TRANSITION OF A REGRESSIVE TO A TRANSGRESSIVE BARRIER ISLAND AS A FUNCTION OF BACK-BARRIER EROSION, CLIMATE CHANGE, AND LOW SEDIMENT SUPPLY, BOGUE BANKS, NORTH CAROLINA, USA.

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ABSTRACT

EMILY ANNE TIMMONS: Transition of a regressive to a transgressive barrier island as a function of back-barrier erosion, climate change, and low sediment supply, Bogue Banks, North Carolina, USA.
(Under the direction of Antonio B. Rodriguez)

Although back-barrier erosion is a prevalent process of island narrowing, it is often overlooked in barrier-island evolution modeling. In many wave-dominated barrier island settings, the absence of overwash precludes the expansion of the back-barrier and hence the island as a whole from sustaining its width. Typically, regressive barriers are wide and exhibit high elevations with the most seaward dune ridge possessing the highest elevation. This morphology may prevent overwash from reaching the back-barrier shoreline for millennia and hence contribute to high rates of back-barrier erosion. Upon continued narrowing and lowering of the island, regressive barriers may reach a critical state, making overwash imminent and transitioning the island to a transgressive state. The modern day morphologic variability along the 40-km long island of Bogue Banks, North Carolina includes both regressive and transgressive segments, making this setting ideal for examining whether or not the transition between these barrier island types is gradual or threshold-driven.

Bogue Banks consists of two discrete compartments characterized by high-elevation beach ridges, large island widths, and stratigraphy consistent with regressive barrier islands. These regressive island segments are separated by a broad, narrow section of the island devoid of any washover fans or other transgressive elements. The analyses of seismic data from the inner continental shelf reveal paleo-channels intersect the wider sections of the island, while the narrow central part of the island occupies an inter-fluvial area. Reworking of fluvial sediment from paleo-channels was an important sediment source for the barrier during regression. Optically Stimulated Luminescence (OSL) dates from the most landward beach ridges constrained initiation of island regression at ~3000 cal yr. BP as the rate of relative sea-level rise slowed to ~0.8 mm/yr. Transects of cores, seismic data, ground-penetrating radar data, and radiocarbon and OSL dates show that prior to ~1500 cal yr. BP the central narrow section of the island was wide and regressive similar to adjacent areas. Back-barrier erosion of the central part of the barrier primarily caused island narrowing as a result of increased storminess, which occurred around the Medieval Warm Period (~1100 cal yr. BP). This part of the island was more vulnerable to erosion than adjacent areas due to increased bay ravinement (Bogue Sound is widest there) and its lower elevation (further away from paleo-channel/sediment source). Relict inlet channels exist along the central portion of the island, formed within the last 250 years, and likely closed shortly after formation. The presence of historical inlets along the narrow central section of the island indicates Bogue Banks may be nearing a critical width threshold and will subsequently transition to a transgressive barrier. Since the change in barrier morphology associated with back-barrier erosion occurred over a period of time when the rate of sea-level rise was relatively low, low sediment supply and climate change (resulting in increased storm frequency) are the main forcing mechanisms of island narrowing. These impacts, in addition to a predicted increase in sea-level rise rates and human modifications (e.g. maintenance of a high-elevation fore-dune, closing of inlets that artificially prevent island overwash and associated sediment supply to the back-barrier shoreline) will likely promote rapid transition of regressive barrier islands to those dominated by transgressive processes.

To God, through whom all things are made possible, and to my parents,

Nancy and Anthony Timmons, who always encouraged me to strive for passion and purpose,

and whose faith, support and unfailing love gave me the strength to find it.

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LIST OF SYMBOLS AND ABBREVIATIONS

PKS	Pine Knoll Shores
EI	Emerald Isle
IB	Indian Beach
AB	Atlantic Beach
GPR	Ground Penetrating Radar
AGC	Automatic Gain Control
OSL	Optically Stimulated Luminescence
DBMSL	Depth Below Mean Sea-Level
cal. yr. BP	Calibrated years before present
Gy	Dose (for OSL)
Gy/ka	Dose Rate (for OSL)
ka	Age (for OSL)

CHAPTER 1

1. INTRODUCTION

The evolution of a barrier island, like most coastal depositional environments, is largely a balance between sediment supply and rate of relative sea-level rise. Galloway and Hobday (1983) recognize aggradational, transgressive, and regressive styles of barrier evolution. Aggradational barriers form when sediment supply equals the rate of relative sea-level rise, and the estuarine and ocean shorelines remain stationary through time forming a thick lithosome like Mustang Island, TX (Simms et al., 2006; Fig. 1a). Transgressive barriers form when sediment supply is less than the rate of relative sea-level rise. The estuarine and ocean shorelines of these islands migrate landward through time by wave erosion and overwash, forming a thin and low-elevation coastal lithosome like Core Banks, NC (Moslow and Heron, 1978; Riggs and Ames, 2003) and Matagorda Peninsula, TX (Wilkinson and Byrne, 1977; Fig. 1b). Regressive barriers form when sediment supply exceeds the rate of relative sea-level rise and the ocean shoreline progrades seaward while the estuarine shoreline remains relatively stable forming a wide and high-elevation barrier with ridge and swale topography like Galveston Island, TX (Bernard et al., 1959) and Morgan Peninsula, AL (Rodriguez and Meyer, 2006; Fig. 1c). Regressive barriers have a larger capacity to buffer estuaries from high-energy storms than transgressive barriers, due to their higher width and elevation. It is common for the number of inlets along a transgressive barrier island chain to increase after a storm (Fisher, 1962; Riggs and Ames, 2007), which

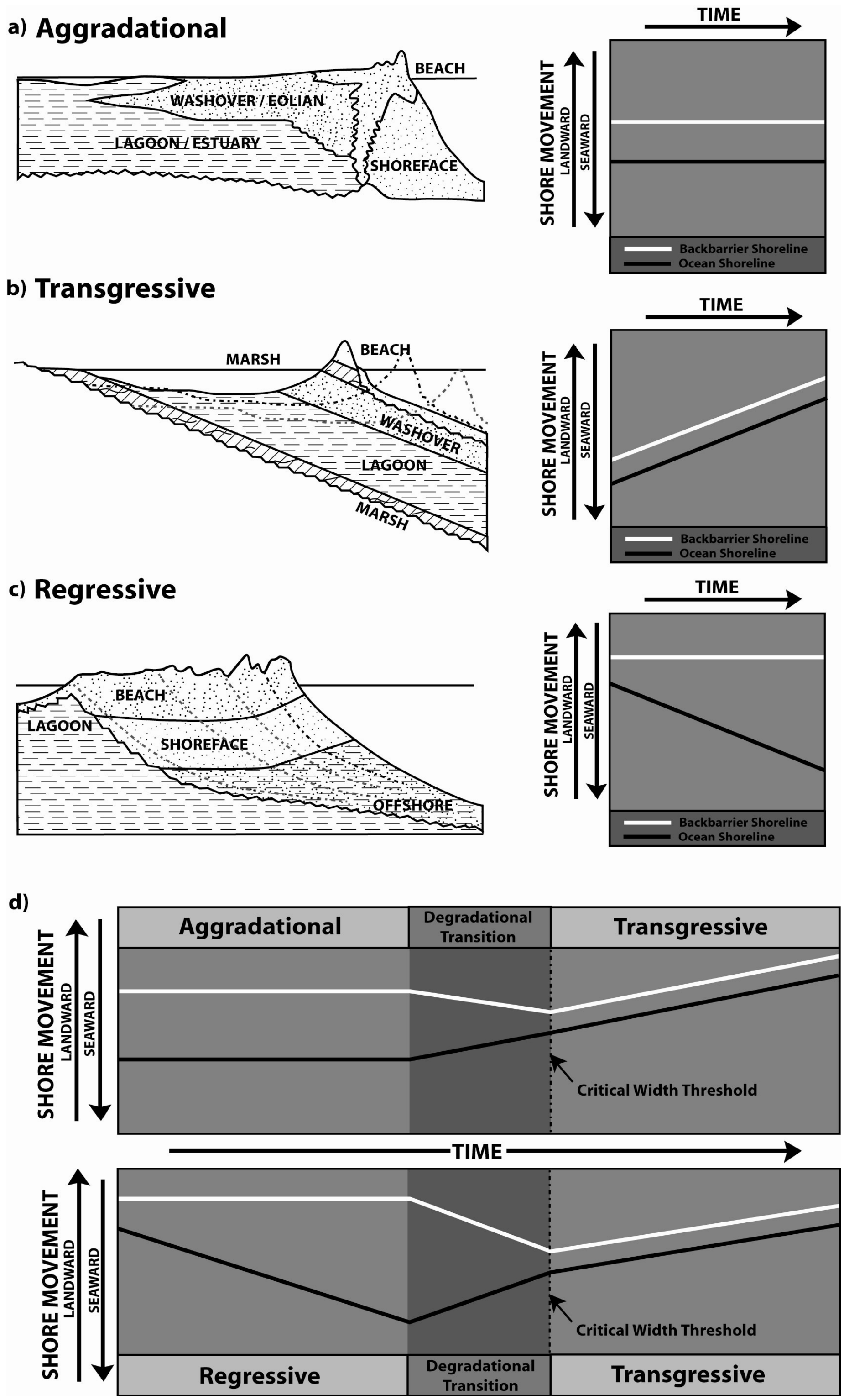


Figure 1. Models of aggradational (a), transgressive (b), and regressive (c) barrier evolution (after Galloway and Hobday, 1983). Aggradational and regressive barriers narrow through erosion of the back-barrier and ocean shorelines during the degradational transition towards transgressive evolution (d).

strongly impacts estuarine tidal dynamics and longshore drift. As sediment supply, and the rate of sea-level rise changes so does barrier evolution. At present, all types of barriers are decreasing their buffering capacity to storms as a result of increasing rates of sea-level rise, decreasing sediment supply, anthropogenic influences, and changing storm climate (Moore et al., 1999; Morton and McKenna, 1999; Pethick 2001; Zhang et al., 2004). In light of these stressors, it is critical to determine whether barrier-island evolution is driven by a continual- or threshold- response to forcing mechanisms.

Regressive barriers, in particular, are thought to exhibit a threshold response to accelerating sea-level rise (Everts, 1984; Pilkey and Davis, 1987). Typically, the seaward-most dune ridge on a regressive barrier is the highest in elevation and may prevent overwash for millennia, allowing erosion of both the ocean and estuarine shorelines (island narrowing) throughout a period known as the degradational transition (Fig. 1d). As the barrier continues to narrow through the degradational transition, it will likely reach a critical width where overwash becomes more prevalent and the island begins to migrate landward (Fig. 1d). Previous research on the evolution of barriers, including barrier-recession models based on the Bruun rule, focus chiefly on the redistribution of sediment along the shoreface in response to rising sea level (Bruun, 1962; Dubois, 1992; Davidson-Arnott, 2005). However, work done by Leatherman (1979, 1983) shows back-barrier erosion to be important, and in some cases, back-barrier erosion rates are greater than open-ocean rates. Back-barrier erosion should be incorporated into barrier-recession models because when regressive or aggradational barriers cross a threshold in island width and elevation, a new transgressive regime ensues (Fig. 1d).

Research on back-barrier erosion attributes the majority of shoreline change as the result of sea-level rise or anthropogenic influence (Everts, 1984; Pilkey and Davis, 1987), downplaying the influence of variations in sediment supply and/or storm climate. Since variations in the underlying geologic framework play a critical role in barrier-island evolution by modulating sediment supply (Riggs et al., 1996; Rodriguez et al., 2004), it will also play an important role in determining when a threshold width may be reached. The focus of this study is to better constrain the transition between regressive and transgressive barrier evolution.

2. STUDY AREA

Bogue Banks, North Carolina is predominantly an east-west trending barrier and is the southern-most island in the Outer Banks barrier-island chain (Fig. 2). Bogue Sound is a lenticular-shaped, shallow (average depth ~1-2 m) lagoon that separates the island from the mainland. The sound is widest (3.75 km) behind the central part of Bogue Banks. At the east end, near Beaufort Inlet, the lagoon is only 0.80 km wide and at the west end, near Bogue Inlet, the mainland is separated from Bogue Banks by narrow tidal channels and marsh platforms. The tidal range in the area is around 1.0 m and the predominant wind direction is southwest during the summer and north/northwest during the winter and fall (Pilkey et al., 1975; Steele, 1980). Bogue Banks varies in morphology along strike. Emerald Isle (EI) and Pine Knoll Shores (PKS) are wide (up to 1.30 km), high elevation (up to ~13.25 m), and contain a series of beach ridges, characteristic of a regressive barrier. Beach ridges in EI predominantly trend east-west, parallel to the modern shoreline. Beach-ridge orientation in PKS varies slightly from EI, with the ridges along the lagoon shoreline

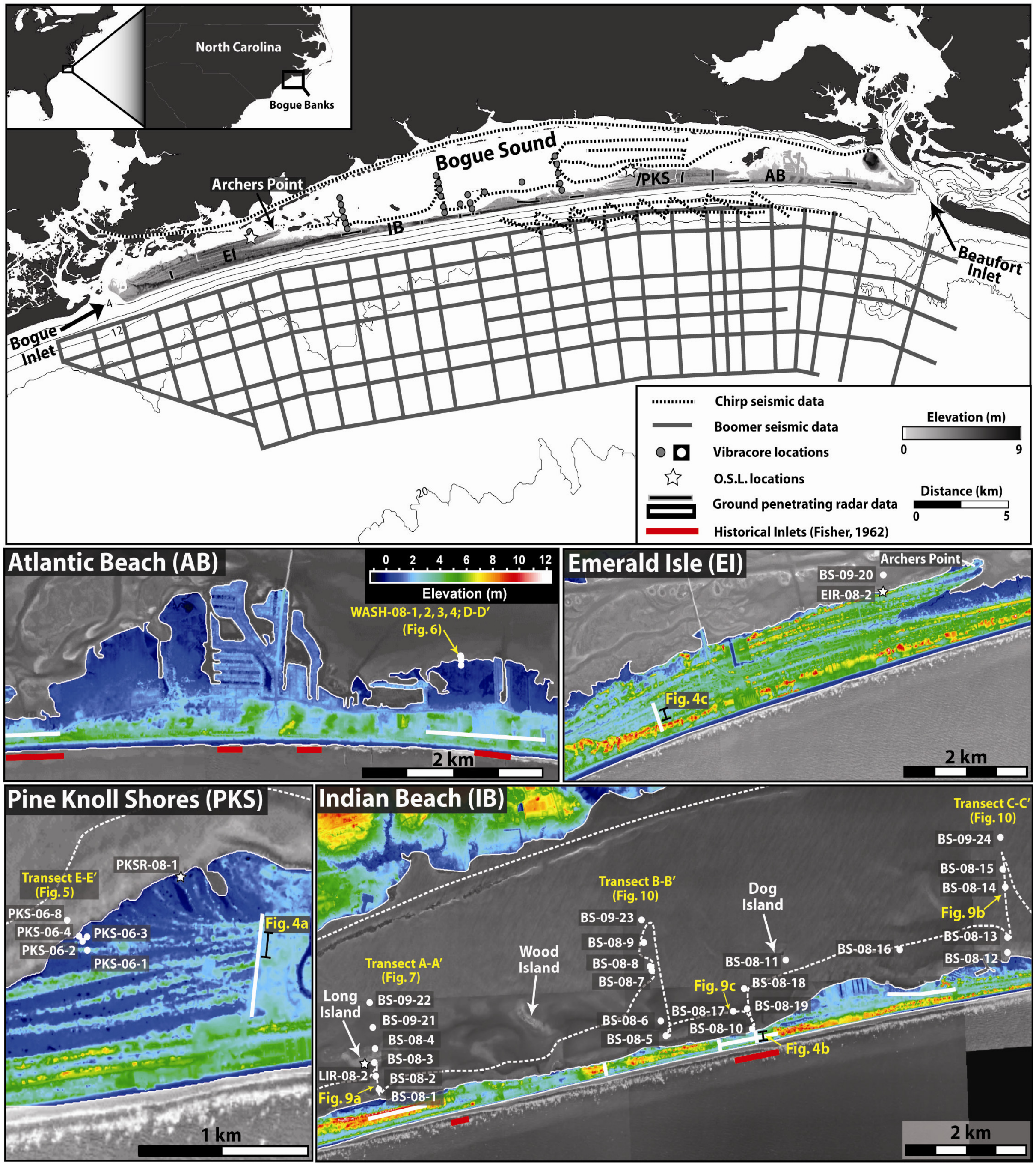


Figure 2. Study area map showing locations of data and subsequent figures. Differences in the morphology of the island at the sections discussed in the text (EI, IB, PKS, and AB), are shown with topography, from LiDAR data, overlain on an aerial photograph. No elevation data available for the chain of small islands in Bogue Sound.

becoming re-curved to the north (Fig. 2). The eastern end of the island, Atlantic Beach (AB), has a discontinuous dune ridge fronting the ocean and coalescing washover fans along the lagoon shoreline characteristic of a transgressive barrier. The evolution of the central portion of the island, Indian Beach (IB), is difficult to infer based on morphology because although it is narrow (~0.22 km) and contains only a single dune ridge fronting the ocean side, it lacks washover fans and ridge-and-swale topography. A 10.16 km-long chain of small islands trends west to east in Bogue Sound extending from the most landward ridge in Emerald Isle (Archers Point) throughout IB. The islands become progressively smaller and lower in elevation toward the east. Although parts of Bogue Banks is considered to have prograded seaward, due to the presence of ridge-and-swale topography in PKS and EI (Fig. 2; Steele, 1980; Heron et al., 1984), presently, all of the ocean shoreline along Bogue Banks is experiencing net erosion in the foreshore and overall, causing barrier narrowing (Pilkey and Davis, 1987). Historical maps presented by Fisher (1962) suggest two inlets were present in the central portion of Bogue Banks from 1755-1804 (Fig. 2). With the exception of breaks in the dune ridge, there is no morphologic evidence in Bogue Sound that these inlets existed.

The varying barrier morphology along Bogue Banks makes it an appropriate site to test whether or not the transition between regressive and transgressive barrier islands is a threshold response to forcing mechanisms and the importance of estuarine shoreline erosion in barrier island narrowing. The morphology of the central portion of Bogue Banks (IB) and the historical record of island breaching suggests that this section may be in transition towards a more typical transgressive evolutionary state, similar to the AB portion of the island. Was IB ever regressive in the past, similar to adjacent EI and PKS? To elucidate the evolutionary history of the IB part of Bogue Banks, we first constrained the facies and stratigraphy of the regressive (EI and PKS) and transgressive (AB) portions of the island and used these results as a benchmark to help interpret the data from IB.

3. METHODS

3.1 Marine seismic data

In Bogue Sound and the inner continental shelf offshore Bogue Banks, we collected approximately 155 km of seismic data using an EdgeTech SB-216S chirper (Fig. 2). The seismic pulse was set at 2-12 kHz and triggered every 0.25 seconds. The Army Corp of Engineers provided us with 478 km of seismic data from the inner continental shelf offshore Bogue Banks for the study. These data were collected in 2002 using an Applied Acoustic Engineering "boomer" seismic source triggered every 0.25 seconds at 100-350 Joules. All marine seismic data sets were interpreted using Chesapeake Technology, Inc. SonarWiz software and maps were generated using Surfer™ 9.0. A velocity of 1500 m/s was used to convert the two-way travel time to depth.

3.2 Ground penetrating radar

Ground penetrating radar (GPR) transects (~10.5 km) were collected using the pulse EKKO Pro system from Sensors and Software, Inc. configured with both 100 and 200 MHz antennae (Fig. 2). Since the limiting factor on depth of penetration with both antennae configurations is the elevation of the salt-water table, given its higher resolution, the 200 MHz data were used for processing and interpretation. Antennae were held 0.5 m apart and traces were collected every 10 cm. A velocity of 0.1 m/ns was used to convert time to depth for all lines, which is within the range of quartz sand reported in Neal (2004). This velocity was verified from a common mid-point survey conducted in PKS and cores from Steele

(1980) that show changes in lithology at the same depths as seismic facies transitions. Traces along the GPR transects were adjusted vertically for variations in topography using a real time kinematic global positioning system and LiDAR data from the North Carolina Floodplain Mapping Program. Data processing included applying a dewow filter, a tapered bandpass filter (20-40-300-600 MHz), and an automatic gain control (AGC), using EKKO View Delux software.

3.3 Cores

The stratigraphy of the barrier was sampled in 33 vibracores which includes four separate transects in Bogue Sound (Fig. 2). The cores are 7.6 cm in diameter, average 3.0-4.0 m in length, and characterize depositional environments, ground truth seismic facies to lithology, and provide shell and wood material for radiocarbon dating. In the lab, we split the cores, photographed, described, and sampled them for lithological, macropaleontological, and radiocarbon analyses. Detailed grain-size analysis of subsamples and identification of shell assemblages helped to differentiate depositional environments. A Cilas 1180 was used to measure particle sizes from 0.04 μm to 2500 μm in 100 size classes by laser diffraction.

3.4 Dating techniques

To accurately place changes in the depositional environments of Bogue Banks into a chronological framework, radiocarbon (accelerator mass spectrometry) and Optically Stimulated Luminescence (OSL) dating techniques were used. The National Ocean Sciences Accelerator Mass Spectrometry Facility at the Woods Hole Oceanographic Institution and Beta Analytic provided the radiocarbon dates on wood and shell material. It is important to ensure samples sent to the lab for dating are *in situ*; therefore, we preferentially selected articulated bivalves (over gastropods or shell fragments) and whole pieces of wood (over bulk organic carbon) for dating. When no articulated bivalves were sampled, an identifiable unpaired valve from the assemblage representative of the respective depositional environment was chosen for dating based on the increased likelihood of original deposition. Samples for OSL dating were collected from trenches dug into the landward-most beach ridge in PKS, Long Island, and EI (Fig. 2). The sample was taken from a wall of the trench by hammering a 1.0 m-long and 7.64 cm diameter aluminum tube horizontally into the base of the cross-bedded dune material, 2.0-4.0 m below the modern soil horizons. Open space in the tube was filled by plastic foam and the ends capped and taped to ensure no light would reach the grains and no mixing of the sample would take place during transportation to the lab. All samples were analyzed at Oklahoma State University. OSL measurements of 120 150-µm quartz separates were carried out with an automated Risø DA-15 TL/OSL system from Risø National Laboratory. The reader is equipped with a bialkali PM tube (Thorn EMI 9635QB) and Hoya U-340 filters (290-370 nm). The built-in $^{90}Sr/^{90}Y$ beta source gives a dose rate of 104 ± 3.9 mGy/s. Optical stimulation was carried out with blue LEDs (470 nm), delivering 31 mW/cm^2 to the sample. The Single-Aliquot Regenerative-Dose procedure (SAR) was applied as proposed by Murray and Wintle (2000) and Wintle and Murray (2006).

4. RESULTS

4.1 Late Quaternary geologic framework

Earlier work by Hine and Snyder (1985) utilized offshore seismic data to map paleochannels along the inner shelf offshore of Bogue Banks. The locations of these paleochannels loosely spatially correlate with EI and PKS, the areas of progradation along Bogue Banks. Given that others have shown geologic framework has a dramatic affect on barrier evolution (Riggs et al., 1995; Riggs et al., 1996; Browder and McNinch, 2006; Harris et al., 2005), a higher resolution map of the nearshore paleochannels was needed to determine their exact placement and morphology. Utilizing the offshore boomer seismic data, a regional surface of erosion, recognized by erosional truncation of the underlying reflectors, onlap of overlying reflectors, and high relief was mapped at a shallow depth (averaging ~5-10 m below the seafloor) throughout the area. The surface map shown in Figure 3 outlines paleochannels that average 10 m deep (measured from the interfluves to the thalweg) in the nearshore and generally bifurcate and broaden seaward. Some seismic lines that cross channels perpendicularly show them to be asymmetrical with a steep cut bank, which suggests meandering. The depth of this regional erosional surface, at the base of the shoreface, corresponds to the depth of the Holocene/Pleistocene surface mapped by Hine and Snyder (1985). The surface is likely the culmination of multiple episodes of incision during Pleistocene time when sea level was lower and the inner continental shelf was exposed (Hine and Snyder, 1985). Multiple paleochannels exist at EI and PKS but IB is an interfluvial area and the disconformity is at a high elevation there. The paleochannels likely connect with small creeks on the north shore of Bogue Sound and/or the White Oak and Newport rivers; however, the seismic penetration in Bogue Sound is too shallow to image the paleochannels. Deep scouring offshore of AB is likely related to more recent inlet processes as opposed to Pleistocene fluvial incision.

Channel fill above the disconformity is defined by bi-directional dipping reflectors interpreted as lateral accretion and a chaotic seismic facies (Fig. 3). Although cores were not collected offshore to verify channel-fill lithology, similar units were described by Hine and Snyder (1985) in the same area and Wellner et al. (2004) on the western Louisiana

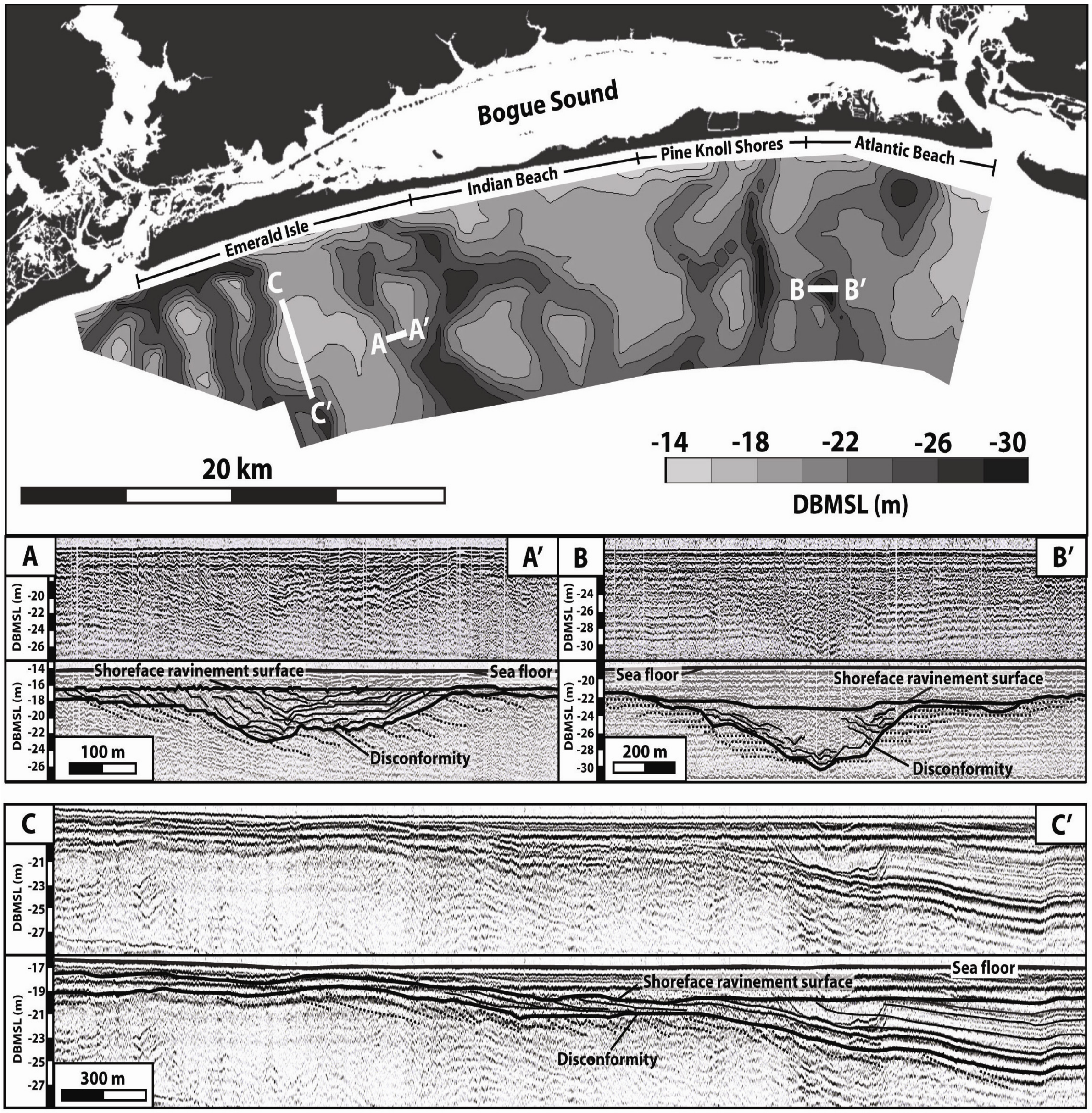


Figure 3. Contoured structure map, in depth below mean sea-level (DBMSL), of the disconformity showing locations of the paleochannels. Examples of seismic data, from which the map is based (A-A', B-B' and C-C'), show the paleochannel-fill facies and the shoreface ravinement surface.

continental shelf, where they were shown to be fluvial sand. A nearly planar seismic surface truncates channel-fill seismic facies and amalgamates with the disconformity in interfluvial areas (Fig. 3). This erosional surface is interpreted as the shoreface ravinement surface. Above the ravinement surface a seismic facies that is generally characterized by parallel horizontal reflectors thins in an onshore direction from ~4.0 m at the most seaward seismic line to ~0.5 m at the toe of the shoreface. This unit is interpreted as reworked sediment deposited above the ravinement surface as the shoreline transgressed across the inner shelf as sea-level rose during the last deglaciation. Many strike-oriented seismic lines show that the ravinement surface is deeper over the channels than in interfluvial areas (Fig. 3). Steele (1980) and Hine and Snyder (1985) show that the disconformity truncates Pleistocene to Tertiary muddy lagoonal deposits, which are close to the seafloor in interfluvial areas. Within the upper 2 m of sediment on the inner continental shelf along Bogue Banks there is likely a lithological difference between areas where paleochannels exist and the surrounding interfluves.

4.2 Regressive Emerald Isle and Pine Knoll Shores

Dip-oriented GPR profiles in PKS and EI show a basal radar facies of seaward-dipping parallel–oblique reflectors, with an average dip angle of 3.5° (Fig. 4). The dip angle decreases in a seaward direction and is consistent with the average modern dip angle of the foreshore-upper shoreface measured at EI and PKS every year since 1999 by the Bogue Banks Beach and Nearshore Mapping Program. These reflections are interpreted to be clinoforms that indicate progradation. Clinoform reflectors have a lateral spacing of several tens of meters, erosionally truncate underlying strata, and overlying strata is conformable or onlaps onto them. The foreshore-upper shoreface facies is truncated by an erosional surface at an average depth of about 0.0 m. Above the erosional surface a 1.0-4.0 m thick unit with a complex radar facies including wavy-parallel horizontal and landward dipping reflectors with localized erosional surfaces exists. This unit is interpreted as eolian dune and the localized erosional surfaces are blowout depressions.

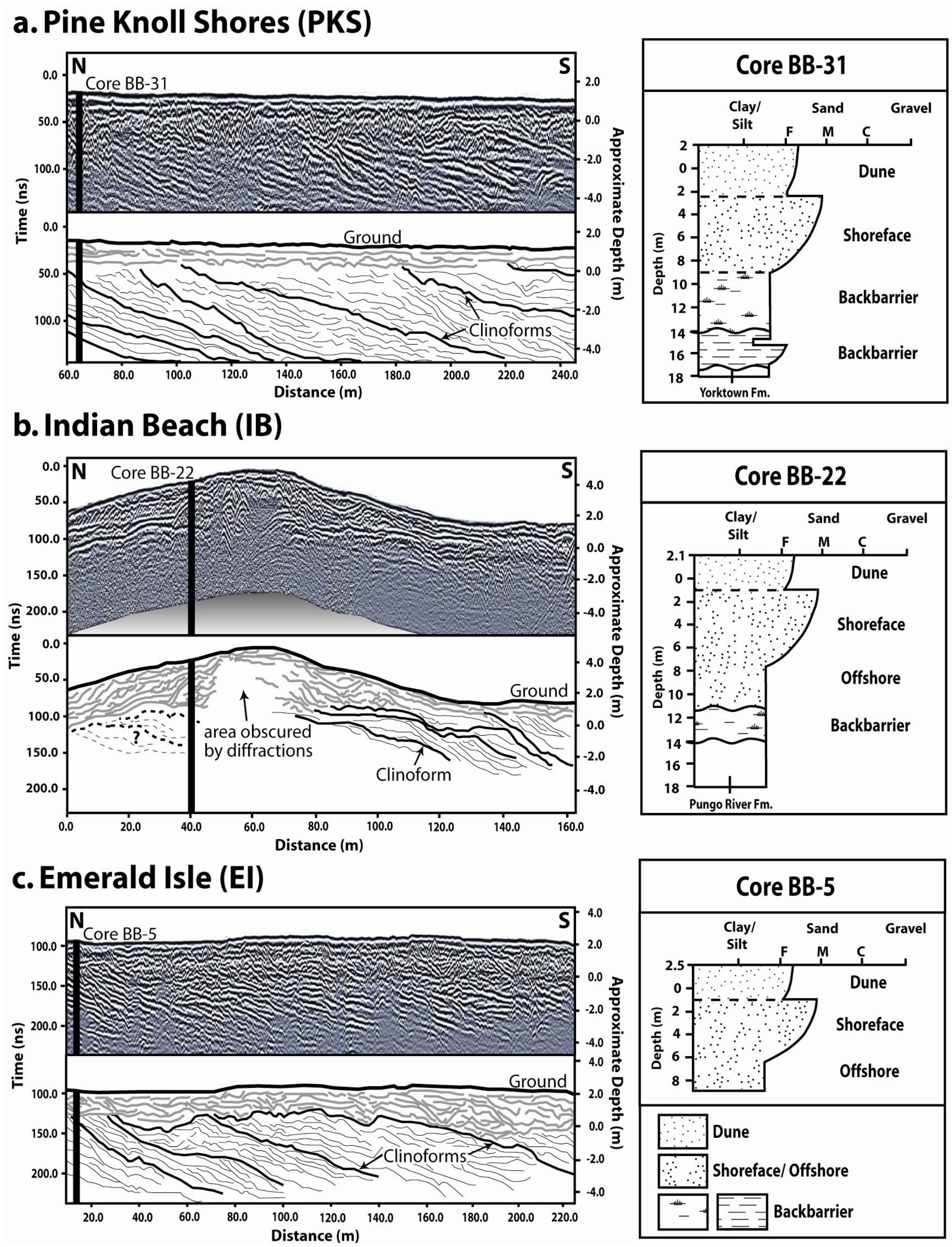


Figure 4. Ground-penetrating radar data examples from PKS, IB, and EI adjusted for topography based on GPS and LiDAR data (depth is relative to NAVD88). Cores from Steele (1980) are projected onto the transects and sampled shoreface at similar depths as those imaged. Aeolian radar reflectors outlined in dark gray and foreshore-upper shoreface reflections outlined in black. See Figure 2 for transect locations.

Cores collected adjacent to the GPR profiles from Steele (1980) show aeolian dune overlying a shoreface unit and dune topography is apparent in areas that have not been developed, which support this interpretation. In addition, these GPR facies and interpretations are similar to other beach-ridge studies (Fitzgerald et al., 1992; van Heteren and van de Plassche, 1997; Smith et al., 1999; Jol et al., 2002; Honeycutt and Krantz, 2003; Moore et al., 2004; Rodriguez and Meyer, 2006).

A north-trending transect of five cores was taken across the back-barrier shoreline in PKS from the edge of a beach ridge, across the swale that is colonized by salt marsh, and into Bogue Sound (Fig. 5). The marsh shoreline is eroding (Pilkey et al., 1975) and is characterized by an overhanging marsh-scarp that formed as wave action undermined the root-mat. The basal unit in each core is a well sorted fine to medium-grained sand, with heavy-mineral laminae (Fig. 5). The elevation of this unit increases towards the beach ridge and it likely correlates with the foreshore-upper shoreface unit imaged with the GPR. Heavy-mineral concentrations are common in this depositional environment (Roy, 1999) and mark clinoform surfaces (Moore et al., 2004). The three cores taken north of the marsh shoreline sampled the sandy marsh platform with relatively low total organic carbon content (5-6%). The two cores taken south of the marsh shoreline sampled a surficial muddy very fine sand unit that thickens northward (into Bogue Sound). The lithologic contact between this lagoonal unit and the underlying foreshore-upper shoreface sand unit is gradational (over ~35 cm) and shows an increase in bioturbation upward. Based on mapping by Pilkey et al. (1975) that shows the lagoonal shoreline migrated through the area over the last 50 years, and the proximity of the northern two cores to the presently-eroding marsh edge, the bioturbated

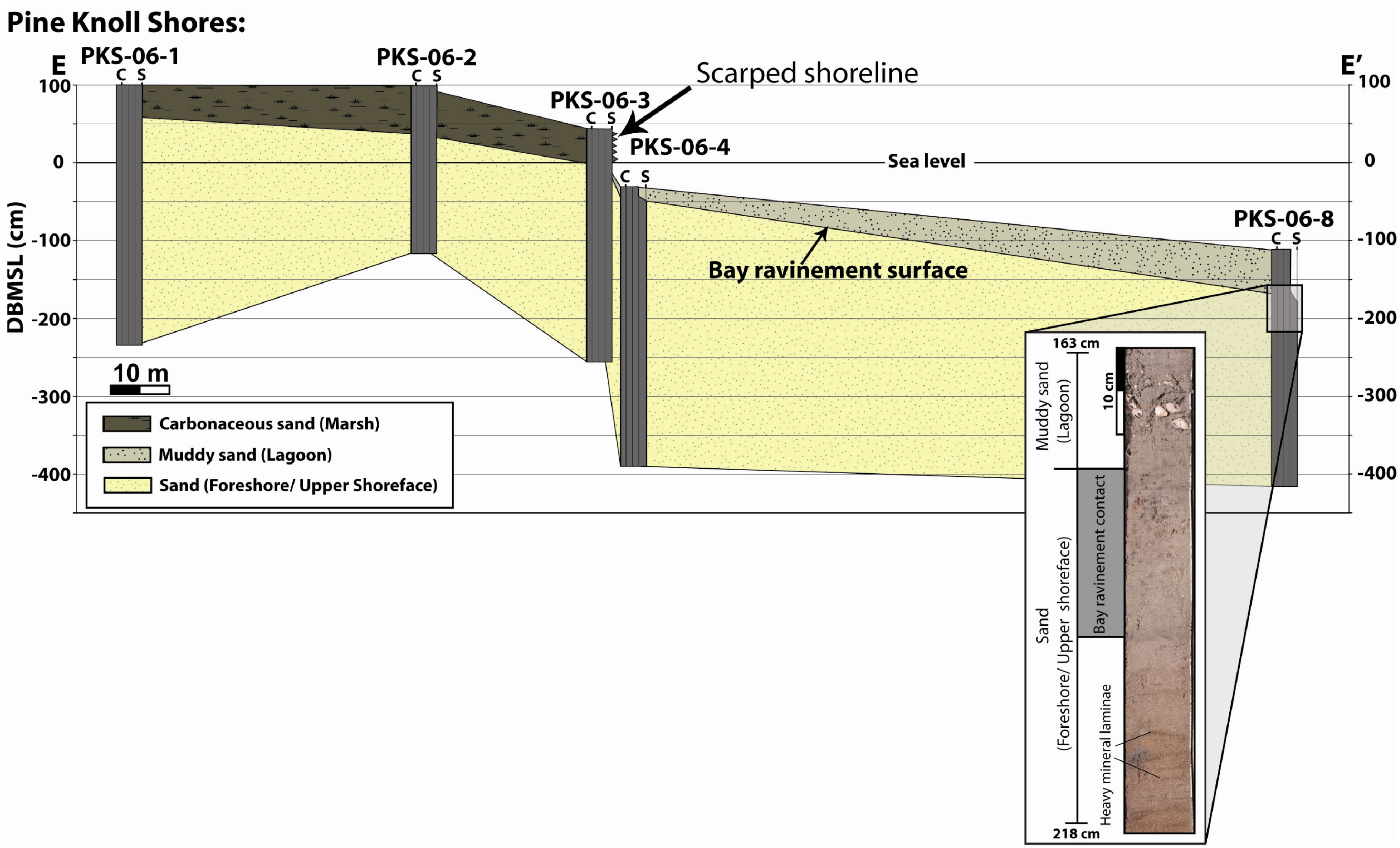


Figure 5. Cross section, based on vibracores, across the lagoonal shoreline in PKS. This shoreline is eroding and core PKS 06-4 and PKS-06-8 sampled the bay ravinement surface as a gradational bioturbated contact. See Figure 2 for transect location. Depth Below Mean Sea Level= DBMSL.

contact between the foreshore-upper shoreface unit and overlying lagoonal sediment likely represents the bay-ravinement surface (Nummendal and Swift, 1987).

4.3 Transgressive Atlantic Beach

The AB portion of the island has a low elevation and contains numerous historical inlets, flood-tidal deltas, and washover fans. A north-trending transect of four cores was collected across the shoreline of a prominent washover fan in Bogue Sound (Figs. 2 and 6). The washover fan is colonized by salt marsh and contains a ~0.5 m-high sandy berm rimming a scarped shoreline. The three most distal cores, WASH-08-2, WASH-08-3, and WASH-08-4, sampled a silty clay unit with abundant *Crassostrea virginica*, and *Gemma gemma* bivalves at the base, which is the lagoonal depositional environment that the washover fan accreted above (Fig. 6). The washover fan is in sharp contact with the lagoonal silty clay and shows a fining upward sequence with coarse sand and distinct 15.0 cm-thick beds of shell hash at the base and medium to fine sand at the top (Fig. 6). This unit also fines and has a lower abundance of shell material in the offshore direction. The sandy portion of the washover fan grades into a clayey very fine sand unit with abundant root and organic material at the top, which is the modern marsh. Core WASH-08-2 sampled the medium-grained sand berm, which is in sharp contact with the underlying marsh deposit (Fig. 6). The berm likely formed as a result of waves and currents eroding the shoreline of the washover fan and transporting the material on top of the scarped shoreline where deposition is facilitated by vegetation.

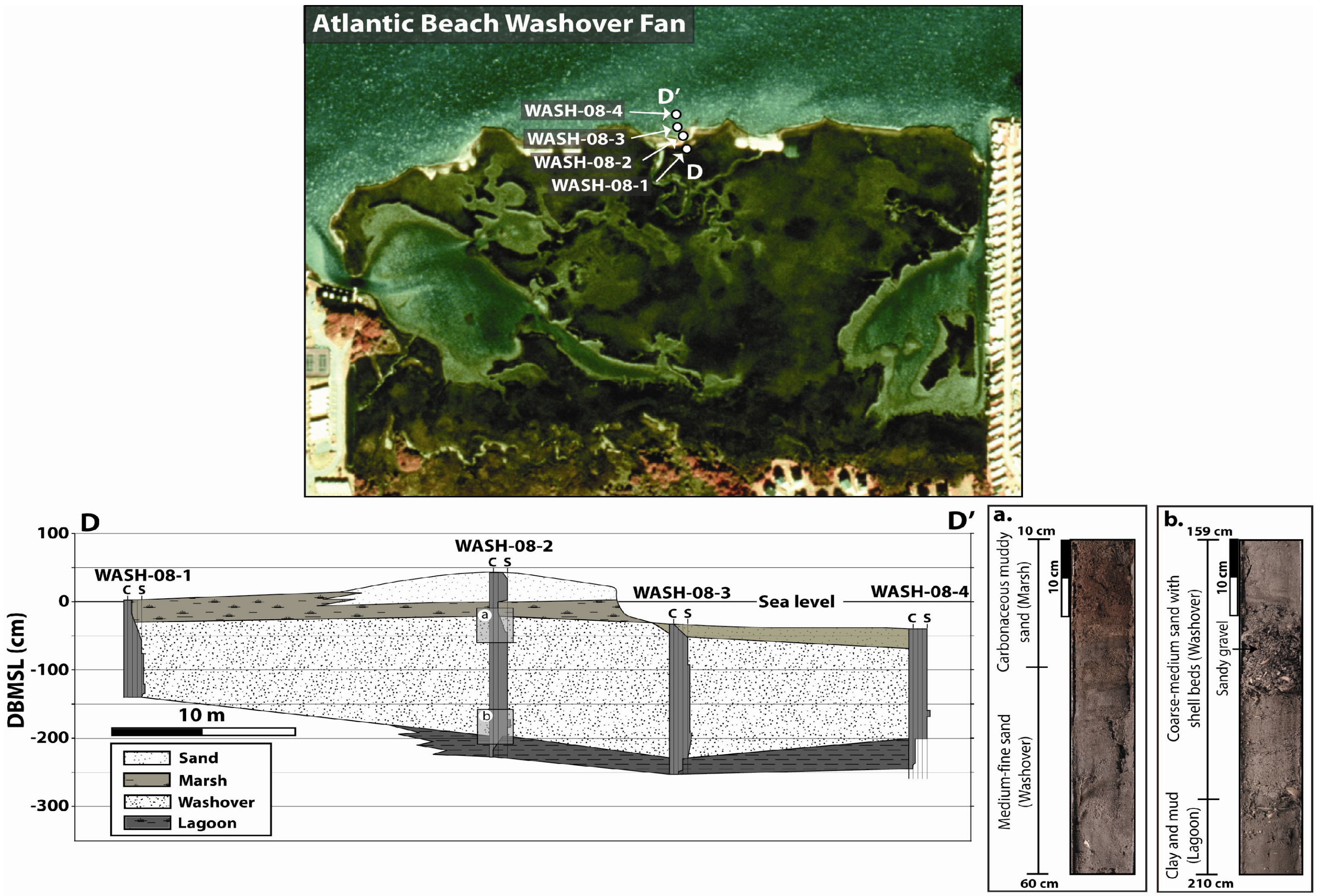


Figure 6. Aerial photograph of a washover fan on AB showing the location of vibracore-cross-section D-D'. Overall, the washover fan is coarsening upward and is colonized by marsh. The lagoon shoreline is being eroded and is scarped. See Figure 2 for the location of the fan; overwash channel that created fan shown in Appendix B. Depth Below Mean Sea Level= DBMSL.

4.4 Indian Beach

A GPR transect from IB shows a basal radar facies that exhibits parallel-oblique to sigmoid-oblique seaward-dipping reflectors from approximately -4.0-0.0 meters (Fig. 4b). The reflectors are interpreted as clinoforms, although they are not imaged as clearly or as deeply at EI or PKS because the salt-water table is likely closer to the surface at this narrower and lower elevation island section. The dip angle of the clinoforms is similar to those imaged at EI and PKS (approximately 3.5-3.8 degrees), suggesting that IB also had an earlier history of progradation. This foreshore-upper shoreface unit is erosionally truncated at an elevation of approximately 0-0.5 m by a similar GPR facies as the aeolian dune imaged at the surface of EI and PKS. This interpretation is also supported by core data from Steele (1980) that shows the same general depositional environments and contact depths.

Long Island, located behind IB, is the largest (0.4 km long) and highest elevation (~8.0 m high) island in Bogue Sound (Fig. 2). An outcrop at the southern shoreline exposes

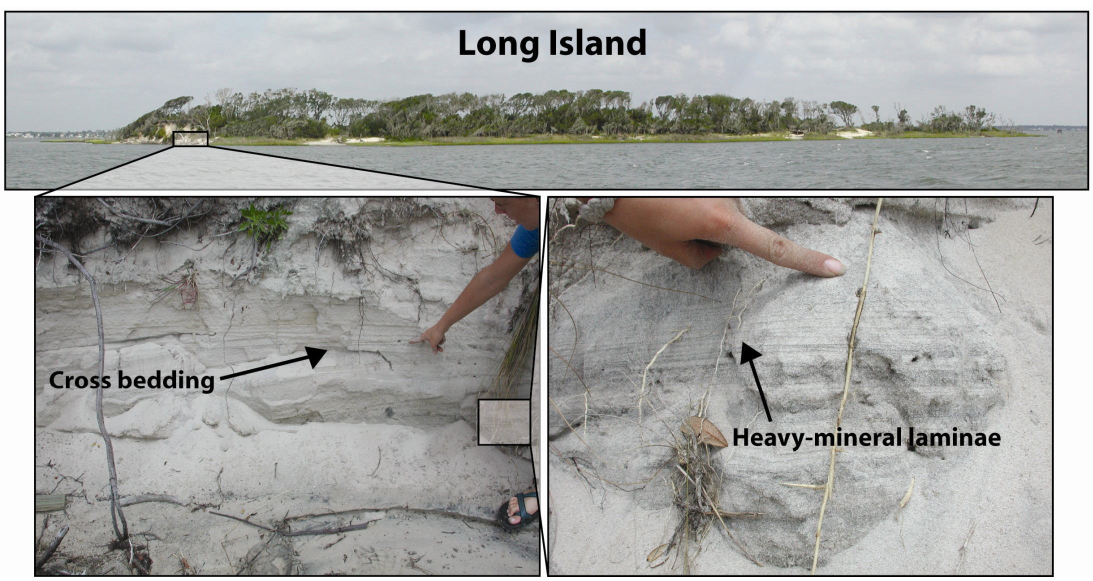


Figure 7. Photograph of Long Island taken looking north from the approximate location of core BS-08-2. The outcrop at the western end of the island shows cross bedding and heavy-mineral laminae at the transition between eolian dune (above) and foreshore (below). This is the same outcrop sampled for OSL dating.

the complete subaerial stratigraphy of the island, which is composed of a cross-bedded, well-sorted medium-grained sand with frosted grains and placer deposits at the base (Fig. 7). This unit is typical of beach ridges and is very similar to what is exposed in a 10.0 m-high outcrop of the oldest EI beach ridge exposed at the Bogue Sound shoreline, near Archers Point, 3 km west of Long Island. It is likely that Long Island was once connected to the oldest EI beach ridge and may have been connected to the oldest PKS beach ridge 14.0 km to the east, as suggested by Fisher (1967). To test this, samples for OSL dating were extracted from the dunes that cap the northern most beach ridges of EI, PKS, and Long Island, the results of which are shown in Table 1. The OSL dates show that the age of the ridge in EI (2100 ± 180

Lab Code: Radiocarbon Samples	General Location	Sample Name	Sample Depth (cm) B.M.S.L.	Material	Conventional C14 Age: Yr BP; 1σ	Calibrated C14 Age: Yr BP; 1σ	Calibrated C14 Age: Yr BP; 2σ
OS-70786	Bogue Sound	BS-08-2	155.2-155.7	*Gemma gemma* *	1,380 ± 30	930 ± 30	920 ± 90
OS-70787	Bogue Sound	BS-08-4	186-191	*Gemma gemma**	750 ± 30	390 ± 50	385 ± 80
OS-70791	Bogue Sound	BS-08-4	277-281	*Crassostrea virginica*	2,780 ± 30	2,525 ± 80	2,520 ± 145
OS-70788	Bogue Sound	BS-08-5	355.4-356.4	*Donax variabilis*	1,960 ± 25	1,515 ± 40	1,505 ± 90
OS-70789	Bogue Sound	BS-08-6	160.9-165.9	*Gemma gemma**	1,520 ± 35	1,080 ± 55	1,068 ± 100
OS-70790	Bogue Sound	BS-08-8	130.4-135.4	*Tagelus plebeius**	1,540 ± 30	1,100 ± 45	1,087 ± 95
Beta-261203	Bogue Sound	BS-09-22	398.6-407.6	*Tagelus plebeius**	4,000 ± 40	4,010 ± 65	4,010 ± 130
Beta-261204	Bogue Sound	BS-09-22	468.6-470.6	plant material	4,570 ± 40	5,300 ± 20	5,120 ± 70
Beta-261205	Bogue Sound	BS-09-22	498.6-500.6	*Crassostrea virginica**	4,510 ± 40	4,730 ± 60	4,700 ± 120
Beta-261206	Bogue Sound	BS-09-22	619.6-621.6	*Semele proficua*	5,160 ± 40	5,525 ± 40	5,520 ± 80
Lab Code: OSL Samples	**General Location**				**Dose (Gy)**	**Dose Rate (Gy/ka)**	**Age (ka)**
EIR-08-2	Emerald Isle				2.29 ± 0.18	1.091 ± 0.036	2.10 ± 0.18
LIR-08-2	Long Island				1.71 ± 0.085	0.971 ± 0.032	1.76 ± 0.11
PKSR-08-2	Pine Knoll Shores				2.68 ± 0.12	0.805 ± 0.023	3.33 ± 0.18

Table 1. AMS Radiocarbon and OSL dates, with relative locations, sample name, sample depth, material type, conventional and calibrated ages given in 1σ and 2σ age ranges, as well as dose (Gy), dose rate (Gy/ ka) and age (ka) for OSL dates.

yr) and Long Island (1760 ± 110 yr) are similar, indicating that the back-barrier dune ridge in EI once extended through Long Island and likely through the other islands to the east, across the present day Bogue Sound. The back-dune ridge sampled in PKS is older (3330 ± 180 yr; Table 1) suggesting that these relict re-curved ridges were likely created during an earlier period of island accretion, and may have been influenced by inlet processes (Otvos, 2000).

To constrain the mechanisms that caused the landward-most beach ridge to break into a series of islands in Bogue Sound, a core transect was taken from the lagoon shoreline of IB through Long Island and into the middle of Bogue Sound (Fig. 8). These cores sampled four distinct lithofacies. Grain size analysis of the lithofacies sampled from multiple cores throughout Bogue Sound show that they are easily distinguishable (Fig. 9). Lithofacies A is a homogenous silt/clay unit with abundant *Crassostrea virginica* shells (whole and fragments) throughout and lithofacies B is a coarse-grained sand to gravel (shell hash). These units are interpreted as lagoon and tidal channel, respectively. Lithofacies C is >2.0 m thick and composed of a moderately well sorted fine to medium-grained massive to laminated (placers) sand (Figs. 8 and 9). Shells, including numerous *Donax variabilis* that live in the foreshore, shell fragments, and wood fragments are present toward the base of this unit, with decreasing abundances at shallower depths. Lithofacies D is a massive muddy very fine sand unit, with organic material, which is sampled at varying depths within the separate cores (Figs. 8 and 9). The shells in this unit include articulated *Gemma gemma*, and fragments of *Tagelus plebius*, which live in lagoons and estuaries. The contact between lithofacies C and D is gradational and shows an upward increase in burrow abundance. In addition, the contact shallows and lithofacies D thins towards IB and Long Island. Lithofacies C likely extends below the aeolian dune through IB, where the seaward-

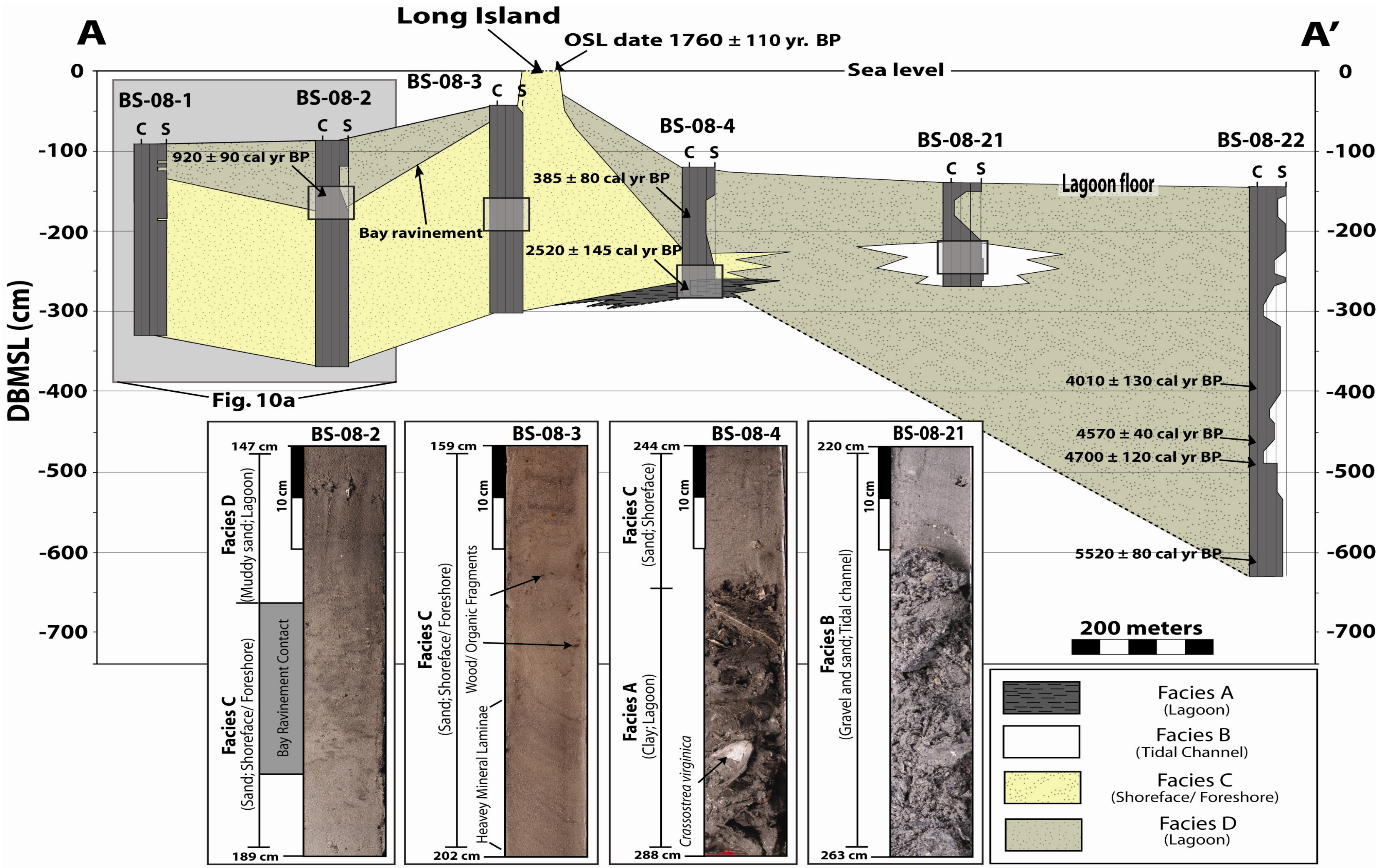


Figure 8. Cross section A-A’ shows that lagoonal sediment has accreted prior to barrier regression, and the preservation of the foreshore/uppershoreface unit below the bay ravinement surface. The location of chirp seismic data in Fig. 10a noted. See Figure 2 for transect location and Table 1 for information on dates. Depth Below Mean Sea Level= DBMSL.

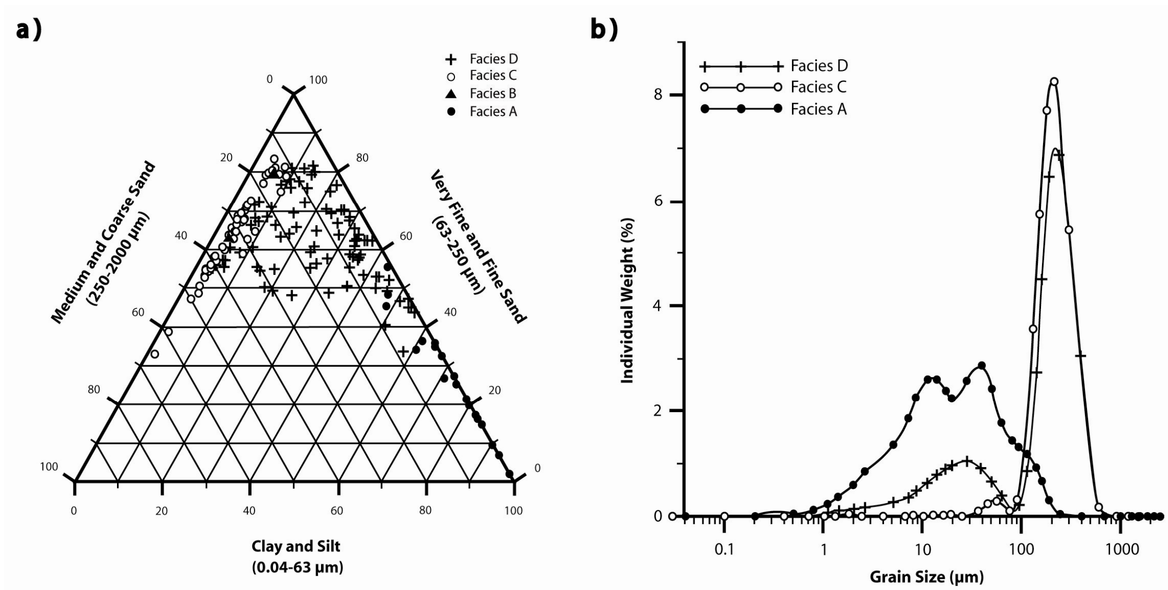


Figure 9. Ternary diagram (a) showing the distribution of assumed facies generally clusters. The facies are visually distinguishable in cores and this is illustrated in the distinct plots of 100 size classes from 0.04 µm to 2000 µm (b). Every 3rd data point is displayed, although the curves are based on the complete number of bins. Abundant gravel is rare, except for in Facies B where it was removed by sieving prior to sample measurement. This is why Facies B plots with Facies C on the ternary diagram and is not displayed in raw data examples (b).

dipping reflectors were imaged with the GPR, and Long Island, where placer deposits are exposed. This unit is interpreted as foreshore-upper shoreface. Facies D extends to the lagoon floor and reflects what is currently being deposited in Bogue Sound. The core transect collected across the lagoonal shoreline of PKS, encompassing an area where the shoreline recently migrated through (Fig. 5), sampled an identical gradational contact between foreshore-upper shoreface and lagoonal units. Given the similarity of the contact between facies C and D to the modern analog, this contact is also interpreted to be a bay-ravinement surface. Cores BS-08-4, BS-08-21 and BS-08-22, on the north side of Long Island, sampled thin massive medium- to fine-grained sand at the sediment-water interface, which thickens to 0.25 m towards the island. This is likely reworked or wind-blown sand from the aeolian dune exposed on Long Island.

Core BS-09-22, from the center of Bogue Sound, sampled the thickest section of lagoonal sediment and radiocarbon dates show deposition since at least 5520 cal yr. BP. Core BS-08-4 sampled lagoonal clay below the foreshore-upper shoreface unit on the north side of Long Island and a *Crassostrea virginica* valve sampled from the lagoonal clay unit is 2525 ±80 cal yr. BP, around 800 years older than the base of the aeolian dune on Long Island and EI. This date and dates from the lagoonal muddy sand in core BS-09-22 show that the lagoon was present before Bogue Banks began to prograde seaward.

Chirp seismic data taken along on the south side of Long Island imaged a high-amplitude continuous reflector at the same depth as the gradational contact was sampled

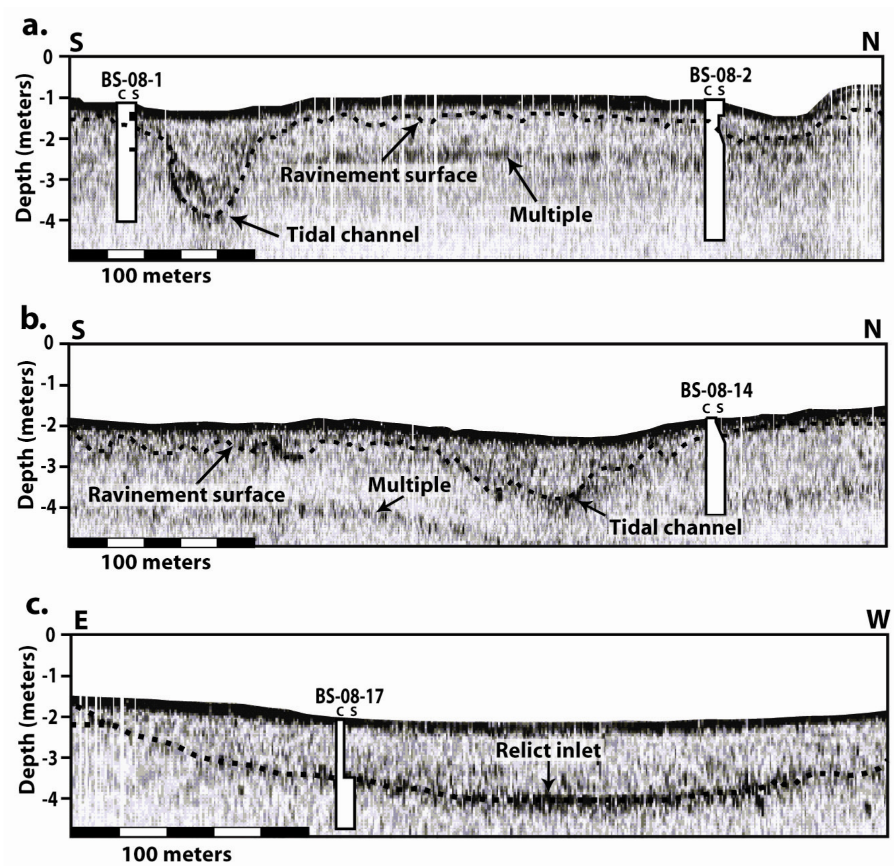


Figure 10. Chirp seismic data collected in Bogue Sound showing the bay-ravinement surface and tidal channels (a, b) and an overwash or inlet channel. The tidal channel has steep flanks while the inlet channel is broad and the fill is shown to be clay in sharp contact with the underlying foreshore/upper shoreface unit (sand). See Figure 2 for transect locations. Depth Below Mean Sea Level= DBMSL.

between the foreshore-upper shoreface (facies C) and lagoonal (facies D) units in cores BS-08-1 and BS-08-2 (Fig. 10a). Overall, there is little relief on this reflector but a channel is imaged on the southern part of the line. This channel is imaged in multiple dip-oriented seismic profiles extending from PKS to EI (e.g. Fig 10b), suggesting it trends in an east-west direction. The feature is interpreted as a tidal channel and although no cores were obtained from it, the basal fill is likely similar to the coarse-grained sediment sampled in core BS-08-21 between 2.20 and 2.84 m below sea-level (Fig. 8).

To test whether the lithologic facies and bounding surfaces, identified in the Long Island transect, exist across Bogue Sound at the central and eastern portion of IB, we obtained additional core transects (Fig. 2). These transects extend from the lagoonal shoreline of Bogue Banks into Bogue Sound, bisecting the trend of the island chain that extends east into the area from Long Island. The cores and seismic data show the same lithologic facies, contacts, and seismic surfaces recognized in transect A-A' (Fig. 11); a lower foreshore-upper shoreface unit separated from an upper lagoon unit by the bay-ravinement surface (Figs. 8, 10b, and 11). A *Donax variabilis* valve sampled from the foreshore-upper shoreface unit in core BS-08-5 is 1505 ± 90 cal yr. BP (Table 1), which is similar to the OSL dates from the northern-most EI beach ridge and Long Island dunes. These cross sections show that the open-ocean shoreline at IB extended to the island chain, which is currently located about 1.4 km north of the lagoon shoreline of Bogue Banks, around 2,000 cal yr. BP. Radiocarbon dates obtained not more than 20 cm above the bay-ravinement surface in cores BS-08-6 and BS-08-8, which are 800 m apart, are 1,080 ±55 and 1,100 ±45, respectively. The similarity of these dates suggests that the bay-ravinement surface moved across the area rapidly.

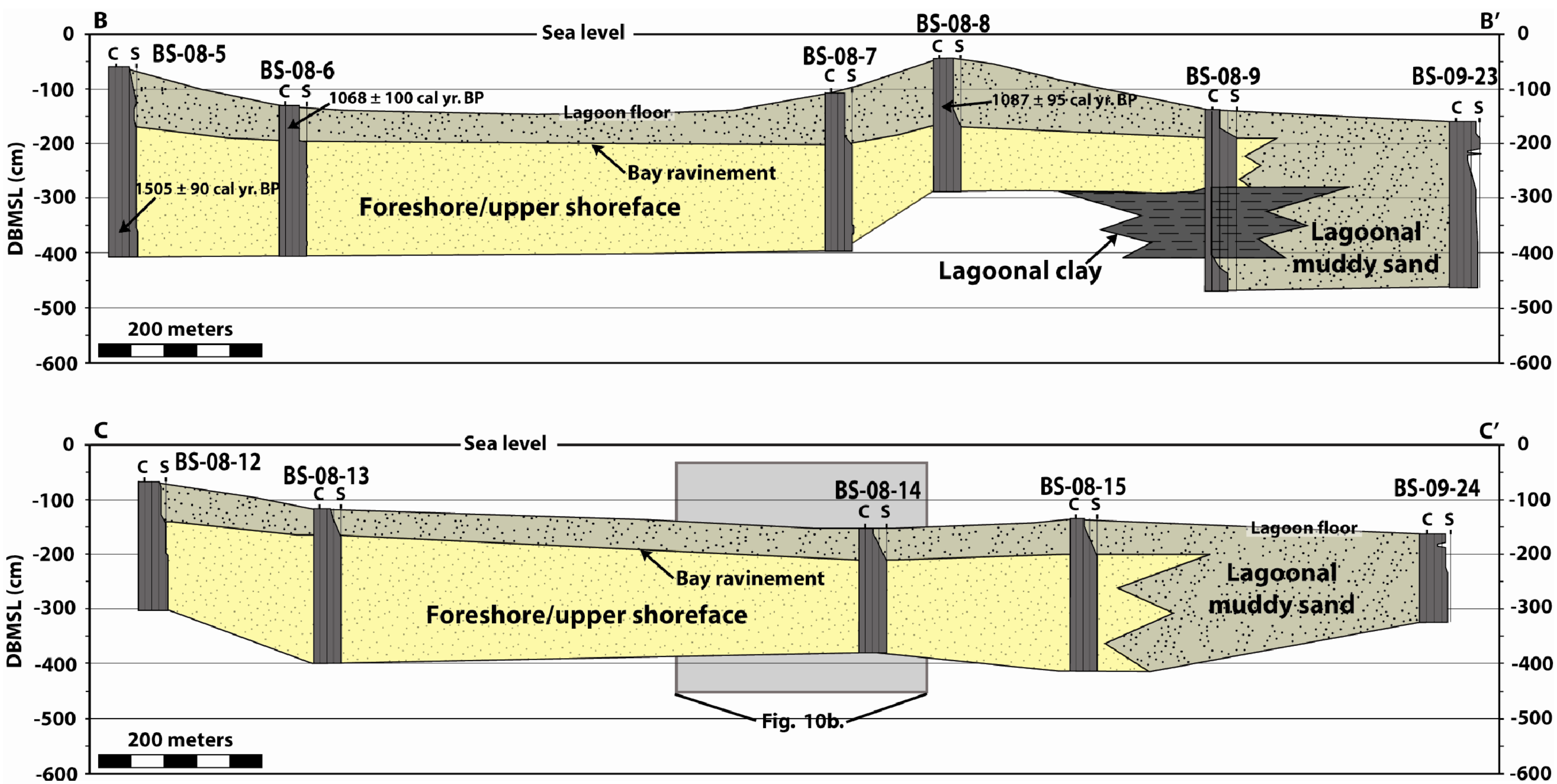


Figure 11. Transects B-B' and C-C' show that the foreshore/upper shoreface unit extend into Bogue Sound throughout the IB area of Bogue Banks. Dates directly above the bay ravinement surface suggest erosion occurred rapidly and around 1100 cal BP. The location of chirp seismic data in Fig. 10b noted. See Figure 2 for transect locations Table 1 for additional information on dates. Depth Below Mean Sea Level= DBMSL.

Strike-oriented chirp seismic lines collected in Bogue Sound along IB image high-amplitude localized reflectors that truncate the bay-ravinement surface (e.g. Fig. 10c). These reflectors outline two broad, concave upward features ~600 meters in width that extend to a depth of ~2-3 meters. The reflectors amalgamate with the sea floor away from the concave upward features (Fig. 10c). Core BS-08-17, taken within one of these broad features to define the lithology of its fill, sampled the lower foreshore-upper shoreface unit in sharp contact with an overlying silt and clay unit and this contact is at the same depth as the high-amplitude reflector. Historical nautical charts, presented by Fisher (1962), show the two inlet features were open along Bogue Banks from ~AD 1755-1804 (Fig. 2). The broad channel features displayed in chirp seismic data correlate spatially with these inlet locations and the locations of breaks in the fore-dune ridge on IB, recognized in the LiDAR data (Fig. 2), and are interpreted as relict inlets. The presence of these historical inlets along the central portion of Bogue Banks shows that the island is narrow enough to allow for breaching to occur. Given that the inlets are filled with fine-grained sediment and are not associated with a washover fan or flood-tidal delta indicates that the breaches healed rapidly.

5. DISCUSSION

Our data are used to reconstruct the evolution of Bogue Banks, including EI, IB, and PKS sections, over the last 4000 years. The late Holocene evolution of AB is not addressed in detail because ephemeral tidal inlets and overwash processes removed the record. Similar to most wave-dominated shorelines, the development of this barrier occurred after the rate of eustatic rise began to decrease around 6000 cal yr. BP. (Toscano and Macintyre, 2003). The width of Bogue Banks has varied at different rates along the barrier throughout its development and this is especially evident at IB. Previous shoreface models identify an increase in the rate of sea-level rise as the dominant cause of changing barrier morphology (Bruun, 1962; Dubois, 1992; Davidson-Arnott, 2005). However, the reduction in barrier width observed at IB occurred during a period when the rate of sea-level rise was low (~0.8 mm/yr.), which is well documented for the region (Horton et al., 2009). The changes in barrier width at IB must be related to other forcing mechanisms, namely hydrodynamics and sediment supply.

Phase 1

During initial development, Bogue Banks was a transgressive barrier island. Evidence for this early transgressive period is the thick lagoonal deposit cored in Bogue Sound that predates barrier progradation by at least 2000 years, but suggest a barrier existed somewhere offshore (Fig. 12a; Phase 1). Relative sea level was rising at ~5.0 mm/yr until around 4000 cal yr. BP when the rate slowed to ~0.8 mm/yr (Horton et al., 2009), which, based on OSL dates of the northern-most beach ridges in PKS, is close to the time Bogue Banks began to accrete at its present location (Figs. 12a and b). The beach-ridge plain at Kitty Hawk, in the northern Outer Banks, NC, also began to accrete at its present location around 4000-3000 cal yr. BP (Mallinson et al., 2008) likely in response to the lower rate of relative sea-level rise during this time (Horton et al., 2009).

Phase 2

Around 3000 cal yr. BP, IB was narrow, similar to the rest of the island. Given the decrease in rate of sea-level rise, sediment supply to the barrier overwhelmed accommodation and the island began to prograde seaward (Fig. 12a and c; Phase 2). In addition to alongshore sediment sources, reworking of offshore paleochannel-fill deposits

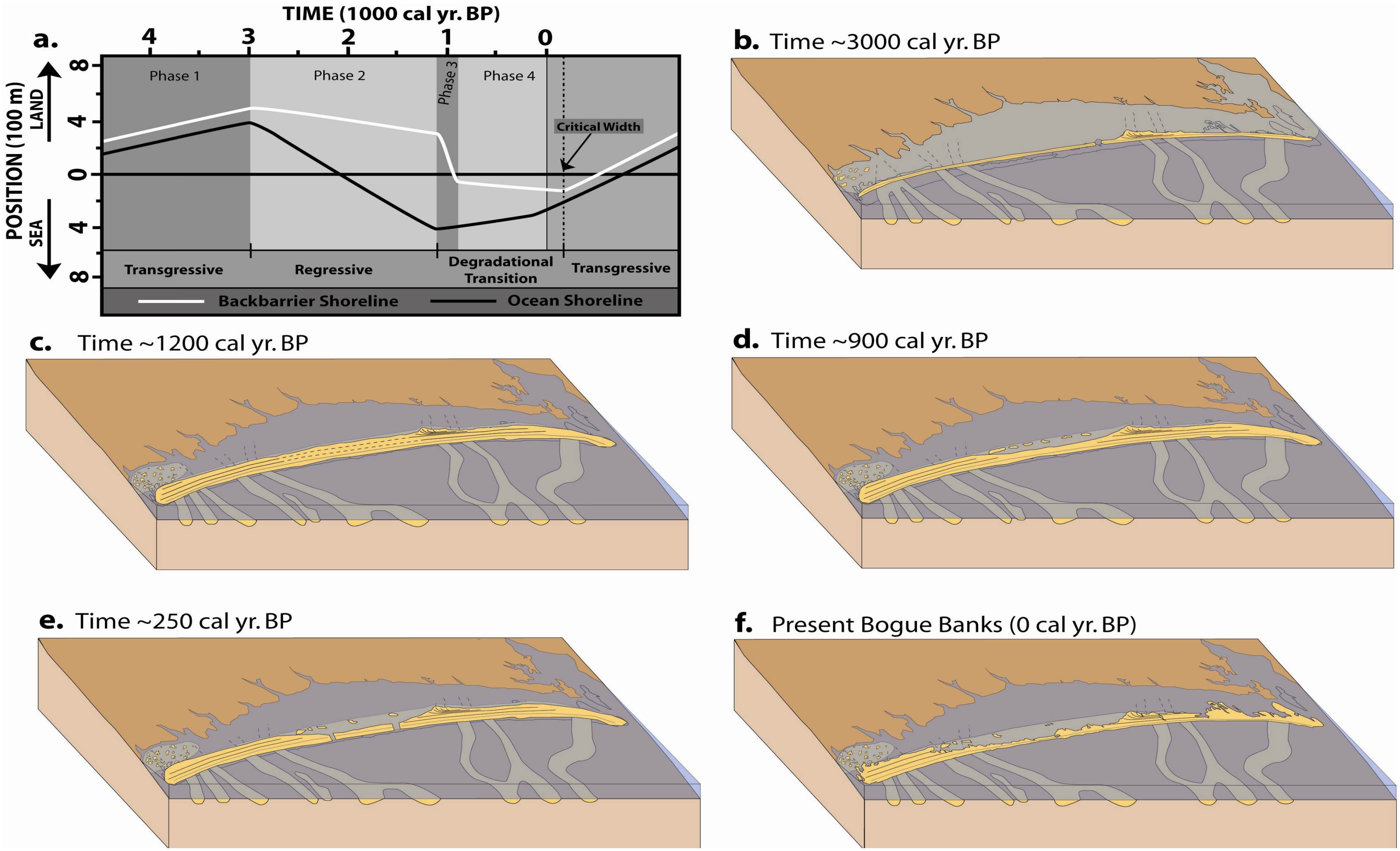


Figure 12. Evolutionary diagram for Bogue Banks over the last ~3000 years. a) Conceptual graph of the Indian Beach section of the barrier illustrating the relative landward or seaward movement of the ocean (black) and back-barrier (white) shorelines from a central datum along Bogue Banks through time. Locations of evolutionary stages in barrier development (b-f) are indicated showing periods of barrier transgression, regression, and transition. Present day is at zero time (Phase 5).

likely contributed to the positive sediment budget of the barrier (Fig. 3). Paleochannels are filled with thick sand and act as localized sand sources, while the interfluvial areas contain fine-grained material close to the seafloor (Hine and Snyder, 1985). The ravinement surface excavated more deeply into the easily erodible paleochannel-fill deposits than the indurative interfluvial areas, which is apparent in the seismic data. Although longshore transport would have caused sediment distribution across the entire shoreface, it is likely that areas of the barrier in close proximity to the paleochannels, e.g. EI and PKS, had a higher sediment supply than areas of the barrier proximal to the interfluves (IB). Given that the chain of islands in Bogue Sound is an extension of the oldest beach ridge in EI, Bogue Banks likely maintained a relatively constant width from east to west during progradation, but the elevations of the areas close to the paleochannels were likely higher than areas close to interfluves, which is still apparent today (Fig. 2). Similarly, shallow terraced fluvial deposits on the Gulf of Mexico inner-continental shelf acted as a localized sediment source, causing along-strike variations in the rate of shoreline transgression during the middle to late Holocene (Rodriguez et al., 2004). Along the northern Outer Banks, sections of the barrier island in proximity to the Roanoke paleochannel, are wider and higher than adjacent interfluvial areas (e.g. Kitty Hawk and Kill Devil Hills; Boss et al., 2002; Havholm et al., 2004) and potentially developed similarly as EI and PKS.

The prograding barrier was not influenced by overwash processes between 3000 and ~1200 cal yr. BP because it was wide and likely had a high-elevation foredune ridge, which still exists today, that prevented breaching. In the absence of large rivers, overwash is the main process by which sediment replenishes the back-barrier shoreline and there is no evidence washover fans ever existed behind EI, IB, and PKS. The sediment-starved sound shoreline was likely eroding during barrier progradation in response to sea-level rise and wave/ current energy. However, overall the sound shoreline was not moving seaward as rapidly as the ocean shoreline, which caused island width to increase.

Phase 3

Based on radiocarbon dates above and below the bay ravinement surface, the sound shoreline of IB eroded rapidly ~1100 cal yr. BP (Fig. 12d). Culver et al. (2007) shows that at this same time, portions of the southern Outer Banks (north of Bogue Banks) “collapsed”, creating a segmented barrier system. It is postulated that this was the result of increased hurricane activity due to warmer temperatures during the medieval warm period (Cronin et al., 2003; Culver et al., 2007). Work conducted by Mann et al. (2009) corroborates this assertion by comparing the sedimentary record of land-falling hurricanes to statistical-model estimates of cyclone activity over approximately the last 1,500 years that shows a period of high cyclone activity in the Atlantic during the medieval warm period, ~1,100-900 cal yr. BP. The sound shoreline at IB was more susceptible to erosion in response to the higher cyclone activity than EI and PKS because of greater fetch due to Bogue Sound being widest here, and this being a low-elevation part of the barrier.

Phase 4

The historical record shows that IB was breached at least as early as AD 1755 (Fisher, 1962), which is supported by breaks in the foredune ridge line and seismic data that image inlet channels (Figs. 2, 10c, and 12e). The clay fill in these relict inlets and lack of flood-tidal delta and washover fan deposits in Bogue Sound demonstrate the ephemeral nature of these features. Island breaching only initiated once the island narrowed as a result of back-barrier and likely foreshore erosion. The ocean shoreline of Bogue Banks has been moving landward over at least the past 50 years (North Carolina Division of Coastal Management), but it is unknown when sediment supply versus accommodation fell below the value required for shoreline regression, because the record was removed by shoreface-ravinement processes. We infer that landward movement of the ocean shoreline initiated at ~1100 cal yr. BP, which corresponds with the increase in sound-shoreline erosion rates (Fig. 12a), resulting from storm related erosion.

The future of Bogue Banks

IB is currently transitioning towards a transgressive barrier, but the critical width and elevation needed for the island to be breached more frequently, causing both the sound and ocean shorelines to begin to migrate landward, has not been reached. The critical width cannot be defined by a single number applicable to any coastline; rather, it varies according to the wave and current energy at the back-barrier and ocean shorelines, which is closely related to climate.

Anthropogenic influence is contributing to the likelihood that the barrier will transition towards transgressive evolution rapidly (Pilkey and Davis, 1987). In an attempt to prevent property loss and flooding, the fore-dune ridge is commonly built up through sand fences, nourishment, and beach scraping. In addition, inlets that form after storms are rapidly closed by machinery. Destruction of the shoreline forest and fringing marsh for development has also been cited as one of, if not the main cause of recent shoreline erosion along Bogue Banks (Pilkey et al. 1975). These activities prevent new sand from nourishing the back-barrier shoreline and inadvertently contribute to island narrowing.

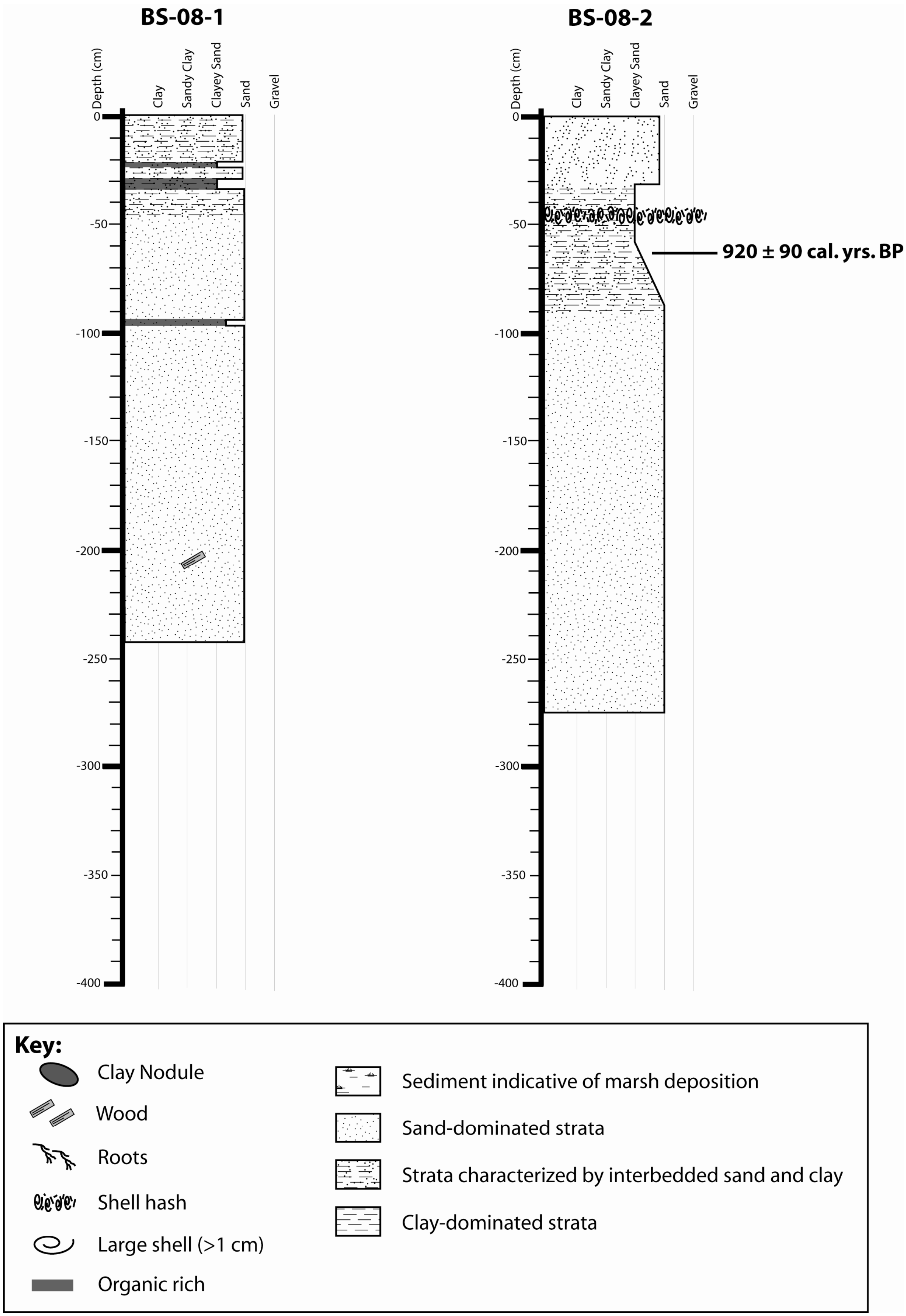
6. CONCLUSIONS

The results from this study support the concept that there exists a degradational transition between regressive and transgressive barrier evolution. The duration of this transition decreases with increasing physical forcing, decreasing sediment supply, and increasing rate of relative sea-level rise. Back-barrier erosion plays a significant role in the narrowing of a regressive barrier. Regressive barriers are typically resilient to overwash, which is the primary source of sediment to the estuarine shoreline, because of their high elevation and width. Due to localized sand sources (paleochannels) near EI and PKS, these sections of Bogue Banks were higher in elevation than IB. Significant narrowing of IB occurred during a period of time when the rate of relative sea-level rise was low, but storm frequency was high. This central part of the barrier is more susceptible to storm-related erosional processes than adjacent EI and PKS due to its lower elevation and the curvature of the mainland shoreline that makes Bogue Sound widest around IB. Therefore, variations in climate, not sea-level rise, caused regional erosion and alteration of the morphology of the North Carolina barriers.

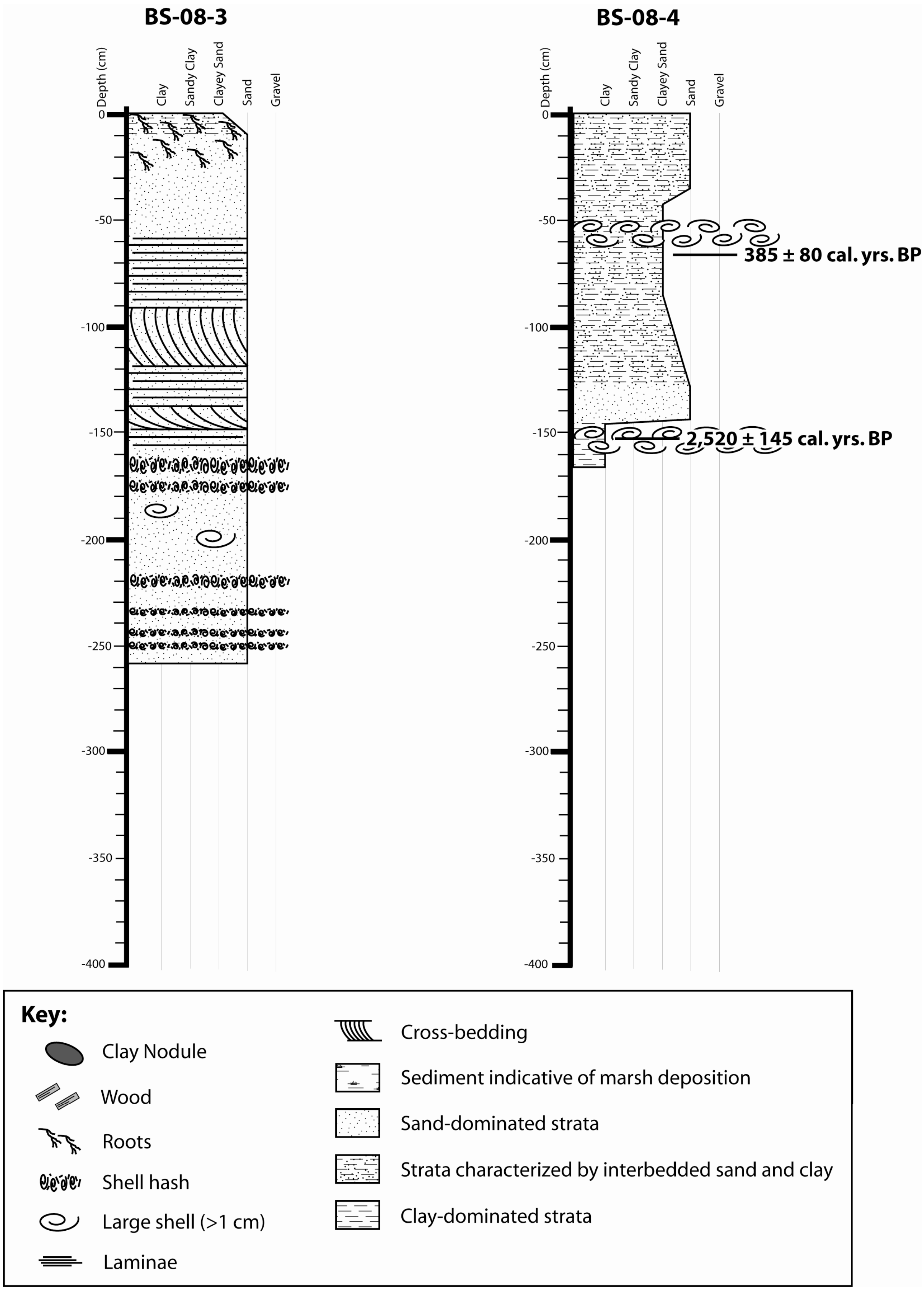
Predictive barrier island models that focus solely on variations in sea-level rise neglect important forcing mechanisms, like storm frequency and localized sediment sources, and run the risk of poorly predicting barrier island evolution as a result. However, it is likely that increased rates of sea-level rise, as are predicted, will further accentuate island narrowing, increasing the rate at which the island moves toward the critical width. In addition, this study brings further attention to the impact variations in climate change play in barrier island morphology, specifically the potential affect future warming will have on increasing the rate of landward movement of this and other barrier islands.

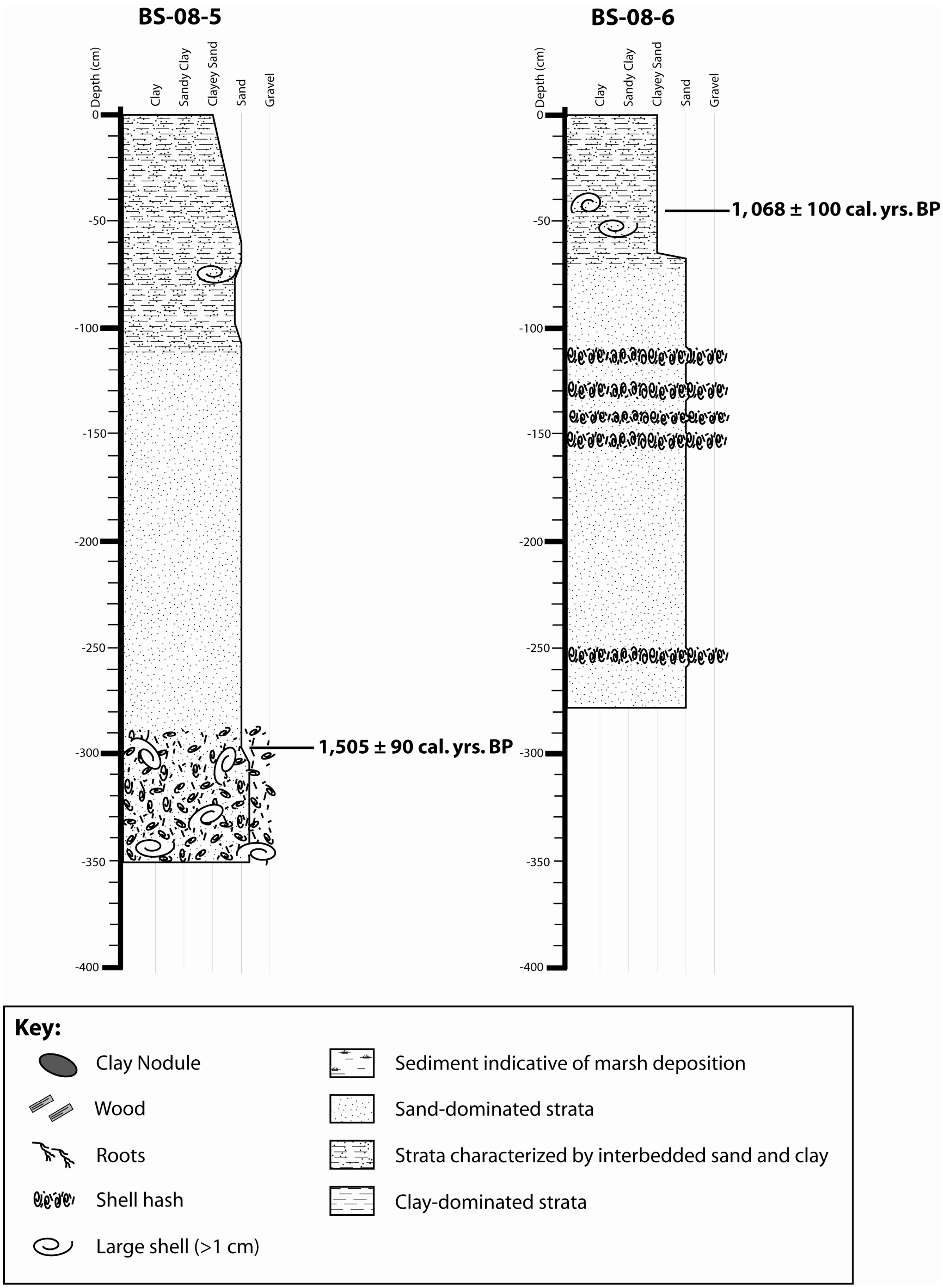
APPENDIX A

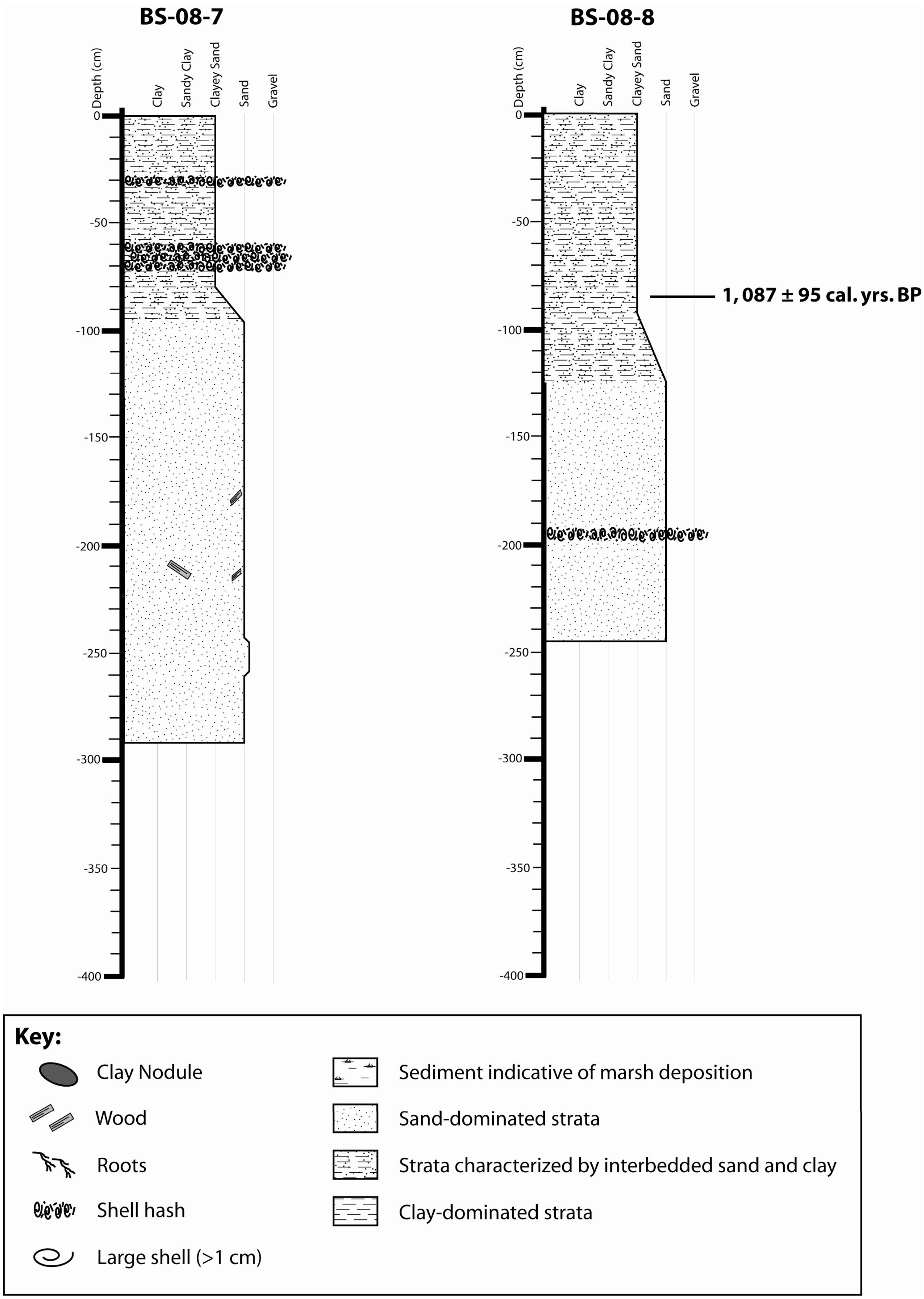
DETAILED CORE DESCRIPTIONS

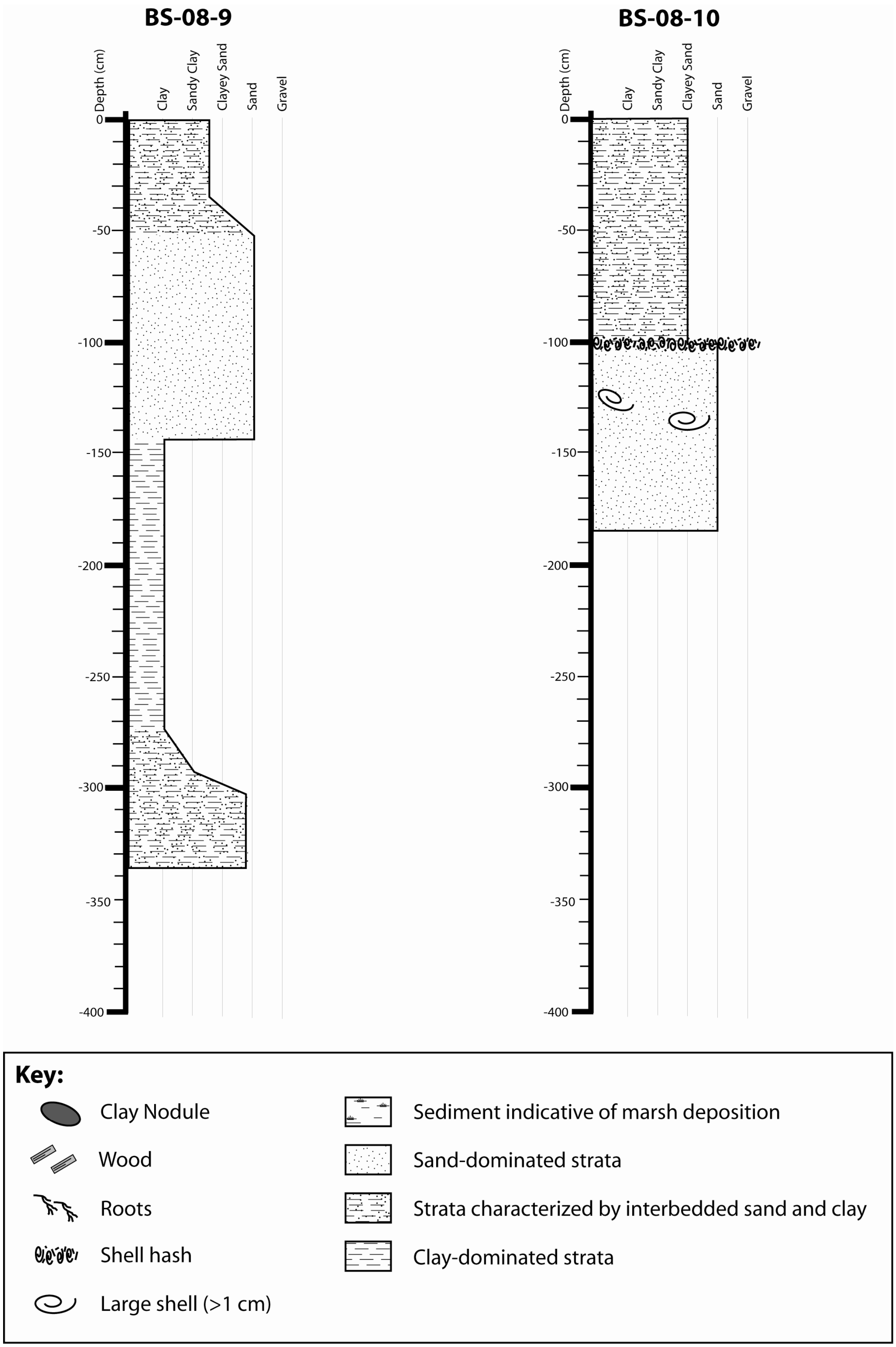


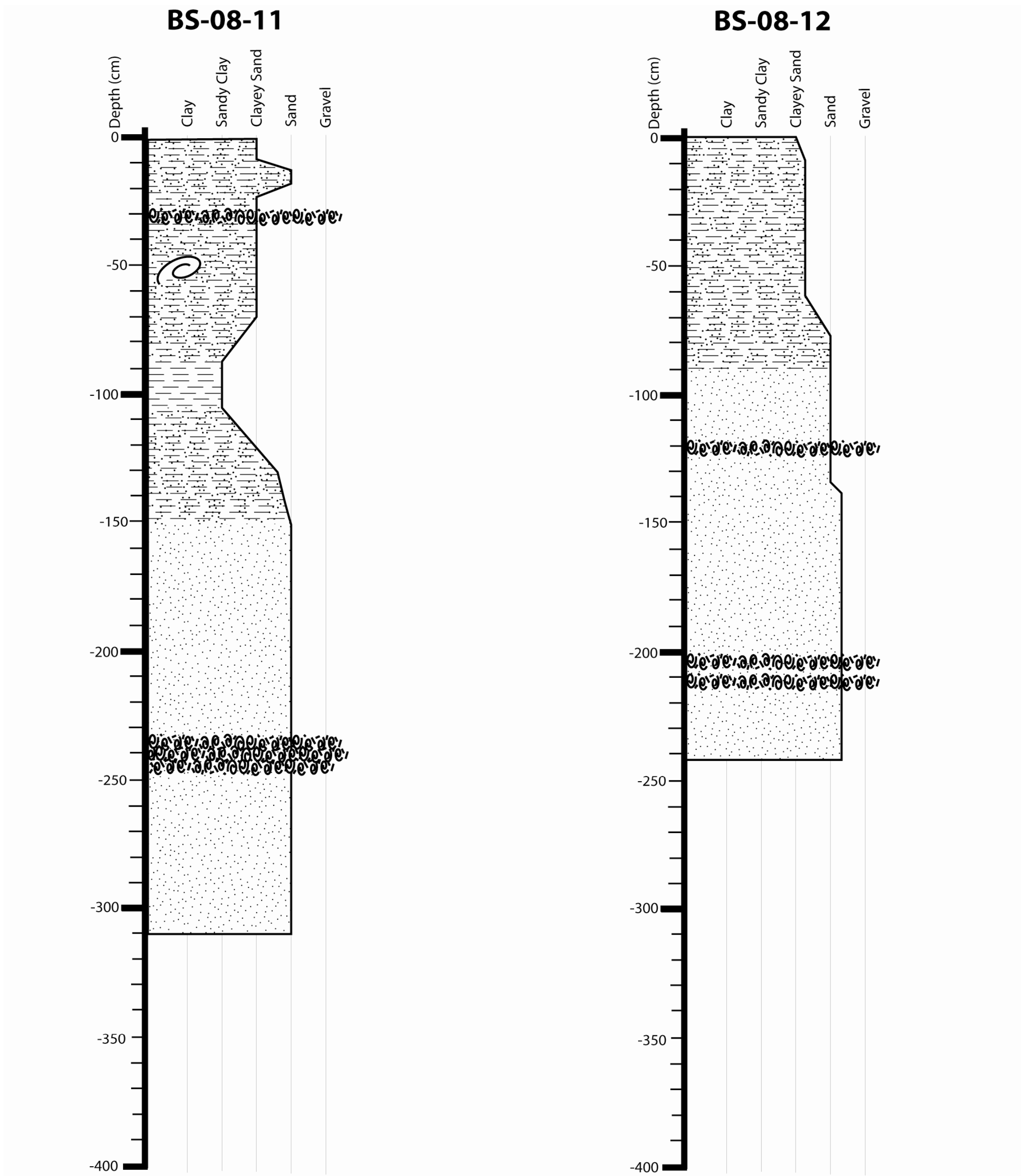
BS-08-1
BS-08-2
Depth (cm)
Clay
Sandy Clay
Clayey Sand
Sand
Gravel
0
-50
-100
-150
-200
-250
-300
-350
-400
920 ± 90 cal. yrs. BP
Key:
Clay Nodule
Wood
Roots
Shell hash
Large shell (>1 cm)
Organic rich
Sediment indicative of marsh deposition
Sand-dominated strata
Strata characterized by interbedded sand and clay
Clay-dominated strata


BS-08-3
BS-08-4
Depth (cm)
Clay
Sandy Clay
Clayey Sand
Sand
Gravel
0
-50
-100
-150
-200
-250
-300
-350
-400
385 ± 80 cal. yrs. BP
2,520 ± 145 cal. yrs. BP
Key:
Clay Nodule
Wood
Roots
Shell hash
Large shell (>1 cm)
Laminae
Cross-bedding
Sediment indicative of marsh deposition
Sand-dominated strata
Strata characterized by interbedded sand and clay
Clay-dominated strata


BS-08-5
BS-08-6
Depth (cm)
Clay
Sandy Clay
Clayey Sand
Sand
Gravel
0
-50
-100
-150
-200
-250
-300
-350
-400
1,505 ± 90 cal. yrs. BP
1, 068 ± 100 cal. yrs. BP
Key:
Clay Nodule
Wood
Roots
Shell hash
Large shell (>1 cm)
Sediment indicative of marsh deposition
Sand-dominated strata
Strata characterized by interbedded sand and clay
Clay-dominated strata

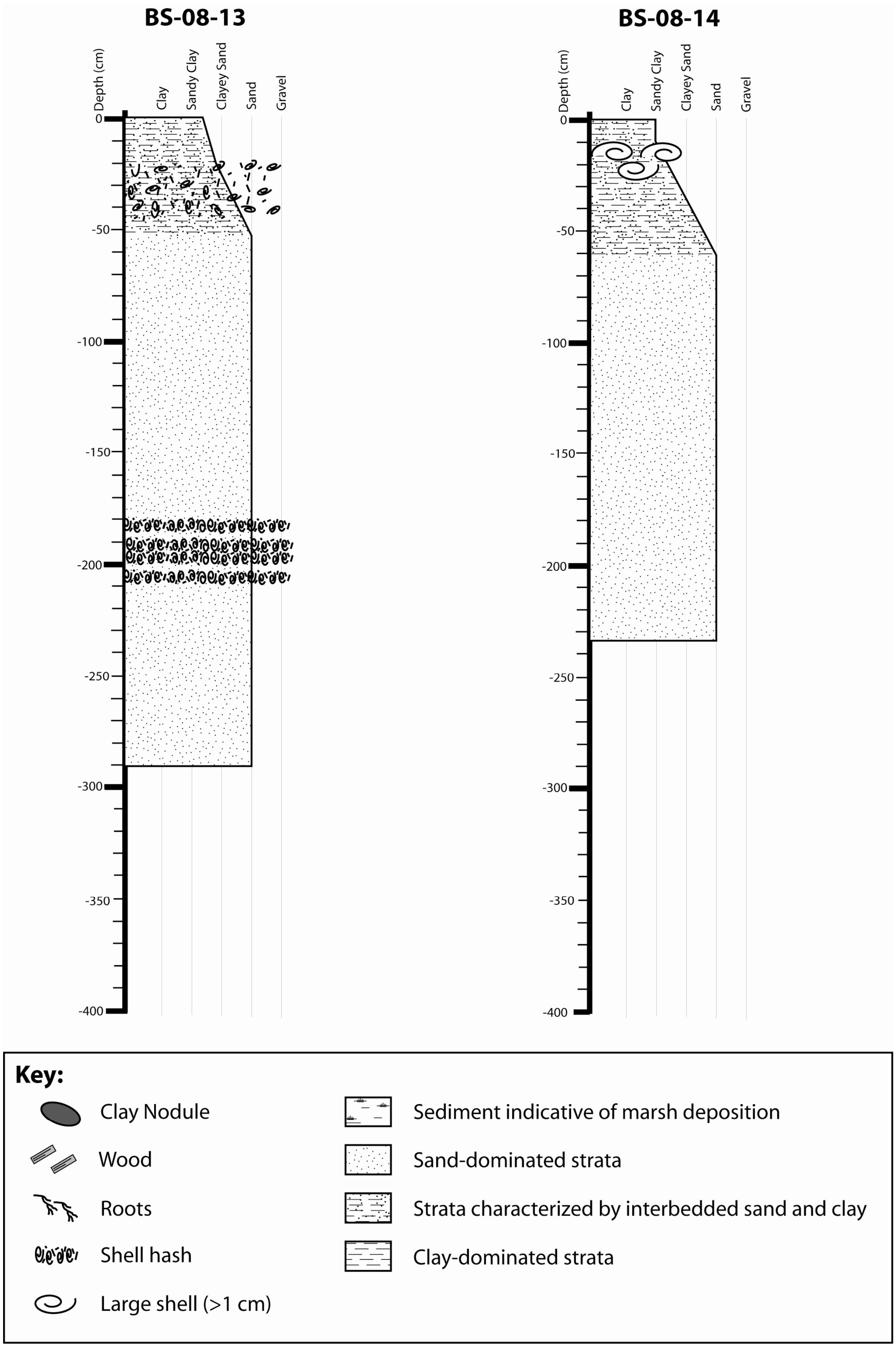

BS-08-7
Depth (cm)
Clay
Sandy Clay
Clayey Sand
Sand
Gravel
0
-50
-100
-150
-200
-250
-300
-350
-400
BS-08-8
Depth (cm)
Clay
Sandy Clay
Clayey Sand
Sand
Gravel
0
-50
-100
-150
-200
-250
-300
-350
-400
1, 087 ± 95 cal. yrs. BP
Key:
Clay Nodule
Wood
Roots
Shell hash
Large shell (>1 cm)
Sediment indicative of marsh deposition
Sand-dominated strata
Strata characterized by interbedded sand and clay
Clay-dominated strata

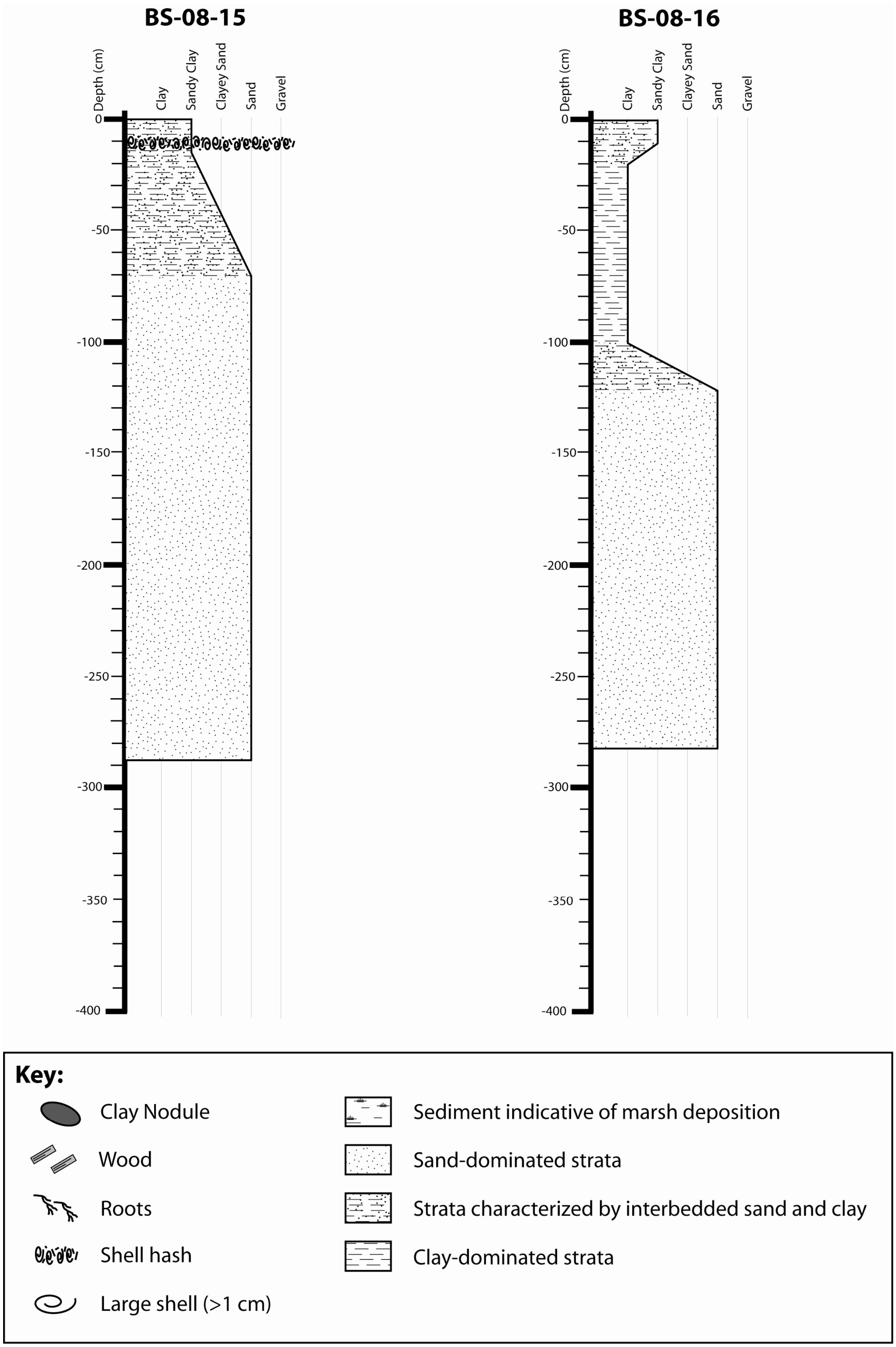

BS-08-9
BS-08-10
Depth (cm)
Clay
Sandy Clay
Clayey Sand
Sand
Gravel
0
-50
-100
-150
-200
-250
-300
-350
-400
Key:
Clay Nodule
Wood
Roots
Shell hash
Large shell (>1 cm)
Sediment indicative of marsh deposition
Sand-dominated strata
Strata characterized by interbedded sand and clay
Clay-dominated strata

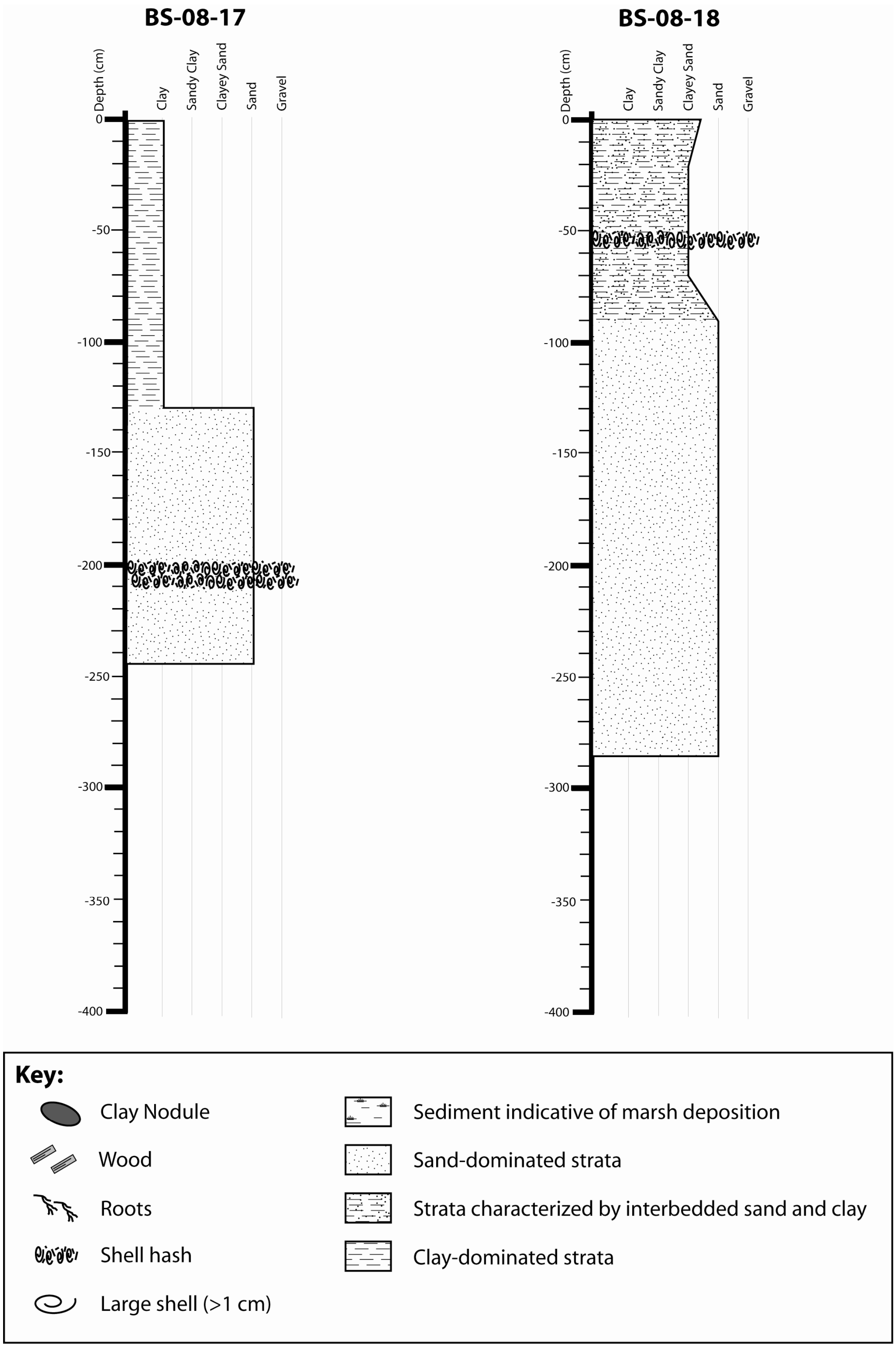


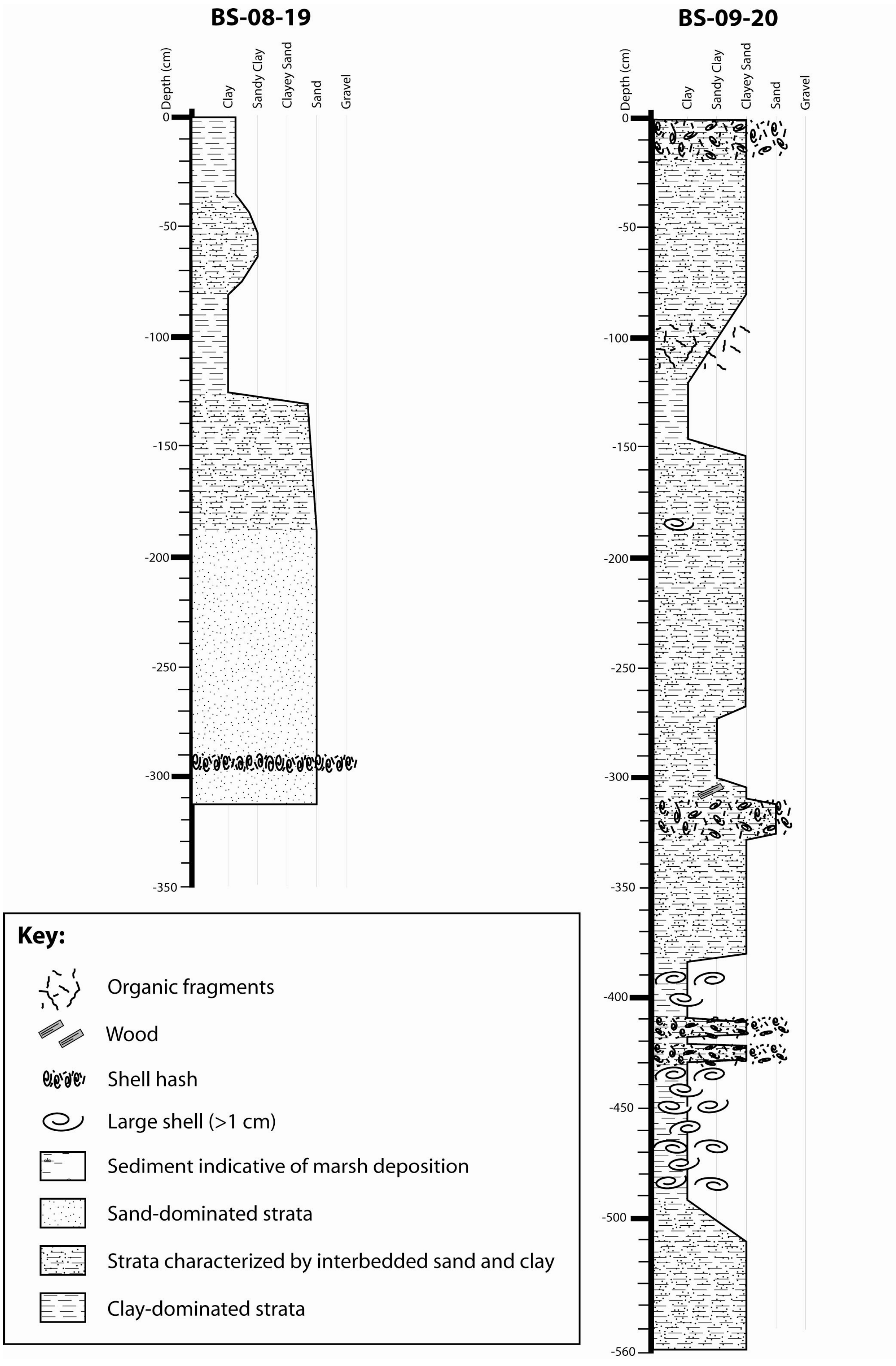
Key:

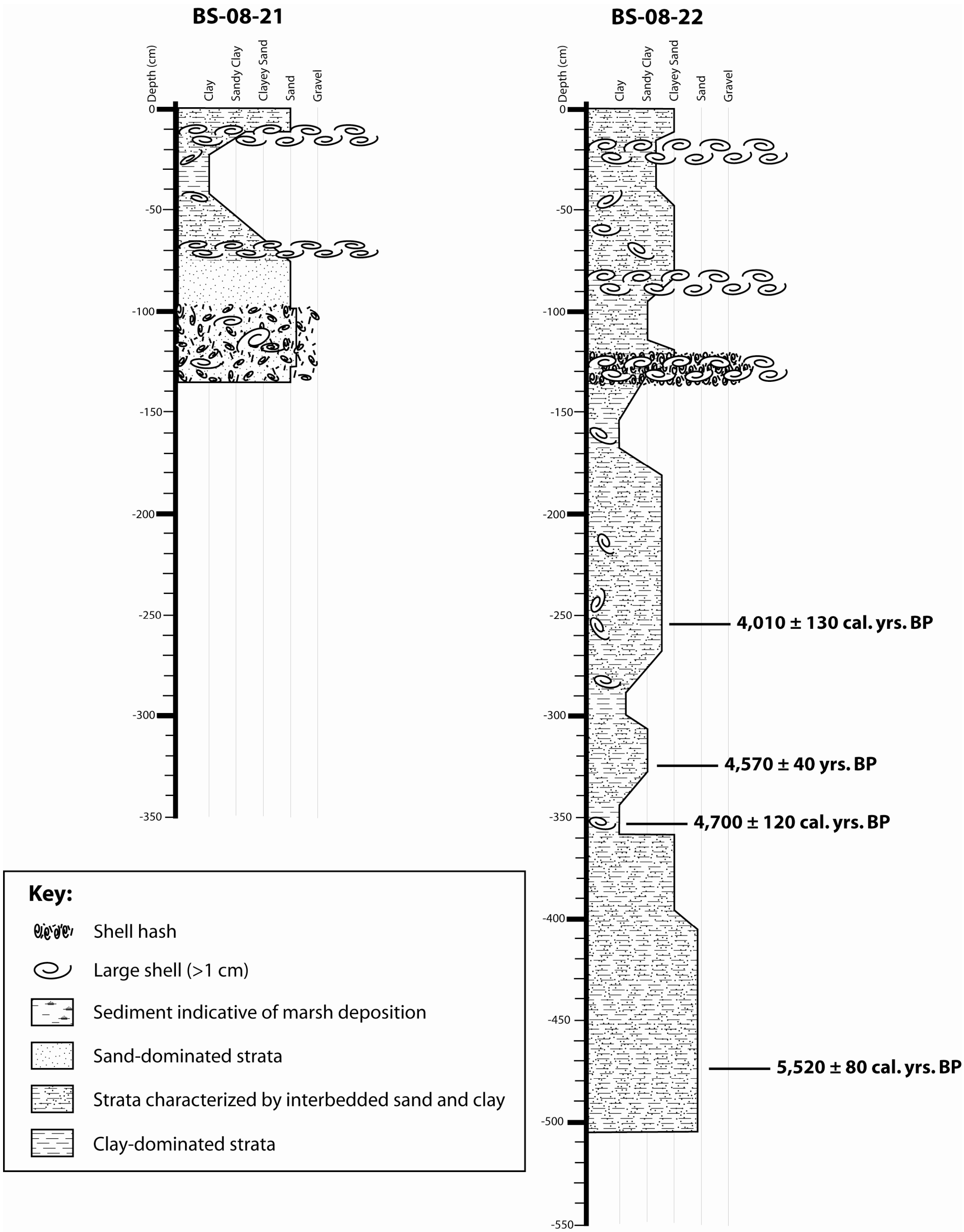
Clay Nodule	Sediment indicative of marsh deposition
Wood	Sand-dominated strata
Roots	Strata characterized by interbedded sand and clay
Shell hash	Clay-dominated strata
Large shell (>1 cm)	


BS-08-13
BS-08-14
Depth (cm)
Clay
Sandy Clay
Clayey Sand
Sand
Gravel
0
-50
-100
-150
-200
-250
-300
-350
-400
Key:
Clay Nodule
Wood
Roots
Shell hash
Large shell (>1 cm)
Sediment indicative of marsh deposition
Sand-dominated strata
Strata characterized by interbedded sand and clay
Clay-dominated strata

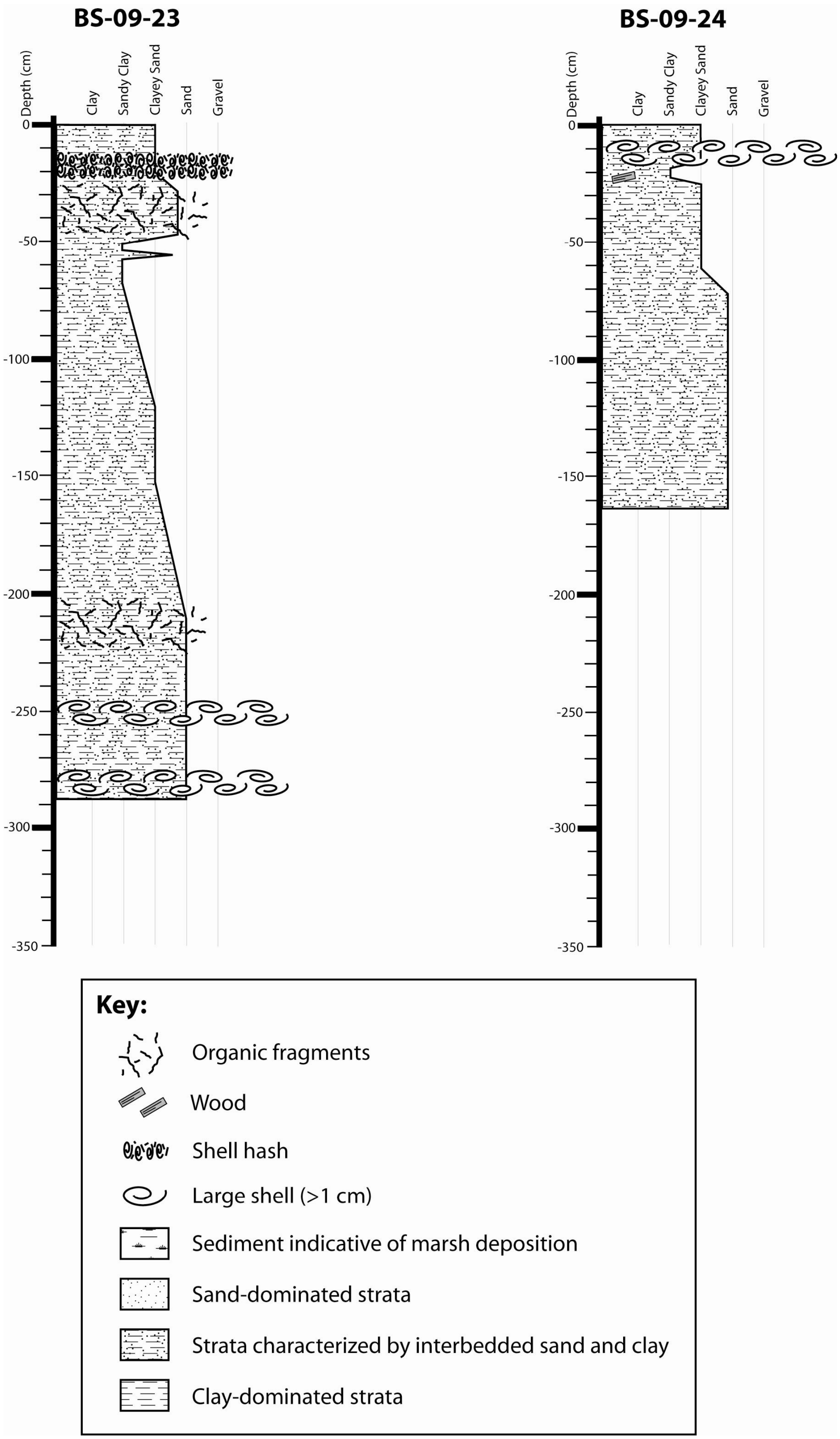

BS-08-15
BS-08-16
Depth (cm)
Clay
Sandy Clay
Clayey Sand
Sand
Gravel
0
-50
-100
-150
-200
-250
-300
-350
-400
Key:
Clay Nodule
Wood
Roots
Shell hash
Large shell (>1 cm)
Sediment indicative of marsh deposition
Sand-dominated strata
Strata characterized by interbedded sand and clay
Clay-dominated strata

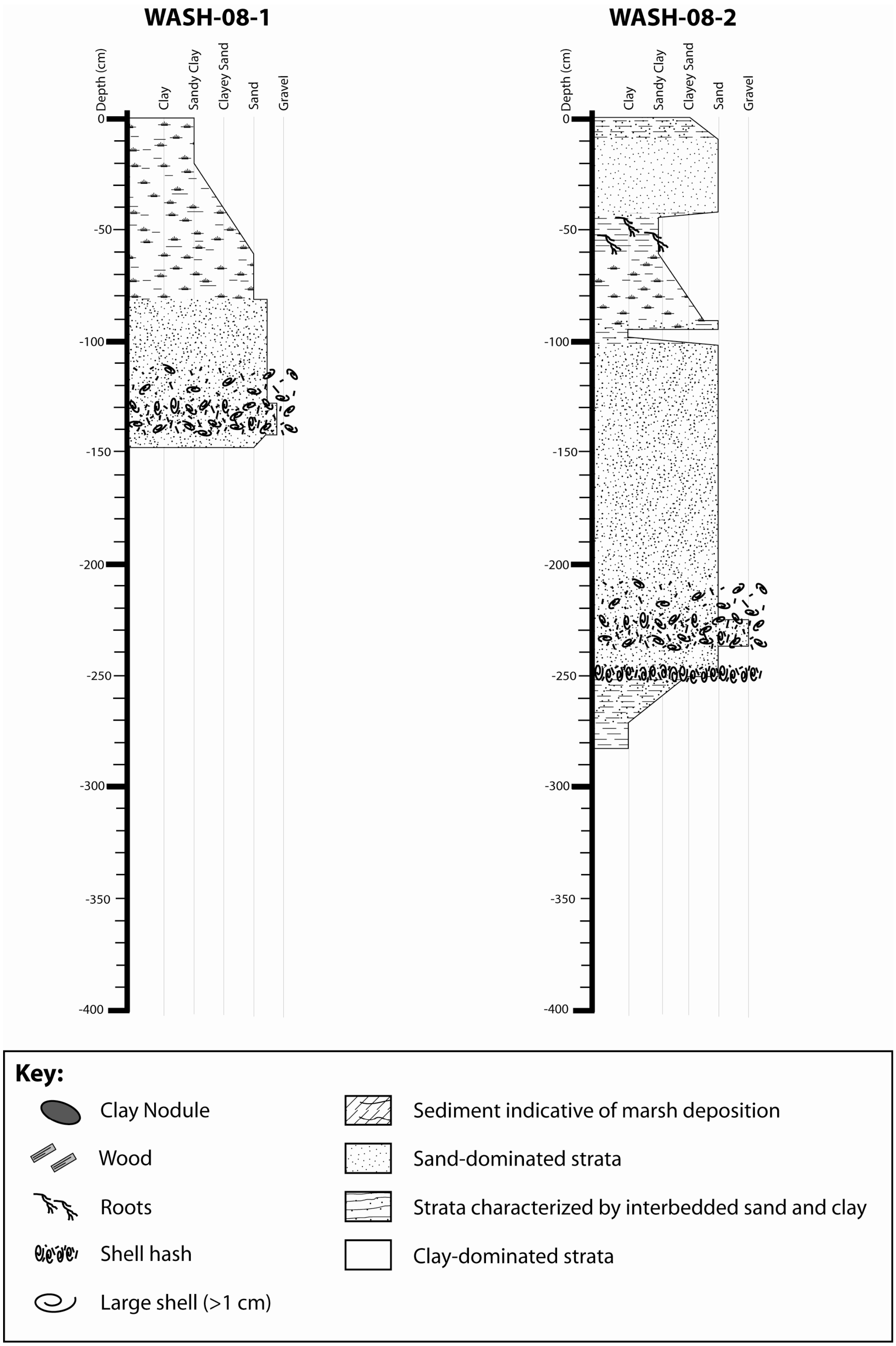

BS-08-17
BS-08-18
Depth (cm)
Clay
Sandy Clay
Clayey Sand
Sand
Gravel
0
-50
-100
-150
-200
-250
-300
-350
-400
Key:
Clay Nodule
Wood
Roots
Shell hash
Large shell (>1 cm)
Sediment indicative of marsh deposition
Sand-dominated strata
Strata characterized by interbedded sand and clay
Clay-dominated strata

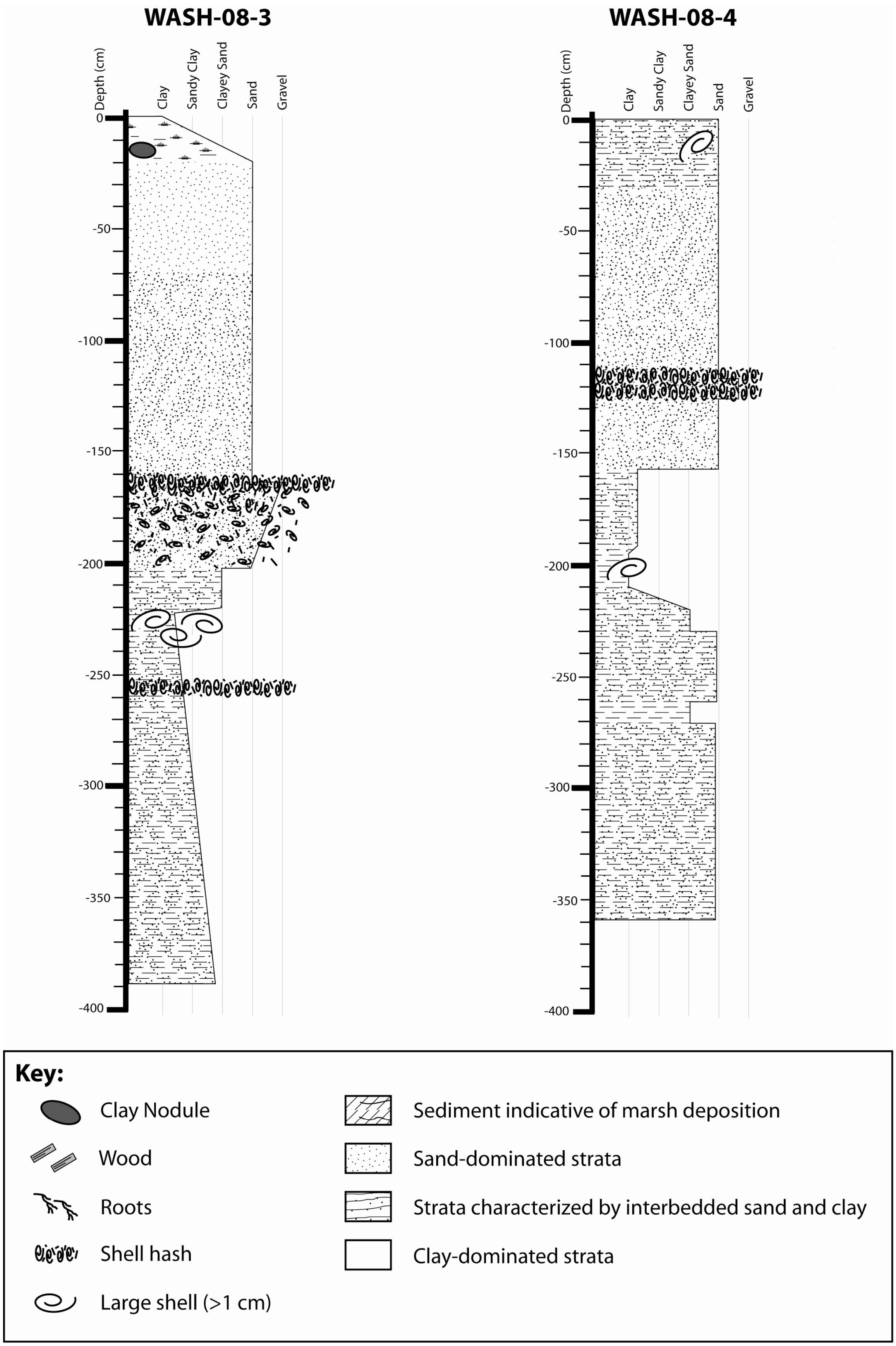

BS-08-19
BS-09-20
Depth (cm)
Clay
Sandy Clay
Clayey Sand
Sand
Gravel
0
-50
-100
-150
-200
-250
-300
-350
-400
-450
-500
-560
Key:
Organic fragments
Wood
Shell hash
Large shell (>1 cm)
Sediment indicative of marsh deposition
Sand-dominated strata
Strata characterized by interbedded sand and clay
Clay-dominated strata



BS-08-21
BS-08-22
Depth (cm)
Clay
Sandy Clay
Clayey Sand
Sand
Gravel
0
-50
-100
-150
-200
-250
-300
-350
-400
-450
-500
-550
4,010 ± 130 cal. yrs. BP
4,570 ± 40 yrs. BP
4,700 ± 120 cal. yrs. BP
5,520 ± 80 cal. yrs. BP
Key:
Shell hash
Large shell (>1 cm)
Sediment indicative of marsh deposition
Sand-dominated strata
Strata characterized by interbedded sand and clay
Clay-dominated strata

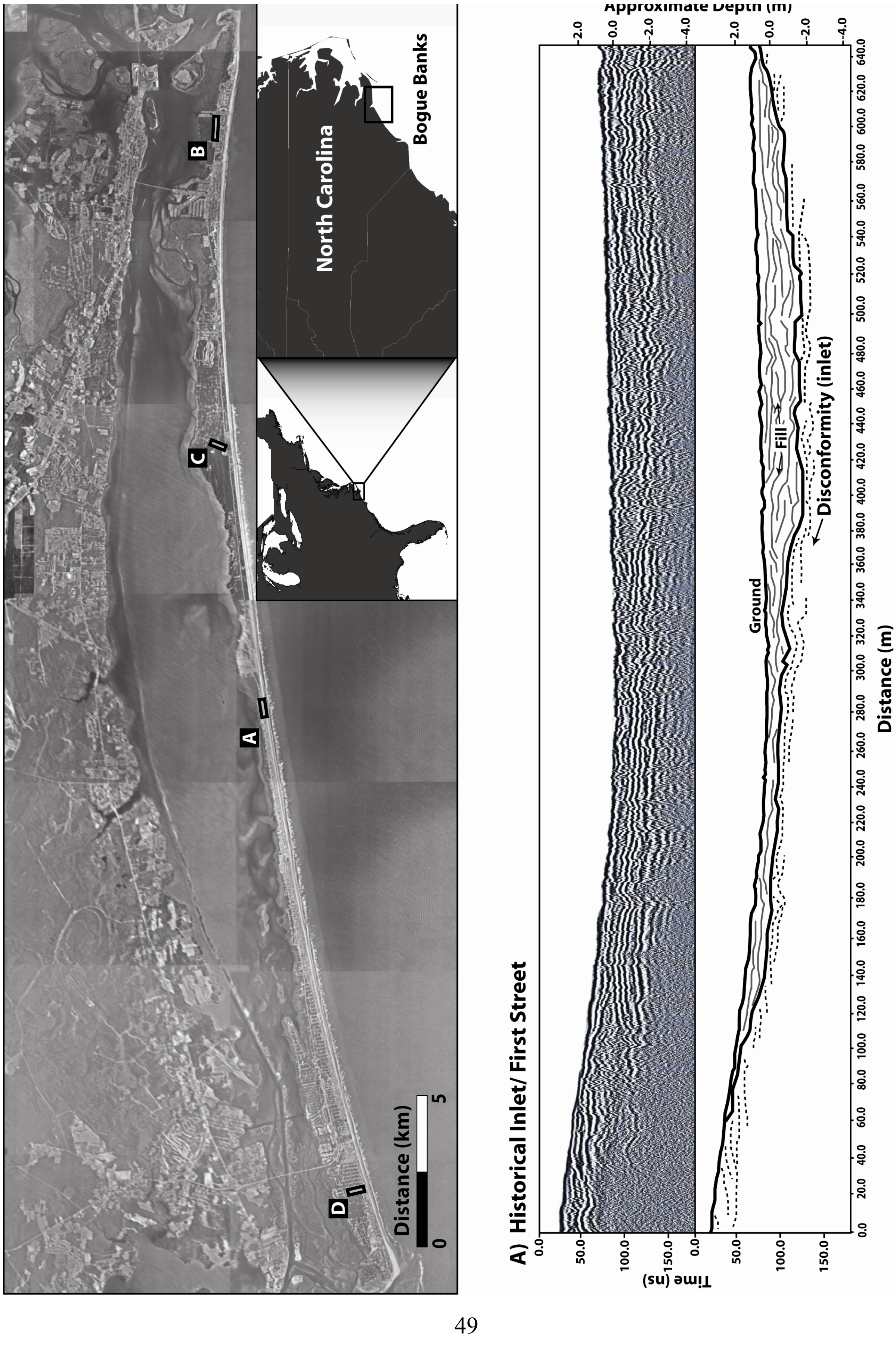

BS-09-23
Depth (cm)
Clay
Sandy Clay
Clayey Sand
Sand
Gravel
0
-50
-100
-150
-200
-250
-300
-350
BS-09-24
Depth (cm)
Clay
Sandy Clay
Clayey Sand
Sand
Gravel
0
-50
-100
-150
-200
-250
-300
-350
Key:
Organic fragments
Wood
Shell hash
Large shell (>1 cm)
Sediment indicative of marsh deposition
Sand-dominated strata
Strata characterized by interbedded sand and clay
Clay-dominated strata


WASH-08-1
WASH-08-2
Depth (cm)
Clay
Sandy Clay
Clayey Sand
Sand
Gravel
0
-50
-100
-150
-200
-250
-300
-350
-400
Key:
Clay Nodule
Wood
Roots
Shell hash
Large shell (>1 cm)
Sediment indicative of marsh deposition
Sand-dominated strata
Strata characterized by interbedded sand and clay
Clay-dominated strata

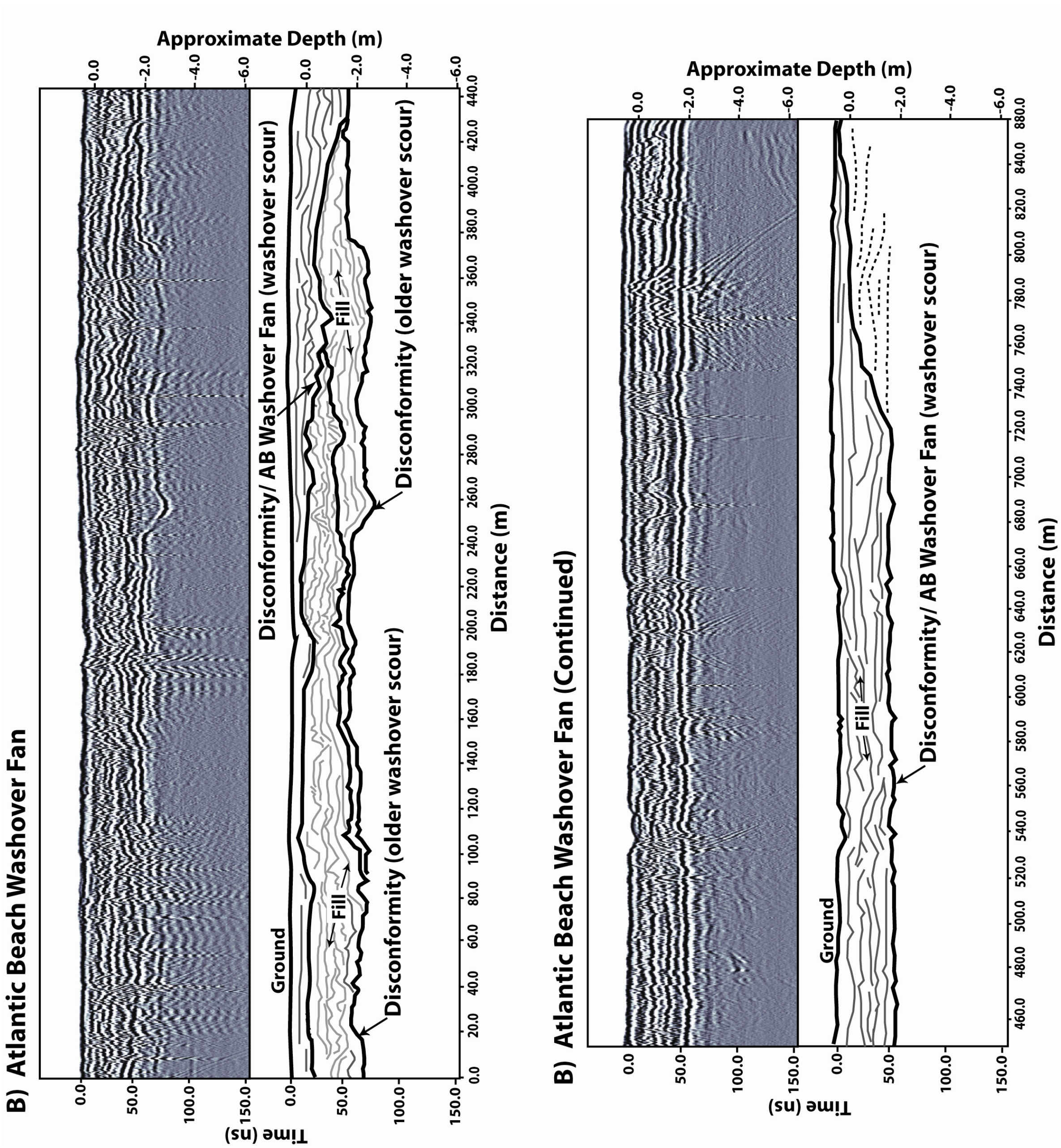

WASH-08-3
Depth (cm)
Clay
Sandy Clay
Clayey Sand
Sand
Gravel
0
-50
-100
-150
-200
-250
-300
-350
-400
WASH-08-4
Depth (cm)
Clay
Sandy Clay
Clayey Sand
Sand
Gravel
0
-50
-100
-150
-200
-250
-300
-350
-400
Key:
Clay Nodule
Wood
Roots
Shell hash
Large shell (>1 cm)
Sediment indicative of marsh deposition
Sand-dominated strata
Strata characterized by interbedded sand and clay
Clay-dominated strata

APPENDIX B

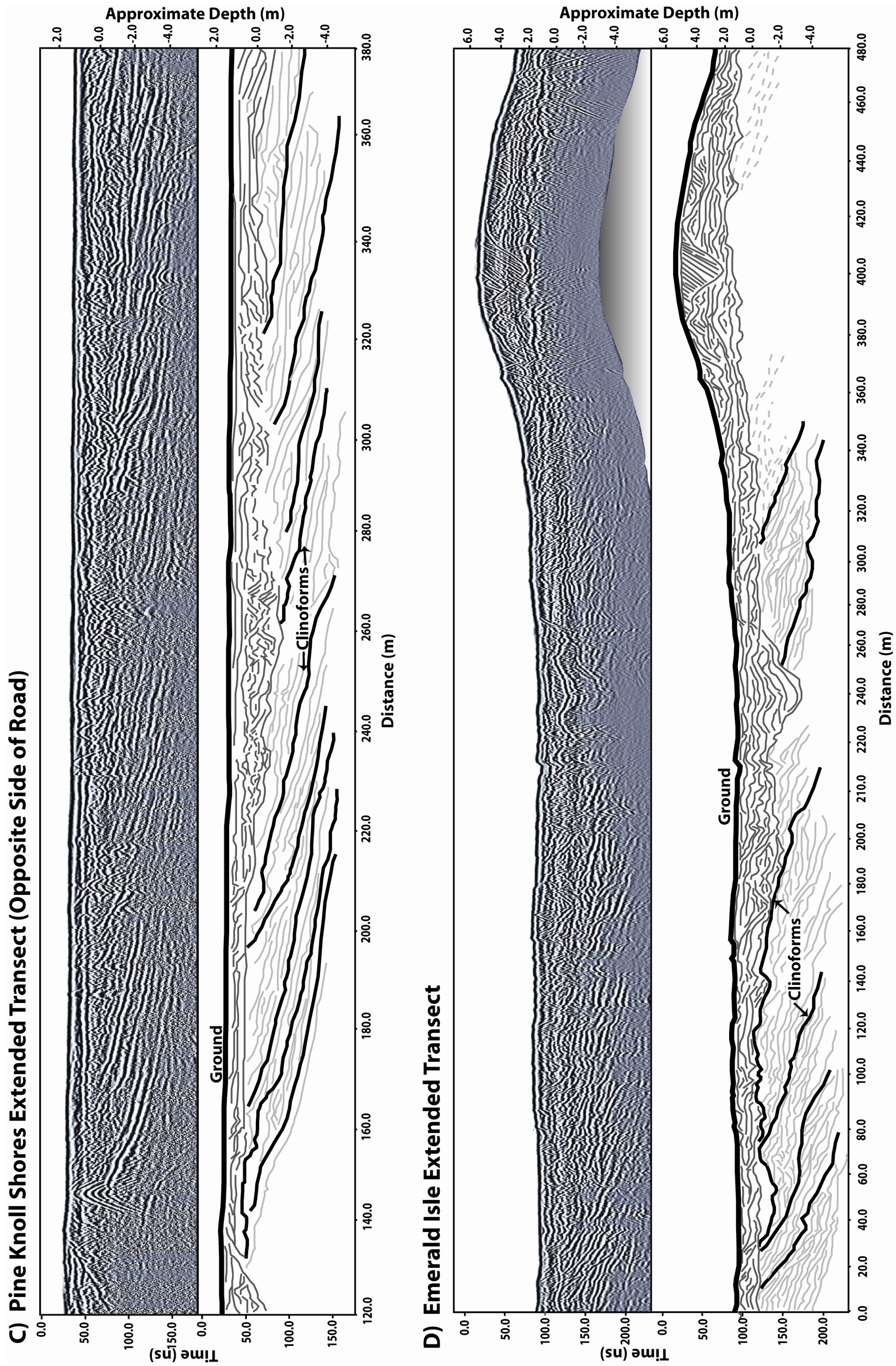
GROUND PENETRATING RADAR



B
C
A
D
Distance (km)
0
5
North Carolina
Bogue Banks
A) Historical Inlet/ First Street
Time (ns)
Approximate Depth (m)
Ground
Fill
Disconformity (inlet)
Distance (m)

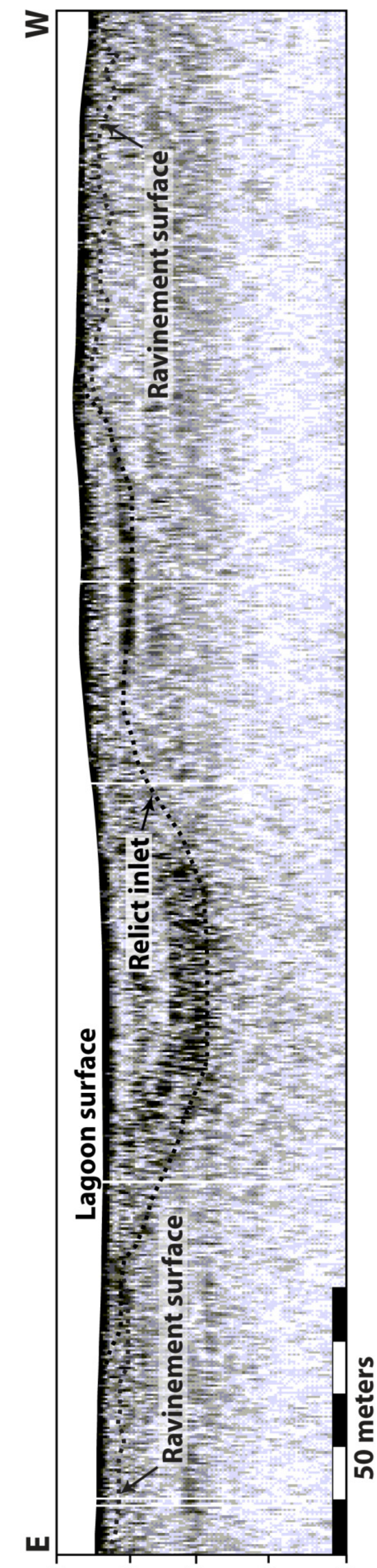


B) Atlantic Beach Washover Fan
Approximate Depth (m)
Time (ns)
Distance (m)
Ground
Fill
Disconformity (older washover scour)
Disconformity/ AB Washover Fan (washover scour)
B) Atlantic Beach Washover Fan (Continued)


C) Pine Knoll Shores Extended Transect (Opposite Side of Road)
Approximate Depth (m)
Time (ns)
Ground
Clinoforms
Distance (m)
D) Emerald Isle Extended Transect
Approximate Depth (m)
Time (ns)
Ground
Clinoforms
Distance (m)

APPENDIX C

CHIRP SEISMIC DATA HISTORICAL INLETS


W
E
Lagoon surface
Ravinement surface
Ravinement surface
Relict inlet
50 meters
Depth (meters)
0
-2
-4
-6
-8

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