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Quaternary depositional patterns and sea-level fluctuations, northeastern North Carolina

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Abstract

A detailed record of late Quaternary sea-level oscillations is preserved within the upper 45 m of deposits along an eight km transect across Croatan Sound, a drowned tributary of the Roanoke/Albemarle drainage system, northeastern North Carolina. Drill-hole and seismic data reveal nine relatively complete sequences filling an antecedent valley comprised of discontinuous middle and early Pleistocene deposits. On interfluves, lithologically similar marine deposits of different sequences occur stacked in vertical succession and separated by ravinement surfaces. Within the paleo-drainage, marine deposits are separated by fluvial and/or estuarine sediments deposited during periods of lowered sea level. Foraminiferal and molluscan fossil assemblages indicate that marine facies were deposited in a shallow-marine embayment with open connection to shelf waters. Each sequence modifies or truncates portions of the preceding sequence or sequences. Sequence boundaries are the product of a combination of fluvial, estuarine, and marine erosional processes. Stratigraphic and age analyses constrain the ages of sequences to late Marine Isotope Stage (MIS) 6 and younger (~140 ka to present), indicating multiple sea-level oscillations during this interval. Elevations of highstand deposits associated with late MIS 5 and MIS 3 imply that sea level was either similar to present during those times, or that the region may have been influenced by glacio-isostatic uplift and subsidence.

Keywords: Late Quaternary; Sea-level record; Northeastern North Carolina; Stratigraphy; Antecedent topography

Introduction

The Mesozoic and Cenozoic deposits of northeastern North Carolina consist of eastward-dipping, seaward-thickening sequences of sediments that form a sedimentary wedge 1.5 to 2.0 km thick (Popenoe, 1985; Klitgord et al., 1988; Riggs et al., 1992). The upper 55 to 60 m of these sediments are Quaternary in age and rest unconformably on the Pliocene Yorktown Formation (Brown et al., 1972; Mallinson et al., 2005). Between the Cape Lookout High to the south and the Norfolk Arch to the north, Quaternary deposits fill a regional depositional basin called the Albemarle Embayment (Ward and Strickland, 1985; Riggs et al., 1995; Foyle and Oertel, 1997) (Fig. 1). The Quaternary section preserved within the Albemarle Embayment is unusually thick for the region. To the north, Quaternary deposits in the Salisbury Embayment of Virginia average 30–35 m in thickness (Foyle and Oertel, 1997). To the south, Quaternary deposits on the Carolina Platform High (Fig. 1) are only preserved as a thin, discontinuous sand prism (Hine and Snyder, 1985). Dissecting the Albemarle Embayment are a series of Quaternary fluvial valleys filled with younger coastal and shelf sediments separated laterally by older stratigraphic units that compose the interfluves (Riggs et al., 1995).

Located within the modern coastal system of northeastern North Carolina, Croatan Sound and Roanoke Sound (Fig. 1) represent two drowned lateral tributaries that flowed northwards to the paleo-Roanoke River (now Albemarle Sound) (Riggs et al., 1992). Roanoke Island is a remnant of the

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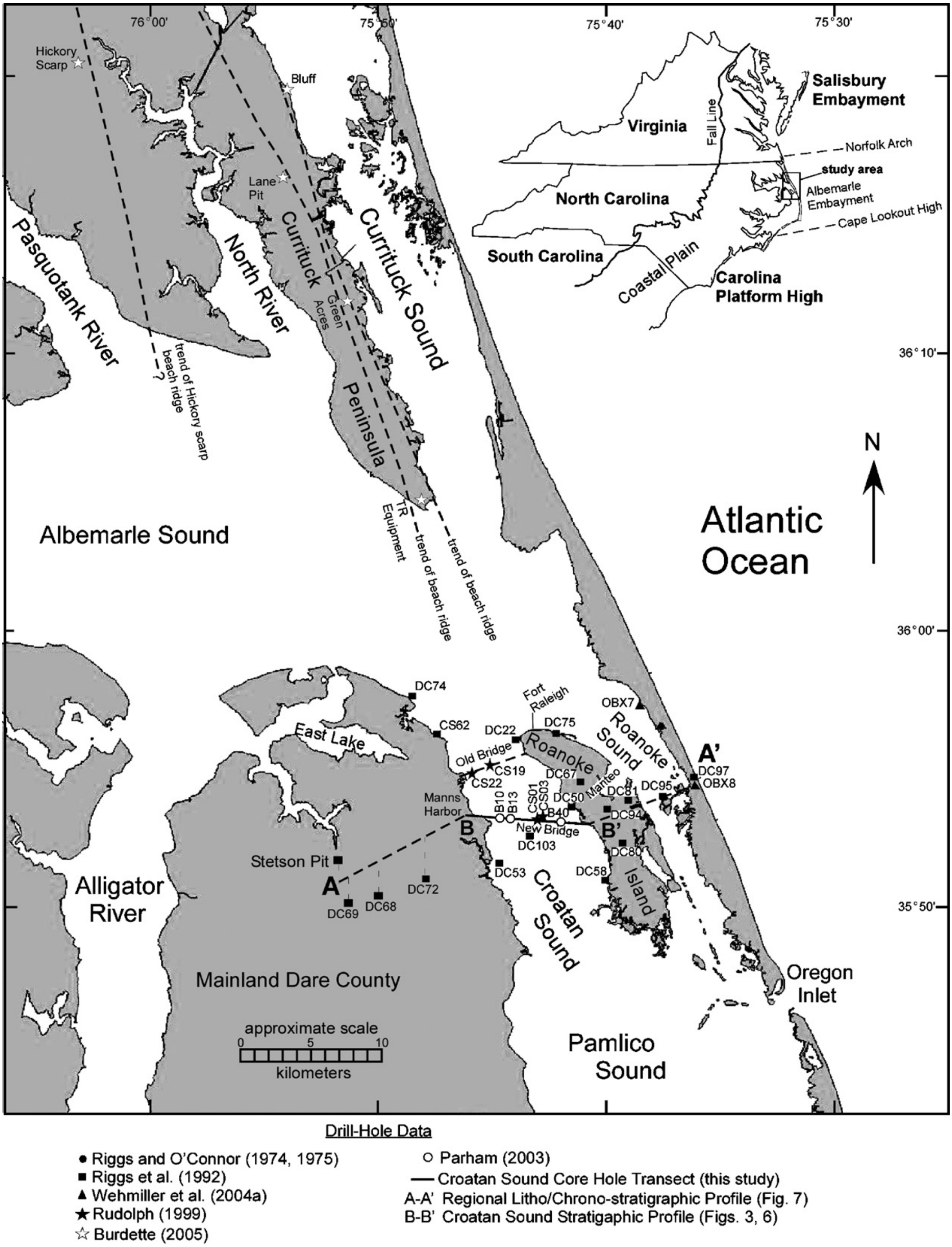

Figure 1. Map of the Croatan Sound study area, northeastern North Carolina, shows the drill hole and outcrop locations containing age data used in this study, the trends of Currituck beach ridges, the location of the Croatan Sound drill hole transect B–B′ (Fig. 2), and the location of regional litho- and chronostratigraphic cross sections A–A′ (Figs. 8 and 9).

interstream divide that separated these two drainages. Croatan Sound is the major outlet to Pamlico Sound and the Atlantic Ocean for the Roanoke/Albemarle drainage system. It ranges in width from 4.2 km to 8 km and averages 5 m in depth, with depths up to 7.5 m in the NW–SE trending channel (Eames, 1983; Riggs et al., 1992).

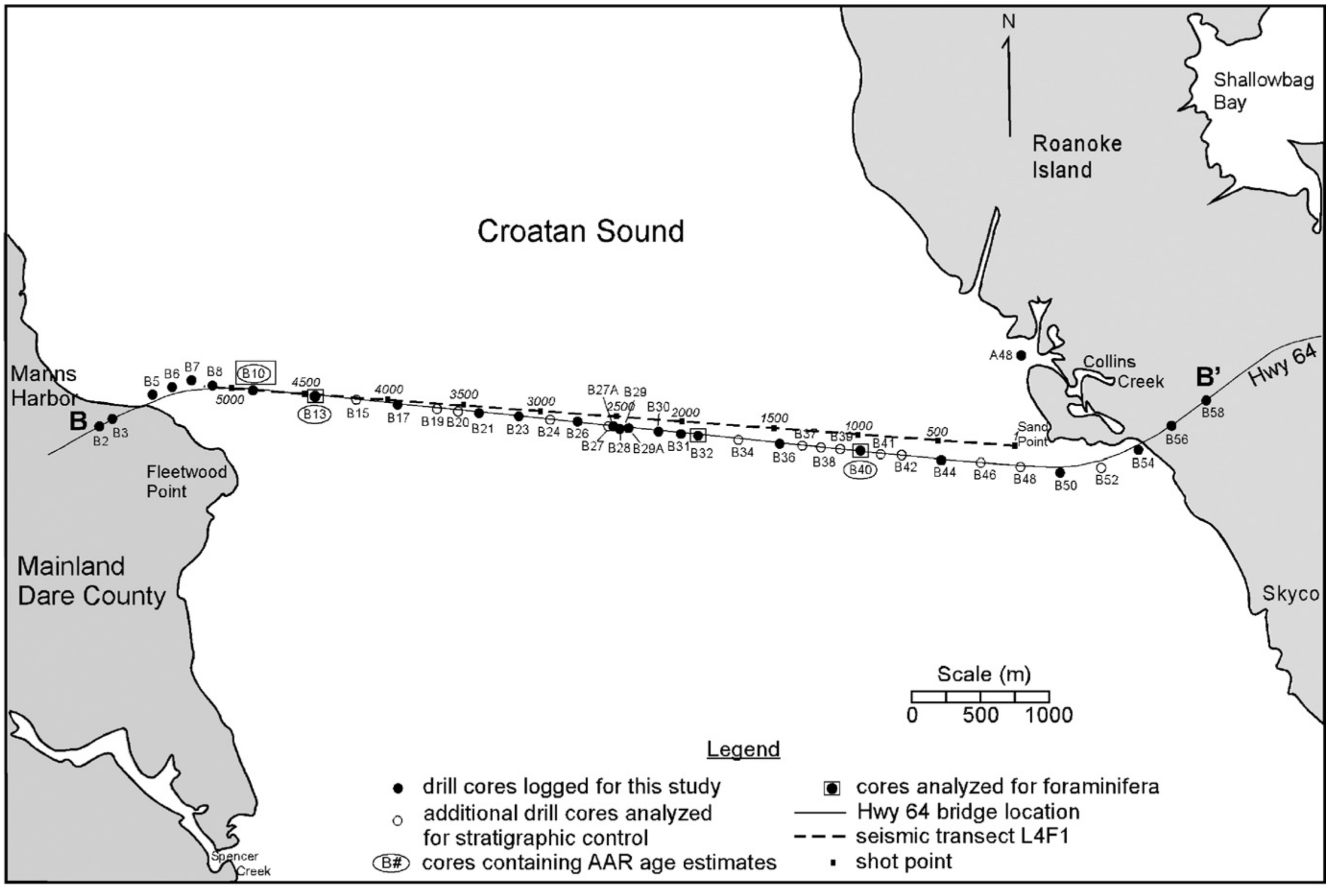

Figure 2. Map of Croatan Sound shows drill hole transect (B–B′) and seismic transect L4F1 surveyed by the USGS in 2001.

The database on the Quaternary section of northeastern North Carolina is fairly extensive and includes numerous drill-hole records, biostratigraphic data, seismic data, and numerical age estimates based on amino-acid racemization (AAR), U-series disequilibrium, optically stimulated luminescence (OSL), and radiocarbon techniques. Based on much of these data, Riggs et al. (1992) recognized seven Quaternary sequences within the upper 33 m of deposits underlying the Croatan and Pamlico Sound regions. More recently, Mallinson et al. (2005) identified 18 seismic sequences within the 55–60 m Quaternary section underlying eastern Albemarle Sound.

The present study of closely spaced drill-holes extending across Croatan Sound (Fig. 2), in concert with high-resolution seismic, chronologic, and biostratigraphic data, provides resolution sufficient to distinguish between Quaternary sea-level events and allows a better understanding of the influence of antecedent topography on Quaternary depositional systems in a coastal setting. This paper describes the depositional patterns resulting from these multiple late Quaternary sea-level oscillations as they are expressed in a tributary estuarine system and builds a geologic history for the region in the context of sea-level cycles. This paper also demonstrates that coastal stratigraphic records can enhance our understanding of Quaternary environmental change by providing an additional line of evidence to test the detailed information gleaned from the more continuous deep-sea sediment and ice-core records.

Methods

Forty test borings were taken along a west-to-east line from Manns Harbor/Spencer Creek on the Dare County mainland to Collins Creek on Roanoke Island (B–B′ in Figs. 1 and 2) (S and ME, 1997). Drill-hole penetration averaged between 40 m to 45 m below MSL. Split-spoon sediment samples, approximately 10 cm in length, were recovered from each hole at about 1.5 m intervals. Twenty-seven drill-cores (Fig. 2) were selected for detailed sediment analysis. The remaining 13 cores were utilized for stratigraphic correlation. Standard Penetration Test (SPT) blow-count records (S and ME, 1997) for each drill-hole aided in determining the depth of lithologic changes.

Cores were analyzed and logged both macroscopically and microscopically. Color, texture, grain size, and mineralogy were determined using Folk's (1974) protocol. Digitized core logs were plotted along the B–B′ transect (Fig. 2) in order to produce a lithologic cross-section of Croatan Sound.

Both macro- and micro-fossils were described, identified, and used as indicators of depositional environments. Twenty-three samples representing seven lithofacies from drill-holes B13, B32, and B40 were sub-sampled for benthic foraminifera.

Foraminiferal assemblages were defined by cluster analysis using Euclidian distance coefficients and Ward's linkage method (Mello and Buzas, 1968).

Table 1
Summary of age data from the Croatan sound region

Location	Sample/ core	Depth (m)	Sample material	Estimated age (ka)	Depositional sequence
Croatan sound[a]	B10	14.5–14.9	*Mulinia*	180–80	CDS5
		34.3–34.7	*Mercenaria*	1200–700	CDS12
	B13	16.2–16.5	*Mulinia*	180–80	CDS5
	B40	20.8–21.2	*Mulinia*	180–80	CDS6
		42.2–42.6	*Mercenaria*	220–180	CDS10
Stetson pit, Dare county[b]	8–2	7.2–11.2	*Mercenaria*	180–80	CDS5 or 6
	8–3	13.0–14.2	*Mercenaria*	550–220	CDS11?
	8–4	17.6–33.0	*Mercenaria*	1200–700	CDS12
Dare county mainland[b]	DC69	8.0–12.3	*Mulinia*	550–220	CDS11?
	DC69	14.6–15.2	*Mulinia*	550–220	CDS11?
Caroon point[b]	DC74	9.8–12.6	*Mulinia*	180–80	CDS5 or 6
Ft. Raleigh Roanoke Is.[b]	DC75	8.0–12.3	*Mulinia*	180–80	CDS5 or 6
Manteo[b]	DC67	8.0–12.3	*Mulinia*	78–51	CDS4
Central Roanoke Is.[b]	DC80	8.6–10.6	*Mulinia*	78–51	CDS4
Whalebone Junction[b]	OBX8	21.3	*Mercenaria*	180–80	CDS5 or 6
	OBX8	34.8	*Mercenaria*	550–220	CDS11?
Nags head[b]	OBX7	31.6	*Mercenaria*	550–220	CDS11?
New bridge Croatan Snd.[c]	CS01	7.8–7.9	*Crassostrea*	4.628±0.21	CDS1
		10.0–10.1	*Cryptopleura*	6.015±0.11	CDS1
	CS03	9.1–9.2	*Cryptopleura*	4.658±0.15	CDS1
Old bridge Croatan Snd.[d]	CS19	7.4–7.5	ORM	>38	CDS3 or 4
	CS22	4.9–4.95	*Mercenaria*	>39.9	CDS3 or 4
Reeds Pt. NW Croatan Snd.[d]	CS62	8.5–9.1	*Mulinia*	>30.6	CDS4 or 5
Ft. Raleigh Roanoke Is.[d]	CS75	2.7–3.1	bivalve	>40	CDS2 or 4
	CS75	6.0–6.1	*Mulinia*	>35.5	CDS2 or 4
	CS75	9.4–9.7	*Mulinia*	>32.3	CDS5
	CS75	12.5–12.7	*Mulinia*	>37	CDS5
Fort Raleigh, Roanoke Is.[e]	RI-3	+0.05	quartz sand	55.3±7.2	CDS2
Currituck Peninsula[e]	Bluff	+0.8	quartz sand	51.7±7.8	CDS2?
	Lane Pit	+0.3	quartz sand	59.6±10.2	CDS3?
	Green Acres	−2.1	quartz sand	50.6±7.3	CDS2?
	Green Acres	−3.4	quartz sand	54.9±6.3	CDS2?
	TR Equip.	−4.1	quartz sand	45.2±5.6	CDS2?

Notes. Depths indicated are below mean sea level (MSL); ORM—organic rich mud; core numbers prefixed by DC were instead prefixed by CS in York (1990) and Riggs et al. (1992); see York (1990) for detailed AAR data for Stetson Pit.

[a] Amino-acid racemization (AAR) age estimates (this study).

[b] AAR age estimates (York et al., 1989; York, 1990; Riggs et al., 1992; Wehmiller et al., 2004a).

[c] Calibrated radiocarbon (cal yr BP) age estimates (Rudolph, 1999; Riggs et al., 2000).

[d] Uncalibrated radiocarbon (^{14}C yr BP) age estimates (Riggs and O'Conner, 1974; Riggs and O'Connor, 1975).

[e] Optically stimulated luminescence (OSL) age estimates (Burdette, 2005; Mallinson, personal communication, 2006).

Mollusk shells from five depths were collected from three drill holes for amino acid racemization (AAR) age estimation. In principle, increasing extent of racemization (increasing D/L ratios) is a measure of sample age, although geochemical and taphonomic factors can influence these interpretations. Whole *Mulinia* valves and *Mercenaria* fragments were analyzed by gas chromatography (Wehmiller and Miller, 2000) to obtain D/L values for as many as seven amino acids. At least three chromatograms were obtained for each specimen. *Mercenaria* shells are more robust than the *Mulinia* shells, hence the *Mercenaria* data are considered to be more reliable. However, the *Mulinia* results obtained here are consistent with those obtained for *Mercenaria*.

The independent radiometric control, upon which AAR age determination in the eastern Dare County region is based, is a U-series date (from a coral sample) of 72,000±4000 yr (Szabo, 1985) for the Stetson Pit locality (Fig. 1). D/L ratios of specimens from the Croatan Sound study site were compared with D/L ratios from other sites in Dare County (Fig. 1) with established aminozones. Thus, age range estimates for the Croatan Sound specimens are based on their relationship with the D/L values of mollusks from established aminozones.

High-resolution, single-channel seismic data for Croatan Sound were acquired in 2001 aboard the USGS R/V Rafael utilizing a Geopulse Uniboom sled and ITI streamer, and Triton ISIS software (Mallinson et al., 2005). Seismic line L4F1 of this survey is coincident with the Croatan Sound drill-hole transect from drill holes B8 to B46 (Fig. 2).

Drill-hole data from several localities and previous studies were synthesized to establish regional chronologic control (Table 1). Figure 1 indicates the drill-hole locations in Dare County where AAR age estimates (York, 1990; Riggs et al., 1992; Wehmiller et al., 2004a; Parham, 2003), and radiocarbon age estimates (Riggs and O'Conner, 1974; Riggs and O'Connor, 1975; Rudolph, 1999) were obtained as well as outcrop locations where samples for OSL age analysis were collected (Burdette, 2005).

Stratigraphy

Characterization of lithofacies

Cross-section B–B′ (Figs. 2, 3) is based upon core data and seismic profiles and depicts Pleistocene and Holocene lithostratigraphic units recognized in Croatan Sound deposits. An idealized trangressive sequence displays a vertical succession of four facies (Fig. 4). (1) The fluvial/non-marine facies (FF) is associated with periods of emergence and is characterized by soil development and subaerial erosion of uplands with concurrent deposition of a spectrum of terrigenous sediments along stream valleys. (2) The estuarine facies (EF) is produced by gradual flooding of stream valleys, resulting in deposition of muds in deeper channel areas and of shoreline erosion-derived sands on shallower interfluve areas (Riggs and Ames, 2003). (3) Barrier island deposits (BI) form as the transitory leading edge of the marine realm. As transgression continues, shoreface erosion largely removes or translates landward BI deposits and partially

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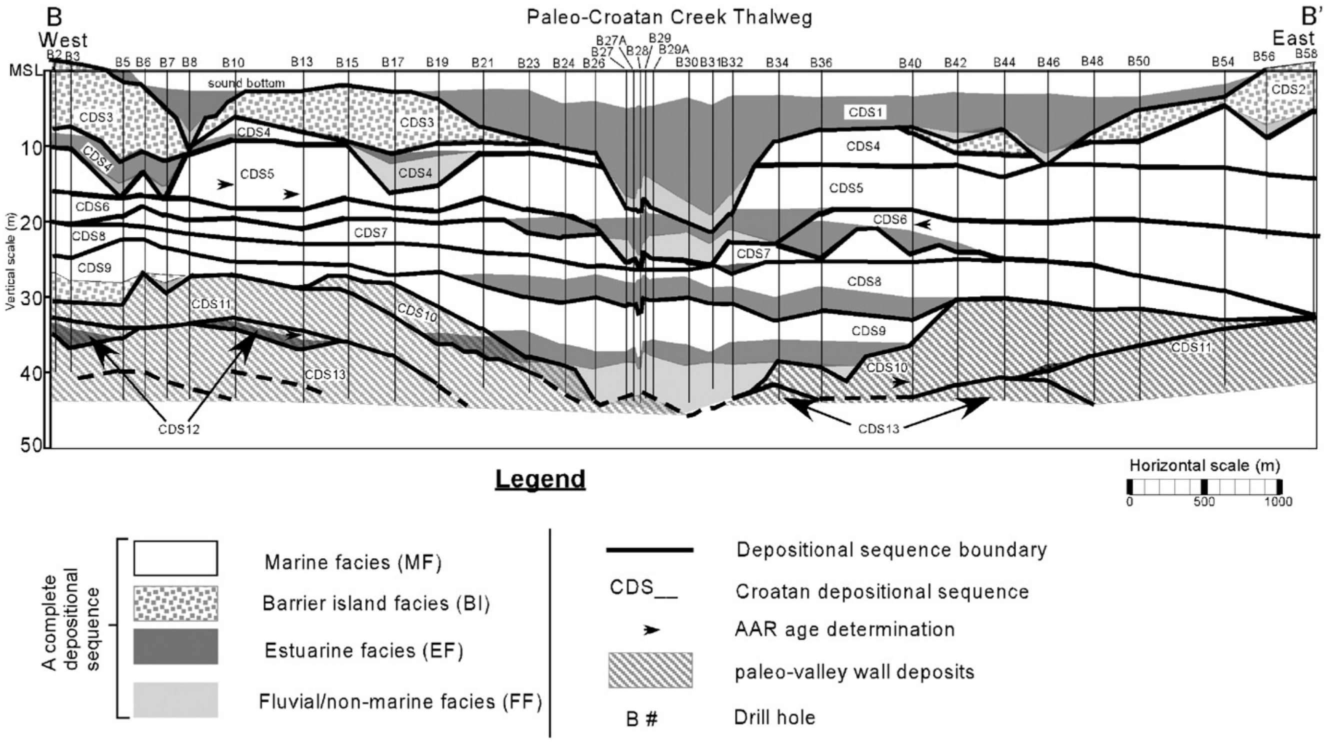


Figure 3. A west-to-east geologic cross section (B–B′) of the drill hole transect across Croatan Sound shows Croatan depositional sequences (CDS) with major depositional facies. Deposits composing the major paleo-valley walls are illustrated by cross-hatching. Drill hole locations and depths are indicated by vertical lines with corresponding numbers along the upper margin.

truncates FF and EF. (4) The ravinement surface (Nummedal and Swift, 1987) produced becomes overlain by the fining upward marine facies (MF). Each succeeding depositional sequence erodes and truncates portions of the preceding sequence or sequences. The result is a stacked series of similar marine deposits on the interfluves that become separated by non-marine and/or estuarine channel deposits in the paleo-valleys (Fig. 3). All four facies of a complete transgressive sequence are only recognized in Croatan Depositional Sequence (CDS) 9 (Fig. 3).

Seismic stratigraphy

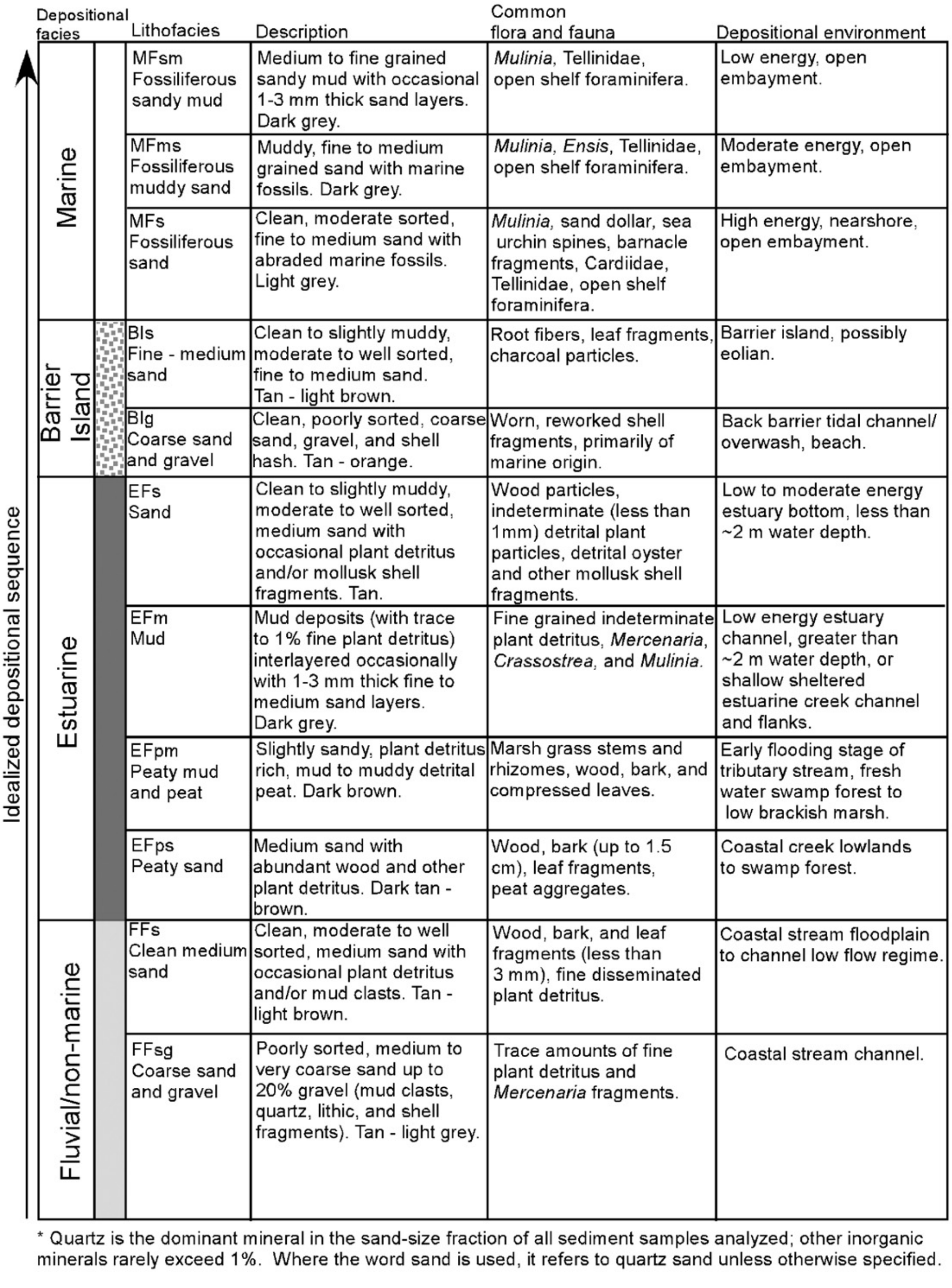
In seismic profile L4F1 (Figs. 2, 5), reflections representing sequence boundaries or abrupt contacts between major lithofacies match well with the lithologic database (Fig. 3). The overall trend of seismic reflections in the upper portion of the section indicates that strata are dipping gently eastward. Concave-up reflections in the lower portion of the section suggest that those deposits conform to the paleo-Croatan Valley profile. Seismic data attenuations in the central thalweg portion of the transect are interpreted to represent the presence of thick accumulations of gaseous organic-rich mud in the Holocene channel (Fig. 5). The overall trend indicates that an antecedent topographic high underlies the Dare County mainland approximately 30 to 35 m beneath the western shoreline of Croatan Sound (Figs 3, 5). Seismic reflection trends and the occurrence of iron-oxidized deposits in drill-holes B34 and B42 through B46 (41 to 44 m below MSL) suggest that a similar antecedent topographic high underlies Roanoke Island (Figs. 3, 5).

Biostratigraphy

Foraminiferal assemblages

Foraminifera were present in most MF deposits. Detailed analysis was performed on fourteen samples from drill-holes B13 and B40. Fifty-one species of foraminifera were identified. Cluster analysis produced three foraminiferal assemblages (Appendix A). Most species within the three assemblages are associated with open-inner continental shelf conditions as recorded by Wilcoxon (1964), Murray (1969), Schnitker (1971), Kafescioglu (1975), Culver and Buzas (1980), and Workman (1981). Some species also occur in a variety of marginal marine communities (e.g., Miller, 1953; Grossman, 1967). Assemblages differ from one another in the number of species per sample and, to a lesser degree, in the total number of foraminiferal specimens per sample (Appendix A). These differences probably result from slight variations in environmental conditions similar to those that occur on the inner shelf today (Schnitker, 1971). The low slope geometry of MF deposits together with the foraminiferal assemblages suggest that the environment of deposition was a shallow, open, normal-salinity embayment. However, one assemblage (assemblage 3, Appendix A) suggests the possibility of deposition in a semi-enclosed embayment.

Foraminiferal and lithologic data indicate the presence of eight distinct zones, each composed of one of the three foraminiferal assemblages (Appendix B). These zones conform to the layered geometry of the depositional sequences.



Depositional facies	Lithofacies	Description	Common flora and fauna	Depositional environment
Marine	MFsm Fossiliferous sandy mud	Medium to fine grained sandy mud with occasional 1-3 mm thick sand layers. Dark grey.	*Mulinia*, Tellinidae, open shelf foraminifera.	Low energy, open embayment.
	MFms Fossiliferous muddy sand	Muddy, fine to medium grained sand with marine fossils. Dark grey.	*Mulinia*, *Ensis*, Tellinidae, open shelf foraminifera.	Moderate energy, open embayment.
	MFs Fossiliferous sand	Clean, moderate sorted, fine to medium sand with abraded marine fossils. Light grey.	*Mulinia,* sand dollar, sea urchin spines, barnacle fragments, Cardiidae, Tellinidae, open shelf foraminifera.	High energy, nearshore, open embayment.
Barrier Island	BIs Fine - medium sand	Clean to slightly muddy, moderate to well sorted, fine to medium sand. Tan - light brown.	Root fibers, leaf fragments, charcoal particles.	Barrier island, possibly eolian.
	BIg Coarse sand and gravel	Clean, poorly sorted, coarse sand, gravel, and shell hash. Tan - orange.	Worn, reworked shell fragments, primarily of marine origin.	Back barrier tidal channel/ overwash, beach.
Estuarine	EFs Sand	Clean to slightly muddy, moderate to well sorted, medium sand with occasional plant detritus and/or mollusk shell fragments. Tan.	Wood particles, indeterminate (less than 1mm) detrital plant particles, detrital oyster and other mollusk shell fragments.	Low to moderate energy estuary bottom, less than ~2 m water depth.
	EFm Mud	Mud deposits (with trace to 1% fine plant detritus) interlayered occasionally with 1-3 mm thick fine to medium sand layers. Dark grey.	Fine grained indeterminate plant detritus, *Mercenaria*, *Crassostrea,* and *Mulinia*.	Low energy estuary channel, greater than ~2 m water depth, or shallow sheltered estuarine creek channel and flanks.
	EFpm Peaty mud and peat	Slightly sandy, plant detritus rich, mud to muddy detrital peat. Dark brown.	Marsh grass stems and rhizomes, wood, bark, and compressed leaves.	Early flooding stage of tributary stream, fresh water swamp forest to low brackish marsh.
	EFps Peaty sand	Medium sand with abundant wood and other plant detritus. Dark tan - brown.	Wood, bark (up to 1.5 cm), leaf fragments, peat aggregates.	Coastal creek lowlands to swamp forest.
Fluvial/non-marine	FFs Clean medium sand	Clean, moderate to well sorted, medium sand with occasional plant detritus and/or mud clasts. Tan - light brown.	Wood, bark, and leaf fragments (less than 3 mm), fine disseminated plant detritus.	Coastal stream floodplain to channel low flow regime.
	FFsg Coarse sand and gravel	Poorly sorted, medium to very coarse sand up to 20% gravel (mud clasts, quartz, lithic, and shell fragments). Tan - light grey.	Trace amounts of fine plant detritus and *Mercenaria* fragments.	Coastal stream channel.

* Quartz is the dominant mineral in the sand-size fraction of all sediment samples analyzed; other inorganic minerals rarely exceed 1%. Where the word sand is used, it refers to quartz sand unless otherwise specified.

Figure 4. Summary of lithofacies characteristics recognized in the Croatan Sound section. Symbols for depositional facies are coordinated with those in Figure 3. Estimates of water depth are based on Tenore (1970).

Macrofaunal assemblages

Macrofaunas also correlate to lithofacies (Fig. 4). Within MF deposits, some taxa are primarily associated with the inner shelf while others, though common to the shelf, are also found in outer estuarine settings. Thus, the shallow embayment depositional environment indicated by the lithology and foraminiferal assemblages is supported by the macrofaunal assemblages. Within EF, macrofossils are relatively rare and dominated by *Crassostrea*, *Mercenaria*, and *Mulinia*.

Sequence boundaries

Three major environmental stages contribute to the final character of sequence boundaries (Table 2). Stage 1 (Fig. 6) corresponds with periods of emergence. During these times, fluvial erosion surfaces were created by fluvial entrenchment (Foyle and Oertel, 1997); on the interfluves, the corresponding hiatal surface is influenced by subaerial erosion and weathering (Fig. 6). As sea level rises, valleys are flooded to produce

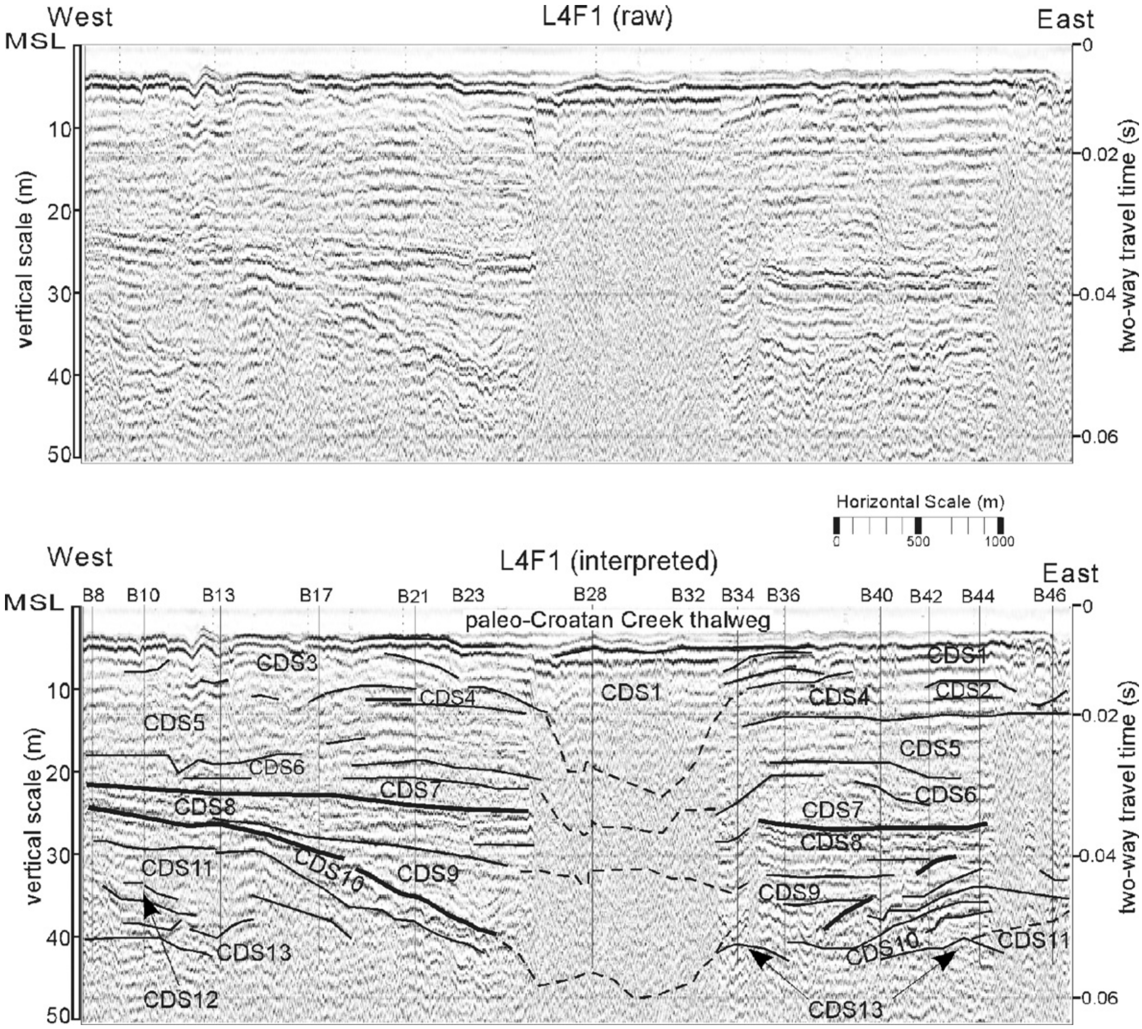


Figure 5. The raw and interpreted high-resolution seismic profile of a portion of the Croatan Sound section (B–B′) between drill holes B8 and B46 (see Fig. 2 for location of seismic line L4F1) illustrates subsurface stratigraphic patterns. In the interpreted profile, solid lines conform to stratigraphic patterns associated with sequence boundaries and facies changes. The loss of data in the paleo-Croatan Creek thalweg results from fine grained, organic and gas-rich muds of EF that fill the paleochannel. Dotted lines in this area represent the geometry of sequence boundaries based on lithologic data. Vertical scale is approximated based an acoustic velocity of 1700 m/s.

estuarine depositional environments in Stage 2 (Fig. 6). Stream channels first back-fill with fluvial sand followed by estuarine mud, effectively burying and preserving the unconformity produced by stream incision. However, on the interfluves, estuarine shoreline erosion progressively eliminates the emergent land surface and produces the bay ravinement surface (Nummedal and Swift, 1987; Foyle and Oertel, 1997). Transgression continues during Stage 3 (Fig. 6) and sediments deposited during Stage 2 are overridden by the marine realm. Segments of the bay ravinement surface are commonly preserved on the flanks of channels where they are overlain by estuarine deposits. However, shoreface recession removes much of the remaining estuarine sediments producing the marine ravinement surface. Thus, the resulting lithologic sequence boundary is a composite of erosional surfaces, each produced during temporally separate phases in the transgressional cycle.

Croatan depositional sequences

Though portions of 13 sequences are recognized in the Croatan Sound section (Fig. 3), only the upper nine are laterally

Table 2
Stages contributing to the development of sequence boundaries

Stage	Erosional surface	Diagnostic criteria	Associated lithofacies
1	Fluvial and paleo-topographic	Iron oxide staining, root fibers, charcoal, FF truncate MF or EF, seismic evidence	FFsg, FFs
2	Bay ravinement	EF truncate MF, seismic evidence	EFps, EFpm, EFm, EFs
3	Marine ravinement	Seismic evidence, age data, changes in foraminiferal assemblages, blow-count changes, lithofacies changes, separation by EF in channel areas	MFs, MFms, MFsm

continuous paleo-valley fill deposits. Remnants of at least four older sequences, with discontinuous and often highly weathered lithofacies, form the floor and walls of this paleo-valley. Radiocarbon, OSL, and AAR age estimates, both from this study and from other investigations, have been incorporated to establish age control (Table 1). Sequence boundaries and lithologic contacts commonly correlate with seismic reflection patterns (Fig. 5).

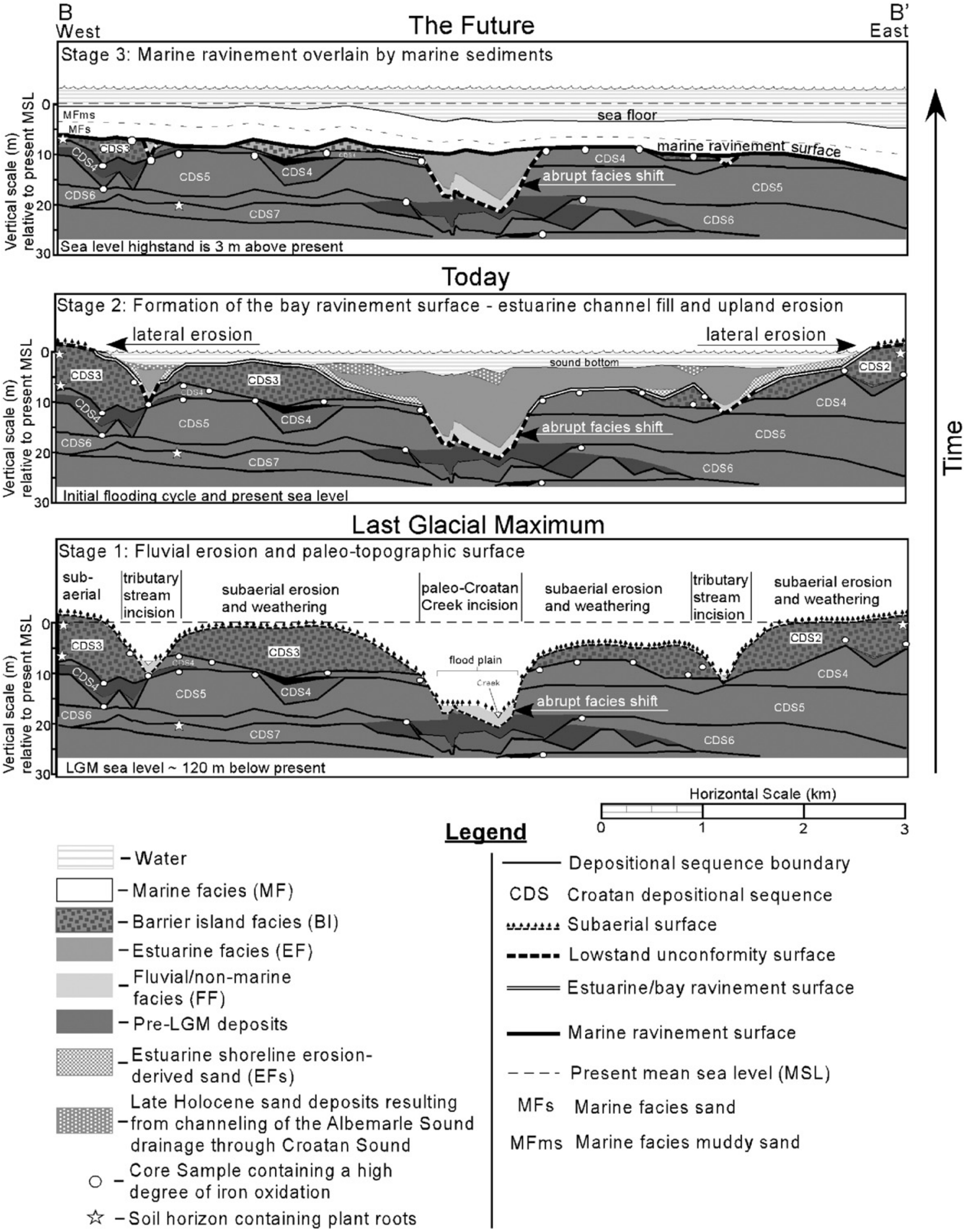


Figure 6. Model depicting the three major stages that contribute to the final character of a depositional sequence boundary. Profiles are based on the geometry of the Holocene section. The stratigraphic profile of the upper 25 m of underlying depositional sequences (shaded) is included for reference. Stage 1 is a schematic portrayal of the B–B′ section during the last glacial maximum showing the influence of stream incision, subaerial weathering, and erosion of the land surface. Stage 2 depicts the B–B′ section as it appears today. Stage 3 portrays the section given an approximate 3-m rise in sea level. The marine ravinement surface geometry depicted for stage 3 is based on the boundary separating CDS5 and CDS6. Although the marine ravinement surface becomes the depositional sequence boundary on the interfluves, in the valleys the depositional sequence boundary is produced by fluvial and estuarine processes.

The lithologic, geometric, and stratigraphic relationships exhibited by Croatan depositional sequence 1 (CDS1) have been used as an analog for interpreting the fluvial/non-marine and estuarine lithofacies of older sequences. CDS1 (Fig. 3) includes the sedimentary facies produced by the Holocene rise in sea level and forms the uppermost sediments in the study area. It is thickest in the thalweg section where it fills the valley incised by paleo-Croatan Creek during the last glacial period (Rudolph, 1999; Riggs et al., 2000). These valley-fill deposits are dominated by estuarine mud (EFm) and thin both east and west into a veneer of mud and sand (EFs) with intermittent minor channels (Fig. 3). Estuarine deposits are underlain by fluvial deposits (FFs and FFsg) along the paleo-Croatan Creek valley floor and along minor stream channels to the east and west (see drill-holes B42–B45 and B8 respectively in Fig. 3). Several calibrated radiocarbon age estimates (Table 1) from the thalweg section of CDS1 (5 to 10 m below MSL) indicate Holocene deposition (Rudolph, 1999; Riggs et al., 2000).

Data from the Croatan Sound section are not sufficient to distinguish CDS2 from CDS3. Their separation is based upon previous research (Riggs and O'Conner, 1974; Eames, 1983; Riggs et al., 1992). CDS2 occurs in the eastern portion of the Croatan Sound profile and is comprised of BI deposits associated with the Roanoke Island paleo-barrier island complex (Eames, 1983; Riggs et al., 1992) (Fig. 3). There is no evidence that FF or EF occur in CDS2 in the B–B′ section.

CDS3 is composed of BI sediments and is confined to the area west of the Croatan Sound thalweg and the eastern portion of mainland Dare County (Figs. 1, 3). It is part of a major sand facies that occurs along the western side of Croatan Sound (Eames, 1983; Riggs et al., 1992). CDS3 crops out along the sound bottom between drill holes B10 and B17 (Rudolph, 1999; Riggs et al., 2000) and is erosionally truncated by Holocene deposits between drill holes B17 and B23 (Fig. 3). The lower boundary of CDS3 is delineated by a seismic reflection between drill holes B17 and B21 (Fig. 5). No direct age data are available for either CDS2 or CDS3.

CDS4 through CDS9 consist of a series of sequences dominated by stacked marine deposits on the interfluves (Fig. 3). Within the thalweg region, the marine facies of each sequence is underlain by its corresponding estuarine facies. In CDS5 and CDS9, estuarine facies are underlain by fluvial deposits. The fluvial facies of CDS4 occurs in two incised channel features in the western portion of the transect (Fig. 3). AAR analyses indicate an estimated age range of 180 to 80 ka for both CDS5 and CDS6. Though direct age estimates are not available for CDS7 through CDS9, their ages are constrained between CDS6 (180 to 80 ka) and CDS10 (220 to 180 ka).

Chronology

The age estimates for the Croatan Sound section (B–B′ in Figs. 1, 3) are based on AAR, radiocarbon, and OSL data. Age estimates have been synthesized from both data from this study as well as from nearby localities (Fig. 1) in order to develop the regional chronostratigraphy (Fig. 7).

Aminostratigraphy

The aminostratigraphy of the northeastern North Carolina region has been studied for over 15 yr (York et al., 1989; Riggs et al., 1992). As analytical methods have evolved and additional samples have become available, the definition of

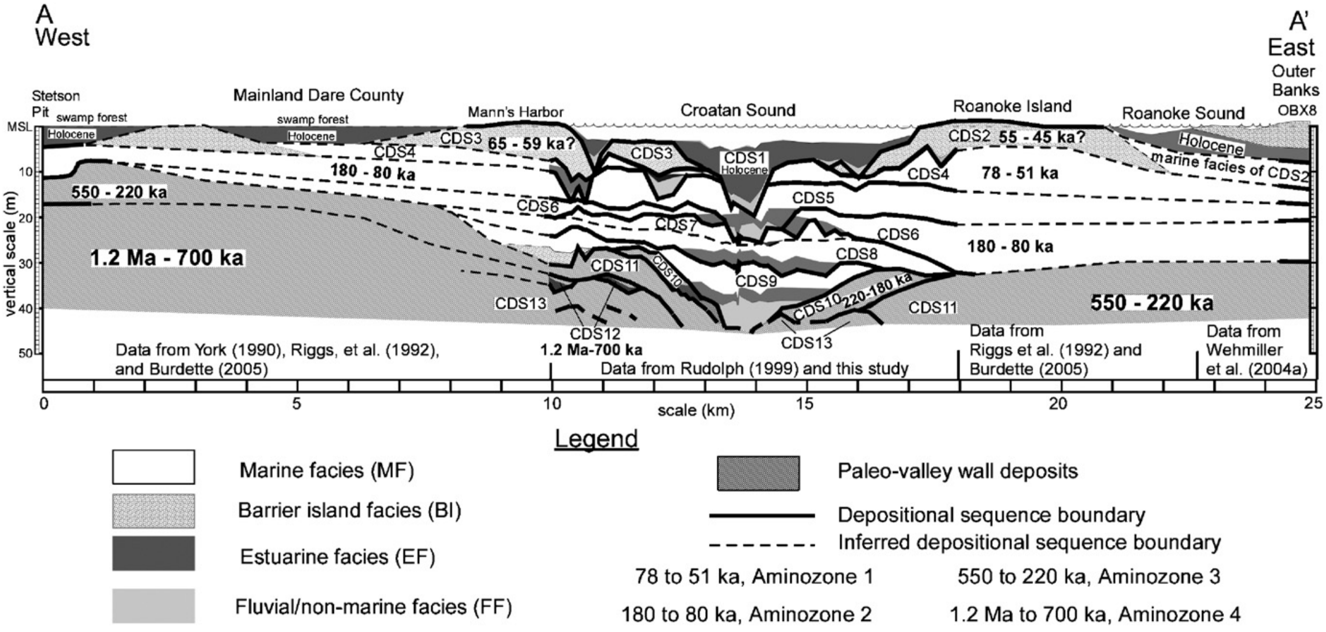


Figure 7. West-to-east geologic cross section extending from Stetson Pit in mainland Dare County east to drill hole OBX8 on the Outer Banks (A–A′ in Fig. 1). The section shows age estimates for deposits, antecedent topography of the pre-CDS9 landscape (cross-hatched), and the distribution of nine late Quaternary sequences (CDS9 through 1). This section is based on lithologic and seismic data from Croatan Sound (Figs. 3 and 5) and regional age estimates from eastern Dare and Currituck Counties (Table 1).

specific aminozones (clusters of D/L values) potentially changes. Current efforts (Wehmiller et al., 2004a) are resulting in new analyses of mollusks from subsurface sections on North Carolina's Outer Banks. Nevertheless, the principal reference section for the region remains the cored section at Stetson Pit, mainland Dare County (Fig. 1). The original data for this section were presented by York et al. (1989) and were placed in a regional context by Riggs et al. (1992). Four aminozones (AZ-1, AZ-2, AZ-3, and AZ-4, from youngest to oldest) were identified in subsurface samples from Dare County (Riggs et al., 1992). The age estimates for these zones are used here to represent the analytical results obtained from Croatan Sound and other Dare County sites. The numerical age estimates derived for aminozones are based on kinetic models, with

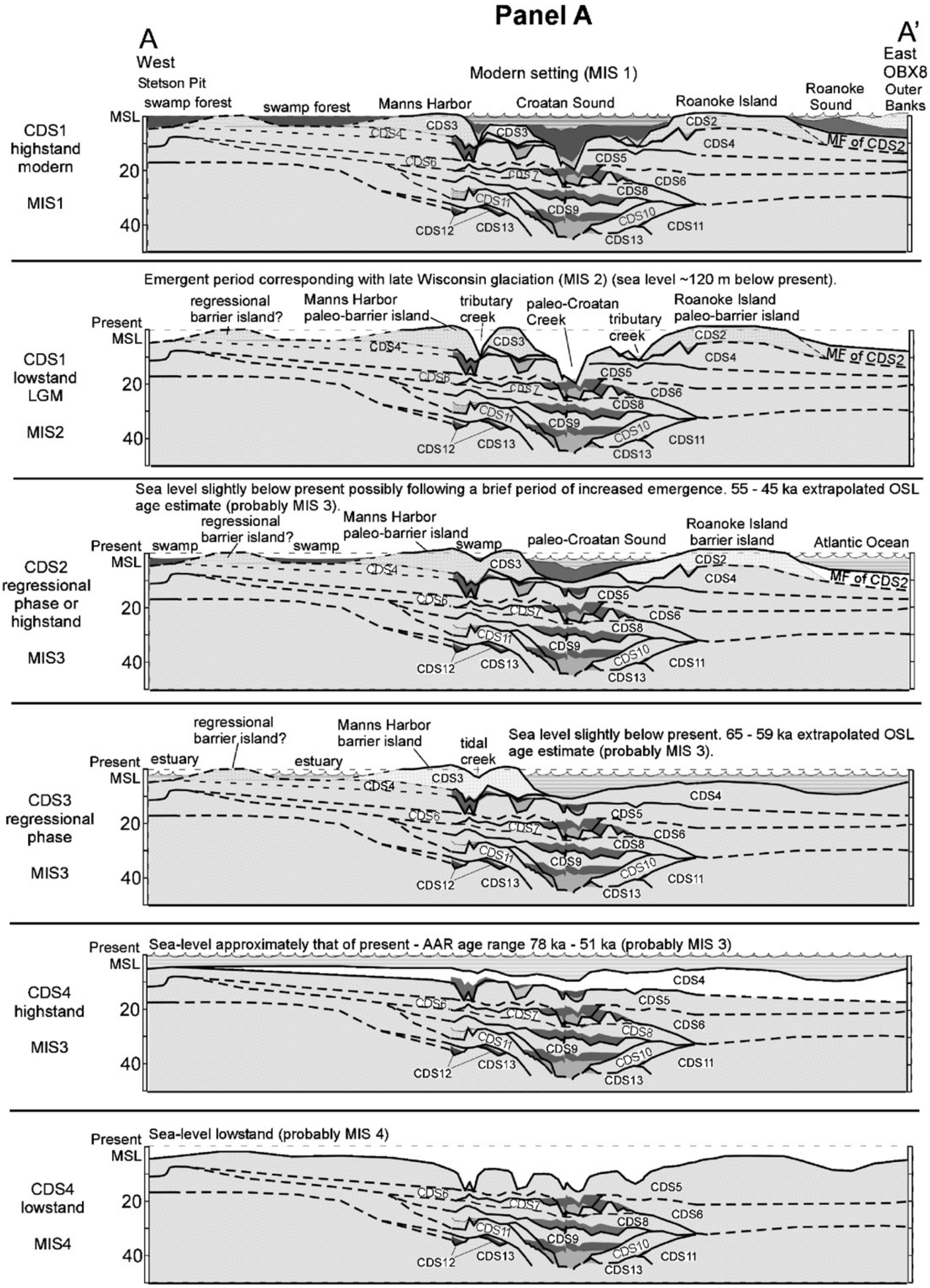


Figure 8. A schematic representation of the evolution of Croatan Depositional Sequences (CDS) 9-1 based on age data and stratigraphic characteristics. Preliminary correlation between depositional sequences and Marine Isotope Stages (MIS) is indicated for each evolutionary stage (see also Fig. 9).

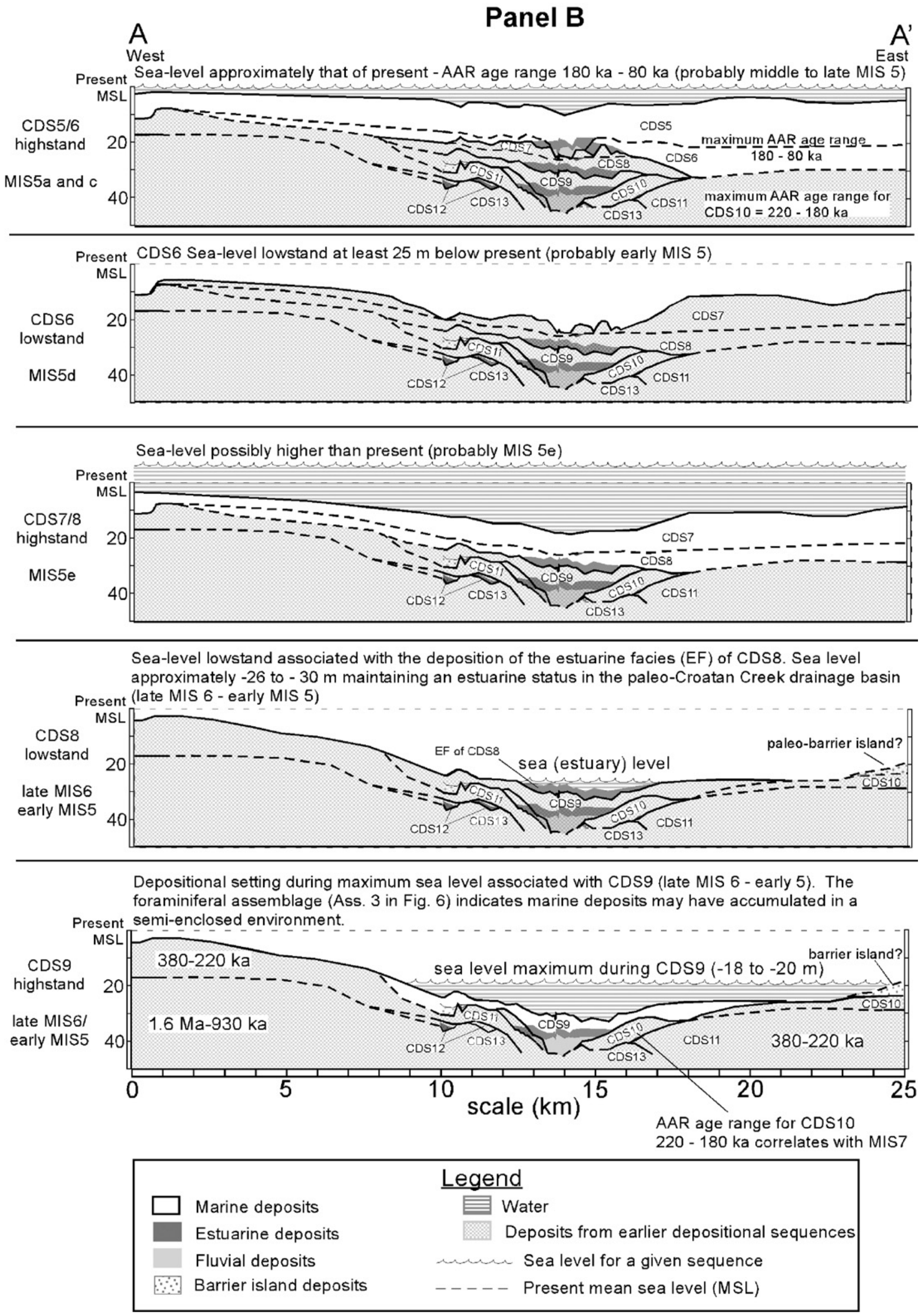


Figure 8 (*continued*).

appropriate local and regional calibration (York et al., 1989; Wehmiller et al., 2004a). Aminozones 2, 3, and 4 are broadly interpreted as late, middle, and early Pleistocene (~180 to 80 ka, ~550 to 220 ka, and ~1.2 Ma to 700 ka), respectively (Table 1). Aminozone 1 is interpreted to range from 78 to 51 ka (York et al., 1989; Riggs et al., 1992) and correlates with the marine deposits of CDS4 of the present study. CDS10 (220 to 180 ka) represents an aminozone not yet recognized elsewhere.

Radiocarbon age data

Radiocarbon age data (Riggs and O'Conner, 1974; Riggs and O'Connor, 1975; Rudolph, 1999; Riggs et al., 2000) from both the B–B′ transect and from other regional localities (Table 1; Fig. 1) aided in constraining the age of younger deposits. Age estimates from EF deposits (CDS1) in the Croatan Sound thalweg indicate a Holocene age. Though samples analyzed from the flanks of the thalweg and from beneath Roanoke Island were radiocarbon dead (Table 1), they nevertheless indicate that these deposits are older than approximately 30 ka.

Optically stimulated luminescence age data

Based on OSL analysis, Burdette (2005) determined the ages of two coast-parallel beach ridges on the Currituck Peninsula (Fig. 1). Data show that the westernmost ridge was deposited between 65 and 59 ka and the easternmost ridge between 55 and 45 ka (Table 1). Southward projection of the trend of these beach ridges into the Roanoke Island area suggests that they are contemporaneous with the barrier island sands of CDS3 and CDS2, respectively, in the present study. The correlation of the easternmost Currituck ridge with CDS2 is further supported by an OSL age estimate of approximately 55 ka (Mallinson, personal communication, 2006) from Fort Raleigh, Roanoke Island (Fig. 1, Table 1).

Geologic history and correlation with the marine oxygen isotope record

Figure 8 is a schematic illustration of the evolution of regional section A–A′ (Fig. 1). The lower sediments (CDS13 to CDS10) in Croatan Sound section B–B′ represent the discontinuous record of deposition during the early and middle Pleistocene (Fig. 3). These older sequences are separated by major hiatal surfaces representing periods of both non-deposition and erosion and form the walls and floor of a major valley formed by paleo-Croatan Creek during a later sea-level lowstand. AAR analysis indicates that CDS12 and CDS10 range in age from 1.2 Ma to 700 ka and 220 to 180 ka, respectively (Figs. 3, 7). Therefore, CDS10 correlates temporally with Marine Isotope Stage (MIS) 7 (Fig. 8). If this is the case, the sea-level lowstand corresponding with MIS 6 was likely responsible for the formation of the valley within which CDS9 through CDS1 were deposited. In comparison to CDS13 through CDS10, CDS9 through CDS1 represent a relatively complete record of late Quaternary deposition. Deposits correlative with CDS9 through CDS7 have yet to be recognized outside the Croatan Sound region. This discrepancy is most likely a result of sparse core coverage.

The fluvial facies of CDS9 probably represents deposition during the MIS 6 lowstand (Fig. 9). As sea level rose from MIS 6 to MIS 5, the paleo-Croatan Creek valley flooded with the concurrent deposition of the estuarine facies (EF) of CDS9. These EF deposits are in turn overlain by the marine facies (MF) of CDS9 (Fig. 8), with foraminiferal data suggesting deposition in a semi-enclosed embayment. The contact between CDS9 and overlying CDS8 is not sharp. Instead, it is characterized by a transition to mud deposits barren of foraminifera and is interpreted to represent either (or both) a climatic shift resulting in increased terrestrial sediment input or a basinward shift to a low-brackish, inner estuarine environment. A fluvial facies of CDS8 is not recognized and there is no lithologic evidence of fluvial entrenchment in the thalweg area.

Based on the environmental implications of foraminiferal data and its stratigraphic relationship with CDS8, the MF of CDS9 is not thought to represent deposition during the MIS 5e major sea-level highstand. Instead, it may represent a relatively minor or short-duration transgression possibly occurring during late MIS 6. Based on 24 globally dispersed sedimentologic

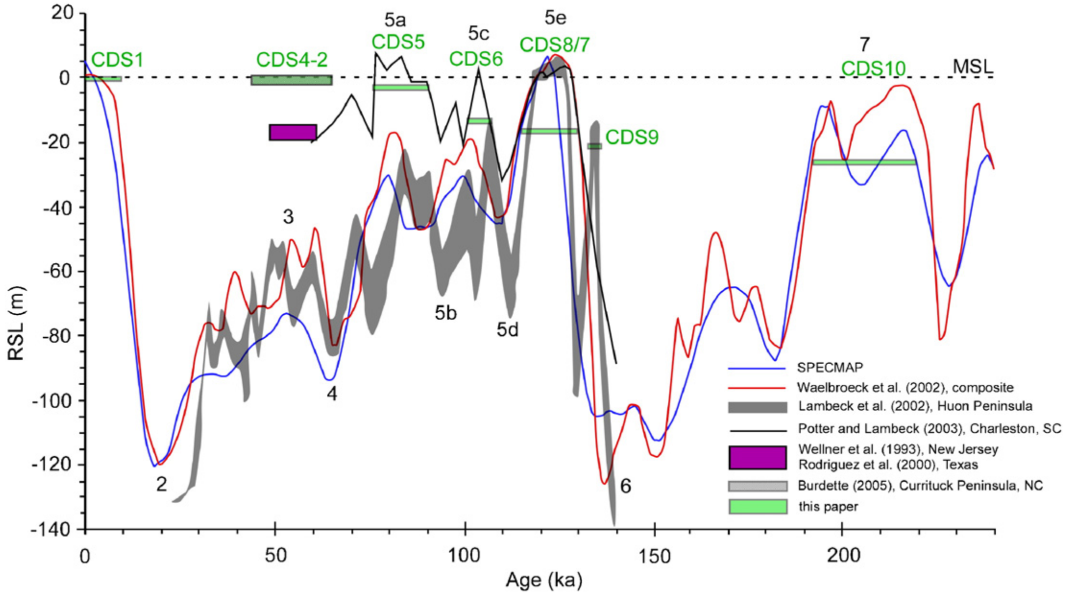


Figure 9. Relative sea level (RSL) records during the last 240 ka. Black numerals indicate oxygen isotope stages and sub-stages. The broad grey line represents the field between the maximum and minimum limits of ice-volume-equivalent sea level for the last glacial cycle inferred from raised coral reefs on the Huon Peninsula, Papua New Guinea (Lambeck et al., 2002). Green fields represent probable periods of deposition and associated sea level elevations for Croatan Depositional Sequences (CDS). The cross-hatched field represents the OSL estimated period and required sea level for deposition of Currituck sand ridges (Burdette, 2005).

records, Seidenkrantz et al. (1996) suggested the existence of such an 'Allerød/Younger Dryas'-type climatic oscillation just prior to the MIS 6/5e boundary. Evidence for this climate oscillation is also seen in the pollen record of a marine core taken off the Iberian Peninsula (Sánchez Goñi et al., 1999), in coral terraces on the Huon Peninsula, Papua New Guinea (Lambeck et al., 2002) (Fig. 9), and in speleothem records from Italy (Antonioli et al., 2004); the latter two records indicate that sea level reached an elevation of approximately −18 to −20 m. This elevation matches well with the sea-level elevation proposed here for the CDS9 highstand (Fig. 8).

If CDS9 correlates with a late MIS 6 sea-level highstand, then CDS8 most likely correlates with the MIS 5e sea-level highstand. This conclusion is supported by the occurrence of the MF of CDS8 as a relatively thick laterally extensive sequence that is only truncated by younger marine deposits in the extreme eastern portion of the Croatan Sound section (Fig. 3). The overlying sequence (CDS7) is distinguished from CDS8 on the basis of mud interpreted to represent estuarine deposits in drill hole B32 (Fig. 3), iron oxide staining of the upper portions of CDS8, and the presence of a relatively strong seismic reflection at the sequence boundary separating CDS8 from CDS7 (Fig. 5). The relatively minor fall in sea level responsible for the CDS7/8 boundary may have occurred during one of four low-amplitude climatic phases (Sánchez Goñi et al., 1999) during MIS 5e (Fig. 9). This sea-level fall must have been short in duration because evidence of stream channel incision and channel deposits (FF) are lacking. It is likely that the erosional geometry of the overlying sequence boundary (CDS7/6 in Fig. 3) between drill holes B34 and B44 is the result of the relative sea-level lowstand associated with MIS 5d (Fig. 8). Based on multiproxy data from North Atlantic and equatorial Pacific deep-sea sediment cores, Chapman and Shackleton (1999) concluded that sea-level minima during both MIS 5d and 5b were approximately −65 m.

CDS6 and 5 are interpreted to correspond with MIS 5c and 5a, respectively (Fig. 9). It is apparent that entrenchment of paleo-Croatan Creek during the lowstand responsible for the CDS6/5 sequence boundary removed lowstand evidence in the thalweg area of the CDS7/6 boundary. However, the CDS7/6 boundary does reveal evidence of valley formation and soil development both east and west of the thalweg (Fig. 3).

The geometry of the CDS6/5 sequence boundary and the distribution of the FF and EF of CDS5 almost exactly duplicate the geometry of the sequence boundary separating CDS1 from underlying deposits and the distribution of overlying FF and EF deposits. This latter sequence boundary was formed during the sea-level low corresponding with the last glacial maximum. CDS5 differs from CDS1, however, in that the upper portions of the EF have been removed by marine ravinement and are overlain by MF deposits. The MF of CDS5 is relatively thick and regionally extensive. AAR analyses (York, 1990; Riggs et al., 1992; Wehmiller et al., 2004a) identified deposits in Stetson Pit and drill hole DC74 on the Dare County mainland, in drill hole DC75 on Roanoke Island, and in drill hole OBX8 on the Outer Banks (Fig. 1) that fall within the same age range (180 to 80 ka) as CDS5 and 6 (Fig. 7) and are considered here to be contemporaneous.

The CDS5/4 sequence boundary is characterized by considerable relief west of the thalweg (Fig. 3). It is tentatively correlated with MIS 4, when sea-level minima appear to have ranged from −81 to −100 m (Chapman and Shackleton, 1999; Cutler et al., 2003). Two channel features in this area are filled with a succession of FF to EF deposits. The western-most probably represents the channel of a tributary of paleo-Croatan Creek. The more eastern incision (in the vicinity of drill hole B17; Fig. 3) could either represent the channel of another tributary or perhaps the site of paleo-Croatan Creek during this period of emergence. Stream incision during the last glacial maximum eroded away evidence of the FF or EF of CDS4 in the thalweg area (Fig. 3).

Deposits from Roanoke Island (DC67 and DC80) yielding AAR age estimates of 78 to 51 ka (Riggs et al., 1992) (Figs. 1 and 7) are considered to be part of CDS4. Projection of the westernmost Currituck beach ridge (Burdette, 2005) suggests that CDS3 may be a remnant of that paleo-shoreline with an age range estimate of 65 to 59 ka (Fig. 1, 7). CDS2 is interpreted to represent the basal portion of barrier-island deposits that compose Roanoke Island and correspond in age with OSL estimates (55 to 45 ka) from Fort Raleigh (Mallinson, personal communication, 2006) and the easternmost Currituck beach ridge (Burdette, 2005) (Fig. 1, Table 1). If these interpretations are correct, both CDS3 and CDS2 were deposited during MIS 3. Based on the lack of evidence of a significant sea-level lowstand separating CDS4 from both CDS3 and CDS2 and the AAR age estimate of 78 to 51 ka for sediments from Roanoke Island (Riggs et al., 1992), CDS4 is also considered to have been deposited during MIS 3 (Fig. 9).

CDS3 is interpreted to be comprised solely of BI deposits. The basis for distinction as a separate sequence is the shift from MF of CDS4 to BI of CDS3. Because of the lack of evidence of major erosional incision along the CDS4/3 boundary and lack of evidence of a FF, EF, or MF in CDS3, it appears that CDS4 and CDS3 were not separated by a sea-level lowstand of the magnitude of MIS 4. Instead, it is considered likely that CDS3 represents the barrier-island facies deposited as part of the falling stage systems tract (Plint and Nummedal, 2000). Similar evidence, highlighted by the lack of a recognized EF, suggests that CDS2 was also deposited as part of this falling stage systems tract. If this interpretation is correct, then these barrier island deposits are part of CDS4 and not separate sequences (Table 2).

A relatively broad valley formed in the Croatan Sound section during the sea-level lowstand associated with the last glacial maximum (Fig. 8). Incision in the main stream channel reached a depth of approximately 20 m. This tributary valley system, like the larger paleo-Roanoke valley into which it fed (Mallinson et al., 2005), was subsequently filled by fluvial and estuarine deposits during the latest Pleistocene and Holocene (Rudolph, 1999; Riggs et al., 2000).

Discussion

The fact that deposits correlative with CDS9 to CDS7 have not been recognized outside the study area is likely a result of drill-hole site selection. Most drill-holes associated with other studies have been land-based. Because most modern land areas are situated upon antecedent topographic highs (Riggs et al., 1995), accommodation is minimal. As a result, the sediments of minor transgressions may never be deposited in these areas or were removed by ravinement during subsequent transgressions.

The stratigraphic record and number of sequences preserved in the Croatan Sound section matches well with global records of sea-level oscillations during the late Quaternary (Fig. 9). However, if correlations of sequences from the Croatan Sound section (CDS6 through CDS2) with the marine oxygen isotope record are correct, then sea-level maximas in the northeast North Carolina region must have been similar to present during MIS 5c, MIS 5a, and MIS 3. Though these sea-level elevations are consistent with other late MIS 5, intermediate field (Stirling et al., 1998) sea-level records for the U.S. southeast coast (Szabo, 1985; Ludwig et al., 1996; Wehmiller et al., 2004b), Bermuda (Muhs et al., 2002), California (Muhs et al., 1994), and Japan (Ota and Omura, 1992), they are significantly higher than those interpreted for far-field localities such as New Guinea (Chappell et al., 1996), Australia (Stirling et al., 1995, 1998), and Hawaii (Sherman et al., 1999). Sea levels during MIS 5 can be expected to vary not only with time but also with location, depending on position relative to the former ice sheets (Lambeck and Nakada, 1992). Higher latitude intermediate-field localities are closer to the limit of MIS 6 ice sheet advance and are hypothesized to have experienced isostatic rebound that elevated late MIS 5 marine deposits to positions above modern sea level (Muhs et al., 2002). In contrast, continental-margin sites far from former ice limits (far-field sites) receive only minimal glacio-isostatic contributions (Lambeck and Johnson, 1998).

Potter and Lambeck (2003) demonstrated that, along a transect from Barbados to the U.S. Atlantic coast, sea level maxima ranged from −19 m to +3 m, respectively during MIS 5a. In contrast, no such gradient was observed for MIS 5e along the same transect. They proposed that the U.S. Atlantic coast is situated on the glacio-isostatic forebulge that was flexed as much as 20 m during MIS 5e. However, during MIS 5a enough time had passed since major glaciation for the forebulge to have subsided to a state of relative equilibrium. Because past sea level estimates are measured relative to present sea level, and the present region's rheological state is similar to that during MIS 5e (i.e., non-equilibrium), strata of MIS 5a and 5c are as much as 20 m higher in elevation than they were when deposited.

If northeast North Carolina is situated on the subsiding forebulge from the last glacial advance, then deposits associated with late MIS 5 in the Croatan Sound region were probably deposited at elevations around 20 m lower than their present position. It seems likely that the relatively short duration and apparent lesser magnitude of glaciation during MIS 4 was not sufficient to isostatically influence this region and resulted in a rheological state during MIS 3 similar to that present during late MIS 5. Evidence from the inner shelves of Texas (Rodriguez et al., 2000) and New Jersey (Wellner et al., 1993) indicate MIS 3 shorelines at −15 m and −20 m respectively (Fig. 9). However, the findings of this paper and Burdette (2005) suggest near-to-present sea levels during MIS 3 in northeast North Carolina. Whether glacio-isostatic adjustment could be responsible for these spatial differences is unknown.

Conclusions

It has been demonstrated that sediment accumulations interpreted to represent nine late Quaternary transgressive sequences occupy an erosional valley formed by paleo-Croatan Creek during a major and prolonged sea-level lowstand corresponding with MIS 6. Though the uppermost of these sequences is principally Holocene in age, the eight older sequences are interpreted to represent deposition from MIS 6 to MIS 3. The stratigraphic relationships and chronological interpretation of these eight sequences suggest that during late MIS 6, sea level rose to approximately −20 m (depositing the MF of CDS9), fell to an indeterminate level then rose again probably above modern sea level to deposit the MF of CDS8 during MIS 5e. Subsequent sequences (CDS7 to CDS5) record sea-level oscillations through the remainder of the MIS 5 interglacial period. This record suggests that relative sea level approached the modern level during both MIS 5c and MIS 5a. OSL and AAR age data indicate that following the relatively minor MIS 4 glacial period, sea level rose again to approximately the modern level during MIS 3 and deposited the MF of CDS4. A subsequent, but possibly oscillatory regression resulted in the accumulation of barrier island deposits (CDS3 and CDS2) that represent abandoned shorelines.

The record of sea-level fluctuations preserved in the Croatan Sound section matches well with the oscillatory frequency of global records for the late Quaternary. Near to present sea-level elevations responsible for sequences associated with late MIS 5 sea-level maxima are in accordance with other intermediate-field localities both in the southeast U.S. coastal region and in other mid-latitude, northern hemisphere areas. In contrast, they are significantly higher than maxima estimated for far-field sites in tropical regions. These differences are attributed to glacio-isostatic factors.

Acknowledgments

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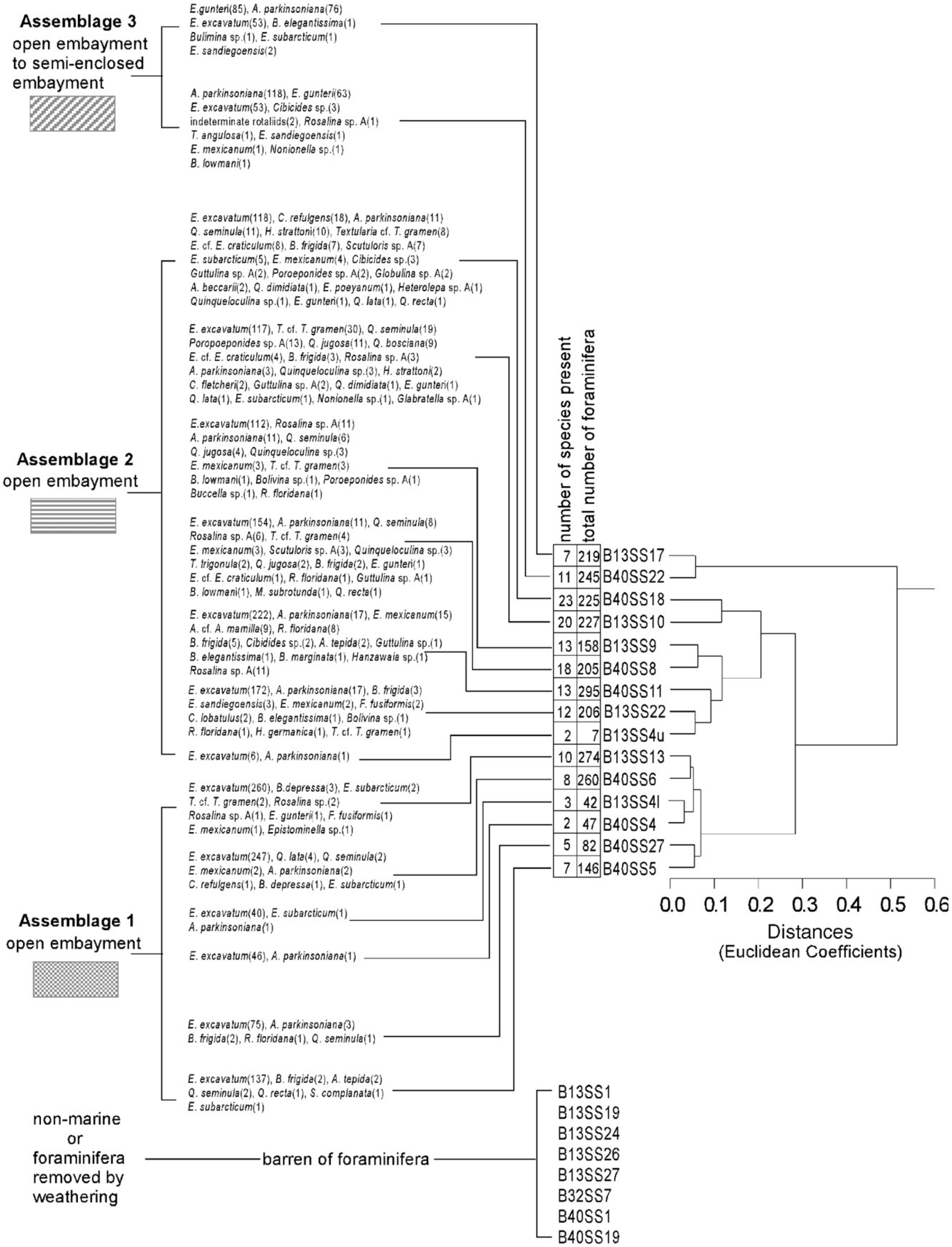
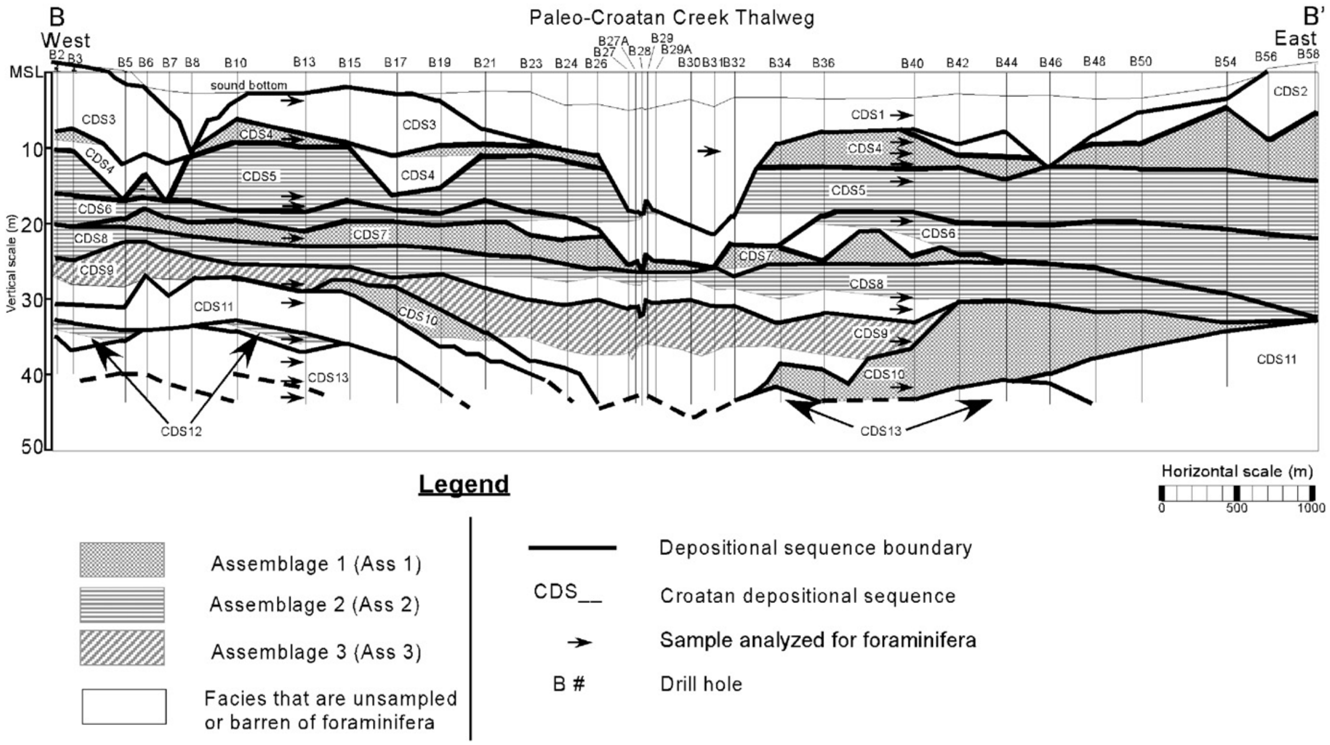
Appendix A

Cluster analysis dendrogram of Croatan Sound foraminiferal data. Species observed in each sample are listed to the left of the dendrogram. Habitat associations are listed on the far left along with shading that coordinates with foraminiferal assemblage distributions on the Croatan Sound section (Appendix B).


Assemblage 3
open embayment to semi-enclosed embayment
E.gunteri(85), A. parkinsoniana(76)
E. excavatum(53), B. elegantissima(1)
Bulimina sp.(1), E. subarcticum(1)
E. sandiegoensis(2)
A. parkinsoniana(118), E. gunteri(63)
E. excavatum(53), Cibicides sp.(3)
indeterminate rotaliids(2), Rosalina sp. A(1)
T. angulosa(1), E. sandiegoensis(1)
E. mexicanum(1), Nonionella sp.(1)
B. lowmani(1)
Assemblage 2
open embayment
E. excavatum(118), C. refulgens(18), A. parkinsoniana(11)
Q. seminula(11), H. strattoni(10), Textularia cf. T. gramen(8)
E. cf. E. craticulum(8), B. frigida(7), Scutuloris sp. A(7)
E. subarcticum(5), E. mexicanum(4), Cibicides sp.(3)
Guttulina sp. A(2), Poroeponides sp. A(2), Globulina sp. A(2)
A. beccarii(2), Q. dimidiata(1), E. poeyanum(1), Heterolepa sp. A(1)
Quinqueloculina sp.(1), E. gunteri(1), Q. lata(1), Q. recta(1)
E. excavatum(117), T. cf. T. gramen(30), Q. seminula(19)
Poropoeponides sp. A(13), Q. jugosa(11), Q. bosciana(9)
E. cf. E. craticulum(4), B. frigida(3), Rosalina sp. A(3)
A. parkinsoniana(3), Quinqueloculina sp.(3), H. strattoni(2)
C. fletcheri(2), Guttulina sp. A(2), Q. dimidiata(1), E. gunteri(1)
Q. lata(1), E. subarcticum(1), Nonionella sp.(1), Glabratella sp. A(1)
E.excavatum(112), Rosalina sp. A(11)
A. parkinsoniana(11), Q. seminula(6)
Q. jugosa(4), Quinqueloculina sp.(3)
E. mexicanum(3), T. cf. T. gramen(3)
B. lowmani(1), Bolivina sp.(1), Poroeponides sp. A(1)
Buccella sp.(1), R. floridana(1)
E. excavatum(154), A. parkinsoniana(11), Q. seminula(8)
Rosalina sp. A(6), T. cf. T. gramen(4)
E. mexicanum(3), Scutuloris sp. A(3), Quinqueloculina sp.(3)
T. trigonula(2), Q. jugosa(2), B. frigida(2), E. gunteri(1)
E. cf. E. craticulum(1), R. floridana(1), Guttulina sp. A(1)
B. lowmani(1), M. subrotunda(1), Q. recta(1)
E. excavatum(222), A. parkinsoniana(17), E. mexicanum(15)
A. cf. A. mamilla(9), R. floridana(8)
B. frigida(5), Cibidides sp.(2), A. tepida(2), Guttulina sp.(1)
B. elegantissima(1), B. marginata(1), Hanzawaia sp.(1)
Rosalina sp. A(11)
E. excavatum(172), A. parkinsoniana(17), B. frigida(3)
E. sandiegoensis(3), E. mexicanum(2), F. fusiformis(2)
C. lobatulus(2), B. elegantissima(1), Bolivina sp.(1)
R. floridana(1), H. germanica(1), T. cf. T. gramen(1)
E. excavatum(6), A. parkinsoniana(1)
Assemblage 1
open embayment
E. excavatum(260), B.depressa(3), E. subarcticum(2)
T. cf. T. gramen(2), Rosalina sp.(2)
Rosalina sp. A(1), E. gunteri(1), F. fusiformis(1)
E. mexicanum(1), Epistominella sp.(1)
E. excavatum(247), Q. lata(4), Q. seminula(2)
E. mexicanum(2), A. parkinsoniana(2)
C. refulgens(1), B. depressa(1), E. subarcticum(1)
E. excavatum(40), E. subarcticum(1)
A. parkinsoniana(1)
E. excavatum(46), A. parkinsoniana(1)
E. excavatum(75), A. parkinsoniana(3)
B. frigida(2), R. floridana(1), Q. seminula(1)
E. excavatum(137), B. frigida(2), A. tepida(2)
Q. seminula(2), Q. recta(1), S. complanata(1)
E. subarcticum(1)
non-marine or foraminifera removed by weathering
barren of foraminifera
number of species present
total number of foraminifera
7 219 B13SS17
11 245 B40SS22
23 225 B40SS18
20 227 B13SS10
13 158 B13SS9
18 205 B40SS8
13 295 B40SS11
12 206 B13SS22
2 7 B13SS4u
10 274 B13SS13
8 260 B40SS6
3 42 B13SS4l
2 47 B40SS4
5 82 B40SS27
7 146 B40SS5
0.0 0.1 0.2 0.3 0.4 0.5 0.6
Distances
(Euclidean Coefficients)
B13SS1
B13SS19
B13SS24
B13SS26
B13SS27
B32SS7
B40SS1
B40SS19

Appendix B

West-to-east geologic cross section (B–B′) of the drill hole transect across Croatan Sound (see Fig. 1 for section location) showing the distribution of foraminiferal assemblages within Croatan depositional sequences (CDS). Arrows indicate sample locations.



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