exhibits a distinct pattern or lifecycle; specifically, each time the inlet forms it typically migrates south in the direction of net longshore sediment transport, rotates counterclockwise, and closes (Hanley, 2015).

Tidal inlets serve as a conduit for water and sediment to be exchanged between the open ocean and estuary. When a new tidal inlet is established, an influx of normal marine salinity water enters the estuary, which alters the environmental conditions (Robinson and McBride, 2006). Additionally, the establishment of new tidal inlets includes the creation of new depositional environments, such as flood and ebb-tidal deltas.

Benthic foraminifera are epifaunal and infaunal protists, which are sensitive to environmental changes, such as salinity, temperature, turbidity, dissolved oxygen, and tidal energy (Murray, 2006). Benthic foraminiferal species require specific environmental conditions to maintain cellular functions and build tests (Sen Gupta, 1999). When calcareous and agglutinated foraminifera die, their tests remain and can be preserved as part of the sedimentary record. Thus, deposited benthic foraminifera have been successfully used to identify past environmental conditions resulting in detailed facies identification and system processes (Culver et al., 1996; Leckie and Olson, 2003). Specifically, benthic foraminifera were previously used to identify barrier island depositional subenvironments, such as salt and brackish marshes, estuarine tidal flats and

marshes, bars, washover fans, flood and ebb-tidal deltas, shoreface, and tidal inlets (Culver et al., 1996; Robinson and McBride, 2006, 2008; Smith et al., 2009; Pruitt et al., 2010).

Grossman and Benson, 1967; Culver and Horton, 2005; Abbene et al., 2006; Vance et al, 2006 studied the foraminifera of long-established tidal inlets, flood-tidal deltas, estuaries, and marshes; however, few studies examine the foraminifera of barrier island breaches and ephemeral tidal-inlet deposits. Several papers examine how the opening of a breach impacts associated features such as estuaries and flood-tidal deltas. For example, Robinson and McBride (2006) observed stark changes in foraminiferal assemblages of the Old Currituck Inlet flood-tidal delta deposits, which supported historical records of the opening and closing of Old Currituck Inlet. Additionally, Grand Pre et al. (2011) determined that normal marine salinity water likely entered Pamlico Sound, NC during two breaching events (4100 to 3700 and 1150 to 500 cal yr BP) as evidenced by distinct changes in foraminiferal assemblages. These studies demonstrate the impacts of breaches on surrounding subenvironments; however, these studies did not specifically examine the foraminiferal assemblages of breach or inlet deposits.

The purpose of this study is to examine the benthic foraminiferal assemblages of ephemeral tidal inlets of Cedar Island, VA, and their associated sedimentary deposits to determine the progression of depositional environments, inlet activity phases, and develop a high-resolution life-cycle model of a wave-dominated tidal inlet. This study will utilize samples from three of 18 previously collected sediment vibracores from the now closed Cedar Island Inlet as part of a dissertation by Hanley (2015). The benthic

foraminiferal assemblages within the sediment cores preserved a record of inlet dynamics and evolution. Through studying these foraminifera, a more accurate geologic interpretation of the subsurface deposits can be determined and yield a detailed depositional model of island breaching and the lifecycle of a wave-dominated tidal inlet (i.e., from inlet opening to closing).

Scope of Study

The principal focus of this study is Cedar Island, Virginia and Cedar Island Inlet, which are located along the Virginia portion of the Delmarva Peninsula (Figure 1). The now closed Cedar Island Inlet has a relict inlet channel and the sedimentary deposits are examined through subsampling previously collected sediment vibracores. The sedimentary facies of the vibracores were previously identified and depositional models for wave-dominated tidal inlets were developed by Hanley (2015) and Seminack (2016). However, here three of the vibracores (C1, C2, and C12), which form a transect across the relict inlet throat and flood-tidal delta, are subsampled for benthic foraminiferal assemblages.

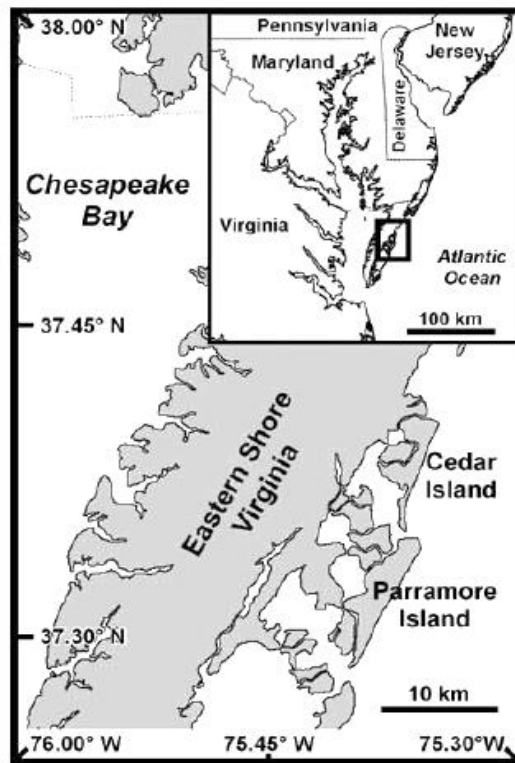


Figure 1: Cedar Island, VA, is a 10.5 km long barrier located along the southern portion of the Delmarva peninsula (figure from Nebel et al., 2013).

Research Questions and Multiple Working Hypotheses

Barrier island systems exhibit distinct geomorphic features and depositional subenvironments, such as tidal inlets, washover fans, flood and ebb-tidal deltas, and estuaries (Oertel, 1985). These subenvironments are also characterized by varying abiotic factors such as system energy, temperature, turbidity, and salinity (Sen Gupta, 1998; Davis and Fitzgerald, 2004). Abiotic factors play a fundamental role in determining the type of organisms, such as benthic foraminifera, that live in the barrier island subenvironments. Specifically, temperature, salinity, and dissolved oxygen

concentrations determine foraminiferal species distribution by impacting foraminiferal osmotic processes, foraminiferal test densities, and viscosity of protoplasm (Sen Gupta, 1999; Murray, 2006). Therefore, two research questions are: 1) how are the estuarine environmental conditions impacted when a barrier-island breach opens as reflected by the benthic foraminiferal assemblage found in the breach deposits and 2) what benthic foraminiferal assemblages characterize breach deposits associated with Cedar Island Inlet? We hypothesize benthic foraminiferal assemblages deposited prior to and after Cedar Island Inlet should contrast with those deposited while the inlet was open. Specifically, higher occurrences of normal marine species will likely be found in sediments deposited while the inlet was open because of the incursion of normal marine salinity water.

Barrier island subenvironments have unique sedimentary facies, which can be determined through examining grain size, shape, and composition, as well as sand to silt to clay ratios. The sedimentary facies of the Cedar Island vibracores were previously identified by Hanley (2015), whereas the foraminiferal biofacies are identified in this study. Thus, the final questions being addressed include: 1) are the sedimentary facies and biofacies correlated in breach deposits of Cedar Island and 2) do sedimentary facies or biofacies provide higher resolution information about lifecycles of ephemeral wave-dominated tidal inlets along Cedar Island? Sedimentary facies and biofacies may be relatively correlated because both facies are sensitive to changes in the energy of the environment as the inlet lifecycle evolves. However, benthic foraminifera are also

sensitive to changes in salinity, temperature, turbidity, and dissolved oxygen, which we hypothesize may provide higher resolution insights into inlet dynamics.

Goals and Scientific Objectives

The goals of this research are to document the response of benthic foraminiferal assemblages to changing estuarine environmental conditions caused by island breaching and to identify diagnostic benthic foraminifera that characterize breach and inlet-fill deposits associated with a wave-dominated tidal inlet. The main objective of these efforts is to identify the benthic foraminiferal assemblages of Cedar Island inlet deposits. The second objective is to determine how benthic foraminifera respond to changing environmental conditions introduced during island breaching (i.e., pre-breach, during breach, and post breach) and throughout the lifecycle of a wave-dominated tidal inlet. The final objective is to compare and contrast the identified foraminiferal biofacies with the sedimentological facies and interpret the activity phases and lifecycle of Cedar Island inlet, a wave-dominated tidal inlet.

Significance

The purpose of this research is to examine benthic foraminiferal assemblages of sediment vibracores from Cedar Island inlet to accurately interpret the depositional environments (estuary, flood-tidal delta, inlet channel, or washover/beach). Foraminiferal assemblages were previously used to identify barrier island depositional subenvironments, such as salt and brackish marshes, estuarine tidal flats and marshes,

bars, washover fans, flood and ebb-tidal deltas, shoreface, and tidal inlets; however, few studies examine breach and ephemeral inlet deposits (Culver et al., 1996; Robinson and McBride, 2006, 2008; Smith et al., 2009; Pruitt et al., 2010). Thus, the Cedar Island Inlet samples offer a unique opportunity to examine breach and ephemeral inlet deposits and foraminiferal assemblages. These data will aid in the understanding of wave-dominated inlet dynamics and lifecycles because the changing foraminiferal assemblages will demonstrate the progression of depositional environments.

Barrier island breaches form in response to storm impacts, and a marked increase in storm durations and intensities has occurred in the last 30 years (Emanuel, 2005). Similarly, recent relative sea level rise produced greater tidal prisms, which promotes barrier island breaching because more inlets are required to facilitate tidal exchange (Hesp and Short, 1999). Storm trends and relative sea level rise are projected to continue and will fuel higher rates of island breaching. Therefore, it is useful to document foraminiferal assemblages and sedimentary deposits of past breaches to better understand future lifecycles of wave-dominated tidal inlets because these phenomena should be more common in the future.

REGIONAL SETTING

Cedar Island lies along the Delmarva Peninsula coast, which includes portions of Delaware, Maryland, and Virginia (Figure 2). The Chesapeake Bay is located to the west of the peninsula and Atlantic Ocean is to the east; while the Delaware Bay is north of the peninsula and the mouth of the Chesapeake Bay is to the south (Figure 2). Cedar Island is located along the eastern-most portion of the Coastal Plain province of Virginia.

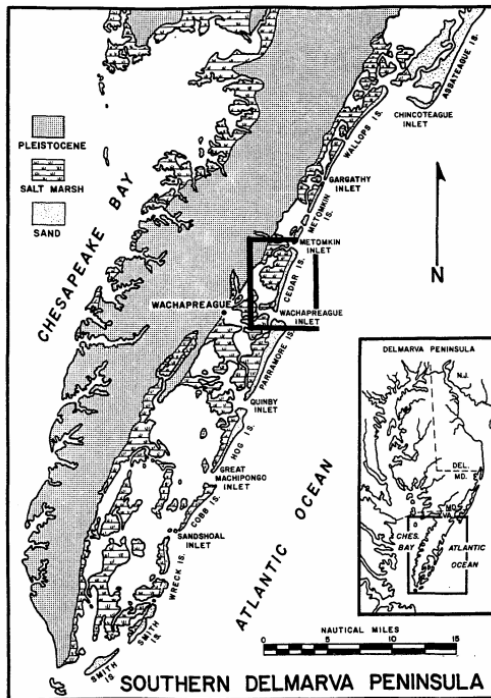


Figure 2: Map of the southern portion of the Delmarva Peninsula with Cedar Island outlined (from Heinsius, 1974).

The Delmarva Peninsula is part of a geologically mature, Amero-trailing edge coast, which is characterized by a wide gently sloping shelf that formed during high sedimentation rates following the breakup of Pangaea (Inman and Nordstrom, 1971). Detritus shed from the ancient Appalachian Mountains was reworked during Cretaceous transgressions and regressions to form a consolidated underlying base, known as the Potomac formation (Heinsius, 1974). Tertiary sediments from the Pliocene and Miocene, including clay, silt, sand, and gravel overlay the Cretaceous deposits, while fluvial and littoral deposits from the Pleistocene overlay Pliocene and Miocene deposits (Heinsius, 1974). These pre-Holocene deposits are approximately 5,250 m thick (Cushing et al., 1973). The surface, Holocene deposits, which include the barrier island, salt marsh, tidal flats, and open bay, were formed 4,000-7,000 years ago, when the rate of sea level rise slowed (Figure 3; Figure 4; Newman and Munsart, 1968;).

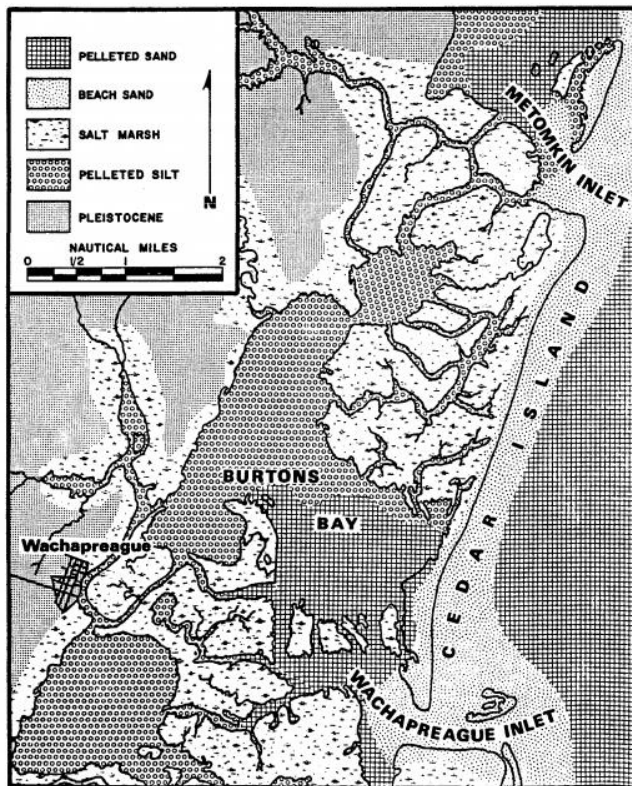


Figure 3: A map showing the sedimentary subenvironments of Cedar Island (from Heinsius, 1974)

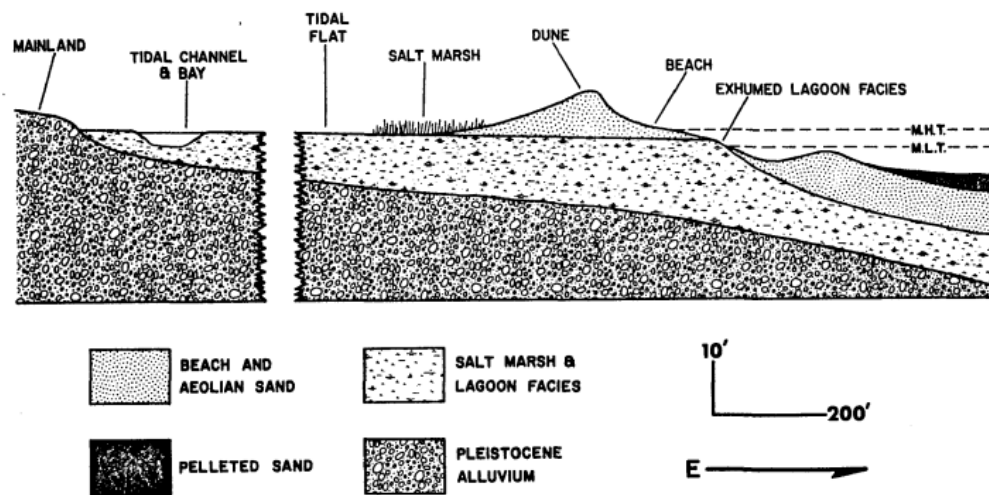


Figure 4: A general cross-section illustrating the sedimentary subenvironments of Cedar Island (from Heinsius, 1974)

Cedar Island lies within a barrier island system that spans most of the U.S. Atlantic coast (Figure 5; Oertel and Kraft, 1994). Cedar Island is part of a mixed-energy tide-dominated barrier island system that includes Wallops, Assawoman, and Metompkin islands to the north, and Parramore, Hog, Cobb Wreck, Ship Shoal, Myrtle, Smith, and Fisherman Islands to the south (Figure 2; Figure 6; Leatherman, 1982; Oertel and Kraft, 1994; Oertel et al., 2008). The barrier island system is subdivided geographically, including a northern portion (Wallops, Assawoman, Cedar, and Metompkin islands) within a 35 km arc of erosion (Chincoteague Bight) caused by the sediment trapping and progradation of the recurved-spit complex at the southern end of Assateague Island, VA (Galgano, 2007, 2009; Richardson, 2012; McBride et al., 2015). The middle portion of the barrier island system (Parramore, Hog, and Cobb islands) includes shorter drumstick shaped, mixed energy, tide-dominated barrier islands that exhibit minor clockwise rotation (Leatherman, et al. 1982; Richardson, 2012; McBride et al., 2015). Finally, the southern portion (Wreck, Ship Shoal, Myrtle, Smith, and Fisherman islands) includes small islands that are heavily tidally influenced (Leatherman et al., 1982; Richardson, 2012). Low order interfluves are the sediment source for the barrier island complex and influence island spacing and location (Oertel and Kraft, 1994).

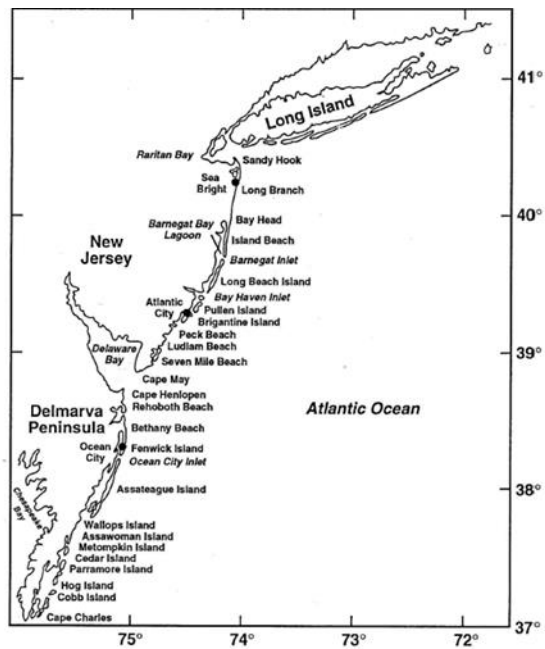


Figure 5: A map detailing the New Jersey and Delmarva barrier islands (Oertel and Kraft, 1994).

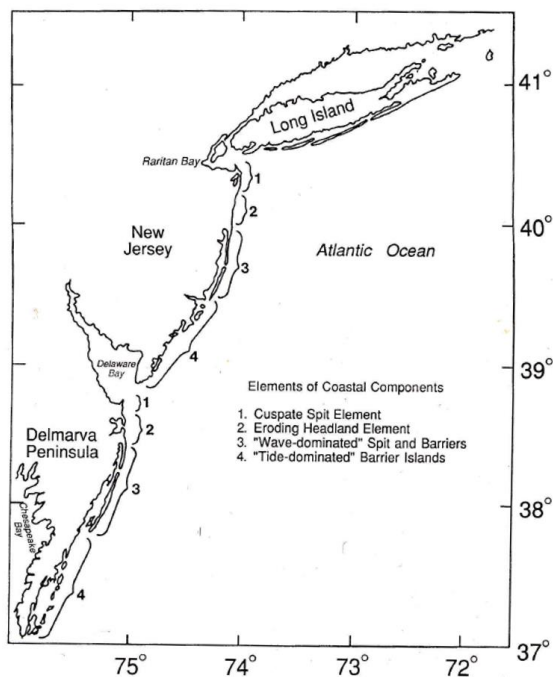


Figure 6: Shoreline types along the coasts of New Jersey and the Delmarva Peninsula (Oertel and Kraft, 1994).

Area of Investigation

Cedar Island is a 10.5 km long, low profile (maximum elevation is less than 3 m above mean sea level), mixed energy, washover dominated, transgressive barrier island (Newman and Munsart, 1968; Nummedal, 1983; Gaunt, 1991; Richardson and McBride, 2011; Fenster and McBride, 2015; Richardson et al., 2015; Hanley et al. 2015, Hanley, 2015; Seminack 2016) The northern end of Cedar Island is separated from Metompkin Island by Metompkin Inlet, and the southern end of Cedar Island is separated from Parramore Island by Wachapreague Inlet (Figure 7). The landward side of the northern two thirds of Cedar Island is dominated by tidal salt marsh, whereas the landward side of the southern third of the island is dominated by an open bay called Burton's Bay (Figure 8). Cedar Island is undeveloped making it an ideal location to study natural barrier island processes, including shoreline migration and breaching events (Richardson and McBride, 2011; Nebel et al., 2012, 2013).



Figure 7: Satellite image of Metompkin Island, Metompkin Inlet, Cedar Island, Wachapreague Inlet, and Parramore Island, VA (Google Earth, 2017)

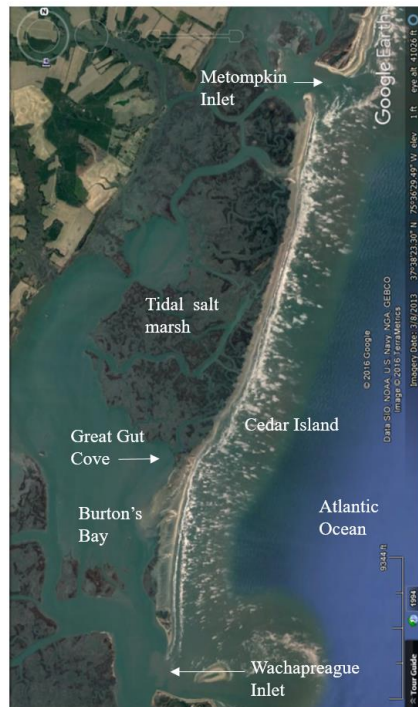


Figure 8: The southern third of Cedar Island is backed by Burton's Bay, which is separated from the northern tidal salt marsh by Great Gut Cove. Cedar Island is bounded by Metompkin Inlet to the north and Wachapreague inlet to the south. (Google Earth, 2017).

Cedar Island has a thin and flat morphology that makes it susceptible to breaching. Since 1956, the southern, open bay backed portion of Cedar Island has been breached at least three times (Figure 9; Table 1; Moyer, 2007). During each breach, an inlet has been established, migrated in the direction of net longshore sediment transport, rotated counterclockwise, experienced hydraulic inefficiency, and closed (Moyer, 2007; McBride et al., 2015; Hanley, 2015).

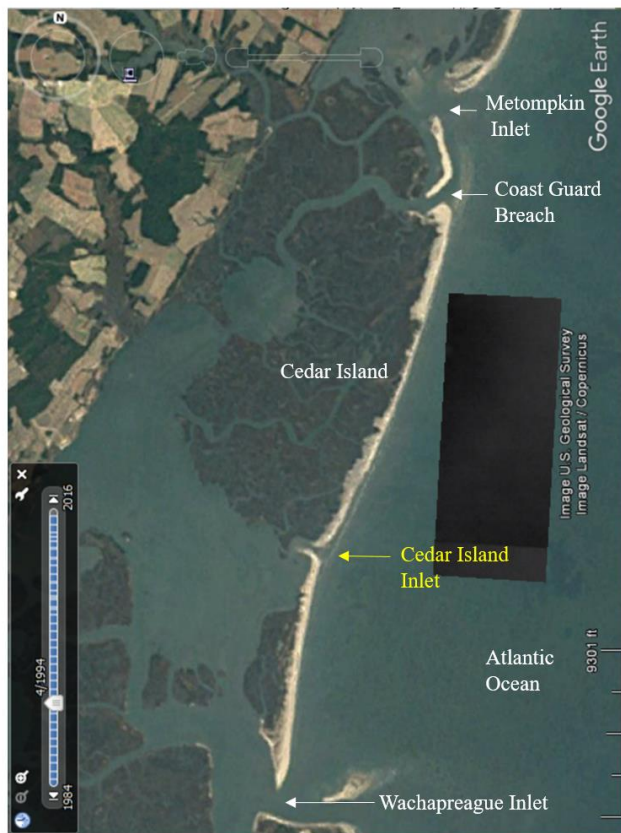


Figure 9: Satellite image of Cedar Island Inlet location on April 4, 1994 (Google Earth, 2017).

Table 1: The record of Cedar Island ephemeral inlet activity since 1956 (from Moyer, 2007).

TIME	STATUS	LIKELY CAUSE
January 1956	Open	January 8-12 Northeaster
March 1962	Closed	March 6-8, “Ash Wednesday Storm”
March 1993	Open	March 12-15 Northeaster
July 1997	Closed	July 24-25 TS Danny
Jan/Feb 1998	Open	Jan 27-28 and/or Feb. 3-5 Northeasters
Dec 2006 or Jan 2007? (confirm closed April 28, 2007)	Closed	Healing by normal coastal processes?

Coastal Processes

Table 2 details the specific coastal processes impacting the study area. Directly south of Cedar Island, Wachapreague inlet has a mean tidal range of 1.22 m, diurnal tidal range of 1.37 m, relative sea-level rise of 5.37 mm/yr, and a tidal prism of $5.64 \times 10^7 \text{ m}^3$ (Richardson et al., 2015; NOAA 2015a; NOAA 2015b). Eustatic sea level rise is 3.2 mm/yr and subsidence is 1.2 mm/yr (IPCC, 2014; Engelhart et al., 2009). The tidal ranges of Burton’s Bay and the tidal salt marsh landward of Cedar Island are relatively equal to the ocean tides; however, these backbarrier areas experience a 15-minute lag time (Figure 8; Oertel and Kraft, 1994).

Table 2: Coastal processes operating along the Cedar Island and Parramore Island

Coastal process	Value	Source
Mean tidal range	1.22 m	NOAA (2015a)
Diurnal tidal range	1.37 m	NOAA (2015a)
Eustatic sea-level rise (1993-2010)	3.2 mm/yr	IPCC (2014)
Relative sea-level rise (1978-2015, Wachapreague, VA)	5.37 mm/yr	NOAA (2015b)
Subsidence rate (Maryland)	1.2 mm/yr	Engelhart et al. (2009)
Wachapreague Inlet tidal prism (2013)	$5.64 \times 10^7 \text{ m}^3$	Richardson et al. (2015)

Relative Sea-Level Rise Rates (NOAA Tide Gage Stations)

Rising relative sea level rates of the mid-Atlantic region are fueled by isostatic subsidence of the region because of glacial forebulge collapse caused by the melting of continental glaciers (i.e., loss of weight) resulting in isostatic rebound in the Hudson Bay area and isostatic subsidence in Virginia (i.e., seesaw effect), as well as eustatic increases from glacier meltwater draining into the oceans (Figure 10; Table 3; Engelhart et al., 2011). Mid-Atlantic tide gage stations from Atlantic City, NJ to Portsmouth, VA indicate the first and second highest rates of relative sea level rise occur to the south (Chesapeake Bay Bridge Tunnel; 5.95 mm/yr) and north (Ocean City Inlet; 5.6 mm/yr) of Cedar Island (Figure 10; Table 3; NOAA, 2015c). Wachapreague Inlet, directly south of Cedar Island, experienced the third largest rise in relative sea level (Figure 10; Table 3; 5.37 mm/yr) (NOAA, 2015c). Therefore, Cedar Island is experiencing some of the highest rates of relative sea level rise in the Mid-Atlantic region.

Table 3: Mid-Atlantic relative sea-level rise based on NOAA (2016) tidal gauge data.

Tide gauge location	Gage Number	Time		MSL trend (mm/yr), ±95% Confidence Interval
		Start	End	
Atlantic City, NJ	8534720	1911	2015	4.07; 0.16
Cape May, NJ	8536110	1965	2015	4.54; 0.55
Lewes, DE	8557380	1919	2015	3.4; 0.24
Ocean City Inlet, MD	8570283	1975	2015	5.6; 0.97
Wachapreague, VA	8631044	1978	2015	5.37; 0.86
Kiptopeke, VA	8632200	1951	2015	3.58; 0.34
Chesapeake Bay Bridge Tunnel, VA	8638863	1975	2015	5.93; 0.77
Sewells Point, VA	8638610	1927	2015	4.59; 0.23
Portsmouth, VA	8638660	1935	1987	3.76; 0.45

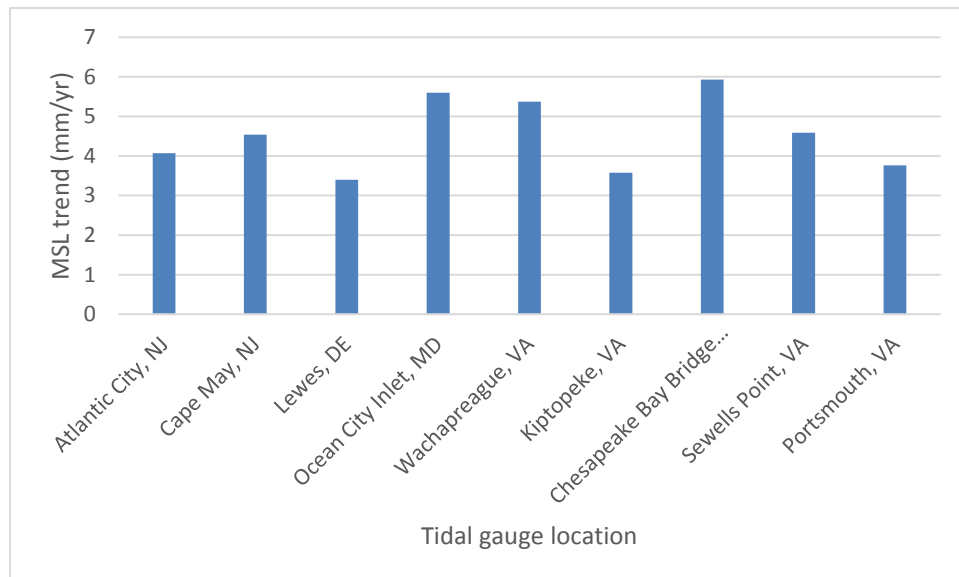


Figure 10: Mid-Atlantic relative sea-level rise rates based on NOAA (2016) tidal gauge data.

Wave Processes

Longshore sediment transport plays a major role in the rates of retreat and advance along barrier islands. Longshore sediment transport (littoral drift) operates along the littoral zone and is the primary current influencing Cedar Island, whereas the Gulf Stream operates farther offshore and flows northeastward. The net longshore sediment transport along Cedar Island is southerly and approximately 115,000 to 460,000 m³ of sand is transported annually (Oertel and Kraft, 1994). Though net littoral drift is southerly, local reversals in littoral drift direction may occur near tidal inlets with pronounced ebb-tidal deltas and in areas that experience changes in shoreline orientation (Oertel and Kraft, 1994). Therefore, the net sediment transport direction varies along barrier islands (Oertel and Kraft, 1994).

During the summer, mean wave and wind direction is from the southeast and in the winter, it is from the northeast (Richardson et al., 2015). The mean annual wave height of Cedar island is 0.55 m with an average summer wave height of 0.3 m to 1.52 m and winter average wave height up to 2.44m (Nebel et al., 2012; Heinsius, 1974). Accordingly, the area experiences modest wave energy and an average significant wave height of 1.1 m (Fenster and McBride, 2015).

Tidal Processes

The daily interaction of tides and waves along barrier islands also contributes to island morphology. Cedar Island has a mean tidal range of approximately 1.2 m and a spring tidal range of 1.4 m (Nebel et al., 2013; Hanley, 2015; NOAA., 2015d). The low

mesotidal area experiences unequal semidiurnal tides that move along the U.S. Atlantic coast from north to south (Oertel and Kraft, 1994; Boon, 2004).

When active, Cedar Island Inlet was a wave-dominated tidal inlet, which competed with Wachapreague Inlet to fill and drain Burton's Bay (Hanley, 2015; Seminack and McBride, 2015). The tidal prism of Wachapreague inlet is $5.64 \times 10^7 \text{ m}^3$, and is reduced by between 2.3% and 17.6% when the Cedar Island ephemeral inlet is open (Richardson et al., 2015; Hanley, 2015). Specifically, Cedar Island Inlet must capture at least 3.1% or $1.64 \times 10^6 \text{ m}^3$ of tidal prism from Wachapreague Inlet to remain open (Hanley, 2015). While active, Cedar Island Inlet maintained a channel depth from 2.6 m to 4.5 m and mean width of approximately 750 m; however, as the ephemeral inlet migrated and rotated it became less hydraulically efficient as the channel lengthened, which caused the tidal prism to decrease, and thus the inlet closed (Moyer, 2007; Hanley, 2015). A relict inlet throat and modest flood-tidal delta are preserved along the landward side of Cedar Island; however, the associated ebb-tidal delta deposits on the seaward side is poorly developed because the inlet is wave dominated (Moyer, 2007; Hanley 2015).

Located south of Cedar Island, Wachapreague Inlet is a stable tide-dominated inlet with one of the largest, most well-developed ebb-tidal-deltas along the Delmarva Peninsula (Richardson et al., 2015). The 21.9 m deep inlet throat is anchored in a Pleistocene stream valley and is slowly migrating in a southerly direction (Morton and Donaldson, 1973; DeAlteris and Byrne, 1975; Richardson et al., 2015). Wachapreague Inlet also has a poorly developed flood-tidal delta, which is characteristic of a tide-

dominated inlet (Richardson et al., 2015). In 2013, the tidal prism of Wachapreague Inlet was $5.64 \times 10^7 \text{ m}^3$ (Richardson et al., 2015).

Landward Migration on Cedar Island, VA

During the first half of the 20th Century, Cedar Island was relatively stable and private lots were sold and developed as vacation homes (Rice, 1976; Richardson, 2012; Hanley, 2015). However, Cedar Island lies within an arc of erosion caused by the recurved spit complex on the southern end of Assateague Island and therefore, has a limited sediment supply (Galgano, 2007, 2009; Richardson, 2012; McBride et al., 2015). The island experienced increased rates of erosional thinning after 1962 because of new breaches along the southern portion of Metompkin Island (Hanley, 2015). The new breaches disrupted southerly longshore sediment transport and caused Cedar Island to become sediment starved and experience erosional thinning (Gaunt, 1991). Similarly, increased storm activity since the 1970's may also be responsible for increased erosion rates on Cedar Island (Riggs and Ames, 2007; Nebel et al., 2012, 2013). Specifically, shorelines accrete, prograde, and recover after storms provided sufficient time has passed between storms; however, increased storm occurrence prevents shoreline recovery spurring ongoing erosion (Morton et al., 1994; Nebel et al., 2012, 2013).

From 1910 to 1986 Gaunt (1991) observed that Cedar Island narrowed by 32% or 2.1 m/yr. Similarly, long term (1852-2007) landward migration rates have ranged from – 4.1 m/yr to –5.5m/yr (Figure 11; Richardson and McBride, 2011; Nebel et al., 2012). Short term, recent (2007-2011) migration rates have increased to –15.4 m/yr (Richardson

2012). Accordingly, private properties on Cedar Island were abandoned because the barrier island continues to rapidly move landward and rollover the coalesced relict flood-tidal deltas, associated with the ephemeral inlet, and saltmarsh deposits, which can be observed outcropping along the foreshore (Figure 12; Nummedal, 1983; Wright and Trembanis, 2003; Richardson, 2012). Cedar Island is one of the most rapidly retreating barrier islands along the U.S. Atlantic coast (Richardson 2012).

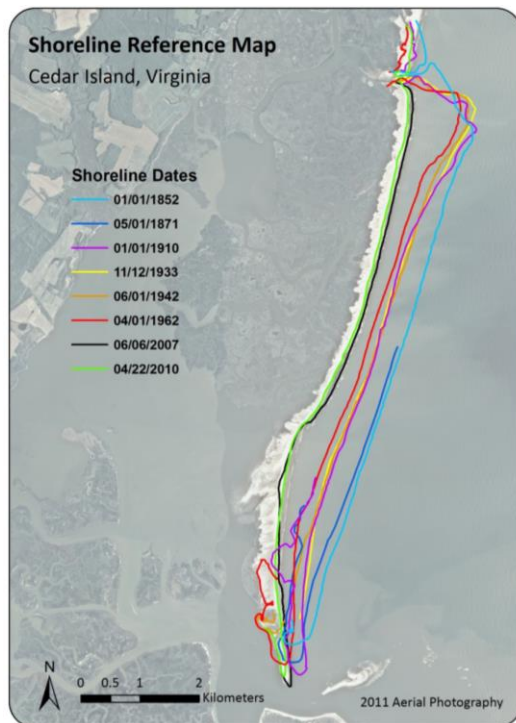


Figure 11: Shoreline retreat of Cedar Island, VA from 1852 to 2010 (from Richardson, 2012).



Figure 12: Relict marsh outcropping along the foreshore of Cedar Island, Virginia, May 3, 2015.

Island Breaching and Inlet Formation on Cedar Island, VA

Island breaching occurs during strong storms with high winds, waves, and water levels. Typically, high, storm waves first erode and remove a foredune ridges and overwash processes deposit washover aprons that decrease the local relief. A landward or seaward directed storm surge incises a topographic low across the island and forms a conduit between backbarrier water bodies and the ocean called a breach. In a landward-directed breach, a narrow portion of the island is eroded and flooded by high velocity waves, which reach the backbarrier estuary. In a seaward-directed breach, storm surge increases local water level in the open bay behind the island and as the tide falls, water rushes seaward to the ocean across the island. If subsequent tidal exchange occurs within

a breach, tidal-inlet formation will occur. The breach depth must be below the low tide level allowing tidal exchange for full tidal cycles to remain open (Headland et al., 1999).

Inlets require significant tidal prism (the volume of water that flows in or out of an inlet during each half-tidal cycle) to flush sediment deposited by longshore sediment transport and maintain depths below low tide to stay open (Richardson, 2012). New inlets must compete with existing inlets to capture sufficient tidal prism to remain open (Seminack and McBride, 2015). Thus, some breaches persist for long periods while others are short lived (Headland et al., 1999).

During storms, island breaching has occurred on Cedar Island. Over the last 60 years, three inlets (1856-1962, 1993-1997, and 1998-2007) were established and remained active for 4 to 9 years (Rice et al., 1976; Moyer, 2007; Nebel et al., 2012; Hanley, 2015). All three inlets demonstrated a similar lifecycle where an inlet was established, migrated southward in the direction of net longshore sediment transport, rotated counterclockwise, and then closed (Figure 9; Figure 13; Figure 14; Figure 15; Richardson 2012; Hanley, 2015; Hanley et al., 2015; McBride et al., 2015; Seminack, 2016). When Cedar Island Inlet was active, sediment and water were exchanged between the open ocean and Burton's Bay. Specifically, the introduction of coarser sediment and normal marine salinity water modified the local depositional environments and ecology (Hanley, 2015; Seminack, 2016). Hanley (2015) demonstrated that these changes are reflected in the sedimentary record of the inlet.

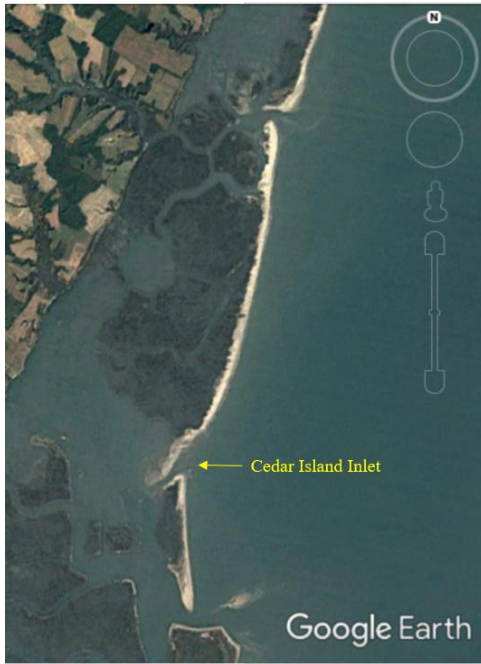


Figure 13: Southern migration, counterclockwise rotation, and channel elongation of Cedar Island inlet, December 2003 (Google Earth; 2017).

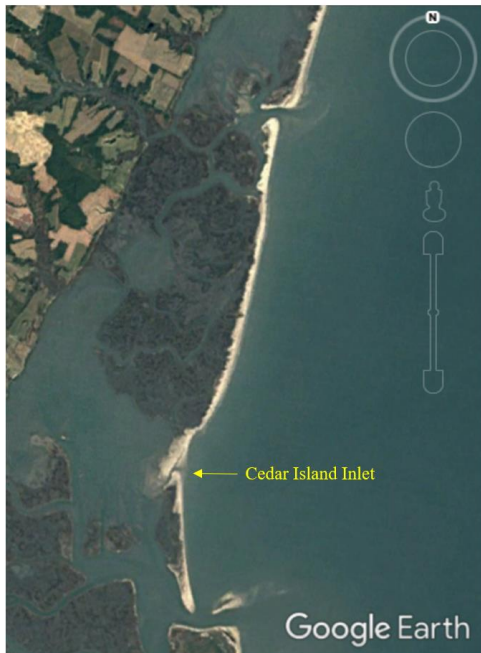


Figure 14: Further counterclockwise rotation, and channel elongation of Cedar Island inlet, December 2006 (Google Earth; 2017).



Figure 15: Closed Cedar Island Inlet, December 2008 (Google Earth; 2017).

PREVIOUS WORK

Tidal-inlet Channel Sedimentary Deposits

Tidal inlets, the narrow channels that separate barrier islands where tides are exchanged, are part of the dynamic barrier island system and therefore are not permanent features (Figure 16; Oertel, 1985; Kraus et al., 2002). Tidal inlets may migrate laterally in the direction of net longshore sediment transport, which results in a distinctive stratigraphy with high preservation potential (Kumar and Sanders, 1974; Moslow and Heron, 1978).

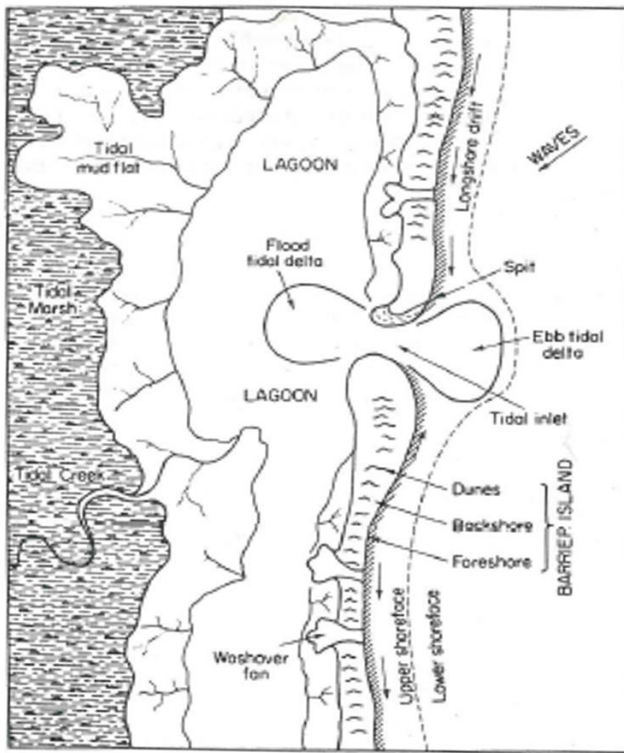


Figure 16: A typical barrier island complex that includes a tidal inlet (from Davis, 1994).

Former tidal-inlet deposits exhibit a distinct sedimentary and stratigraphic succession (Figure 17; Kumar and Sanders, 1974; Moslow and Heron, 1978; Moslow and Tye, 1985). The lower-most unit has a coarse shell, pebble, and/or gravel lag that represents the inlet channel floor (Kumar and Sanders, 1974; Moslow and Heron, 1978). Overlying the inlet channel floor deposit is the channel deposit with medium to coarse sand including shells and pebbles (Kumar and Sanders, 1974; Moslow and Heron, 1978). The channel deposit exhibits a fining upward succession because as the channel migrates laterally, the axis of tidal flow shifts downdrift and the updrift bank experiences lower tidal velocities and finer sediment is deposited (Kumar and Sanders, 1974; Moslow and Heron, 1978). Kumar and Sanders 1974 further subdivide channel deposits into deep

channel and shallow channel subenvironments based on grain size and bedforms. Next, the succession is topped by an inlet margin unit composed of fine to medium quartz sand (Moslow and Heron 1978). Kumar and Sanders (1974) divide the topmost tidal-inlet deposit into subaqueous spit platform and subaerial spit environments. The subaqueous spit platform is marked by a unit of medium to coarse sand with fining upward succession that represent bottomset, foreset, and topset components (Kumar and Sanders 1974). A subaerial spit unit completes the inlet-fill succession composed of coarse to medium quartz sands (Kumar and Sanders 1974). In wave-dominated environments, dunes and washover deposits typically overlie tidal-inlet deposits, whereas in tide-dominated environments tidal creek and marsh deposits commonly overlie tidal-inlet deposits (Figure 18; Moslow and Tye, 1984).

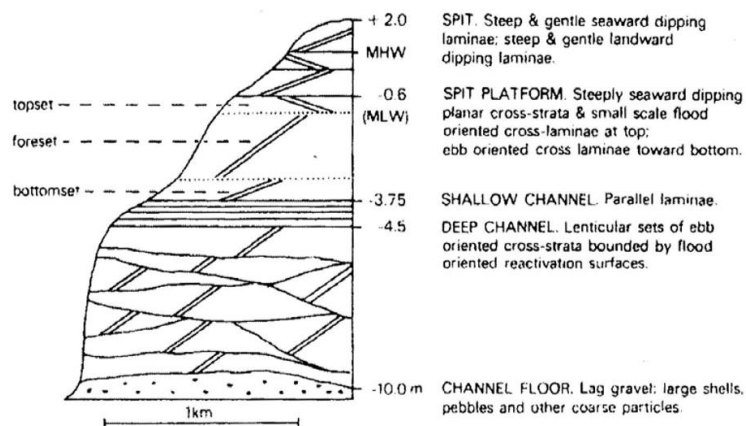


Figure 17: Vertical tidal-inlet stratigraphy of Fire Island Inlet, NY, USA (from Donselaar and Nio, 1982).

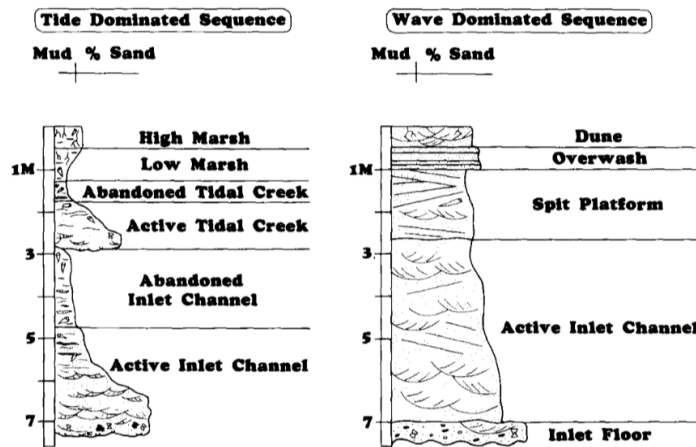


Figure 18: Vertical stratigraphy of tide and wave-dominated tidal-inlet deposits (from Moslow and Tye, 1984).

Wave-dominated Tidal-inlet Lifecycle Model

In general, wave-dominated, tidal-inlet lifecycles include six stages as observed in Figure 19 (Seminack, 2016). First a barrier island is breached in response to a storm. Second, the breach must capture sufficient tidal prism to proceed to stage two where a tidal inlet is established (Seminack, 2016). Stage three is impacted by a variety of factors including the availability of accommodation space for the building flood-tidal deltas and shifts in the flood-tidal delta depocenter (Seminack, 2016). Therefore, three possible scenarios have been proposed for stage three, including no rotation, clockwise rotation, and counter-clockwise rotation (Seminack, 2016).

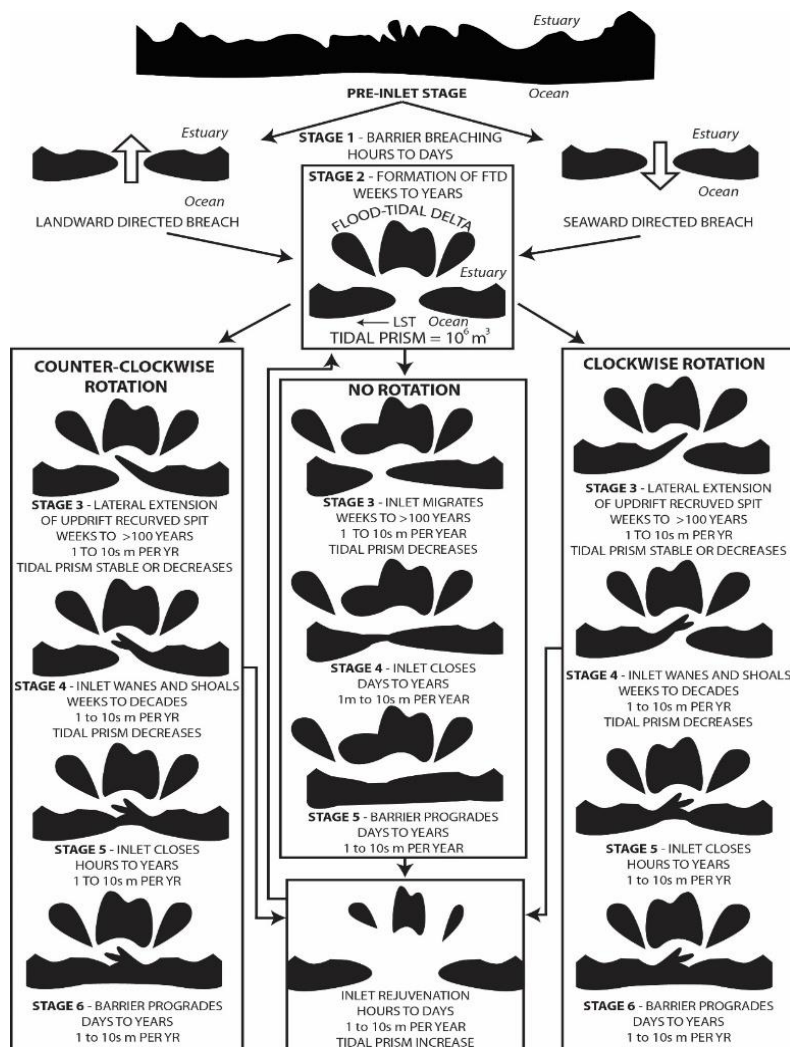


Figure 19: A lifecycle model for wave-dominated tidal inlets along Amero-trailing-edge and marginal-sea coasts of North America (from Seminack, 2016).

Inlets that do not rotate exhibit minimal downdrift migration, which occurs as accommodation space is filled by the building of flood-tidal deltas (Seminack, 2016). Tidal prism gradually wanes and the inlet closes in stage four where a swash-aligned (waves strike shoreline nearly parallel or parallel and onshore sediment transport dominates) closure ridge connects the recurved spits bounding the inlet (Seminack,

2016). In stage five the shoreline progrades through the deposition of swash-aligned closure ridges. (Orford et al., 1991; Seminack, 2016).

Stage three of clockwise-rotating inlets involves an updrift shift in the depocenter of the flood-tidal delta, which prompts the drift-aligned (waves strike shoreline obliquely and longshore sediment transport dominates) extension of the downdrift then updrift recurved spits. The inlet will close in stage four when the downdrift recurved spit extends downdrift forming a swash-aligned, shore concave ridge that welds to the updrift recurved spit (Seminack, 2016). The opposite occurs in counter-clockwise rotating inlets where downdrift depocenter shifts of the flood-tidal delta cause the extension of the updrift then downdrift recurved spits. Similarly, inlet closure occurs in stage four when the updrift recurved spit extends and welds to the downdrift recurved spit (Seminack, 2016). Stage six for clockwise and counter-clockwise rotating inlets includes shoreline progradation characterized by swash-aligned closure ridges.

Cedar Island Depositional Model

Dissertation research, by Hanley (2015), included the collection and analysis of 18 vibracores, eight pulse augers, and one push core from the former Cedar Island Inlet area (Figure 20). The vibracores contained sand, shell, and mud deposits and were organized into fifteen primary facies, which represent beach-washover-aeolian (sand and shell), tidal-inlet (sand and shell), flood-tidal delta (sand), and estuarine (mud) depositional environments (Hanley, 2015). Since 1950, Cedar Island Inlet has opened and closed at least three times and the sedimentary deposits retrieved are attributed to the

most recent 1998-2007 inlet and potentially another older inlet (Figure 21; Hanley, 2015). Vibracore C12, collected from the former inlet throat, contains the complete preserved former tidal-inlet succession including a bottom unit composed of estuarine mud, overlain by a coarse shell lag deposit, interpreted as the inlet channel floor, overlain by a fining upward succession that represents channel fill deposits, and capped by beach/washover/aeolian deposits (Hanley, 2015).

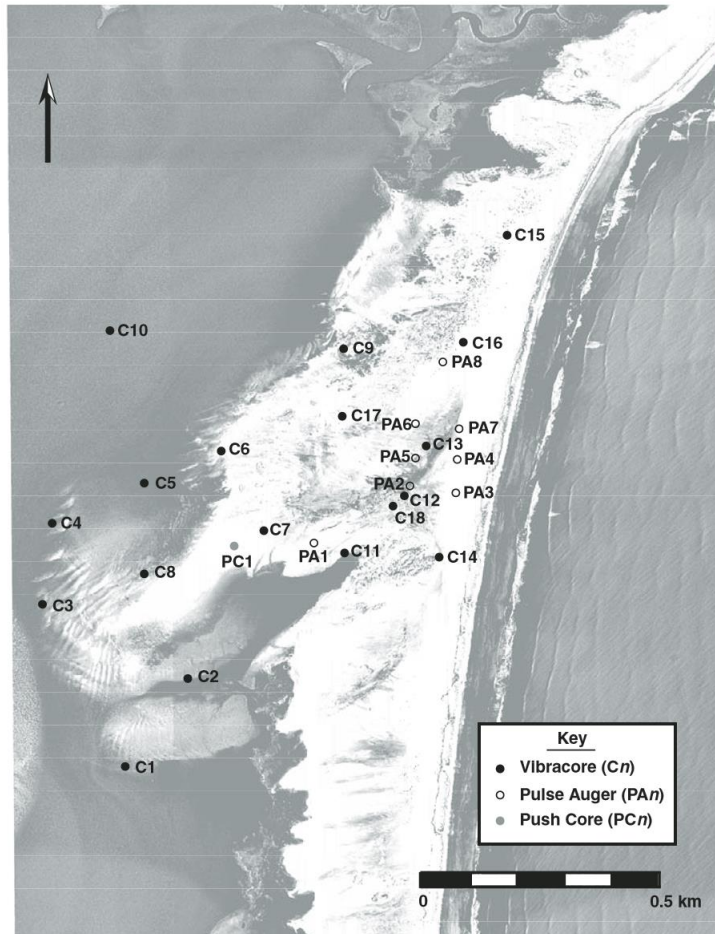


Figure 20: Location of 18 sediment cores, 8 pulse augers, and one push core collected from the former Cedar Island Inlet area (from Hanley et al., 2015).

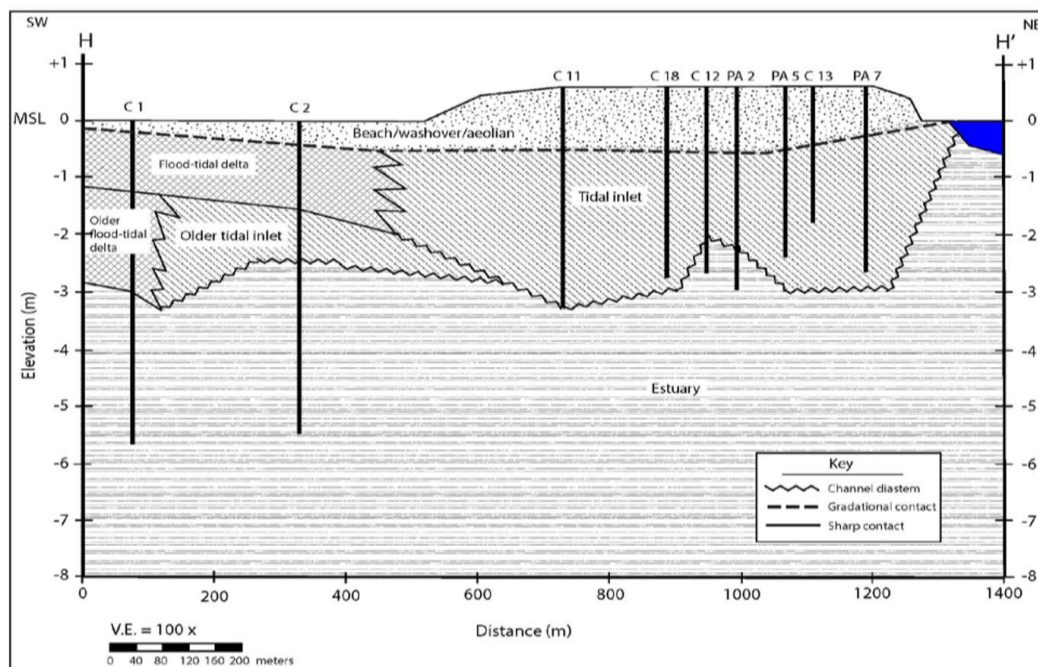


Figure 21: A geologic cross section through the former Cedar Island Inlet showing the preserved deposits from the 1998-2007 inlet and an older former inlet (from Hanley, 2015).

Through satellite imagery and core analyses, an eight-stage lifecycle model of Cedar Island inlet was synthesized (Figure 22; Figure 23; Hanley, 2015). In stage one the island is breached, then if the breach captures sufficient tidal prism, a tidal inlet is established (Hanley, 2015). Next, a flood-tidal delta is formed, the inlet migrates in the direction of net longshore sediment transport, and the channel rotates counterclockwise and lengthens, which causes the inlet to become hydraulically inefficient and lose tidal prism (Hanley, 2015). The inlet then fills with sediment deposited by longshore sediment transport and finally closes (Hanley, 2015).

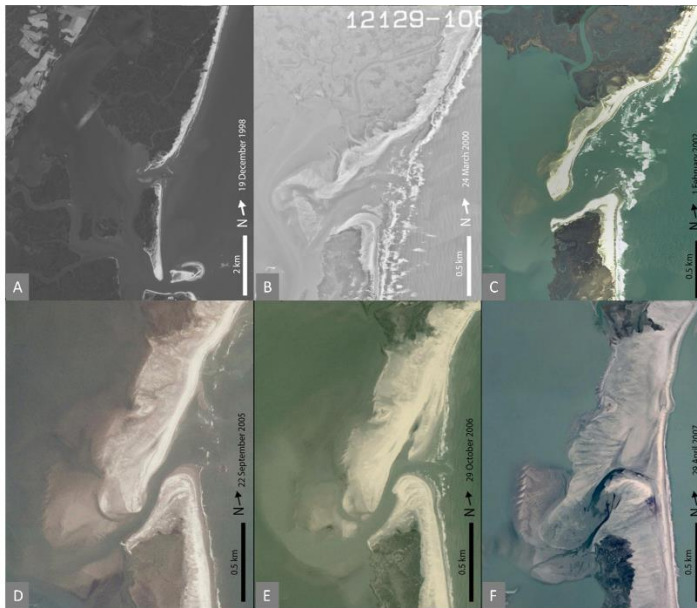


Figure 22: Aerial imagery showing the opening, counter clockwise rotation, and closure of Cedar Island Inlet between 1998 and 2007 (from Seminack, 2016).

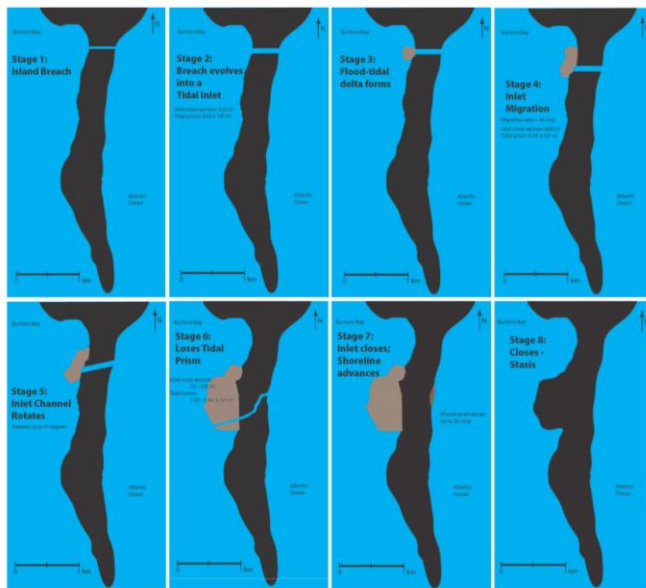


Figure 23: Eight-stage geomorphic model for Cedar Island Inlet (figure from Hanley, 2015).

Seminack (2016) further refined a lifecycle model for Cedar Island Inlet that identified three distinct stages of ridge development, which facilitated the closing of

Cedar Island Inlet (Figure 24). First, inlet downdrift migration prompts the development of several drift-aligned, recurved-spit ridges (Seminack, 2016). Next, northerly prograding, drift-aligned, recurved spit ridges located to the south of the inlet channel form in response to channel counterclockwise rotation, channel lengthening, and channel shoaling (Seminack, 2016). Finally, concave-seaward, swash-aligned closure ridges are observed, indicating the inlet is closed (Seminack, 2016).

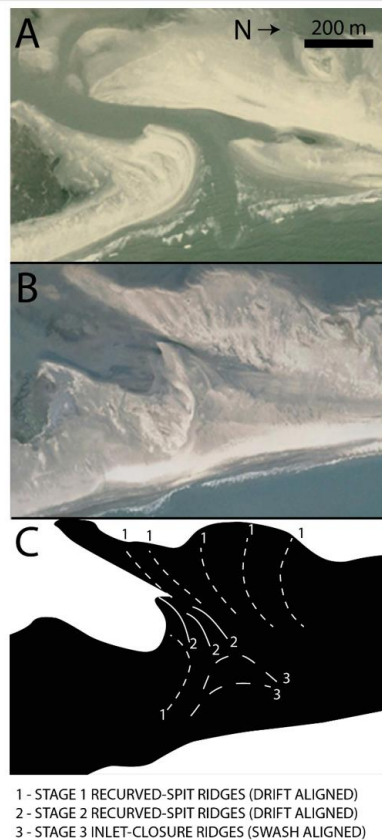


Figure 24: Cedar Island Inlet closure processes. A) Northern and southern recurved spits bound Cedar Island Inlet in October 2006. B) Cedar Island Inlet closed by October 2008. C. Three stages of ridge development were identified that document the closure of Cedar Island Inlet (figure from Seminack, 2016).

Benthic Foraminiferal Biofacies of Tidal-inlet Deposits

Many studies have examined the modern benthic foraminiferal assemblages of depositional environments associated with active tidal inlets, including tidal-inlet channels, washover fans, ebb-tidal deltas, flood-tidal deltas, and estuaries (Schnitker, 1971; Grossman and Bensen 1967; Culver et al., 1996; Woo et al., 1997; Scott et al., 2001; Culver et al., 2006; Abbene et al., 2006; Vance et al., 2006). Unique benthic foraminiferal assemblages are diagnostic of each of these depositional environments and have been successfully used to identify past barrier island depositional environments in the stratigraphic record (Figure 25; Culver et al., 1996; Robinson and McBride, 2006, 2008; Smith et al., 2009; Pruitt et al., 2010). Foraminiferal assemblages along the U.S. Atlantic coast have been identified; however, it is most useful to examine studies conducted in close proximity to Cedar Island, such as the Virginia barrier islands along the Delmarva Peninsula and the Outer Banks, NC, which may have similar foraminiferal assemblages (Culver and Buzas, 1980).

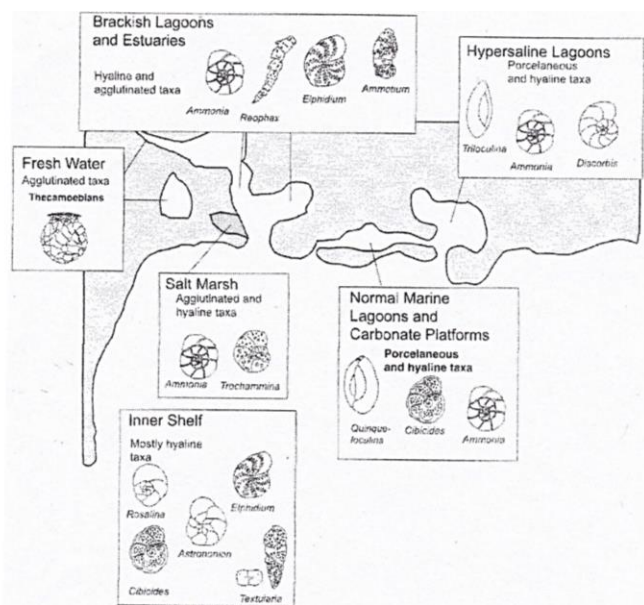


Figure 25: Generalized foraminiferal species (*Ammonia*, *Reophax*, *Elphidium*, *Ammotium*, *Triloculina*, *Discorbis*, *Trochammina*, *Quinqueloculina*, *Cibicides*, *Rosalina*, *Textularia*, *Astrorionion*) and thecamoebian species distribution in nearshore environments (from Scott et al., 2001).

Tidal-inlet Channel Biofacies

Tidal inlets of the Outer Banks, NC are wave-dominated and separate long barrier islands (Figure 26). Tidal exchange occurs through these inlets and tidal-inlet channels have the highest salinities in Pamlico Sound (Figure 27; Abbene et al., 2006). Sediments reflect a high-energy environment and are dominated by medium sand (Abbene et al., 2006).

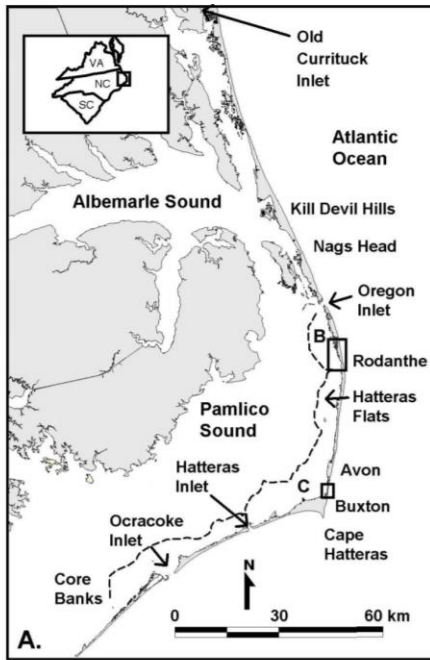


Figure 26: Map of the Outer Banks, NC barrier islands and tidal inlets. (from Smith et al., 2009).

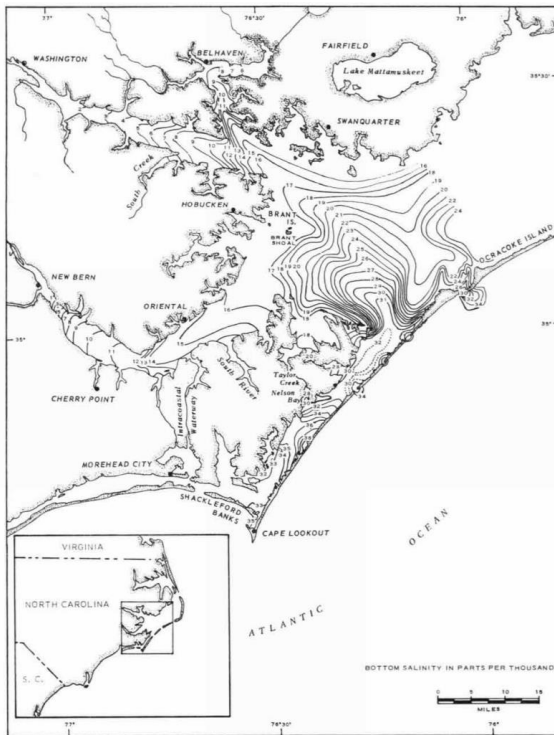


Figure 27: Salinity in estuary increases toward tidal inlets (from Grossman 1967).

The tidal-inlet channels of Ocracoke, Hatteras, and Oregon Inlets along the Outer Banks have similar foraminiferal assemblages with low species richness and abundance (Abbene et al., 2006; Vance et al., 2006). Ocracoke and Hatteras Inlets are characterized by *Cibicides lobatulus*, *Elphidium galvestonense*, *Elphidium mexicanum*, *Elphidium subarcticum*, *Hanzawaia strattoni*, and *Quinqueloculina seminula* (Abbene et al., 2006). Similarly, the Oregon Inlet foraminiferal assemblage includes *Hanzawaia strattoni* and *Elphidium subarcticum* but uniquely is dominated by *E. excavatum* (89%) and contains *Ammonia parkinsoniana* and *Ammonia tepida* (Vance et al., 2006).

Flood-tidal Delta Biofacies

Flood-tidal deltas are shoal deposits on the landward side of a tidal inlet in wave-dominated barrier island systems (Figure 16; Hayes, 1979). Sediment of flood-tidal deltas in Pamlico Sound, NC is predominately medium to coarse quartz sand with few silt size particles (Grossman 1967).

High foraminiferal species richness is found in flood-tidal delta environments because shelf species are transported landward and deposited by the flood tide and similarly estuarine and marsh species are also transported seaward and deposited by the ebb tide (Luck, 1936; Grossman and Benson, 1967). For example, the flood-tidal deltas of Ocracoke and Drum Inlets, NC are dominated by *Elphidium excavatum* with significant abundances of shelf and estuarine species, including *Quinqueloculina spp.*, *Triloculina sp.*, *Cibicides lobatulus*, and *Hanzawaia concentrica* (Grossman and Benson, 1967). Similarly, the flood-tidal delta assemblage at Old Currituck Inlet, NC, investigated by Robinson and McBride (2006), was also dominated by *Elphidium excavatum* and

contained *Ammonia parkinsoniana*, *Buccella frigida*, *Cibicides lobatulus*, *Elphidium galvestonense*, *Elphidium mexicanum*, *Elphidium subarcticum*, *Hanzawaia strattoni*, and *Quinqueloculina seminula*.

Estuarine Biofacies

Estuaries vary greatly in size and morphology; however, the estuaries landward of the Virginia barrier islands along the Delmarva Peninsula (south of Cedar Island) are tide-dominated, have many inlets, and contain diverse depositional environments including tidal channels, marshes, tidal and subtidal flats, bars, berms, exposed and restricted bays, and inlets (Figure 28; Culver et al., 1996). Each of these depositional environments has unique environmental conditions including degree of tidal inundation, grain size, and salinity. Woo et al. (1997) determined that the live foraminiferal assemblages of the Virginia estuaries along the Delmarva Peninsula clustered into seven habitat zones including (1) brackish valley marshes, (2) exposed headland and backbarrier fringe marsh, (3) protected valley marsh and tidal channel margins, (4) inner and mid-lagoon environments, (5) washover fan, (6) outer lagoon (sandy), and (7) ebb-tidal delta shoals and barrier island shoreface seafloor (Figure 29;

Table 4).

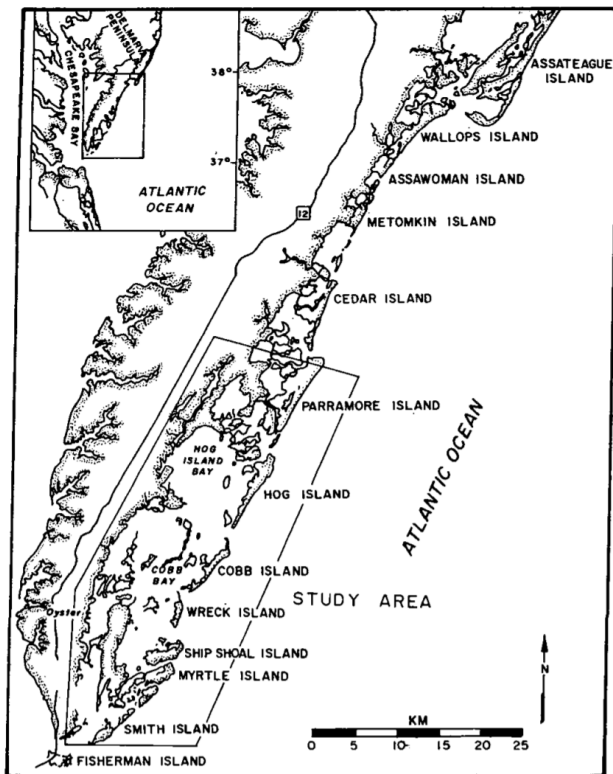


Figure 28: The Virginia barrier islands along the southern Delmarva Peninsula (from Culver et al., 1996).

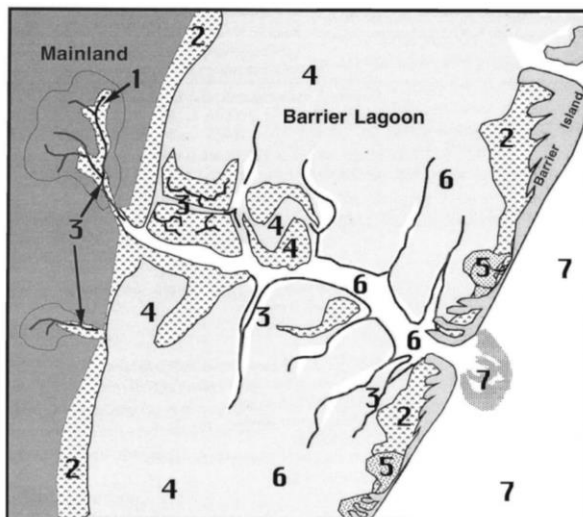


Figure 29: Idealized sketch of a tide-dominated estuary of the Virginia barrier islands along the southern Delmarva Peninsula indicated by foraminiferal communities including (1) brackish environments, (2) fringe marsh, (3) valley marsh and tidal channel margins, (4) inner and mid-lagoon environments, (5) washover fan, (6) outer lagoon environments, (7) shoreface and delta shoals (from Woo et al., 1997).

Table 4: Habitat zones or environments of the Virginia barrier islands along the southern Delmarva Peninsula showing diagnostic foraminiferal species (from Woo et al., 1997).

Habitat Zone	Subenvironments (<i>a priori</i> nos. in parens.)	Characteristic Species
1. Brackish environments	(1) Mainland valley marsh and Channel (brackish and protected)	<i>Ammonia beccarii</i> <i>Trochammina inflata</i> <i>Trochammina "squamata"</i>
2. Fringe marsh	(11) Mainland fringe marsh (exposed headland) (13) Back-barrier fringe marsh (protected and exposed)	<i>Ammobaculites exiguus</i> <i>Ammonia beccarii</i> <i>Elphidium excavatum</i> <i>Jadammina macrescens</i> <i>Miliammina fusca</i> <i>Textularia earlandi</i> <i>Trochammina inflata</i>
3. Valley marsh and tidal channel margins	(10) Mainland valley marsh (protected, low runoff) (14) Tidal channel margin	<i>Ammonia beccarii</i> <i>Elphidium excavatum</i> <i>Haynesina germanica</i> <i>Miliammina fusca</i>
4. Inner and mid-lagoon environments	(2) Tidal bays and flats (restricted circulation) (3) Muddy sand flat (inner lagoon) (5) Sand flat (inner lagoon) (8) Mud flat (inner lagoon) (12) Island marsh (15) Tidal channel (intermediate depth)	<i>Ammonia beccarii</i> <i>Elphidium excavatum</i> <i>Haynesina germanica</i>
5. Washover fan	(17) Washover fan	<i>Ammonia beccarii</i> <i>Elphidium excavatum</i> <i>Quinqueloculina seminula</i>
6. Outer lagoon (sandy)	(4) Muddy sand flat (mid and outer lagoon) (6) Sand flat (middle lagoon) (7) Sand flat (outer lagoon) (9) Mud flat (outer lagoon) (16) Deep tidal channel (18) Ebb delta axial channel	<i>Elphidium excavatum</i>
7. Shoreface and delta shoals	(19) Ebb delta inlet shoals (20) Shoreface	<i>Elphidium excavatum</i> <i>Elphidium mexicanum</i>

Brackish valley marsh environments occur along the mainland shoreline where small drainage basins meet the estuary (Woo et al., 1997). Low salinities of < 10 ppt and muddy substrate are observed in the brackish subenvironment, which serves as a transition zone between freshwater tributaries and the backbarrier estuary (Woo et al., 1997). Brackish channels are characterized by calcareous *Ammonia beccarii* while the brackish marsh is characterized by agglutinated *Trochammina inflata* and *Trochammina squamata* (Woo et al., 1997). Agglutinated forms were readily found in the brackish subenvironments likely because of low salinities, which reduce available calcium carbonate (Hada, 1957; Woo et al., 1997).

The fringe marsh habitat zone includes open and shielded mainland and backbarrier marsh environments (Woo et al., 1997). Calcareous *Ammonia beccarii* and *Elphidium excavatum*, as well as, agglutinated, *Jadammina macrescens*, *Miliammina fusca*, and *Trochammina inflata*, dominate the fringe marsh subenvironment (Woo et al., 1997).

Valley marsh and tidal channel margins exhibit hypersaline conditions with sediment pore-water salinities of 40-60 ppt because of limited flushing and the ponding of saltwater lenses on marsh surfaces (Woo et al., 1997). This stressful environment is characterized by *Ammonia beccarii*, *Elphidium excavatum*, *Haynesina germanica* and *Miliammina fusca* (Woo et al., 1997).

Inner and mid-lagoon environments have normal marine salinities of 30-32 ppt and are well mixed by tidal currents and wind-fetch-derived waves (Woo et al., 1997).

Accordingly, high turbidities and high pore water oxygen concentrations are observed (Woo et al., 1997). Foraminiferal assemblages of inner and mid-lagoon environments have limited diversity, being dominated by *Ammonia beccarii* and *Elphidium excavatum* (Woo et al., 1997). Additionally, many samples also contain significant numbers of *Haynesina germanica* (Woo et al., 1997).

Outer lagoon (sandy) environments have sandy substrates, are well mixed, and contain normal marine salinity water (Woo et al., 1997). *Elphidium excavatum* completely dominates this environment likely because of high mixing rates (Woo et al., 1997).

Washover Fan Biofacies

Located on the back-barrier side of barrier islands, washover fans are deposited when landward-directed storm surge and waves overtop a barrier island and deposit sediment along the landward side (Figure 16). Washover fans include layered sand and mud deposits, where sand layers are deposited by storm surge and waves and thin mud lenses are deposited in quiescent estuarine conditions.

Offshore foraminifera are transported landward and incorporated into washover fan deposits during storm events (Culver et al., 1996; Woo et al., 1997; Collins et al., 1999; Hippensteel and Martin, 1999). For example, washover deposits along Pea Island, NC are characterized by normal marine salinity species *Elphidium excavatum*, *Elphidium subarcticum*, *Elphidium mexicanum*, *E. galvestonense*, *Hanzawaia strattoni*, *Ammonia parkinsoniana*, and *Buccella inusitata*, which have been documented in offshore and inner shelf environments (Culver et al., 2006) Similarly, washover deposits located

between Oregon Inlet and Cape Hatteras, NC are dominated by normal marine salinity species *Buccella inusitata* and *Hanzawaia strattoni*, as well as *Elphidium excavatum*, all of which have been transported landward (Smith et al., 2009). Washover fans along the Virginia barrier islands, south of Cedar Island, are characterized by a high density of living *Quinqueloculina seminula* and also contained *Ammonia beccarii* and *Elphidium excavatum*, which reflects similar conditions to the outer lagoon environment with the addition of turbulent disturbances (Woo et al., 1997).

DATASETS, DEFINITIONS, AND METHODS

Vibracore Dataset

Between September 2010 and March 2011, 18 vibracores were collected from the former Cedar Island Inlet area as part of a PhD dissertation by Hanley (2015) as shown in Figure 30: Map depicting the 18 vibracore locations collected as part of a PhD dissertation by Hanley (2015). Figure 30. Vibracore collection involved the extraction of continuous, unconsolidated, water saturated sediment cores through the application of high frequency, low amplitude vibrations, which caused liquefaction of fine sediment and allowed core tubes to penetrate sediments (Lanesky et al., 1979; Smith, 1984). After a core tube completely penetrated sediment, or would no longer advance at depth, water was poured into the top of core tube and the tube was capped to create a vacuum (Hanley, 2015). The core tube, containing the sediment core, was then retrieved using a tripod and come-along (Hanley, 2015). The cores were then cut into one-meter sections, split lengthwise, photographed, described, and subsampled at 4 cm intervals for grain size analysis and future micropaleontological analysis (Hanley, 2015).

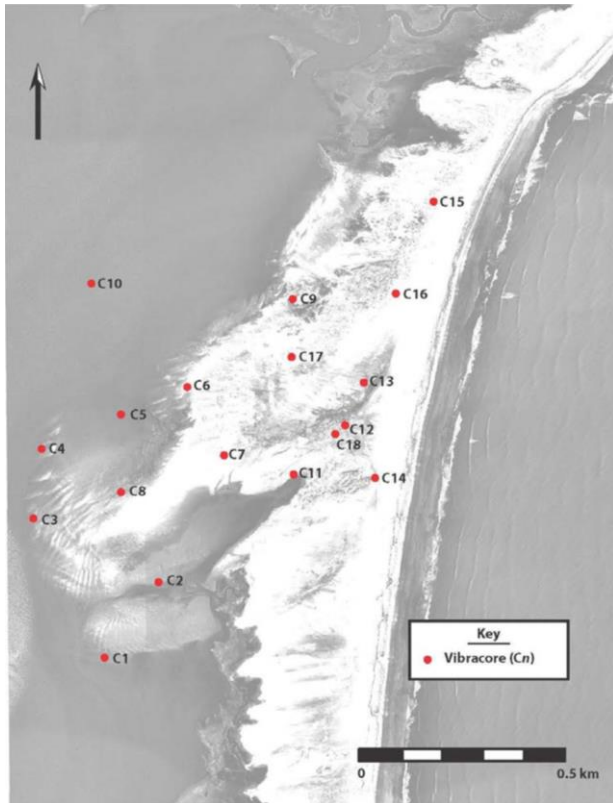


Figure 30: Map depicting the 18 vibracore locations collected as part of a PhD dissertation by Hanley (2015).

Three vibracores (C1, C2, and C12) form a dip cross section through the former inlet throat and flood-tidal delta of Cedar Island Inlet and were selected for detailed micropaleontological analysis (Figure 30; Figure 31; Figure 32; Figure 33; Figure 34).

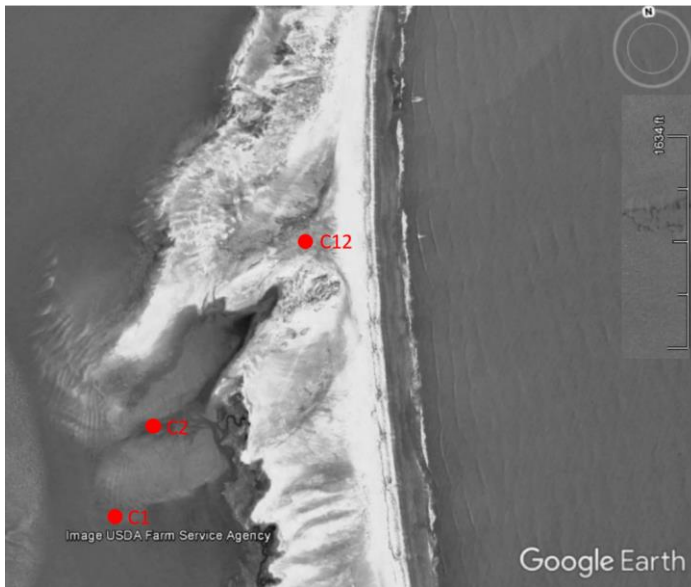


Figure 31: Vibracore locations of C1, C2 and C12 (Google Earth, 2017).

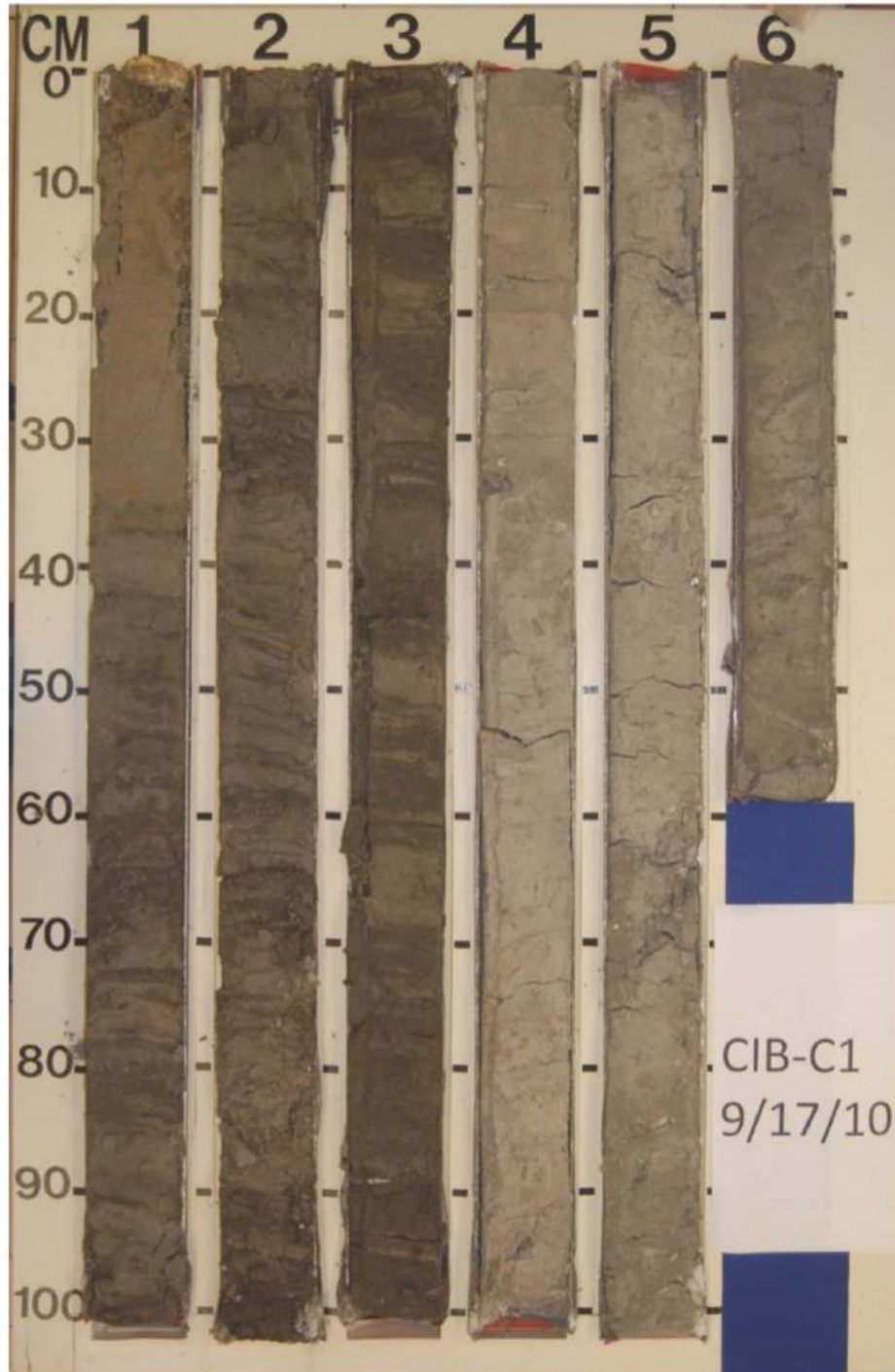


Figure 32: Core photograph of vibracore C1 (from Hanley, 2015). Scale in centimeters. Core bottom is lower right and core top is upper left.

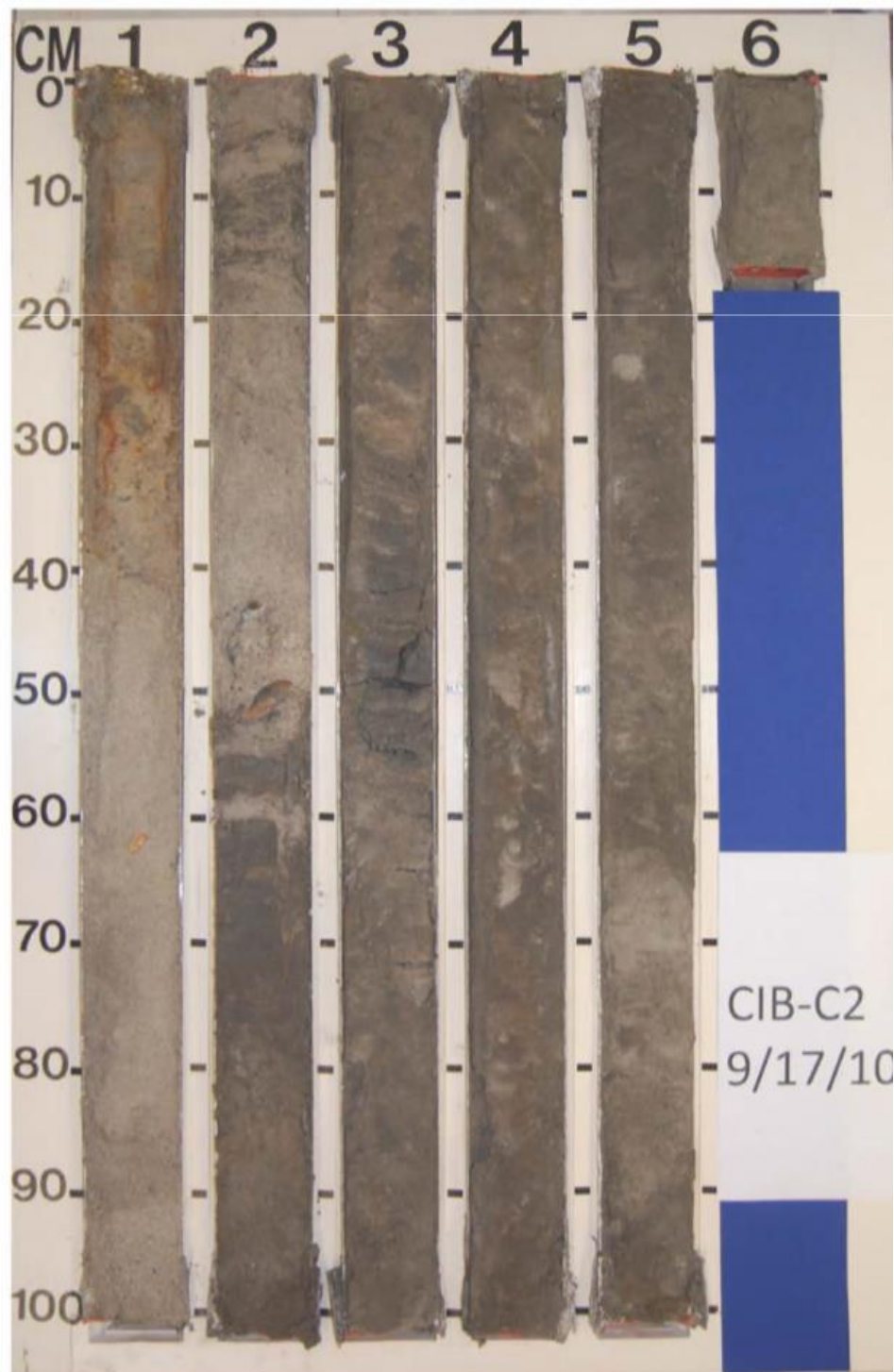


Figure 33: Core photograph of vibracore C2 (from Hanley, 2015). Scale in centimeters. Core bottom is lower right and core top is upper left.



Figure 34: Core photograph of vibracore C12 (from Hanley, 2015). Scale in centimeters. Core bottom is lower right and core top is upper left.

Definitions

Foraminiferal biofacies are defined by Mello and Buzas, (1968) as an area that is distinguished by the presence of a species or group of species. The term biofacies is also used here, and in other foraminiferal studies, synonymously with foraminiferal assemblage and community.

Euryhaline species including *Elphidium excavatum* and *Ammonia parkinsoniana* can tolerate a wide range of salinities and are dominant in coastal environments (Schnitker, 1971; Culver et al., 2007)

Foraminiferal Laboratory Methods

Foraminiferal analysis was performed at approximately 25 cm intervals for vibracores C1 and C2; whereas foraminiferal analysis was conducted at a higher resolution for vibracore C12 (Figure 35; Figure 36; and Figure 37). Overall, methods by Culver et al., (1996), Smith (2004), and Tichenor (2016) were used to perform foraminiferal processing. All samples were weighed on filter paper using a digital balance prior to micropaleontological processing. The purpose of sample weighing was to later calculate the number of foraminifera per gram to determine foraminiferal abundance.

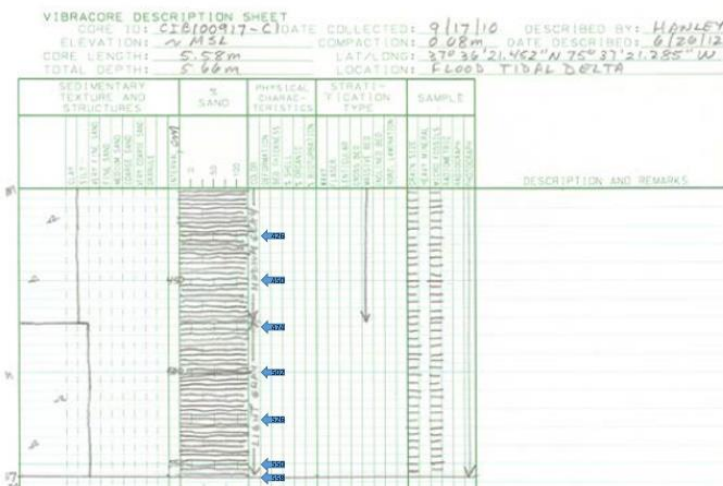
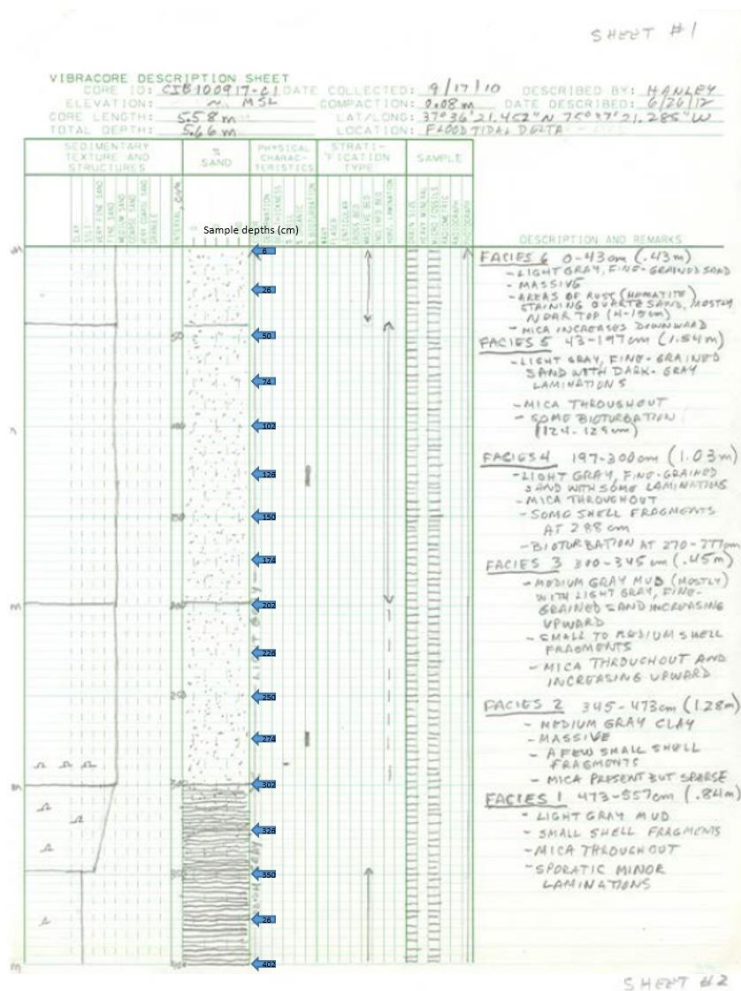


Figure 35: The core description sheet for vibracore C1 (from Hanley, 2015). Blue arrows indicate sample locations for foraminiferal analysis.

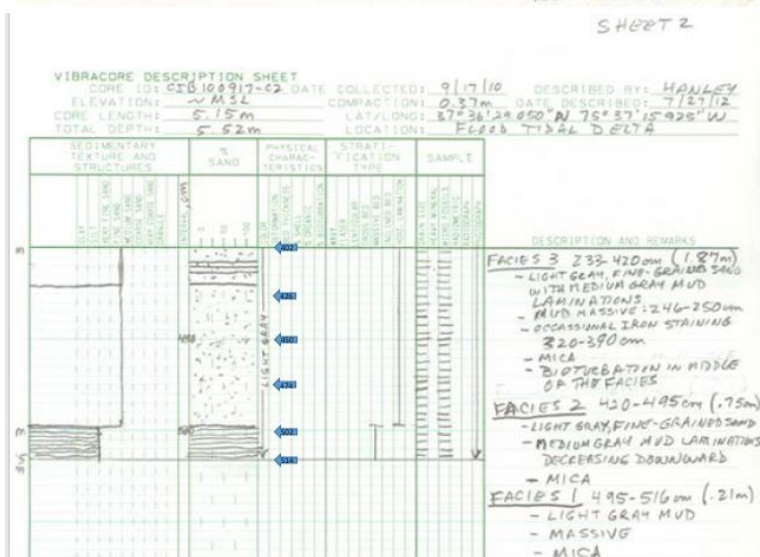
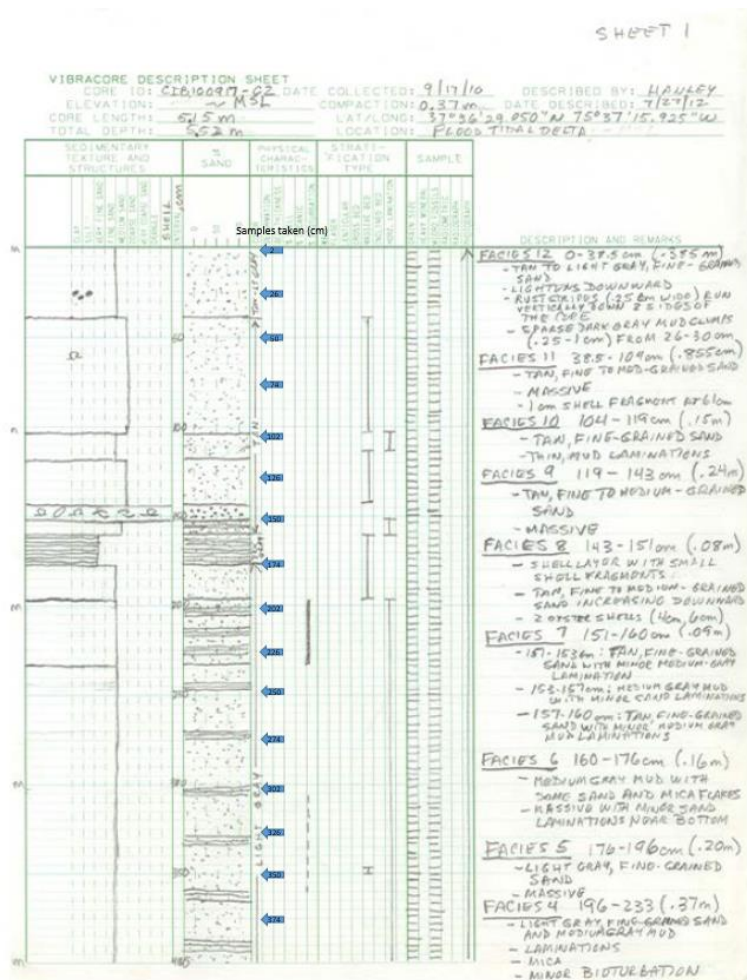


Figure 36: The core description sheet for vibracore C2 (from Hanley, 2015). Blue arrows indicate sample locations for foraminiferal analysis.

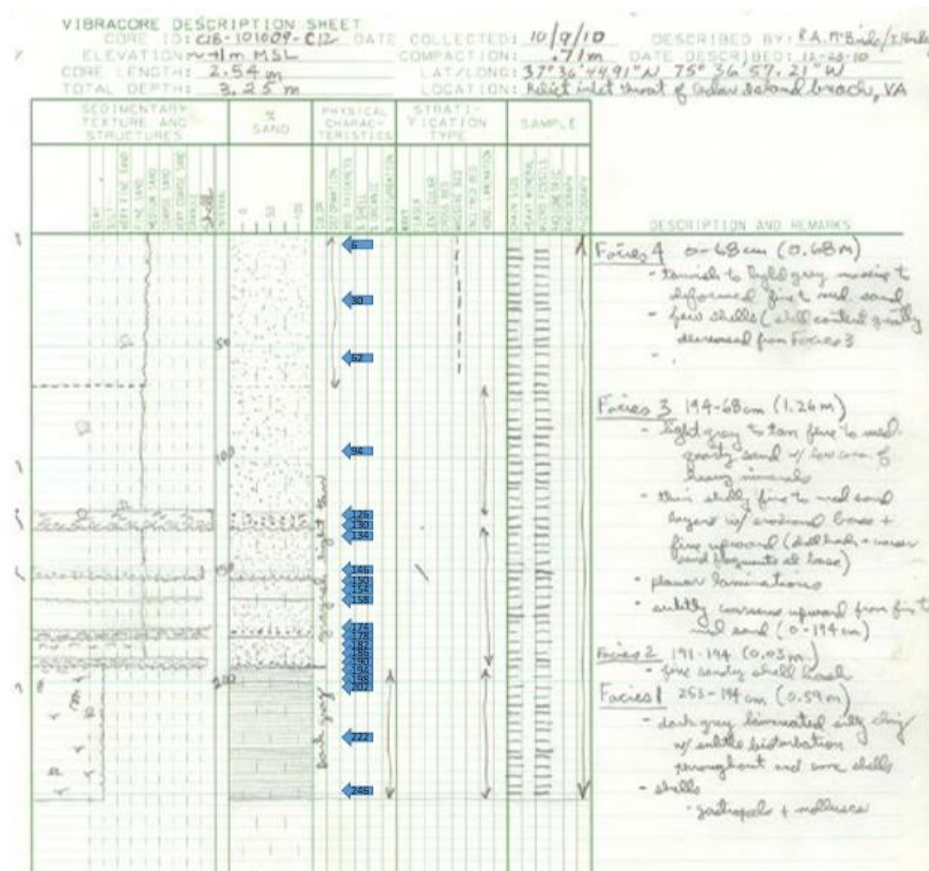


Figure 37: The core description sheet for vibracore C12 (from Hanley, 2015). Blue arrows indicate sample locations for foraminiferal analysis.

Clay-rich mud samples were soaked in 400 mL of deionized water for 24 hours to disaggregate sediment clumps. The disaggregated samples were then washed over a 63 μ m sieve to remove clay and silt sized particles. Samples were dried on filter paper over a hot plate.

A sodium polytungstate float was utilized to remove large proportions of quartz grains and concentrate foraminifera in quartz sand-rich samples (Figure 38; Munsterman and Kersholt, 1996). Specifically, the air-filled chambers of foraminifera cause the tests to float on the surface of the heavy liquid (sodium polytungstate), while heavy quartz

grains sink, which are unable to establish adequate surface tension (Munsterman and Kersholt, 1996). The concentrated “float” samples were washed utilizing deionized water and dried over a hotplate. To ensure that no individuals were left behind in the “sink” quartz fraction, each time floats were performed one “sink” sample was examined to determine if any foraminifera were present. If foraminifera were found, then the density of the sodium polytungstate was increased to ensure tests would float and “sink” samples were reexamined until the necessary fluid density was attained.



Figure 38: Munsterman and Kersholt (1996) sodium polytungstate float set up.

A split of 200 individuals, (representative of species proportions in samples) was sought from $< 500\ \mu\text{m}$ and $> 125\ \mu\text{m}$ fraction (Smith, 2004; Tichenor et al., 2016). Though many samples contained less than 200 individuals, some samples required the use of a microsplitter to attain about 200 individuals. Using a Nikon SMZ1500 trinocular stereo microscope, foraminifera were then picked out of the sediments, sorted, preliminarily identified, and glued to 60 square micropaleontological assemblage slides (Figure 39). Extended field depth images were taken of each species using the trinocular stereo microscope and Nikon software. Species identification was confirmed through comparison with publications and type specimens of the Cushman Collection at the Smithsonian Museum of Natural History, Washington, D.C.

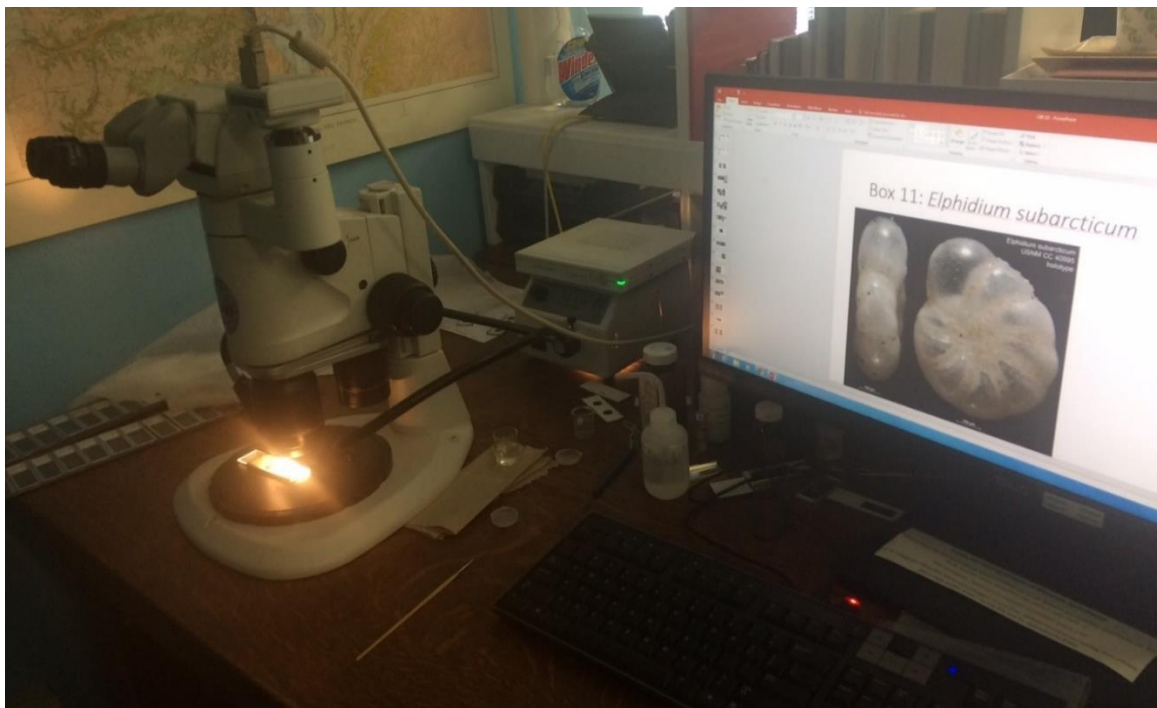


Figure 39: A trinocular stereo microscope was utilized to pick, identify, and photograph foraminifera.

In this study, foraminifera from the $< 500\ \mu\text{m}$ and $> 125\ \mu\text{m}$ size fraction were examined because this is the typical size range of benthic foraminifera found along the U.S. Mid-Atlantic coast. However, to ensure that foraminifera in the $> 500\ \mu\text{m}$ and $< 125\ \mu\text{m}$ fractions were not overlooked, four samples from different stratigraphic units that represent four different sedimentary depositional environments in C1, C2, and C12 were reanalyzed. No additional specimens were found in the $> 500\ \mu\text{m}$ and $< 125\ \mu\text{m}$ fractions. All sediment fractions were placed in vials and stored for future study.

Cluster Analysis

Cluster analysis allows for the interpretation of large data sets by clustering or grouping like samples together into biofacies (Mello and Buzas, 1968). Fossil foraminiferal samples are preserved ecological communities (biofacies) that are reflective of past depositional environments.

First, in a Q-mode cluster analysis, a matrix of similarity coefficients compares samples and those with the highest relationships are grouped (Mello and Buzas, 1968). Next, arithmetic averages of similar coefficient groups are compared to further define relationships among samples (weighted pair average) (Mello and Buzas, 1968). A dendrogram is produced from a cluster analysis and depicts the relatedness of samples (Figure 40; Mello and Buzas, 1968). Meaningful clusters are identified by selecting groupings within the dendrogram based on sample similarity (Mello and Buzas, 1968). Clusters are not necessarily exclusively found on one demarcated level of the dendrogram but rather several levels (Mello and Buzas, 1968).

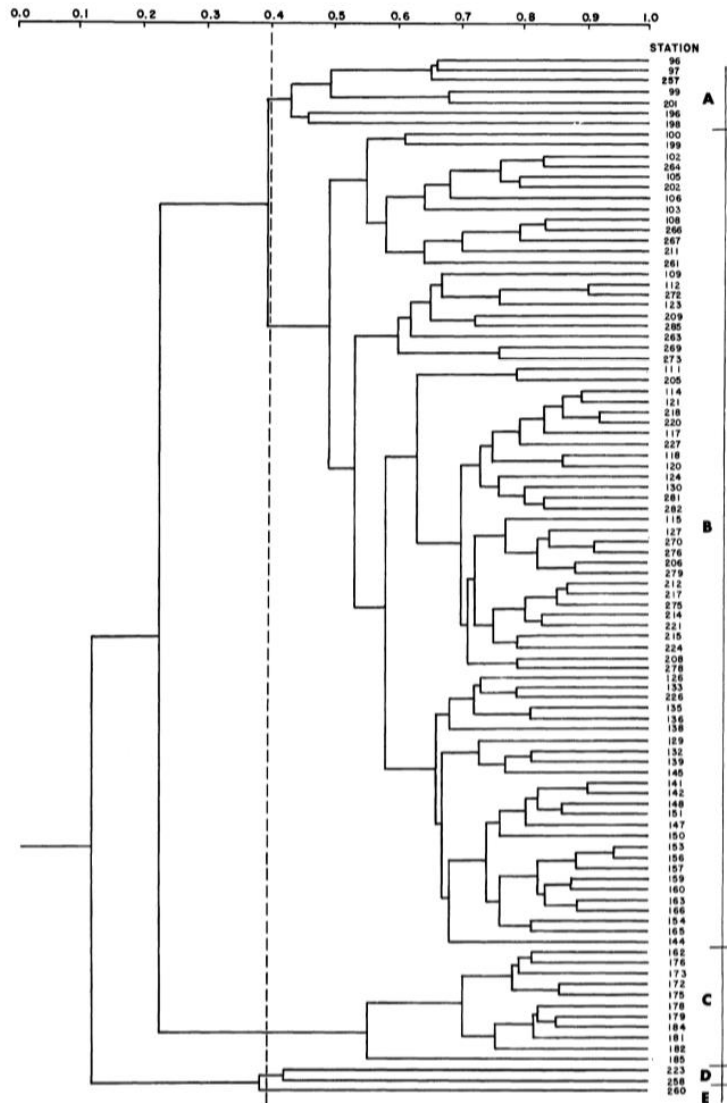


Figure 40: Example of a dendrogram produced by Q-mode cluster analysis (from Mello and Buzas, 1968)

Here, rare species, which accounted for less than two individuals in the entire combined data set, were removed from the data set utilized for cluster analysis. Also, a transformation of $\ln(x+1)$ was applied to the data set, where x is the number of

individuals, to ensure dissimilarities between samples are attributed to the whole community (Brooks, 1967; Buzas, 1968; Bates and Spencer, 1979). The Q-mode cluster analysis, described above, was performed using R software and a dendrogram was produced and analyzed to determine foraminiferal biofacies (Mello and Buzas, 1968). Additionally, the patterns of foraminiferal abundance (number of foraminifera per gram of sediment), and species distribution for C1, C2, and C3 were determined and analyzed.

RESULTS

Vibracores C1, C2, and C12 yielded 14 species of benthic foraminifera from 71 samples (Figure 41; Appendix A: Foraminifera of Cedar Island Inlet Systematics). For each core, **Error! Reference source not found.**, **Error! Reference source not found.**, and **Error! Reference source not found.** show percent of individual species per sample, number of individuals per gram of sediment, and species richness. Appendix B: Foraminiferal Count Data, contains the raw species counts for each sample. All three cores contain mud and or clay units that are barren of benthic foraminifera. Vibracores C1 and C2 had deeper penetration and have foraminiferal zones above and below the barren zones, whereas C12 has foraminifera zones exclusively above the barren zone.



Figure 41: Extended field depth images of 1, 2 *Ammonia parkinsoniana*; 3, 4 *Ammonia tepida*; 5, 6 *Buccella frigida*; 7, 8 *Cibicides lobatulus*; 9, 10 *Trochammina inflata*; 11 *Elphidium subarcticum*; 12 *Haynesina germanica*; 13 *Elphidium excavatum*; 14 *Elphidium mexicanum*; 15 *Elphidium galvestonense*; 16 *Elphidium gunteri*; 17 *Nonionella atlantica*. Scale bar = 100 μ m.

Table 5: Vibracore C2 benthic foraminiferal assemblages including percent of species, total specimens picked, extrapolated total number of individuals, individuals per g of sediment, and species richness for each sample.

depth (cm)	% <i>Ammonia parkinsoniana</i>	% <i>Ammonia tepida</i>	% <i>Buccella frigida</i>	% <i>Cibicides lobatulus</i>	% <i>Elphidium excavatum</i>	% <i>E. gabriellense</i>	% <i>Elphidium gunteri</i>	% <i>Elphidium mexicanum</i>	% <i>Elphidium</i> sp.	% <i>Elphidium subarcticum</i>	% <i>Haynesina germanica</i>	% <i>Nonionella atlantica</i>	% <i>Quinqueloculina</i> sp.	% <i>Trochammina inflata</i>	total specimens picked	extrapolated total	individuals per gram of sediment	species richness
6	5	-	2	-	93	-	-	-	-	-	-	-	-	-	43	43	2	3
26	3	0.5	1	-	92	0.5	1	-	-	1	-	-	-	-	214	263	10	7
50	4	4	1	-	91	-	1	-	-	-	-	-	-	-	227	0	0	5
74	0.4	1	2	0.4	90	0.4	1	-	0.4	2	0.4	0.8	-	-	263	4160	162	11
102	1	1	6	-	85	-	-	-	0.4	7	-	-	-	-	226	3616	139	6
126	-	2	3	-	95	-	1	-	-	-	-	-	-	-	241	2570	88	4
150	2	-	3	-	84	0.5	0.5	-	2	7	-	-	-	-	209	4553	165	7
174	2	2	1	-	88	0.3	1	0.7	0.3	3	-	-	-	-	286	4576	136	8
202	3	3	3	0.4	88	0.4	-	-	0.4	2	-	-	-	-	274	1253	38	8
226	3	2	2	-	88	-	0.5	1	-	1	-	-	3	-	373	853	26	8
250	3	2	2	-	87	0.5	-	1	-	4	-	0.5	-	-	215	11026	321	8
274	2	4	0.5	-	86	-	-	-	1	5	-	-	1	-	201	1072	31	7
302	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0	0
326	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0	0
350	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0	0
374	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0	0
402	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0	0
426	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0	0
450	2	-	4	-	95	-	-	-	-	-	-	-	-	-	132	132	6	3
474	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0	0
502	3	1	5	0.5	89	-	0	-	-	2	-	-	-	-	214	311	9	7
506	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0	0
526	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0	0
550	-	-	-	-	80	-	-	-	20	-	-	-	-	-	5	4	0	2
554	-	-	6	-	92	0.9	-	-	-	-	-	-	2	-	108	108	4	4
558	6	-	-	-	94	-	-	-	-	-	-	-	-	-	16	16	1	2

Table 6: Vibracore C2 benthic foraminiferal assemblages including percent of species, total specimens picked, extrapolated total number of individuals, individuals per g of sediment, and species richness for each sample.

depth (cm)	% <i>Ammonia parkinsoniana</i>	% <i>Ammonia tepida</i>	% <i>Buccella frigida</i>	% <i>Cibicides lobatulus</i>	% <i>Elphidium excavatum</i>	% <i>E. galvestonense</i>	% <i>Elphidium gunteri</i>	% <i>Elphidium mexicanum</i>	% <i>Elphidium</i> sp.	% <i>Elphidium subarcticum</i>	% <i>Haynesina germanica</i>	% <i>Nonionella atlantica</i>	% <i>Quinqueloculina</i> sp.	% <i>Trochammina inflata</i>	total specimens picked	extrapolated total	individuals per gram of sediment	species richness
2	11	-	-	-	89	-	-	-	-	-	-	-	-	-	19	19	1	2
26	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0	0
50	4	1	1	-	88	-	-	-	2	3	-	-	0.5	-	216	275	14	7
74	-	4	2	-	88	-	-	-	0.5	4	-	0.5	-	-	201	1608	87	6
102	0.5	0.5	2	-	93	0.5	-	1	0.5	2	-	-	-	-	202	323	16	8
126	3	-	0.5	-	93	1	-	1	0.5	-	0.5	-	-	-	202	323	15	7
150	2	-	2	-	94	0.5	-	1	-	-	-	-	-	-	209	319	18	5
174	-	-	-	-	100	-	-	-	-	-	-	-	-	-	8	8	0	1
202	2	-	4	-	91	-	-	-	-	2	-	-	-	-	45	45	3	4
226	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0	0
250	3	3	1	-	88	-	-	1	-	5	-	-	-	-	80	80	4	6
274	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0	0
302	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0	0
326	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0	0
350	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	10	0	0
374	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0	0
402	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0	0
426	-	-	16	-	84	-	-	-	-	-	-	-	-	-	19	19	0	2
450	4	2	5	-	85	-	-	-	2	1	-	-	-	-	202	539	21	6
474	3	2	3	-	91	-	-	-	0.5	-	-	-	-	-	208	3328	135	5
486	5	-	3	-	92	-	-	-	-	-	-	-	-	-	207	2436	97	3
502	-	0.4	4	-	95	-	-	0.4	-	0.4	-	-	-	-	237	1264	41	5
506	5	1	3	-	90	-	-	0.4	0.4	1	-	-	-	-	229	916	28	7
514	2	-	7	-	89	-	-	0.5	-	0.5	1	-	-	-	213	3408	99	6

Table 7: Vibracore C12 benthic foraminiferal assemblages including percent of species, total specimens picked, extrapolated total number of individuals, individuals per g of sediment, and species richness for each sample.

depth (cm)	% <i>Ammonia parkinsoniana</i>	% <i>Ammonia tepida</i>	% <i>Buccella frigida</i>	% <i>Elphidium excavatum</i>	% <i>E. galvestonense</i>	% <i>Elphidium gunteri</i>	% <i>Elphidium mexicanum</i>	% <i>Elphidium</i> sp.	% <i>Elphidium subarcticum</i>	% <i>Haynesina germanica</i>	% <i>Quinque loculina</i> sp.	total specimens picked	extrapolated total	individuals per gram of sediment	species richness	% <i>Elphidium excavatum</i>
6	-	-	-	92	-	-	-	-	8	-	12	48	11	2	92	
30	-	-	-	83	-	17	-	-	-	-	6	48	6	2	83	
62	3	-	-	89	-	-	0.5	-	8	-	204	408	17	4	89	
94	1	-	-	93	-	2	-	1	2	-	87	87	5	5	93	
126	1	-	0.5	97	0.5	-	0.5	1	-	-	215	286	21	6	97	
130	-	-	-	72	-	25	3	-	-	-	36	36	3	3	72	
134	2	0.6	2	94	-	2	1	-	-	-	176	176	13	6	94	
146	2	0.5	1	96	0.5	-	-	-	-	-	214	623	45	5	96	
150	1	2	1	95	0.3	-	-	0.3	1	-	319	83	5	7	95	
154	2	-	-	85	-	13	-	-	-	-	53	53	3	3	85	
158	2	1	1	96	-	-	1	0.5	-	-	200	533	25	6	96	
174	2	-	-	92	-	4	2	-	-	-	164	569	31	4	92	
178	2	-	1	96	0.4	-	-	0.4	1	-	257	257	19	6	96	
182	-	-	2	81	0.9	-	-	0.9	1	14	218	872	22	6	81	
186	2	-	0.4	97	-	-	0.4	-	0.4	-	225	1442	35	5	97	
190	0.4	-	1	92	0.9	-	-	2	3	0.4	235	3000	61	7	92	
194	3	-	5	54	1	-	6	1	0.5	29	203	270	9	8	54	
198	5	-	5	68	1	-	2	0.4	1	18	237	474	13	8	68	
202	-	-	19	76	-	-	-	-	5	-	21	21	1	3	76	
222	-	-	-	0	-	-	-	-	-	-	0	0	0	0	0	
246	-	-	-	0	-	-	-	-	-	-	0	0	0	0	0	

Cluster Analysis

Two distinct groups determined by the total number of individuals, species richness, and species proportions are revealed through cluster analysis. The larger cluster can be further divided into two groups, A and B based their positions on the dendrogram because of the distribution and proportions of species present (Figure 42). The smaller cluster can also be subdivided into clusters C and D by their dendrogram level and species distribution (Figure 42). Appendix C: Biofacies Count Data contains the percent data for each species in the biofacies.

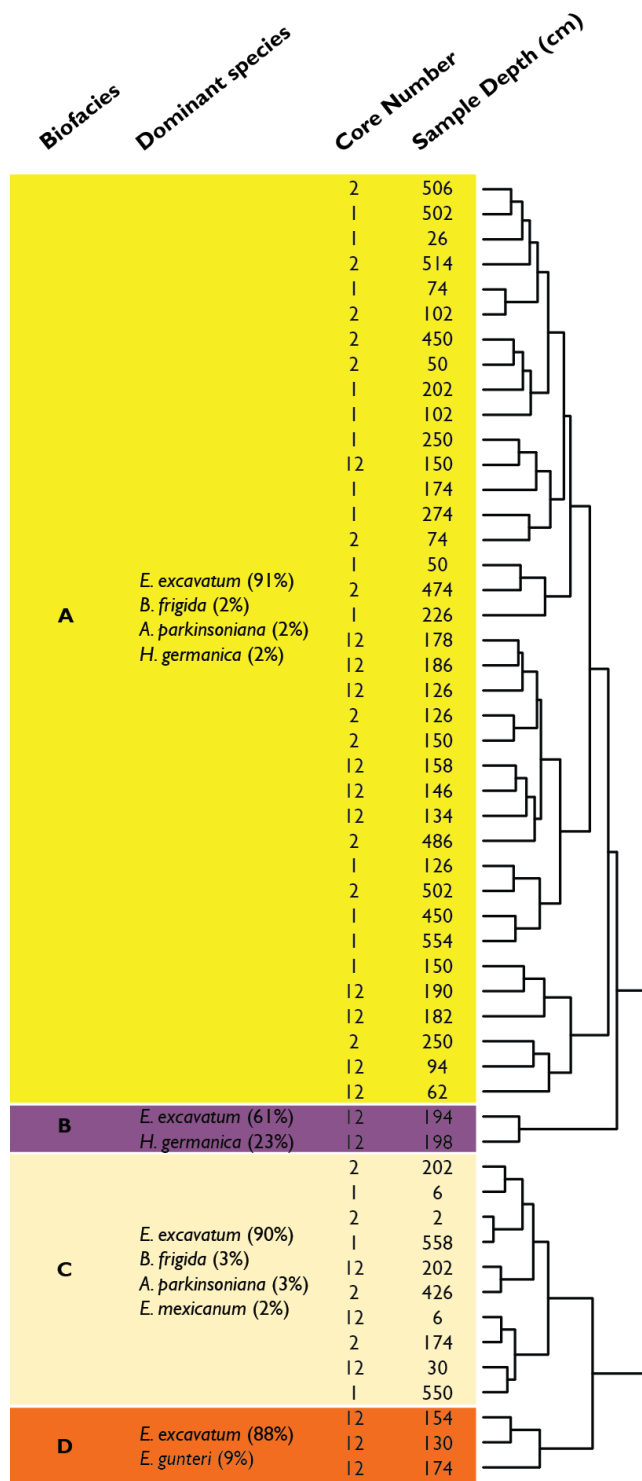


Figure 42: Dendrogram produced by cluster analysis showing four groups or biofacies (A, B, C, and D).

Biofacies A is characterized by a strong dominance of *Elphidium excavatum* (91%) with the next most abundant species being *Buccella frigida* (2%), *Ammonia parkinsoniana* (2%), and *Haynesina germanica* (2%). Species that make up less than 2% of the biofacies include *Ammonia tepida* (1%), *Elphidium mexicanum* (0.4%), *Elphidium subarcticum* (0.4%), *Elphidium galvestonense* (0.2%), *Trochammina inflata* (0.2%), *Elphidium sp.* (0.1%), *Elphidium gunteri* (0.1%), *Quinqueloculina sp.* (0.1%), *Nonionella atlantica* (0.03%) and *Cibicides lobatulus* (0.04%). Biofacies A is the most heterogeneous biofacies with highest species richness containing all 14 species found in this study. Biofacies A occurs in diverse lithologies including sand, and sandy muds, and clays.

The two samples that comprise biofacies B are found in C12 at the base of an unconformity. Biofacies B is also dominated by *Elphidium excavatum* (61%) but is also dominated by *Haynesina germanica* (23%) containing the highest proportion of a subsidiary species in all biofacies. Additionally, the sample is composed of *Buccella frigida* (5%), *Ammonia parkinsoniana* (5%), *Elphidium galvestonense* (1%), *Elphidium mexicanum* (4%), *Elphidium subarcticum* (1%), and *Elphidium sp.* (1%). Accordingly, the second highest species richness of 8 species occurs in biofacies B. Biofacies B is found at the bottom of and just below a shell hash layer.

Biofacies C, like biofacies A, is completely dominated by 90% *Elphidium excavatum*; however, it has a lower species richness containing only 7 species. Other species include *Buccella frigida* (3%), *Ammonia parkinsoniana* (3%), *Elphidium gunteri*

(2%), *Elphidium mexicanum* (1%), *Haynesina germanica* (1%) and *Elphidium subarcticum* (0.3%). Lithologies where biofacies C occur include sand, mud, and clay.

Biofacies D is comprised of three samples, which occur exclusively in C12 within one sandy sedimentary facies. Biofacies D has the lowest species richness containing only four species including *Elphidium excavatum* (88%), *Elphidium gunteri* (9%), *Ammonia parkinsoniana* (2%), and *Elphidium mexicanum* (2%).

Figure 43, Figure 44, and Figure 45 display the distribution of the biofacies within each core. The foraminiferal facies do not always correlate to the sedimentary facies; however, in general the base of the cores are predominantly fossiliferous poor to barren muds and clays (C1, C12) or fossiliferous to barren laminated sand and mud (C2), whereas the top portions are all fossiliferous rich sand.

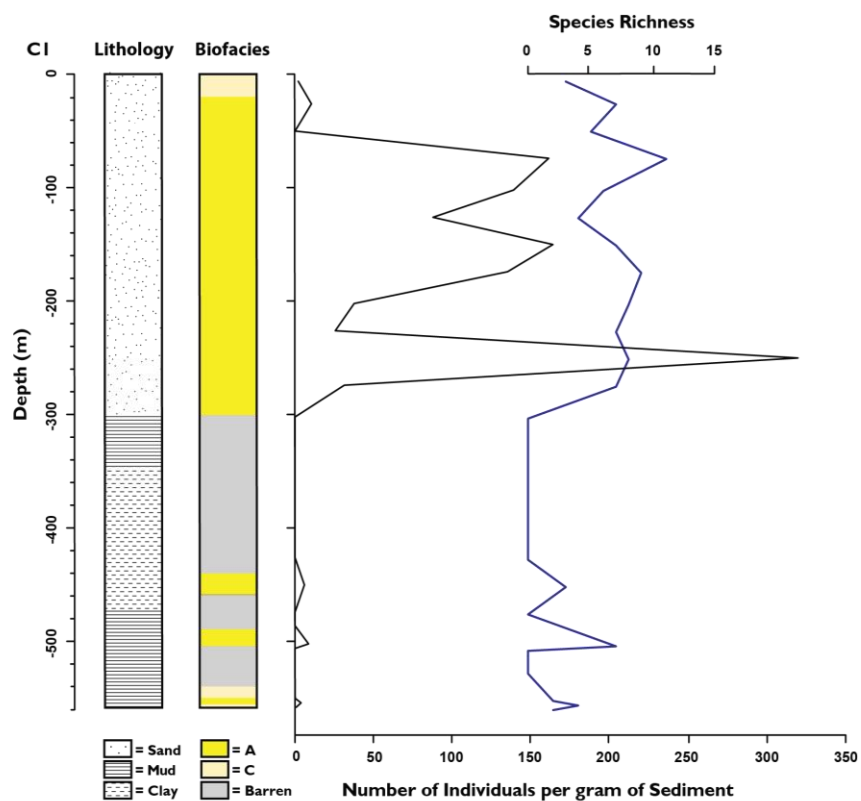


Figure 43: Lithology, foraminiferal biofacies, number of individuals per gram of sediment, and species richness for Vibracore C1.

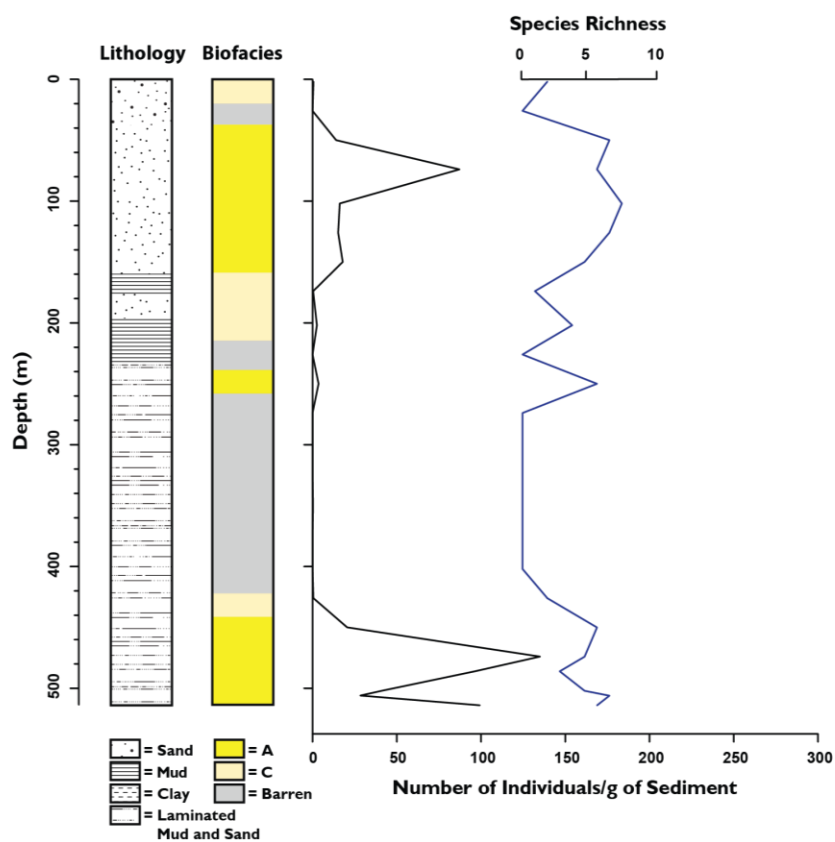


Figure 44: Lithology, foraminiferal biofacies, number of individuals per gram of sediment, and species richness for Vibracore C2.

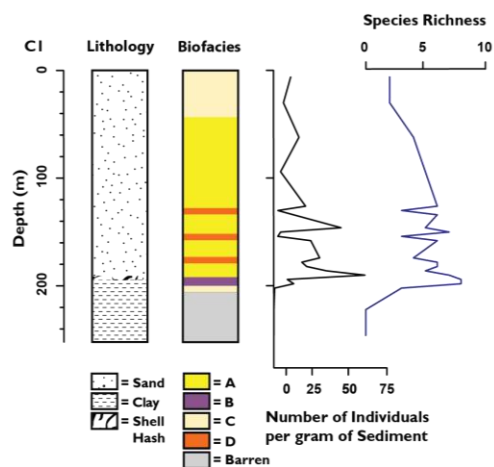


Figure 45: Lithology, foraminiferal biofacies, number of individuals per gram of sediment, and species richness for Vibracore C12.

Cross Section

A geologic cross section from the inlet throat (C12) through the flood-tidal delta (C1 and C2) was constructed by correlating the vertical distribution of biofacies within the three vibracores (Figure 46). The top and bottom of the cross section is characterized by two large biofacies A deposits both capped by biofacies C. The top biofacies A deposit encompasses all three cores, has a biofacies C base, and contains biofacies B and D within the inlet throat (C12). Between the biofacies A deposits is a barren deposit intersected by several thin occurrences of biofacies A deposits. These biofacies A deposits do not all correlate; for example, the two thin bottommost occurrences in C1 are not reflected in C2.

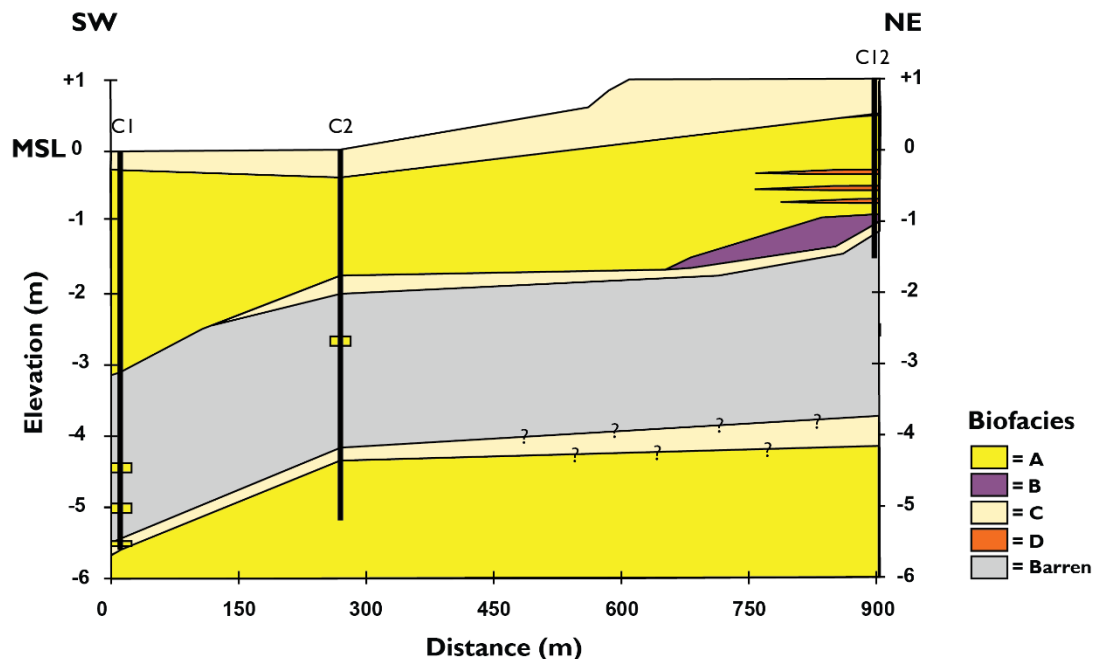


Figure 46: Cross section through C1, C2, and C12 showing the distribution of biofacies.

DISCUSSION

Barrier island systems and their associated depositional environments are dynamic in nature just like the benthic foraminiferal assemblages deposited in these sedimentary environments. The relict Cedar Island Inlet, studied here, is an area where marine and estuarine waters are exchanged and marine benthic foraminifera from nearshore and shelf environments are also transported and deposited mixing with in situ estuarine populations (Luck, 1936; Grossman and Benson, 1967; Wang and Murray, 1983). Foraminiferal assemblages of tidal-inlet deposits provide information about the environment of deposition including salinity as well as the degree of tidal mixing (Wang and Murray, 1983).

Elphidium excavatum completely dominates all Cedar Island samples that contain foraminifera. *Elphidium excavatum* is a euryhaline species that is well adapted to a variety of environments and is readily found in nearshore and inner shelf environments (Scott et al., 2001; Culver et al., 1996; Woo et al., 1997; Hayward et al., 2004; Abbene et al., 2006; Culver et al., 2007). *Elphidium excavatum* is successful and completely dominates environments that characterize Cedar Island Inlet biofacies, which are low in organics, with sandy substrates, and salinities ranging from near normal marine salinity to high salinity (Culver et al., 1996; Woo et al., 1997; Hayward et al., 2004).

Four foraminiferal biofacies characterize the assemblages from the former Cedar Island Inlet and have been interpreted to represent estuary, inlet channel floor, high energy inlet fill, flood-tidal delta/inlet fill and washover/beach/aeolian environments (Table 8; Figure 47).

Table 8: Lithology, biofacies, paleontology, specimen count, species richness, occurrence, and depositional environment interpretation of Cedar Island Inlet.

Lithology	Biofacies	Paleontology	Specimen Count	Species Richness	Occurrence	Interpretation
Sands, Muds and Clays	C	<i>Elphidium excavatum</i> , <i>Buccella frigida</i> , <i>Ammonia parkinsoniana</i> , <i>Elphidium gunteri</i> , <i>Elphidium mexicanum</i> , <i>Haynesina germanica</i> , and <i>Elphidium subarcticum</i>	5-45	1-7	C1, C2, and C12	Washover/Beach/Aeolian
Sands, Muds and Clays	A	<i>Elphidium excavatum</i> , <i>Buccella frigida</i> , <i>Ammonia parkinsoniana</i> , <i>Haynesina germanica</i> , <i>Ammonia beccarii</i> , <i>Elphidium mexicanum</i> , <i>Elphidium subarcticum</i> , <i>Elphidium galvestonense</i> , <i>Elphidium sp.</i> , <i>Elphidium gunteri</i> , <i>Trochammina inflata</i> , <i>Nonionella atlantica</i> , <i>Cibicides lobatulus</i> , <i>Quinqueloculina sp.</i>	80-11026	3-12	C1, C2, and C12	Flood-tidal delta/Inlet fill
Sand	D	<i>Elphidium excavatum</i> , <i>Elphidium gunteri</i> , <i>Ammonia parkinsoniana</i> , and <i>Elphidium mexicanum</i>	36-64	3-4	C12	High energy inlet fill
Sand, Shell Hash	B	<i>Elphidium excavatum</i> , <i>Haynesina germanica</i> , <i>Buccella frigida</i> , <i>Ammonia parkinsoniana</i> , <i>Elphidium galvestonense</i> , <i>Elphidium mexicanum</i> , <i>Elphidium subarcticum</i> , and <i>Elphidium sp.</i>	203-237	8	C12	Inlet channel floor
Sands, Muds and Clays	N/A	N/A	0	0	C1, C2, and C12	Estuary

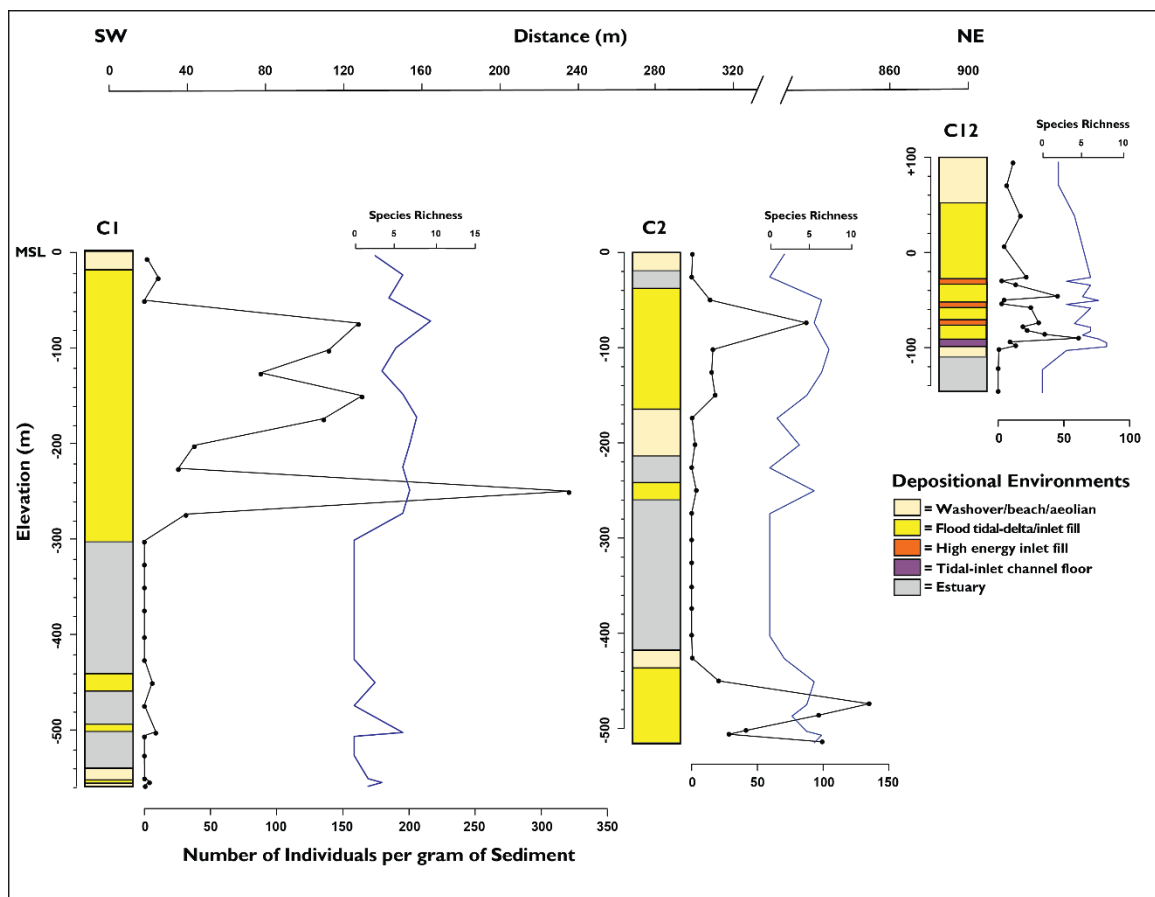


Figure 47: Depositional environment designation of vibracores C1, C2, and C12. All assemblages are dominated by *E. excavatum*. The estuarine deposits are barren. The inlet channel floor assemblage is defined by a significant proportion of *H. germanica*. High energy inlet fill deposits are distinguished by three accessory species *E. gunteri*, *E. mexicanum*, and *A. parkinsoniana*. The flood-tidal delta/inlet assemblages are characterized by *B. frigida*, *A. parkinsoniana*, and *H. germanica*. The washover/beach/aeolian assemblage is differentiated from high energy inlet fill by a higher species richness and higher proportion of *E. gunteri*.

Estuary (barren samples)

The estuary depositional environment is characterized by mud, clay, and laminated muds and clays and is found in the bottom portions of C1 and C12 and in the center of C2. Finer grain sizes reflect a lower energy environment.

The facies is barren of foraminifera and this is likely because of complete taphonomic loss. Culver et al. (1996) examined the relationship between living and fossil

foraminiferal assemblages of an estuary just south of Wreck Island, VA, which is 36 km south of Cedar Island and observed that less than 1% of individuals were preserved. The significant loss of fauna is attributed to intense bioturbation, which mechanically destroys tests because of abrasion, and predatory boring, which causes test dissolution (Culver et al., 1996).

Inlet channel floor

Biofacies B occurs exclusively in core (C12) at just above the erosional contact (disconformity) between the underlying muds and coarse shell hash (Figure 48). The erosional surface and coarse shell hash indicate a higher energy environment consistent with an inlet channel floor (Hanley, 2015).

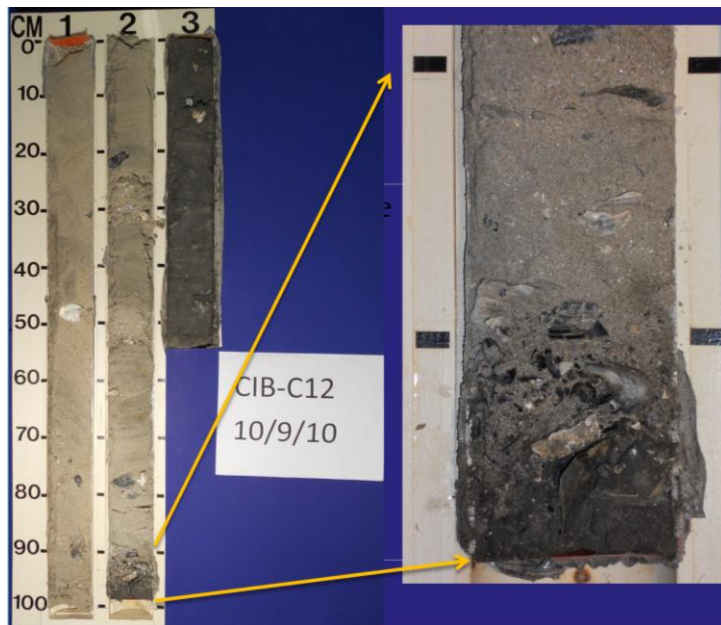


Figure 48: Core photograph of vibracore C12 highlighting the unconformity at 198 cm and coarse shell hash layer from 198 cm-190cm (from Hanley, 2015). Scale in centimeters. Core bottom is lower right and core top is upper left

Like modern tidal-inlet depositional environments observed in the Outer Banks, NC, biofacies B has relatively low species richness and low abundances consistent with the higher energy, harsh tidal-inlet environments (Abbene et al., 2006; Vance et al., 2006). Biofacies B, like the tidal-inlet foraminiferal assemblage of Oregon Inlet, NC shares several key species including dominant *Elphidium excavatum*, as well as, *Ammonia parkinsoniana*, *Ammonia tepida*, *Buccella frigida*, *Elphidium galvestonense*, and *Elphidium subarcticum* (Vance et al., 2006). Biofacies B also includes one estuarine species, *Haynesina germanica*. The assemblage contains mostly shelf species but high abundances of *Haynesina germanica* demonstrate the strong marine influence of mixing tides (Vance et al., 2006).

High Energy Inlet fill

Biofacies D comprises three samples that occur exclusively within one sand facie of the tidal-inlet channel (C12) and is interfingering between biofacies A (flood-tidal delta/inlet fill). Therefore, spatially, biofacies D likely reflects a depositional environment and process that occurred as the tidal inlet filled and closed. Biofacies D also exclusively occurs within three grain size spikes observed by Hanley (2015) that were interpreted to represent increases in energy associated with higher flow velocities

potentially associated with storms, spring tides (syzygy), or perigean spring tides (perigee-syzygy) as discussed in Seminack (2016) (Figure 49).

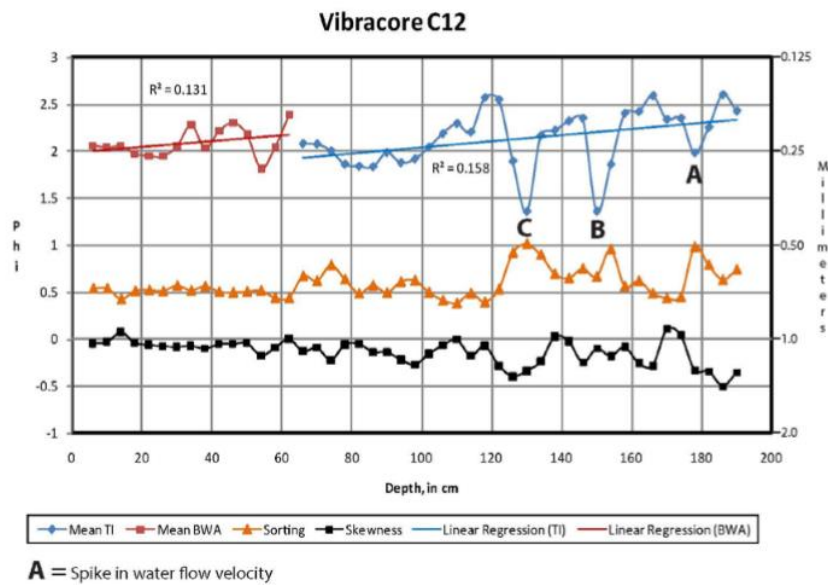


Figure 49: Mean grainsize, sorting, and skewness trends for C1 including three energy spikes A, B, and C, which represent increased flow velocities (From Hanley, 2015). Core bottom is to the right and core top is to the left.

Foraminiferal assemblages of biofacies D are similar to the shoreface and ebb-tidal delta assemblages of the VA Delmarva barrier islands studied by Woo (1997). Specifically, low species richness, low abundance, and exclusively marine species are observed. Therefore, the foraminifera of biofacies D likely were transported from the shoreface and or ebb-tidal delta on the seaward side of Cedar Island into the inlet channel during depositional events in the tidal inlet such as a major storm, spring tides, or perigean spring tides.

Flood-tidal delta/Inlet fill

Biofacies A occurs in C1 and C2 where satellite imagery indicates a flood-tidal delta was present when Cedar Island Inlet was open in September 2005 but biofacies A also occurs within C12 or the inlet channel (Figure 50). Therefore, it is not spatially conceivable for flood-tidal delta deposits to persist in the inlet throat. Thus, biofacies A likely represents a horizontal gradation between two depositional environments, flood-tidal delta and inlet fill, which were not differentiated by cluster analysis.



Figure 50: Cedar Island Inlet September 2005 and vibracore locations (Google Earth, 2017).

The uppermost occurrences of biofacies A in all three cores are characterized by sand lithologies, typical of a flood-tidal delta/inlet fill environment. However, lower

occurrences in C1 and C2 are found in mud and clay layers with intermittent laminations and bioturbation. The sandy laminations and fractions likely are the origin for the foraminiferal assemblages found that cluster within biofacies A. These sand laminations could be the result of island breaching events where a small flood-tidal delta is established and thin layer deposited but shut off when the breach closes or they may represent the distal portions of larger flood-tidal deltas.

Foraminiferal assemblages of Biofacies A consist of the most diverse, robust, and widely distributed samples. Samples are overwhelmingly calcareous; however, three samples contain the only occurrence in all biofacies of agglutinated *Trochammina inflata* in cores C1 and C2. Biofacies A has the highest species richness, which has been observed in flood-tidal delta environments because of the mixing of estuarine and normal marine species via tidal exchange (Grossman and Benson, 1967, Robinson and McBride, 2006). The foraminiferal assemblage of biofacies A is similar to the flood-tidal delta assemblage observed by Robinson and McBride, 2006; specifically high abundances were observed and similar species distributions including *Elphidium excavatum* (dominant), *Ammonia parkinsoniana*, *Buccella frigida*, *Cibicides lobatulus*, *Elphidium galvestonense*, *Elphidium mexicanum*, *Elphidium subarcticum*, and *Quinqueloculina* sp. Biofacies A also contains estuarine species *Haynesina germanica*, *Ammonia tepida* and *Trochammina inflata*, as well as marine species *Elphidium gunteri* and *Nonionella atlantica*.

Inlet fill derived from subaqueous spit platforms, is a shallower, lower energy environment because as the axis of tidal flow shifts downdrift, lower tidal velocities and

finer sediment is deposited updrift (Kumar and Sanders, 1974; Moslow and Heron, 1978). Therefore, the inlet fill assemblage likely clusters with the flood-tidal delta assemblage because they represent similar physical environments where sediment is readily deposited, tidal exchange occurs, and similar communities live. Similarly, Moslow and Heron (1978) observed inlet fill and flood-tidal delta deposits had indistinguishable assemblages containing a mixture of shelf and backbarrier mollusks.

Washover/Beach/Aeolian

All three cores are topped with biofacies C in sands and therefore likely represent washover/beach/aeolian deposits because Cedar Island is frequently overwashed by storm surge and large storm waves during nor'easters and hurricanes. A year prior to core collection, in November 2009, a large nor'easter, Nor'Ida, heavily impacted Cedar Island with 1.43 m of storm surge (Collins, 2009; Virginia Institute of Marine Science, 2009). Extensive washover/beach/aeolian deposits occurred during Nor'Ida and is likely responsible for all or most of the deposition of biofacies C (Figure 51). Like biofacies A, biofacies C also occurs in mud and clay layers with intermittent laminations and bioturbation where the sandy portions are likely the origin for the foraminiferal assemblages. These laminations could be the result of additional washover events in response to strong storms.



Figure 51: Low angle oblique photographs of Cedar Island, VA (A) pre-Hurricane Nor'Ida (May 21, 2009) and (B) post Hurricane Nor'Ida (December 4, 2009) (USGS, 2016).

Biofacies C has a similar foraminiferal assemblage to washover depositional environments observed on Pea Island, NC, where normal marine salinity species dominate and few minor estuarine species are included (Culver et al., 2006; Smith 2009). Here the assemblage is slightly different containing euryhaline species *Elphidium excavatum* and *Ammonia parkinsoniana*, normal marine salinity species *Buccella frigida* *Elphidium gunteri*, *Elphidium mexicanum*, and *Elphidium subarcticum*, as well as one estuarine species *Haynesina germanica*.

Biofacies Regional Comparisons

The closest regional studies performed near Cedar Island include the Virginia Delmarva Peninsula barrier islands south of Cedar Island, and it was expected that Cedar Island Inlet biofacies would readily correlate with environments identified in these studies as found in Figure 29 and Table 4 (Culver et al., 1996; Woo et al., 1997). However, only biofacies D, interpreted to represent, high energy inlet fill is similar to the shoreface and ebb-tidal delta assemblages identified by Woo et al., (1997). Whereas,

biofacies A (flood tidal delta/inlet fill), biofacies B (inlet channel floor), and biofacies C (washover/beach/aeolian) are similar to corresponding environments found in studies along the Outer Banks, N.C. (Grossman and Benson, 1967, Abbene et al., 2006; Culver et al., 2006; Robinson and McBride, 2006, Vance et al., 2006; Smith 2009

The Virginia barrier islands studied by Culver et al. (1996) and Woo et al. (1997) are mixed energy, tide-dominated barrier islands separated by tide-dominated inlets with well-developed ebb-tidal deltas. However, Cedar Island is a transitional, mixed-energy barrier island, and Cedar Island Inlet is a wave-dominated tidal inlet with a flood tidal delta. The barrier islands of the Outer Banks, N.C. are wave-dominated and, like Cedar Island, have wave-dominated tidal inlets with well-developed flood tidal deltas. Thus, Cedar Island Inlet morphology and biofacies reflect a wave-dominated verses a tide-dominated environment.

Depositional Environments in Cross Section

A cross section of the depositional environments indicated by biofacies distribution reveal two distinct tidal-inlet openings and potentially several minor breaches or distal inlet openings within the area of C1, C2, and C12 (Figure 52).

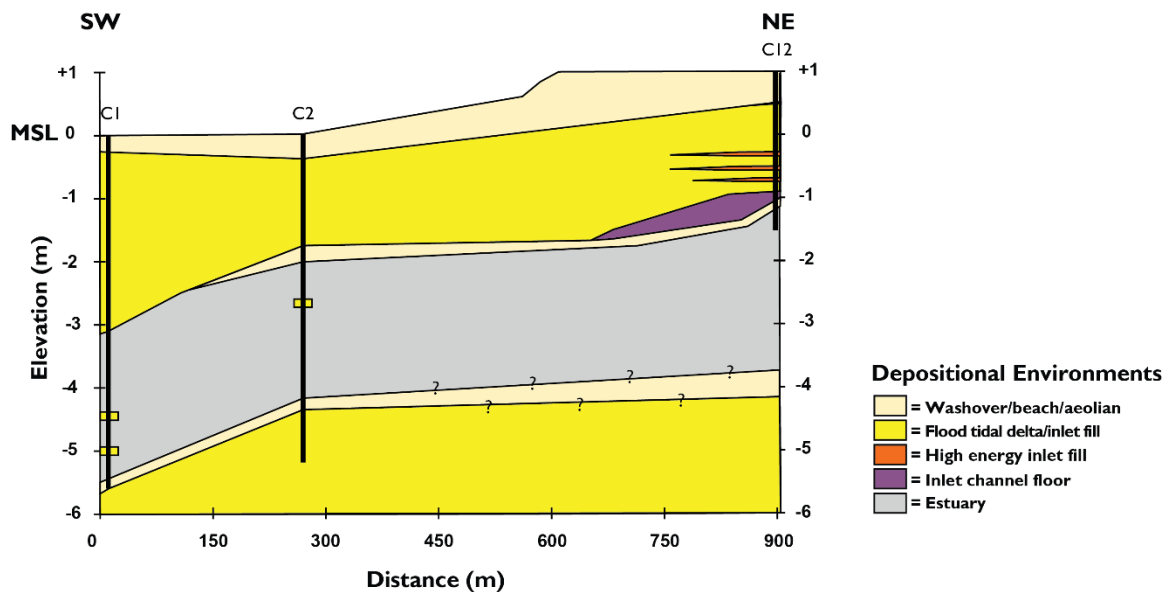


Figure 52: Cross section through C1, C2, and C12 showing the distribution of depositional environments based on biofacies occurrence. Question marks (?) represent areas of extrapolation where supporting core data are not available.

The oldest tidal inlet opening occurs at the base of C1 and C2 below the vibracore penetration of C12. A thick flood-tidal delta/inlet fill environment is observed in C2 (-474 cm to -514 cm) and may occur below the level of vibracore penetration in C1 (Figure 52). The thick flood-tidal delta/inlet fill deposit is capped by a thin washover/beach/aeolian deposit observed in C1 (-550 cm and -558 cm) and C2 (-424 cm) (Figure 52). Within the C1 washover/beach/aeolian deposit one sample (-554 cm), indicative of flood-tidal delta/inlet fill environments is found and may represent sediment transported during scouring of an overwash event (Figure 52).

Thin flood-tidal delta/inlet fill deposits are found within the large, central estuarine deposit C1 (-450 cm and -502 cm) and C2 (-250 cm) (Figure 52). However, the coarse sampling interval and occurrence depths make it difficult to correlate these deposits.

The most recent tidal-inlet opening occurs towards the core tops and begins with a basal washover/beach/aeolian surface in C2 (-174 cm to -202 cm) and C12 (-102 cm), which may have been deposited during initial barrier island breaching(s) ((Figure 52). This washover/beach/aeolian deposit is pinched out before reaching C1. Up core, in C12 an inlet channel floor (-94 cm to -98 cm) and high energy inlet fill (-30 cm, -54 cm, and -74 cm) environments are found (Figure 52). A thick flood-tidal delta/inlet fill deposit characterizes the bulk of this second tidal-inlet opening forming a thick deposit in all three cores. Finally, the sequence is capped with an overwash deposit most likely caused by a major nor'easter, Nor'Ida, which caused significant island overwash just prior to vibracore collection (Figure 52).

Sedimentary Facies vs. Biofacies

Sedimentologic and foraminiferal analyses reveal similar depositional environment interpretations of the upper 300 cm of C1, C2, and C12 with a basal estuarine deposit, inlet channel floor, high energy inlet fill, flood-tidal delta/inlet fill, and washover/beach/aeolian environments in comparable positions within each core (Figure 53; Hanley, 2015).

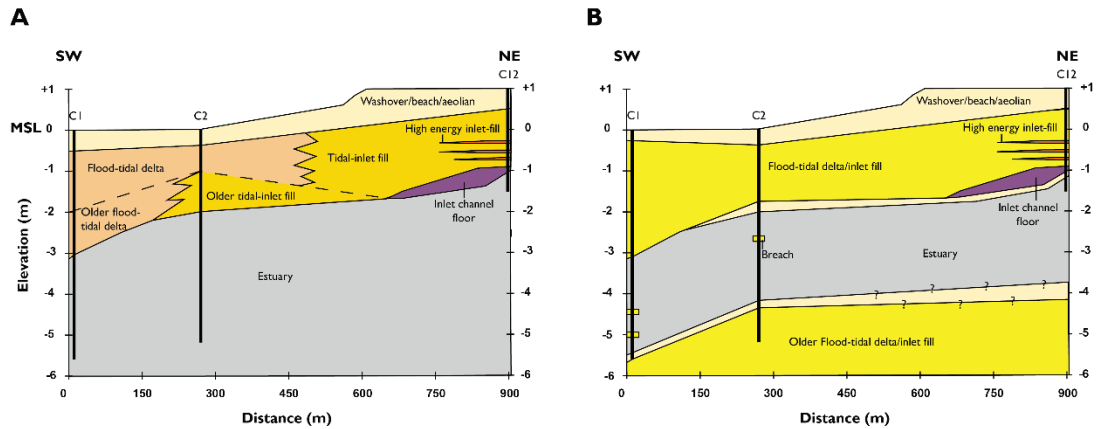


Figure 53: Comparison of (A) Hanley (2015) sedimentary facies and (B) biofacies cross section interpretations. Question marks (?) represent areas of extrapolation where supporting core data are not available.

However, sedimentary facies interpretations exclusively separate tidal-inlet and flood tidal-delta deposits which are grouped together in the biofacies cross section interpretation (Figure 53; Hanley, 2015). Additionally, sedimentologic analysis revealed two fining upward successions in C1 and two coarsening upward successions in C2 that are interpreted to represent two stacked tidal inlet openings (Figure 53A; Figure 54; Figure 55; Hanley, 2015).

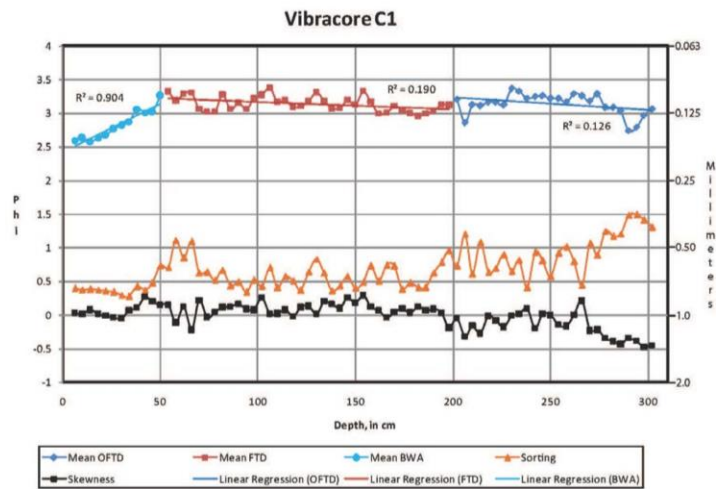


Figure 54: Mean grainsize, sorting, and skewness trends for Vibracore C1 and interpretation of depositional environment (from Hanley, 2015). Core bottom is to the right and core top is to the left.

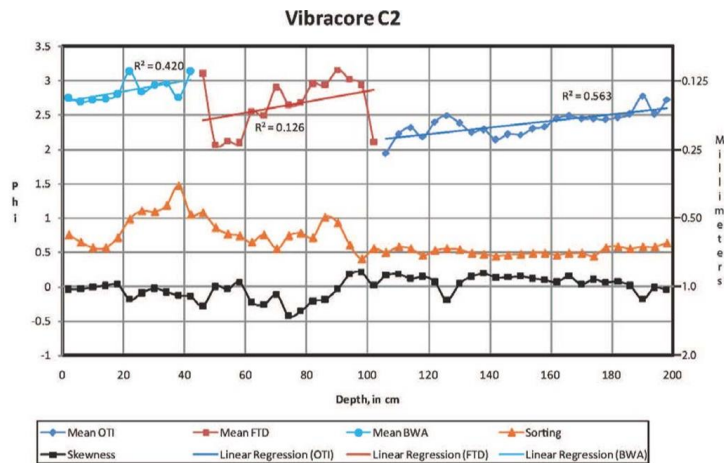


Figure 55: Mean grainsize, sorting, and skewness trends for Vibracore C2 and interpretation of depositional environment (from Hanley, 2015). Core bottom is to the right and core top is to the left.

Foraminiferal analysis exclusively revealed in C2 and C12 a washover/beach/aeolian deposit between the estuarine base and the overlying tidal-inlet deposits (Figure 53B). Foraminiferal analysis also revealed higher resolution detail of the lower 250 cm of C1 and C2, which sedimentologic analysis identified as estuarine

deposits (Figure 53B; Hanley, 2015). Specific thin flood-tidal delta/tidal-inlet deposits were identified within the estuarine deposit and an older significant flood-tidal delta and washover/beach/aeolian deposit was discovered at the base of C1 and C2 (Figure 53B).

Compare to Wave-dominated Inlet Lifecycle Model

The Seminack (2016) wave-dominated inlet lifecycle model accounts for surface features, such as the development of a series of closure ridges, but also includes associated subsurface grainsize trends (Figure 19). Figure 24 demonstrates how the most recent geomorphology of Cedar Island Inlet fits into the wave-dominated lifecycle model for inlet channels that rotate counterclockwise; however, here the subsurface grainsize trends will be examined in terms of the model.

A cross section through the proximal final position of Cedar Island Inlet including vibracores C11, C12, C13, and C18 was selected because closure ridges have been previously identified at or near these locations in Figure 56 and findings are summarized in Table 9 (Seminack, 2016). Approximately the top 40 to 100 cm of each core exhibits a coarsening upward trend associated with washover and aeolian activity, therefore only the trends below will be attributed to inlet fill (Table 9; Hanley, 2015).

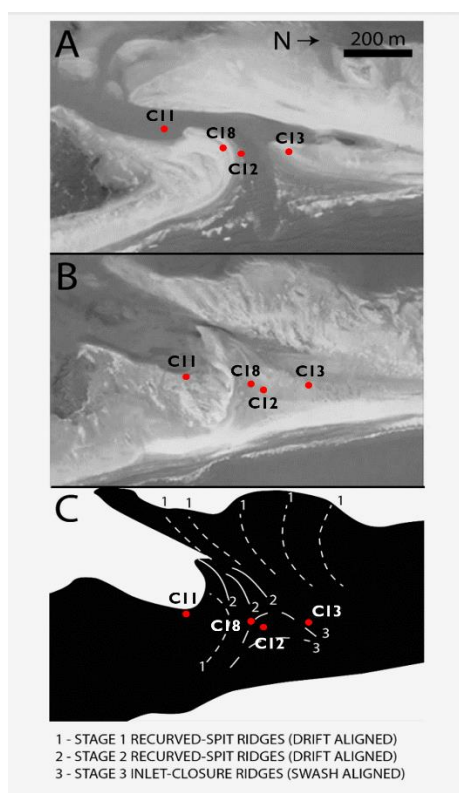


Figure 56: Vibracore locations at Cedar Island Inlet. (A) 2006 aerial photograph, (B) 2007 aerial photograph, and (C) The Seminack (2016) inlet lifecycle model.

Table 9: Cedar Island Inlet vibracores C11, C12, C13, and C18 in the context of the wave-dominated inlet lifecycle model.

Vibracore	C11	C18	C12	C13
Lifecycle Model Stage	4	4	5	4
Ridge Alignment	N/A	drift aligned	swash aligned	drift aligned
Stage of Closure Ridge Development	N/A	1	3	1
Grain Size Trends (top to bottom) and Interpretation	CUS- washover/beach/aeolian FUS- waning inlet channel CUS- active inlet channel	CUS- washover/beach/aeolian FUS- downdrift recurved spit	CUS- washover/beach/aeolian CUS- closure ridge	CUS-washover/beach/aeolian Neither- updrift recurved spit
Grain Size Graph				
Foraminiferal Evidence	N/A	N/A	High energy inlet fill assemblages	N/A

Consistent with stage 3 of the Seminack (2016) wave-dominated inlet lifecycle model, satellite imagery shows that from September 2005 to October 2006 the southern and northern spits extended thus forming drift-aligned ridges as shown by subaerial sand accumulations observed at C13 and C18 (Figure 59; Hanley, 2015). Seminack (2016) observed a smooth subtle fining upward succession or no upward trend associated with laterally prograding recurved spit ridges, which are also observed in C13 and C18 (Table 9; Hanley, 2015). A first order coarsening upward succession with second order spikes

was observed for inlet-closure ridges in Seminack (2016) and in C12 (Table 9; Hanley, 2015).

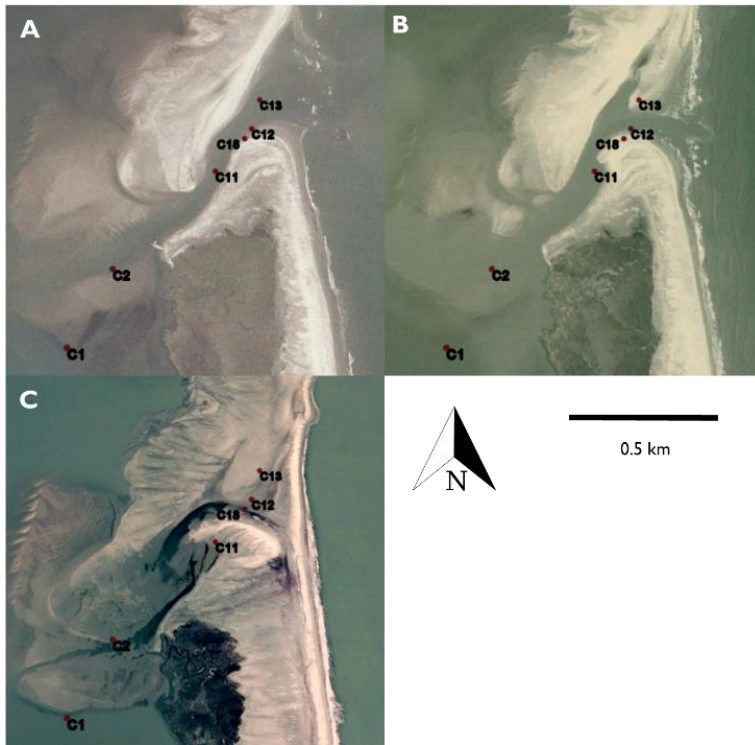


Figure 57: Vibracore locations used to construct a cross section through Cedar Island Inlet (Google Earth, 2017). (A) Air photo from September 22, 2005, (B) Air photo from October 29, 2006, and (C) Air photo from March 29, 2007.

Though not within the ridges zone, C11 also offers information about inlet closure because it is located within the proximal inlet channel. Basal deposits show a coarsening upward succession, which may represent the inlet channel floor followed by a fining upward succession that may represent the gradual decrease in tidal prism and flow velocity associated with the waning inlet (Hanley, 2015). Grain size trends associated with Cedar Island Inlet closure are consistent with those observed in Seminack (2016) further

supporting that Cedar Island Inlet fits within the wave-dominated inlet lifecycle model (Table 9).

Compare to Hanley (2015) Cedar Island Inlet Lifecycle Model

Moyer (2007), Richardson and McBride (2011), Richardson (2012), and Hanley (2015) have explained that Cedar Island has a distinct lifecycle pattern characterized by breaching, southerly migration, counter-clockwise channel rotation, and closure (Figure 23: Eight-stage geomorphic model for Cedar Island Inlet (figure from Hanley, 2015).Figure 23; Figure 58). However, newly found imagery suggests that Cedar Island Inlet does not follow this prescribed pattern each time the inlet opened.

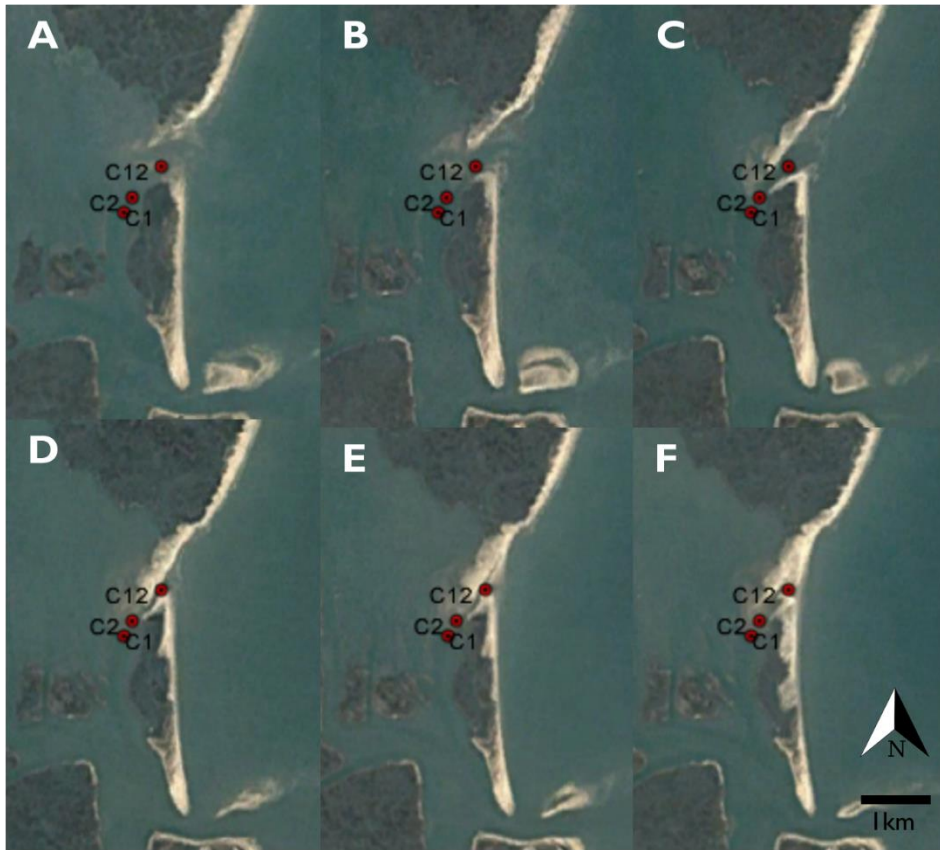


Figure 58: Lifecycle of the January 1998 to January 2007 Cedar Island Inlet and vibracore locations showing counter-clockwise inlet channel rotation. (A) December 1998, (B) December 1999, (C) December 2001, (D) December 2003, (E) December 2005, (F) December 2007 (Google Earth, 2017).

A 1957 aerial photograph of the 1956-1962 Cedar Island Inlet shows a slight clockwise rotation of the inlet channel, with further clockwise rotation as documented in the December 9, 1959 aerial photograph (Figure 59). Additionally, the inlet throat from 1957 to 1959 migrated south in the direction of net longshore sediment transport. Consistent with the Seminack (2016) model, an updrift shift occurs in depocenter of the flood-tidal delta contributing to clockwise rotation. Therefore, unlike the counter-clockwise rotation pattern of the most recent inlet channel, the 1956 to 1962 inlet channel migrated south, rotated clockwise, and closed.

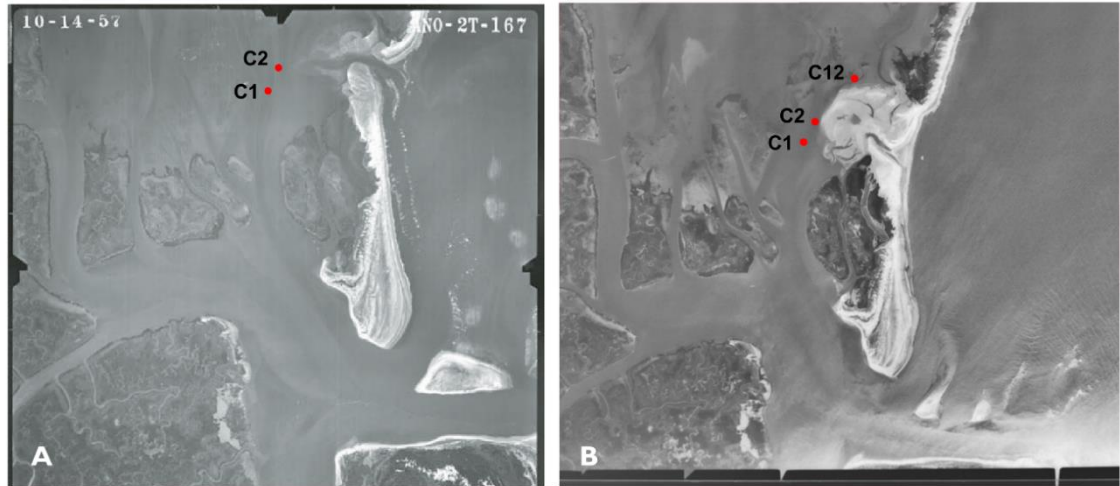


Figure 59: Aerial photographs of the Cedar Island January 1956 – March 1962 Inlet showing clockwise inlet channel rotation (from the U.S. Department of Agriculture Aerial Photography Field Office, 1957). (A) October 14, 1957 and locations of vibracores C1 and C2. (B) December 9, 1959 and locations of C1, C2, and C12.

As documented by Moyer (2007), Cedar Island Inlet was next open from March 1993 to July 1997. As shown in Figure 60, the inlet channel displayed little to no lateral migration or rotation and therefore falls into the non-rotating tidal-inlet classification scheme of Seminack (2016).

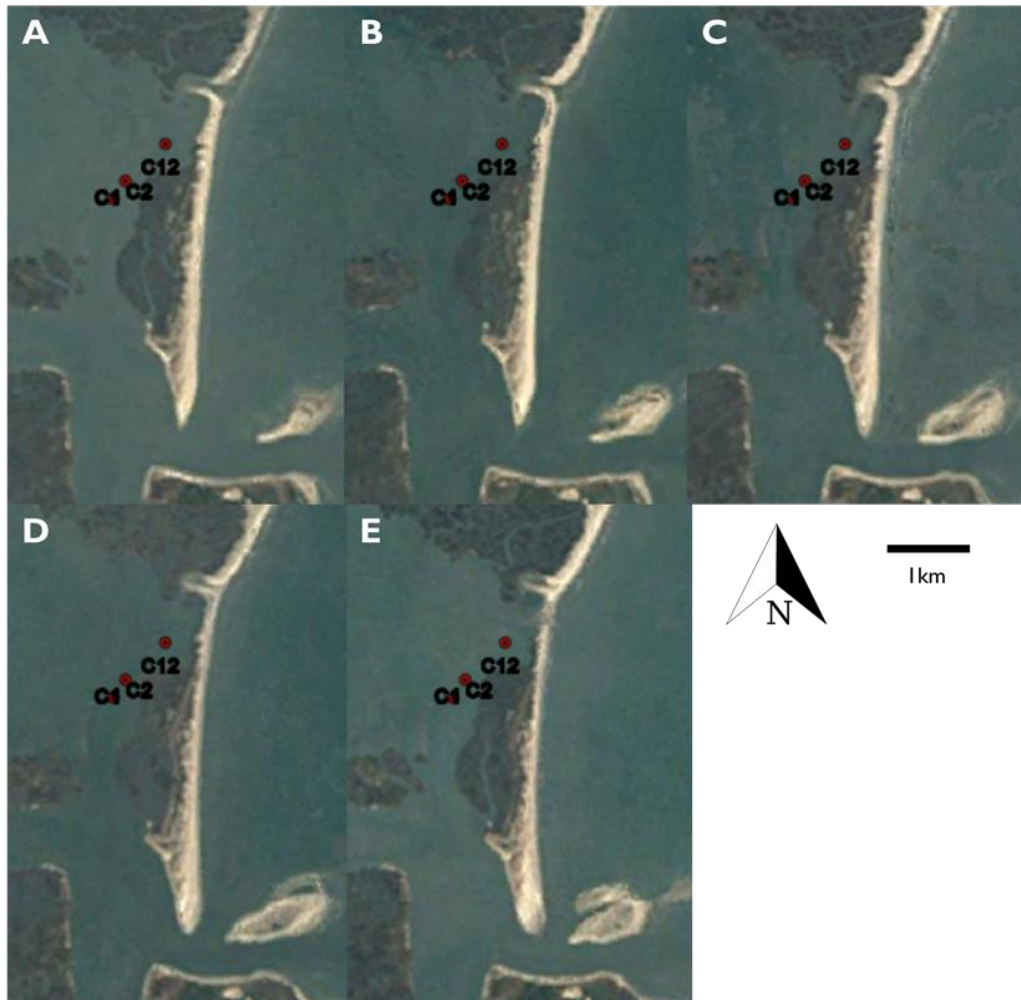


Figure 60: Satellite imagery of the Cedar Island March 1993 - July 1997 Inlet lifecycle showing little to no inlet channel rotation. (A) December 1993, (B) December 1994, (C) December 1995, (D) December 1996, (E) December 1997 (Google Earth, 2017).

High Resolution Cedar Island Inlet Model

The variation in the lifecycles of the Cedar Island Inlets observed in aerial imagery further supports that the conclusions of Seminack (2016) that all wave-dominated tidal inlets do not exhibit the same lifecycle pattern (Figure 19). Specifically, all three rotational schemes have been observed; with the earliest Cedar Island Inlet

channel rotating clockwise (January 1956 to March 1962), the March 1993 to July 1997 inlet channel experiencing non-rotation, and the most recent inlet channel rotating counter clockwise (January 1998 to January 2007). Therefore, unlike Hanley (2015) suggests, no prescribed rotational pattern exists for Cedar Island Inlet. Tidal Prism, accommodation space, and sediment supply were likely different for each of the Cedar Island tidal inlets and impacted the degree of channel migration and rotation direction.

Unfortunately, a lack of dating information and sedimentation rates make it difficult to attribute subsurface vibracore deposits to specific Cedar Island Inlets. Additionally, the foraminiferal assemblages of the flood-tidal delta and the bulk of inlet fill cluster together in one biofacies and do not provide discrete signals for separate superimposed inlet openings. However, careful examination of the lifecycle of each Cedar Island Inlet recorded through aerial imagery and detailed foraminiferal facies analysis offer unique insights.

Aerial photography suggests that the oldest inlet (1956-1962) had a substantial flood-tidal delta east of C1 and C2 and southeast of C12 (Figure 59). Therefore, the 1956-1962 Cedar Island Inlet may have left a small flood-tidal delta deposit or none (Figure 59). The 1993-1997 Cedar Island Inlet breached and persisted exclusively north of C1, C2, and C12, and potentially no vibracore deposits reflect this inlet opening (Figure 60). Finally, the most recent 1998-2007 inlet breached at or just above C12 and rotated counter-clockwise toward its final position in the direction of C1 and C2 (Figure 58). Therefore, a significant deposit can be attributed to the most recent Cedar Island

Inlet. Two hypotheses may explain the vibracore deposits including an expansion of the Hanley (2015) hypothesis and a new separate inlet openings hypothesis.

The hypothesis developed by Hanley (2015) explains that two inlets (1998-2007 and an older inlet) are recorded in the upper 300 and 200 cm of C1 and C2, whereas only deposits from the most recent inlet (1998-2007) are found in C12 (Figure 21; Figure 53). Two fining upward successions in C1 and two coarsening upward successions in C2 are interpreted to represent the two separate superimposed inlet openings (Figure 54; Figure 55; Hanley, 2015).

Consistent with the Hanley (2015) hypothesis, C12 foraminiferal facies confirm former inlet throat and inlet fill deposits (Figure 61). Foraminiferal facies in C1 and C2 do not refute the Hanley (2015) hypothesis that two inlet openings are superimposed because flood-tidal delta and inlet fill foraminiferal facies cluster together and do not provide separate signals for superimposed flood-tidal deltas or inlet fill (Figure 61A).

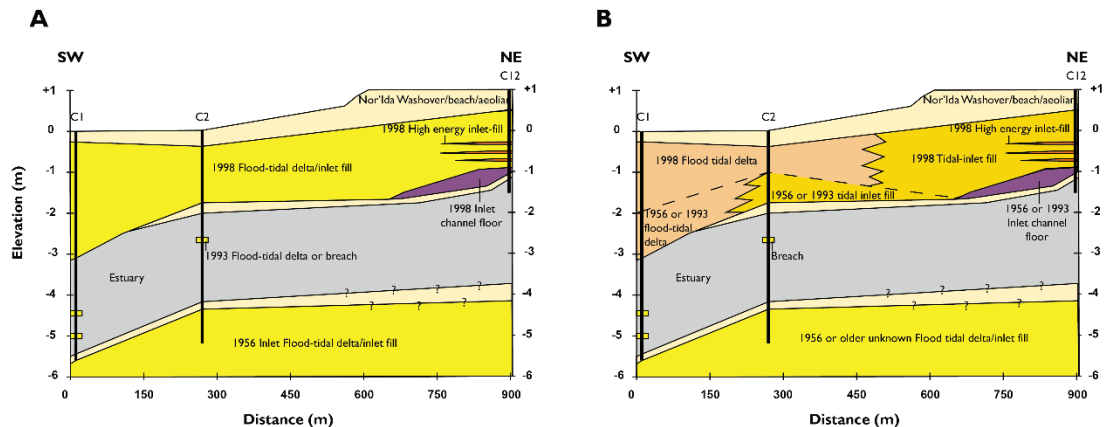


Figure 61: Cross section through C1, C2, and C12. (A) Separate inlet openings hypothesis. (B) The expanded Hanley (2015) hypothesis. Question marks (?) represent areas of extrapolation where supporting core data are not available.

If the topmost C1 and C2 flood-tidal delta/inlet deposits represent two inlet openings, then aerial imagery suggests the deposits are likely from the 1956-1962 and 1998-2007 Cedar Island Inlets because the 1993-1997 inlet and flood-tidal delta did not migrate within the vicinity of C1 and C2 (Figure 60; Figure 61B). The basal washover/beach/aeolian located from -174 cm to -202 cm in C2 may be attributed to breaching of the 1956-1962 inlet and not the 1998-2007 inlet, because in 1998 island breaching occurred north of C2, and C2 was shielded from washover by a fringe marsh (1956-1962 flood-tidal delta) (Figure 58; Figure 59; Figure 61B). No corresponding basal washover/beach/aeolian is correlated in C1, possibly because 1956 washover did persist as far west as C1 or a thin washover deposit was not captured by the broad sampling interval (Figure 61B). Up core in C1 and C2 the flood-tidal delta deposits from the 1956-1962 inlet grade into the most recent 1998-2007 inlet (Figure 61B). Finally, the 1998-2007 deposits are capped with washover/beach/aeolian.

Unfortunately, sediment analysis was only performed on the upper 300 cm and 200 cm of C1 and C2 respectively because the deeper samples were predominant clay and silt and too small for sieve analysis. Therefore, the sedimentologic investigation, performed by Hanley (2015), did not reveal the bottommost flood-tidal delta/inlet fill deposit of C1 and C2, which was discovered here exclusively through foraminiferal analysis. Expanding on the Hanley (2015) hypothesis, this deposit is likely attributed to the 1956-1962 inlet or an older inlet beyond the current known scope of inlets (Figure 61B).

The expanded Hanley (2015) hypothesis is further supported if sedimentation rates of 0.8 mm/yr observed on the landward side of Hog Island, VA (south of Cedar Island) are similar to those of the estuary environment that persists when the inlet is not active (Culver et al., 2006). Specifically, a maximum of 2.88 mm of sediment would have been deposited between the 1956-1962 and 1998-2007 inlets and may not be captured in the sampling intervals used in sedimentologic and foraminiferal investigations.

Alternatively, another hypothesis (separate inlet openings hypothesis) explains that the flood-tidal delta/inlet fill deposits in C1 and C2 represent single tidal-inlet opening where the bottommost flood-tidal delta/inlet fill deposit, found exclusively in C1 and C2, is from the 1956-1962 inlet and the topmost flood-tidal delta/inlet fill deposit is from the 1998-2007 inlet (Figure 61A). Specifically, the 1956-1962 inlet is recorded by a thick flood-tidal delta/inlet fill deposit in C2 (-450 cm to -515 cm) and one sample in C1 (-554 cm). The 1956-1962 inlet opening is capped with washover/beach/aeolian found in C1 (-550 cm and -558 cm) and C2 (-426 cm) (Figure 61A). The 1998-2007 breaching is recorded in C2 (-202 cm) and C12 (-102 cm) by a basal washover/beach/aeolian deposit (Figure 61A). Up core, C12 exhibits inlet channel deposits (-94 to -98 cm), and all three cores have thick flood-tidal delta/inlet fill deposits and a washover/beach/aeolian cap (Figure 61A). The isolated flood-tidal delta deposits, found within the C1 and C2 estuarine deposits, between the 1956-1962 and 1998-2007 inlets, may represent minor breaches that occurred between major inlet openings and up core occurrences maybe attributed to the distal edges of the 1993-1997 flood-tidal delta.

The separate inlet openings hypothesis requires a substantial sedimentation rate; specifically, approximately 200 cm of sediment separates the two inlet openings (1998-2007 and 1956-1962 inlets) that occurred 36 years apart. Therefore, a sedimentation rate of 5.5 cm/year is required to support this hypothesis. However, overwash processes and barrier island roll over could account for a high sedimentation rate on the landward side of low-profile, washover-dominated barrier island like Cedar Island.

Therefore, aerial imagery and depositional environment interpretations from sedimentary and foraminiferal analysis support both the expanded Hanley (2015) and separate inlet openings hypotheses. The only way to prove one hypothesis over the other would be to date the material to determine which facies are associated with inlet openings. All three data sets were essential in constructing and interpreting cross sections because imagery revealed the nuanced evolution of each inlet, sedimentary analysis revealed the contact of the stacked inlet openings, and foraminiferal analysis provided higher resolution interpretations of washover/beach/aeolian and inlet channel floor environments. Similarly, Smith et al. (2009) noted individual foraminiferal, lithologic, stratigraphic, and historical data sets were insufficient to definitively identify a tidal-inlet opening but rather a combination of all data sets yielded sound interpretations.

CONCLUSIONS

This study of Cedar Island Inlet has 1) tested the hypothesis that benthic foraminiferal biofacies are impacted by Cedar Island Inlet activity 2) documented different foraminiferal biofacies associated with multiple openings and closings of Cedar Island Inlet, and 3) presented a model of Cedar Island Inlet activity based on foraminiferal, sedimentologic, and imagery analysis. The major conclusions of this research are listed and described below.

1. Dominance of *Elphidium excavatum*. All non-barren vibracore samples are completely dominated by the euryhaline species *Elphidium excavatum*. *Elphidium excavatum* comprises 54-100% of all non-barren samples, representing 51 of 71 samples.
2. *Elphidium excavatum* distribution in vibracores. *Elphidium excavatum* is the dominant species in all three cores comprising 80-95%, 84-100%, 54-95% of all non-barren samples in vibracores C1, C2, and C12 respectively.
3. *Elphidium excavatum* spatial distribution. *Elphidium excavatum* is the dominant preserved species in depositional environments associated with Cedar Island Inlet.

4. *Elphidium excavatum* and substrate. *Elphidium excavatum* is most successful in depositional environments with sandy substrates (Culver et al., 1996; Woo et al., 1997). All vibracore samples of the former Cedar Island Inlet, that contain foraminifera, are predominantly sand; representing ideal conditions for *Elphidium excavatum* to be successful. Concurrently, samples comprised predominately of muds and clays were barren of *Elphidium excavatum* as these represent non-ideal conditions for the species.
5. *Elphidium excavatum* and salinity. *Elphidium excavatum* dominates nearshore and inner shelf environments along the U.S. Atlantic coast partially because of its ability to thrive in a range of marine salinities from ~30 ppt to ~36 ppt (Culver et al., 1996; Woo et al., 1997; Scott et al., 2001; Hayward et al., 2004; Abbene et al., 2006) The depositional environments associated with Cedar Island Inlet range from normal marine salinity to slightly above normal marine salinity, which is likely ideal for *Elphidium excavatum*, and allows the species to dominate.
6. *Elphidium excavatum* and organic pollutants. *Elphidium excavatum* typically dominates environments low in organics (Woo et al., 1997). Cedar Island is a relatively pristine coastal ecosystem, owned and protected by the Nature Conservancy, with limited organic inputs and pollution. Therefore, *Elphidium excavatum* likely dominates deposits associated with Cedar Island Inlet because the area represents a natural ecosystem, with limited organic inputs, which may

represent ideal conditions for *Elphidium excavatum* to readily grow and reproduce.

7. Foraminiferal biofacies. Non-barren samples were grouped into four foraminiferal biofacies through cluster analysis. The biofacies were compared with other local and regional studies and identified to represent the following depositional environments: 1) inlet channel floor, 2) high energy inlet fill, 3) flood tidal-delta/inlet fill, and 4) washover/beach/aeolian.

8. Inlet channel floor biofacies. Low abundances characterize the high energy, harsh inlet channel floor depositional environment. Bi-directional flow of estuarine and marine water, during tidal exchange, is reflected in the biofacies, which contains a mixture of marine and estuarine species including (61% *Elphidium excavatum*, 23% *Haynesina germanica*, 5% *Buccella frigida*, 5% *Ammonia parkinsoniana*, and 4% *Elphidium mexicanum*). Comparable low diversity and low abundance biofacies, dominant in *Elphidium excavatum* and *Ammonia parkinsoniana*, as well as containing *Ammonia tepida*, *Buccella frigida*, *Elphidium galvestonense*, and *Elphidium subarcticum*, have been observed in the modern tidal-inlet channel floor depositional environments of the Outer Banks, NC (Abbene et al., 2006; Vance et al., 2006).

9. High energy inlet fill biofacies. Low abundances and species richness comprise the high energy inlet fill biofacies. *Elphidium excavatum* comprises 88% of the biofacies and secondary species are shelf species (9% *Elphidium gunteri*, 2% *Elphidium mexicanum*, 2% *Ammonia parkinsoniana*) which were transported from offshore and deposited in the tidal inlet, possibly during higher-energy events, such as storms (northeasters or tropical systems), spring tides (syzygy), and/or perigean spring tides (perigee-syzygy). Cedar Island Inlet high energy inlet fill biofacies are comparable to the *Elphidium excavatum* dominated shoreface and ebb-tidal delta assemblages of the VA Delmarva barrier islands south of Cedar Island, which indicates a proximal nearshore and or inner shelf foraminiferal source (Woo et al., 1997).
10. Flood tidal-delta/inlet fill biofacies. Foraminiferal biofacies from flood tidal-delta and inlet fill depositional environments cluster together comprising the most abundant and diverse biofacies. Tidal exchange is reflected by a robust mixture of estuarine and marine species including 91% *Elphidium excavatum*, 2% *Buccella frigida*, 2% *Ammonia parkinsoniana*, 2% *Haynesina germanica* and the only occurrence of an agglutinated species *Trochammina inflata* (0.4%). Cedar Island Inlet flood tidal-delta/inlet fill biofacies are most similar to biofacies observed in the Old Currituck Inlet relict flood-tidal delta with high abundances and similar species distributions including *Elphidium excavatum* (dominant), *Ammonia parkinsoniana*, *Buccella frigida*, *Cibicides lobatulus*, *Elphidium galvestonense*,

Elphidium mexicanum, *Elphidium subarcticum*, and *Quinqueloculina* sp.

(Robinson 2005; Robinson and McBride, 2006).

11. Washover/beach/aeolian biofacies. Low abundances and low diversity characterize washover/beach/aeolian biofacies dominated by 90% *Elphidium excavatum*. Secondary species are dominated by shelf species, including 3% *Buccella frigida*, 3% *Ammonia parkinsoniana*, and 2% *Elphidium gunteri*, which were transported landward during washover events in response to storm impacts. Similarly, Pea Island, NC washover biofacies are dominated by normal marine salinity species with few minor estuarine species; however, the biofacies is different than the Cedar Island washover/beach/aeolian biofacies potentially because of the difference in latitude (Culver et al., 2006; Smith et al, 2009).
12. Foraminiferal assemblages of the mixed energy, tide-dominated Virginia Delmarva Peninsula barrier islands, south of Cedar Island, largely differ from those of Cedar Island Inlet; however, biofacies D (high energy inlet fill) is similar to the shoreface and ebb-tidal delta assemblages identified by Woo et al., (1997). Cedar Island Inlet biofacies A (flood tidal delta/inlet fill), biofacies B (inlet channel floor), and biofacies C (washover/beach/aeolian) readily correlate with the wave-dominated environments of the Outer Banks, N.C. Therefore, Cedar Island Inlet biofacies reflect that Cedar Island Inlet is a wave-dominated tidal inlet.

13. Barren samples. Samples barren of foraminifera are found in fine grained muds, clays, and laminated muds and clays. These samples are interpreted to represent a low energy, estuarine environment where a lack of benthic foraminifera existed and/or high bioturbation rates occurred, which may account for complete taphonomic loss of foraminifera. Similar extreme taphonomic loss was also observed in the estuary south of Wreck Island, VA (Culver et al., 1996).
14. Cedar Island Inlet activity and foraminiferal biofacies. Pre-inlet, active inlet, and post-inlet foraminiferal biofacies differ. When Cedar Island Inlet is closed, estuarine conditions persist and foraminifera are not readily preserved. However, when Cedar Island Inlet is open, depositional environments associated with an active tidal-inlet including, inlet channel floor, flood-tidal delta/inlet fill, and high energy inlet fill are reflected in distinct foraminiferal biofacies that contain unique proportions of estuarine and marine species. Washover/beach/aeolian depositional environments are reflected by high concentrations of marine species.
15. Sedimentary facies vs. foraminiferal facies. Sedimentary and foraminiferal facies are correlated throughout the three vibracores. However, each data set provides unique insights. For example, sedimentary facies exclusively identify a separation between two stacked flood-tidal deltas at 198 cm in C1 and 102 cm in C2 (Figure 54; Figure 55). Foraminiferal facies exclusively reveal flood-tidal delta/inlet fill deposits at the base of C1 and C2, as well as two additional

washover/beach/aeolian deposits (Figure 53). Overall, foraminiferal facies reveal a higher resolution analysis of sedimentary deposits; however, sedimentary facies also provide critical information about tidal-inlet deposits.

16. Newly identified tidal-inlet deposit. Foraminiferal facies exclusively reveal flood-tidal delta/inlet fill and washover/beach/aeolian deposits at the base of C1 and C2. The newly identified basal deposits occur 200 cm below previously identified tidal-inlet deposits.

17. Cedar Island Inlet deposits interpretations. This investigation yielded new high-resolution cross-sections through the final Cedar Island Inlet position (C1, C2, and C12) and new interpretations of Cedar Island Inlet deposits (Figure 61). One interpretation is the expanded Hanley (2015) hypothesis where three or four Cedar Inlet openings are recorded in deposits (Figure 61B). Specifically, the bottommost flood-tidal delta/inlet fill deposits capped by washover/beach/aeolian deposits in C1 and C2 represents the earliest known Cedar Island Inlet (1956-1962) or an older previously undocumented inlet. Next, an approximately 200 cm thick, estuarine deposit with thin flood-tidal delta/inlet fill deposits was deposited during normal estuarine conditions with occasional minor breaches. Then, washover/beach/aeolian deposits and flood-tidal delta/inlet fill deposits (from the 1956-1962 or 1998-2007 inlets) are finally overlain by inlet channel floor, flood-tidal delta/inlet fill, high energy inlet fill, and washover/beach/aeolian from

the 1998-2007 inlet. Alternately, the separate inlet openings hypothesis attributes deposits to two or three Cedar Island Inlet openings (Figure 61A). Specifically, the bottommost C1 and C2 flood-tidal delta/inlet fill deposits and washover/beach/aeolian represents the earliest known Cedar Island Inlet (1956-1962). The thin flood-tidal delta/inlet fill deposits within the approximately 200 cm thick, estuarine deposit are attributed to minor breaches and potentially the 1993-1997 Cedar Island Inlet. Finally, the washover/beach/aeolian deposits, flood-tidal delta/inlet fill, inlet channel floor, flood-tidal delta/inlet fill, high energy inlet fill, and washover/beach/aeolian are from the 1998-2007 inlet.

18. Channel rotation of Cedar Island Inlet. Two aerial photographs from the earliest known inlet (1956-1962) indicate that Cedar Island Inlet channel migrated in a southerly direction, rotated clockwise, and closed. Five satellite images of the 1993-1997 inlet indicate Cedar Island was breached, an inlet was established, the inlet channel showed little to no southerly migration, it did not rotate, and then closed. Finally, ten satellite images show the most recent inlet channel (1998-2007) opened, migrated to the south, rotated counter-clockwise, and closed.

19. Cedar Island Inlet lifecycle. Previous studies explain that Cedar Island Inlet has exhibited a distinct lifecycle each time the inlet has opened where Cedar Island is breached, an inlet is established, migrates south, rotates counterclockwise, and closes (Moyer, 2007; Richardson and McBride, 2011; Richardson, 2012; and

Hanley, 2015). However, here newly uncovered aerial imagery reveals that Cedar Island Inlet did not follow the same lifecycle behavior each time it was open. Instead, all three inlet-channel rotational modes (i.e., no rotation, clockwise rotation, and counter-clockwise rotation), of the Seminack (2016) wave-dominated inlet lifecycle model, have been observed the last three times Cedar Island Inlet was open.

Future Research

Sedimentologic, foraminiferal, and imagery analysis of the Cedar Island Inlet have yielded high resolution interpretations of the Cedar Island Inlet lifecycle and associated deposits. However, the only way to firmly attribute specific deposits to Cedar Island Inlet openings would be to perform quartz optically stimulated luminescence (OSL) dating and accelerator mass spectrometry (AMS) dating. Additionally, another extension of this research would be to perform higher resolution foraminiferal sampling, like that performed during sedimentologic analysis (4 cm intervals), so direct comparisons could be made. Similarly, foraminiferal sampling could also be extended to the other 15 available vibracores. Finally, a detailed sedimentologic analysis of the lower fine sediments of C1 and C2 may provide additional insights to the flood-tidal delta/inlet fill and washover/beach/aeolian deposits discovered through foraminiferal analysis.

APPENDIX A: FORAMINIFERA OF CEDAR ISLAND INLET SYSTEMATICS

Fourteen taxa were recognized in this investigation. Twelve species were identified to the species level and two taxa to the genus level. Holotypes, paratypes, and hypotypes from the collections of the Smithsonian Institution, National Museum of Natural History, Washington DC were compared with foraminifera of this study and utilized to confirm taxa identifications. Systematics below are organized in the Loeblich and Tappan (1988) classification system.

Order FORAMINIFERIDA Eichwald, 1830
Suborder TEXTULARINA Delage and Herouard, 1896
Superfamily TROCHAMMINACEA Schwager, 1877
Family TROCHAMMINIDAE Schwager, 1877
Subfamily TROCHAMMININAE Schwager, 1877
Genus *Trochammina* Parker and Jones, 1859
Trochammina inflata (Montagu)

Figure 41

Nautilus inflatus MONTAGU, 1808, p. 81, pi. 18, fig. 3.

Rotalina inflata (Montagu). WILLIAMSON, 1858, p. 50, pl. 4, figs. 93, 94.

Trochammina inflata (Montagu). PARKER and JONES, 1859, p. 347. PARKER, 1952a, p. 407, pi. 4, figs. 6, 10. PARKER, 1952b, p. 459, pi. 3, figs. 12, b. RONA, 1955, p. 144, pi. 20, fig. 1. PARKER and ATHEARN, 1959, p. 341, pi. 50, figs. 18-20. TODD and LOW, 1961, p. 15, pi. 1, figs. 22, 23. MILLER, 1953, p. 54, pi. 8, fig. 9. LIDZ, 1965, p. 399, fig. 11. GROSSMAN and BENSON, 1967, p. 50, pi. 5, figs. 9-12. ELLISON and NICHOLS, 1970, p. 16, pi. 1, figs. 8, 9. COLE and FERGUSON, 1975, p. 43, pi. 4, figs. 3, 4. SCOTT and MEDIOLI, 1980, p. 44, pi. 3, figs. 12-14, pi. 4, figs. 1-3.

Material. 15 tests.

Description. Test arenaceous, trochospiral, with rounded periphery, and concavo-convex with involute umbilical side with an open, deeply depressed umbilicus, where only the final whorl is visible and evolute spiral side where all chambers are visible; 5 to

6 inflated chambers within the final whorl, wall imperforate and made up of finely agglutinated sand grains; sutures nearly straight and depressed; aperture interiomarginal arched slit at the boarder of the final and first chambers of the final whorl on the umbilical side.

Remarks. Brown arenaceous tests with dark proloculus and first whorl. Small specimens found in this study.

Occurrence. All specimens are found in the flood tidal delta/inlet fill biofacies; 14 specimens in C1 and one specimen in C2.

Suborder MILIOLINA Delage and Hérourard, 1896
Superfamily MILIOLACEA Ehrenberg, 1839
Family HAUERINIDAE Schwager, 1976
Subfamily HAUERININAE Schwager, 1876
Genus Quinqueloculina d'Orbigny, 1826
Quinqueloculina sp.

Material. 5 tests

Description. Test calcareous, ellipsoidal periphery, 5 half coil length visible chambers; wall imperforate porcelaneous, depressed sutures, ovate aperture with a simple tooth.

Remarks. All specimens poorly preserved with broken chambers as well as etched and abraded tests.

Occurrence. All specimens found in the flood tidal delta/inlet fill biofacies; three specimens in C1 and one specimen in C2 and C12 respectively.

Suborder ROTALIINA Delage and Hérourard, 1896
Superfamily PLANORBULINACEA Schwager, 1877
Family CIBICIDIDAE Cushman, 1927
Subfamily CIBICIDINAE Cushman, 1927
Genus *Cibicides* de Montfort, 1808
Cibicides lobatulus (Walker and Jacob)

Figure 41

Nautilus lobatulus WALKER and JACOB, in Kanmacher, 1798, p. 642, pi. 14, fig. 36.

Cibicides lobatulus (Walker and Jacob). CUSHMAN, 1944, p. 36, pi. 4, figs. 27, 28.

Material. 3 tests.

Description. Test calcareous, low trochospiral, rounded periphery, planoconvex, with involute, convex umbilical side and evolute, slightly convex/flat spiral side; wall finely perforate on spiral side and coarsely perforate on umbilical side; wide sutures, spiral sutures flush to elevated and umbilical sutures depressed; low interiomarginal aperture on spiral side.

Remarks. Most specimens poorly preserved with etched and abraded tests.

Occurrence. All specimens found in the flood tidal delta/inlet fill biofacies of C1.

Superfamily NONIONACEA Schultze, 1854

Family NONIONIDAE Schultze, 1854

Subfamily NONIONINAE Schultze, 1854

Genus *Haynesina* Banner and Culver, 1978

Haynesina germanica (Ehrenberg)

Figure 41

Nonionina germanica EHRENBURG, 1840, p. 23. EHRENBURG, 1841, pi. 2, figs. L a-g.

Nonion germanicum (Ehrenberg). CUSHMAN, 1930, p. 8, pi. 3, 5a, b.

Nonion tisburyensis BUTCHER, 1948, p. 21-22, figs. 1-3.

Protelphidium tisburyensis (Butcher). PARKER and ATHEARN, 1959, p. 333-334, pi. 50, figs. 26-32.

Protelphidium anglicum MURRAY, 1965, p. 149,150, pi. 26, figs. 1-6.

Haynesina germanica (Ehrenberg). BANNER and CULVER, 1978, p. 191-195, pi. 4, figs. 1-6, pi. 5, figs. 1-8, pi. 6, figs. 1-7, pi. 7, figs. 1-6, pi. 8, figs. 1-10, pi. 9, figs. 1-11, 15,18. BUZAS and SEVERIN, 1982, p. 38,39, pi. 8, fig. 10. BUZAS et al., 1985, p. 1089, figs. 8.4, 8.5.

Material. 275 tests.

Description. Test calcareous, planispiral, rounded periphery, involute, biumbilicate, with depressed umbilicus; 8 to 9 chambers in final whorl, wall perforate; sutures depressed, curved, small pustules are found in the umbilicus and extend out into sutures; aperture forms a low arch at the base of the last chamber and is hidden behind pustules.

Remarks. Lack of sutural bridges defines *Haynesina germanica* from *Elphidium excavatum*. Specimens found in this study are also generally smaller than *Elphidium excavatum*

Occurrence. Found in three of the four biofacies including tidal inlet channel floor, flood tidal delta/inlet fill, and washover/beach/aeolian; 54 specimens in C1, 33 specimens in C2, and 164 specimens in C12.

Genus *Nonionella* Cushman, 1926

Nonionella atlantica Cushman

Figure 41

Nonionella atlantica CUSHMAN, 1947, p. 90, pi. 20, figs. 4, 5. PARKER, 1952b, p. 453, pi. 3, figs. 15a, b. TODD and BRONNIMAN, 1957, p. 32, pi. 5, figs. 30, 31. BUZAS and SEVERIN, 1982, p. 41, pi. 10, figs. 10-12.

Material. 2 tests.

Description. Test calcareous, low trochospiral, rounded periphery, biconvex, involute umbilical side with depressed umbilicus, and evolute spiral side with an umbilical plug; 10-12 chambers; wall very finely perforate; sutures depressed and marginally curved, small pustules are found in the umbilicus and extend out into sutures; aperture forms a low arch at base of the last chamber.

Remarks. Largest specimens found in samples of this study.

Occurrence. Two specimens found in flood tidal delta/inlet fill biofacies; one specimen in C1 and C2 respectively.

Superfamily CHILOSTOMELLACEA Brady, 1881

Family COLEITIDAE Loeblich and Tappan, 1984

Genus BUCCELLA Anderson, 1952

Buccella frigida (Cushman)

Figure 41

Pulvinulina frigida CUSHMAN, 1922, p. 144.

Eponides frigida (Cushman). CUSHMAN, 1931, p. 45. BANDY, 1940, pl. 22, figs. 5a-c; CUSHMAN and TODD, 1947, p. 21, pl. 3, fig. 20; CUSHMAN, 1948, p. 71, pl. 8, fig. 7; BANDY, 1953, p. 171, pl. 23, figs. 5a-c.

Buccella frigida (Cushman). ANDERSEN, 1952, p. 144, figs. 4-6. LAGOE, 1979, p. 261, pl. 1, figs. 1, 2; PATTERSON, BURBRIDGE, and LUTERNAUER, 1998, p. 22, pl. 25, figs. 6-8; MCGANN, 2007, p. 67, pl. 11, figs. F1, F2; VÁZQUEZ RIVEIROS and PATTERSON, 2008, Figs 13.3a-c.

Material. 202 tests.

Description. Test calcareous, trochospiral, broadly rounded periphery, biconvex with involute umbilical side and evolute spiral side; open and depressed umbilicus with many pustules that extend along sutures, final whorl has 7-8 chambers; wall finely perforate; spiral sutures slightly curved and limbate while umbilical sutures slightly depressed and radial; interiomarginal, arched aperture at base of the final chamber hidden by pustules.

Remarks. Abundant pustules at umbilicus and in umbilical sutures.

Occurrence. Found in three of the four biofacies including tidal inlet channel floor, flood tidal delta/inlet fill, and washover/beach/aeolian; 85 specimens in C1, 71 specimens in C2, and 46 specimens in C12.

Superfamily ROTALIACEA Ehrenberg, 1839

Family ROTALIIDAE Ehrenberg, 1839

Subfamily AMMONIA Saidova, 1981

Genus AMMONIA Brunnich, 1772

Ammonia parkinsoniana (d'Orbigny)

Figure 41

Rosalina parkinsoniana D'ORBIGNY, 1839, p. 99, pi. 4, figs. 25-27.
Rotalia beccarii (Linne) forma parkinsoniana (d'Orbigny). PHLEGER and PARKER, 1951, p. 23, pi. 12, fig. 6.
Ammonia parkinsoniana (d'Orbigny) forma typica POAG, 1978, p. 397, 400-402, pi. 1, figs. 5, 6, 8, 9, 13, 15, 19, 21. POAG, 1981, p. 38, pi. 45, fig. 1, pi. 46, figs. 1a-b.
Ammonia beccarii (Linne). ELLISON and NICHOLS, 1970, p. 15, pi. 2, figs. 9,10. SCHNITKER, 1971, p. 193, pi. 7, figs. 1a-c. SCOTT and MEDIOLI, 1980, p. 35, figs. 8, 9. BUZAS and SEVERIN, 1982, p. 36, pi. 7, figs 9, 10. CULVER et al., 1996, p. 486, figs. 10.8,10.9.
Ammonia parkinsoniana (d'Orbigny). LOEBLICH and TAPPAN, 1994, p. 165, pi. 368, figs. 7-9, 11, 13-16.
Material. 188 tests.
Description. Test calcareous, trochospiral, rounded periphery, biconvex, with evolute spiral side and involute umbilical side; depressed umbilicus with umbilical plug(s); final whorl had 7-8 chambers, wall moderately perforate; umbilical sutures flush to depressed, spiral sutures slightly raised; interiomarginal extraumbilical aperture forms an arch at the base of the last chamber
Remarks. Abraded and broken specimens common in C12.
Occurrence. Found in all biofacies; 69 specimens in C1, 62 specimens in C2, and 57 in C12.

Ammonia tepida (Cushman)

Figure 41

Rotalia beccarii Linnaeus forma tepida CUSHMAN, 1926, p. 79, pi. 1. PARKER, 1952b, p. 457-458, pi. 5, fig. 8.
Rotalia beccarii (Linne) variants. PARKER, 1954, p. 531, pi. 10, figs. 1, 2, 5, 6.
Ammonia beccarii tepida (Cushman). ELLISON and NICHOLS, 1970, p. 15, pi. 2, fig. 11, 12.
Streblus beccarii (Linne) forma tepida (Cushman). TODD and BRONNIMANN, 1957, p. 38, figs. 5-10.
Ammonia parkinsoniana (d'Orbigny) forma tepida POAG, 1978, p. 397, 400-402, pi. 1, figs. 3,4, 11, 12, 18. POAG, 1981, p. 38, pi. 45, fig. 2, pi. 46, figs. 2a-b.
Ammonia tepida (Cushman). GROSSMAN and BENSON, 1967, p. 56, pi. 9, figs. 5,9. LOEBLICH and TAPPAN, 1994, p. 166, pi. 371, figs. 5-10. DEBENAY et al., 1998, p. 238-240, pi 1, fig 2.
Material. 95 tests.

Description. Test calcareous, marginally lobate periphery, trochospiral, biconvex with involute umbilical side and evolute spiral side; umbilicus open, deeply depressed; 6-8 chambers in final whorl; umbilical chambers come to a point at umbilicus forming a ragged edge covered in pustules, wall finely perforate; umbilical sutures deeply depressed, spiral sutures flush to depressed; interiomarginal extraumbilical aperture forms an arch at the base of the last chamber.

Remarks. Distinguished from *Ammonia parkinsoniana* by rounded chambers
Occurrence. Exclusively found in the flood tidal delta/inlet fill biofacies; 59 specimens in C1, 27 specimens in C2, and 9 specimens in C12.

Family ELPHIDIIDAE Galloway, 1933
Subfamily ELPHIDIINAE Galloway, 1933
Genus ELPHIDIUM de Montfort, 1808
Elphidium excavatum (Terquem)

Figure 41

Polystomella excavata TERQUEM, 1875, p. 20, pi. 2, figs. 2a, b.

Elphidium excavatum (Terquem). CUSHMAN, 1944, p. 26, pi. 3, fig. 40. PARKER, 1952a, p. 412, pi. 5, fig. 8. PARKER, 1952b, p. 448, pi. 3, fig. 13. BUZAS and SEVERIN, 1982, p. 37, pi. 8, fig. 2. BUZAS et al., 1985, p. 1083-1084, figs. 6.7-6.10, 7.1, 7.2. CULVER et al., 1996, p. 486, fig. 10.11, 10.12.

Elphidium clavatum Cushman. RONAI, 1955, p. 146, pi. 21, fig. 7. GROSSMAN and BENSON, 1967, p. 58, pi. 8, figs. 13, 14. ELLISON and NICHOLS, 1970, p. 16, pi. 2, figs. 7, 8. KRAFT and MARGULES, 1971, p. 251, fig. 17. SEN GUPTA, 1971, p. 89, pi. 2, figs. 28, 29. SCHNITKER, 1971, p. 198, pi. 7, fig. 5.
Material. 7,672 tests.

Description. Test calcareous, planispiral, rounded to lobate periphery, bilaterally symmetrical, involute; umbilicus slightly depressed or has one or more bosses; 8-10 chambers; wall finely perforate; depressed sutures with many irregular sutural bridges; aperture comprised of a series of pores along at the base of the last chamber.

Remarks. Highly variable species defined by irregular sutural bridges.

Occurrence. Overwhelmingly the most abundant species, found in all biofacies; 2,889 specimens in C1, 2066 specimens in C2, and 2,717 specimens in C12.

Elphidium galvestonense Kornfeld

Figure 41

Elphidium gunteri COLE forma *galvestonensis* KORNFELD, 1931, p. 87, pi. 15, fig. 1. PHLEGER and PARKER, 1951, p. 10, pi. 5, figs. 13, 14. BANDY, 1954, p. 136, pi. 30, fig. 2.

Elphidium galvestonense (Kornfeld). PARKER et al., 1953, p. 7, pi. 3, figs. 15, 16. MILLER, 1953, p. 55, pi. 9, fig. 7. PARKER and ATHEARN, 1959, p. 342, pi. 50, figs. 33-35. GROSSMAN and BENSON, 1967, p. 60, pi. 7, figs. 1, 2. ELLISON and NICHOLS, 1970, p. 16, fig. 9.3. POAG, 1978, p. 403-404, pi. 3, fig. 12. BUZAS and SEVERIN, 1982, p. 37, pi. 8, fig. 3.

Material. 23 tests.

Description. Test calcareous, planispiral, rounded periphery, biconvex, bilaterally

symmetrical, involute; one, large, umbilical plug; numerous chambers (13 or more); wall perforate; deeply depressed sutures with wide, regularly spaced sutural bridges causing a pitted appearance; aperture comprised of a series of pores along at the base of the last chamber.

Remarks. Distinguished by pitted suture appearance and large, raised umbilical plug.

Occurrence. Found in inlet channel floor and flood tidal delta/inlet fill biofacies; 7 specimens in C1, 3 specimens in C2, and 13 in C12.

Elphidium gunteri Cole

Figure 41

Elphidium gunteri COLE, 1931, p. 34, pi. 4, figs. 9, 10. PARKER and ATHEARN, 1959, p. 342, pi. 50, fig. 36. BUZAS et al., 1985, p. 1084, figs. 7.4, 7.5.

Material. 31 tests.

Description. Test calcareous, planispiral, rounded periphery, biconvex, bilaterally symmetrical, involute; raised umbilical area with many large, irregularly shaped bosses; numerous chambers (8-11); wall coarsely perforate; thick, flush sutures with numerous regularly spaced sutural bridges; aperture comprised of a series of pores along at the base of the last chamber.

Remarks. Distinguished by many large, irregular-shaped umbilical bosses and regular sutural bridges.

Occurrence. Found in three biofacies including flood tidal delta/inlet fill, high energy inlet fill, and washover/beach/aeolian; 2 specimens in C1 and 29 specimens in C12.

Elphidium mexicanum Kornfeld

Figure 41

Elphidium incertum forma *mexicanum* KORNFELD, 1931, p. 89, pi. 16, fig. 1.

Elphidium galvestonense Korneld forma *mexicanum*. POAG, 1978, p. 403, pi. 3, figs. 1, 2, 4-11, 17, 18.

Elphidium mexicanum Korneld. BUZAS and SEVERIN, 1982, p. 37, pi. 8, fig. 6.

BUZAS et al., 1985, p. 1087, figs. 7.9, 7.10.

Material. 53 tests.

Description. Test calcareous, planispiral, rounded periphery, biconvex, bilaterally symmetrical, involute; one large, umbilical boss with surrounding pustules; numerous chambers (8-11); wall finely perforate; depressed, curved sutures with many short, regularly spaced sutural bridges; aperture comprised of a series of pores along at the base of the last chamber.

Remarks. Specimens are optically granular with dull white tests.

Occurrence. Found in all biofacies; 20 specimens in C1, 9 in C2, and 24 in C12.

Elphidium subarcticum Cushman

Figure 41

Elphidium subarcticum CUSHMAN, 1944, p. 27, pi. 3, figs. 34, 35. PARKER, 1952a, p. 412, pi. 5, fig. 9. GROSSMAN and BENSON, 1967, p. 60, pi. 7, figs. 3, 6. SCHNITKER, 1971, p. 198, pi. 7, fig. 3. SEN GUPTA, 1971, p. 89, pi. 2, figs. 30, 31. BUZAS et al., 1985, p. 1087, figs. 8.1, 8.2.

Material. 38 tests.

Description. Test calcareous, planispiral, rounded periphery, biconvex, bilaterally symmetrical, involute; flush umbilicus covered with numerous pustules which extend into sutures; 8-10 chambers; wall finely perforate; sutures wide and depressed; aperture comprised of a series of pores along at the base of the last chamber.

Remarks. Smaller than the other *Elphidium* species found in these cores.

Occurrence. Found in three biofacies including, inlet channel floor, flood tidal delta/inlet fill, and washover/beach/aeolian; 12 specimens in C1 and 13 specimens in C2, and 13 specimens in C12.

Elphidium sp.

Material. 15 tests.

Description. Test calcareous, heavily etched, planispiral, rounded periphery, biconvex, bilaterally symmetrical, involute; flush umbilicus; 8-11 chambers; wall perforate; sutures flush to slightly depressed; aperture comprised of a series of pores along at the base of the last chamber.

Remarks. Tests etched and abraded with no umbilical bosses or pustules.

APPENDIX B: FORAMINIFERAL COUNT DATA

Vibracore C2																	extrapolated total	individuals per gram of sediment
depth (cm)		<i>Ammonia parkinsoniana</i>	<i>Ammonia tepida</i>	<i>Buccella frigida</i>	<i>Cibicides lobatulus</i>	<i>Elphidium excavatum</i>	<i>E. gabrielsonense</i>	<i>Elphidium gunteri</i>	<i>Elphidium mexicanum</i>	<i>Elphidium</i> sp.	<i>Elphidium subarcticum</i>	<i>Hoynesina germanica</i>	<i>Nonionella atlantica</i>	<i>Quinqueloculina</i> sp.	<i>Trochammina inflata</i>	total		
2	2	-	-	-	17	-	-	-	-	-	-	-	-	-	-	19	19	1
26	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0
50	8	3	3	-	191	-	-	-	-	4	6	-	-	1	-	216	275	14
74	-	9	4	-	177	-	-	-	-	1	9	-	1	-	-	201	1608	87
102	1	1	4	-	188	1	-	2	-	1	4	-	-	-	-	202	323	16
126	6	-	1	-	188	2	-	3	1	-	-	1	-	-	-	202	323	15
150	4	-	4	-	197	1	-	3	-	-	-	-	-	-	-	209	319	18
174	-	-	-	-	8	-	-	-	-	-	-	-	-	-	-	8	8	0
202	1	-	2	-	41	-	-	-	-	-	1	-	-	-	-	45	45	3
226	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0
250	2	2	1	-	70	-	-	1	-	-	4	-	-	-	-	80	80	4
274	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0
302	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0
326	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0
350	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	10	0
374	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0
402	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0
426	-	-	3	-	16	-	-	-	-	-	-	-	-	-	-	19	19	0
450	8	4	11	-	172	-	-	-	-	4	3	-	-	-	-	202	539	21
474	7	4	6	-	190	-	-	-	-	1	-	-	-	-	-	208	3328	135
486	11	-	6	-	190	-	-	-	-	-	-	-	-	-	-	207	2436	97
502	-	1	10	-	224	-	-	1	-	-	1	-	-	-	-	237	1264	41
506	11	3	6	-	205	-	-	1	-	1	2	-	-	-	-	229	916	28
514	5	-	14	-	189	-	-	1	-	1	3	-	-	-	-	213	3408	99

Vibracore C12															
	depth (cm)	<i>Ammonia parkinsoniana</i>	<i>Ammonia tepida</i>	<i>Buccella frigida</i>	<i>Elphidium excavatum</i>	<i>E. galvestonense</i>	<i>Elphidium gutteri</i>	<i>Elphidium mexicanum</i>	<i>Elphidium</i> sp.	<i>Elphidium subarcticum</i>	<i>Hoyesina germanica</i>	<i>Quinqueloculina</i> sp.	total	extrapolated total	individuals per gram of sediment
	6	-	-	-	11	-	-	-	-	1	-	12	48	11	
	30	-	-	-	5	-	1	-	-	-	-	6	48	6	
	62	6	-	-	181	-	-	1	-	16	-	204	408	17	
	94	1	-	-	81	-	2	-	1	2	-	87	87	5	
	126	2	-	1	208	1	-	1	-	2	-	215	286	21	
	130	-	-	-	26	-	9	1	-	-	-	36	36	3	
	134	3	1	3	165	-	3	1	-	-	-	176	176	13	
	146	5	1	2	205	1	-	-	-	-	-	214	623	45	
	150	3	5	2	304	1	-	-	1	-	3	319	83	5	
	154	1	-	-	45	-	7	-	-	-	-	53	53	3	
	158	4	2	1	191	-	-	1	1	-	-	200	533	25	
	174	3	-	-	151	-	7	3	-	-	-	164	569	31	
	178	4	-	3	246	1	-	-	1	2	-	257	257	19	
	182	-	-	4	177	2	-	-	2	31	-	218	872	22	
	186	4	-	1	218	-	-	1	-	1	-	225	1442	35	
	190	1	-	3	217	2	-	-	4	7	1	235	3000	61	
	194	7	-	11	109	2	-	12	3	1	58	203	270	9	
	198	13	-	11	161	3	-	4	1	2	42	237	474	13	
	202	-	-	4	16	-	-	-	-	1	-	21	21	1	
	222	-	-	-	0	-	-	-	-	-	-	0	0	0	
	246	-	-	-	0	-	-	-	-	-	-	0	0	0	

APPENDIX C: BIOFACIES COUNT DATA

[illegible]

Core and depth (cm)	<i>Ammonia parkinsoniana</i>	<i>Buccella frigida</i>	<i>Elphidium excavatum</i>	<i>Elphidium gunteri</i>	<i>Elphidium mexicanum</i>	<i>Elphidium subarticum</i>	<i>Haynesina germanica</i>
C1 6	2	1	40				
C1 558	1		15				
C1 550			4		1		
C2 202	1	2	41				1
C2 2	2		17				
C2 426		3	16				
C2 174			8				
C12 202		4	16				1
C12 6			11				1
C12 30			5	1			
Sum	9	10	324	8	4	1	3
Percent	3	3	90	2	1	0.3	1
Species Richness = 7							

Biofacies D: High energy inlet fill					
	<i>Core and depth (cm)</i>	<i>Ammonia parkinsoniana</i>	<i>Elphidium excavatum</i>	<i>Elphidium gunteri</i>	<i>Elphidium mexicanum</i>
	C12 154	1	45	7	
	C12 130		26	9	1
	C12 174	3	151	7	3
	Sum	4	222	23	4
	Percent	2	88	9	2
	Species Richness = 4				

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