Micropaleontologic record of Pliocene and Quaternary paleoenvironments in the southern
Albemarle Embayment, North Carolina, U.S.A.

Stephen J. Culver^{a*}, Kathleen M. Farrell^b, David J. Mallinson^a, Debra A. Willard^c, Benjamin P.
Horton^d, Stanley R. Riggs^a, E. Robert Thiel^e, John F. Wehmiller^f, Peter R. Parham^g, Jessica
Pierson Moore^{b, h}, Scott W. Snyder^a, Caroline Hillierⁱ

^a*Department of Geological Sciences, Graham Rm 101, East Carolina University, Greenville,
NC 27858, USA*

^b*North Carolina Geological Survey, Coastal Plain Office and Core Repository, MSC 1620,
Raleigh, NC 27699, USA.*

^c*U.S. Geological Survey, 926A National Center, Reston, VA 20192, USA.*

^d*Department of Marine and Coastal Sciences, Rutgers University, New Brunswick, NJ 08901,
USA.*

^e*Institute of Earth, Ocean, & Atmospheric Sciences, Rutgers University, New Brunswick, NJ
08901, USA.*

^f*Division of Earth Sciences and Earth Observatory of Singapore, Nanyang Technological
University, 639798, Singapore.*

^g*U.S. Geological Survey, Coastal and Marine Geology Program, 384 Woods Hole
Road, Woods Hole, MA 02543, USA.*

^h*Department of Geological Sciences, University of Delaware, Newark, DE 19716,*

ⁱ*USA. Southeast Asia Disaster Prevention Research Initiative (SEADPRI), Universiti Kebangsaan*

Malaysia (National University of Malaysia), Malaysia

^j*West Virginia Geological Survey, 1 Mont Chateau Road, Morgantown, West*

Virginia 26508-8079, USA.

^k*Argus Ecology Ltd., Annfield Plain, Durham DH97XN, UK.*

**Corresponding author. Tel: 252.328.6360, Fax: 252.328.4391, E-mail address:*

culvers@ecu.edu (S.J. Culver)

Abstract

The Albemarle Embayment, a Cenozoic depositional basin on the Atlantic coast of the USA, is an ideal setting to understand the temporal and spatial variation of eustatic sea-level fluctuations, glacio-hydro-isostasy, tectonics, subsidence, environments and sedimentation patterns of a passive margin Quaternary section. A NE-SW transect of cores and seismic data in the southern Albemarle Embayment were analysed using micropaleontologic (foraminifera, diatoms, pollen), sedimentologic, stratigraphic, and geochronologic data to reconstruct the paleoenvironmental evolution and paleoclimates in the nearly 90 m thick Quaternary section. The study area is a very low gradient Quaternary landscape that is cross-cut by several Pleistocene incised valleys; a Holocene barrier island complex forms its eastern margin. In the subsurface, the Albemarle Embayment basin is bordered to the north by the Norfolk Arch and to the south by the depositionally-constructed Cape Lookout High, which is positioned on the northern flank of the structural Carolina Platform.

The Quaternary section overlies mid-Pliocene carbonates in three cores; the contact rises in elevation towards the Cape Lookout High. Fossils and sediment characteristics suggest a subtropical, shallow, high energy marine environment during the Pliocene. Overlying units include incomplete Pleistocene, clastic, transgressive-regressive (T-R) deposits. These have similar ages and stratigraphic signatures as the T-R cycles in the central and north-central Albemarle Embayment, although mid-Pleistocene deposits may be older in the southern region. The bulk of the early and mid-Pleistocene record consists of inner to mid-shelf sand and muddy sand. In contrast, late Pleistocene sands are of inner shelf origin, reflecting the infilling of the basin. Lowstand paleovalleys, with fluvial, wetland and estuarine fill, dissect the early, mid- and late Pleistocene marine units; their locations reflect antecedent topography. Holocene sediments

were deposited in shoreface and barrier island environments. Quaternary foraminiferal assemblages in the southern Albemarle Embayment exhibit greater species richness than those in the central and north-central embayment reflecting the presence of a major biogeographic boundary at the same location as the modern biogeographic boundary at Cape Hatteras.

Keywords: Foraminifera; diatoms; pollen; paleoenvironments; Pleistocene; Holocene.

1. Introduction

The Atlantic continental margin is a classic passive continental margin (Grow and Sheridan, 1988), where glacial isostatic adjustment (Raymo et al., 2011), dynamic topography driven by mantle convection (Rowley et al., 2013) and tectonics (van de Plassche et al., 2014) complicate stratigraphic patterns along its length. The Albemarle Embayment, North Carolina, USA (Fig. 1) contains one of the thickest and most complete Quaternary sections on the North American Atlantic margin (Riggs et al., 1992; Mallinson et al., 2005, 2010) and thus provides an excellent opportunity to investigate passive continental margin evolution. Understanding the dynamic genetic processes and the spatial and temporal patterns of passive continental margin sedimentary environment evolution in the Quaternary is facilitated by the use of several chronostratigraphic (e.g., Lu and Fulthorpe, 2004) and micropaleontological approaches. Foraminiferal, diatom and pollen data are proven as valuable tools for reconstructing paleoenvironmental change in the late Pliocene to Holocene sedimentary record in the Albemarle Embayment (Culver et al., 2008, 2011; Grand Pre et al., 2011).

The purpose of this paper is to present micropaleontological (foraminifera, diatoms and pollen) and sedimentological data from four deep rotational cores (Fig. 1B) in the southern Albemarle Embayment, to interpret paleoclimatic conditions, to reconstruct Quaternary

environments, and to integrate with the similar data from further north in the Embayment. Correlation to the paleoenvironmental interpretations of the Quaternary strata in north-central and central Albemarle Embayment (Culver et al., 2008, 2011) provides an approximately strike-oriented section across most of the basin. The north-central embayment was dissected by fluvial processes during the last glacial period (Culver et al., 2008). The central embayment is a relatively undissected interfluvial region and includes a more complete stratigraphic record of the late Pleistocene (Culver et al., 2011). The southern embayment described herein contains both of these geomorphic elements (interfluvial and incised drainages) as well as the southern margin of the late Cenozoic depositional basin; subtropical facies are present here and not further north. A geometric framework is provided by high-resolution single channel seismic data (Mallinson et al., 2005, 2010) and a temporal framework is provided by radiocarbon, amino acid racemization, and Sr-isotope age estimates (Mallinson et al., 2010; Wehmiller et al., 2010; Wehmiller et al., 2012).

2. Regional Setting

The Albemarle Embayment, a region of thick (>2.5 km) Late Jurassic through Cenozoic deposits on the east coast of the USA (Gohn, 1988), occurs on the seaward-dipping northern flank of the Carolina Platform, a crystalline basement high consisting of rifted continental crust (Gohn, 1988; Klitgord et al., 1988). The Albemarle Embayment is bounded to the north and south by structural highs, the Norfolk Arch and the Mid-Carolina Platform High (a.k.a., the Cape Fear Arch), respectively (Brown et al., 1972; Snyder et al., 1982; Ward and Strickland, 1985; Gohn, 1988; Klitgord et al., 1988). The Cape Lookout High (CLH), an Oligocene depositional feature (Snyder et al., 1982), extends into the Albemarle Embayment region, and defines the

southern edge of a Plio-Pleistocene basin comprising the units discussed in this manuscript (Fig. 1A; Mallinson et al., 2010). Pliocene shelf deposits within the embayment are composed of at least seven, southward prograding seismic sequences (Mallinson et al., 2005) and the overlying 90 m thick Quaternary section (depocenter shown in Fig. 1A) contains up to 18 seismic sequences (Riggs et al., 1992). The Pleistocene record is predominantly subhorizontal, inner to mid-shelf sand and muddy sand with minor estuarine and fluvial units within remnants of incised valleys occurring beneath marine transgressive surfaces (Mallinson et al., 2005, 2010; Culver et al., 2008, 2011; Farrell et al., 2013). The youngest valleys, incised during the last glacial lowstand by the paleo-Roanoke, paleo-Neuse and paleo-Tar rivers (Riggs et al., 1992; Mallinson et al., 2005, 2010; Culver et al., 2007, 2008, Farrell et al., 2013), are filled by latest Pleistocene fluvial gravel and estuarine silt and mud overlain by early to mid-Holocene shallow shelf and bay deposits and late Holocene barrier island and estuarine sediments (Culver et al., 2008, 2011; Grand Pre et al., 2011; Kemp et al., 2011; Farrell et al., 2013). Holocene deposits are almost 30 m thick in the paleo-Roanoke valley (Mallinson et al., 2005; Culver et al., 2008, Farrell et al., 2013) and less than 1 m thick along the mainland coast of Pamlico Sound (Hoffman et al., 2007; Farrell et al., 2013). The paleo-Roanoke River valley dissects the north-central Albemarle Embayment (Mallinson et al., 2005; Culver et al., 2011; Farrell et al., 2013) and the southern embayment is eroded by the paleo-Neuse/paleo Tar drainage (Mallinson et al., 2010). The central embayment is relatively undissected and contains a more complete stratigraphic record for the later Pleistocene (Mallinson et al., 2010; Culver et al., 2011; Farrell et al., 2013).

3. Materials and Methods

Well-recovered continuous rotasonic cores (OBX-14, 15, 16) were taken on Ocracoke Island, southern Outer Banks; a mainland core (MLD-02) was taken on Cedar Island (Fig. 1B; Table 1). These cores continue and complete the generally strike-oriented section of cores across the Albemarle Embayment documented by Mallinson et al. (2005, 2010), Culver et al. (2008, 2011) and Farrell et al. (2013) (Fig. 1A, C, D). Core sites were selected based on geophysical data in the adjacent Pamlico Sound (Mallinson et al., 2005; 2010), geographic coverage and accessibility. Cores were logged (following Farrell et al., 2012, 2013; modified from Folk, 1980) and sampled for radiocarbon, amino-acid racemization (AAR), and Sr-isotope age estimation and microfossil study. Samples for foraminifera, diatoms and pollen (approximately 3 cm-thick quarter-rounds of core) were taken above and below contacts and at varying intervals within thicker units.

3.1 Foraminifera

Ninety-two samples from the four cores were processed (using the protocol of Culver et al., 2008) and foraminifera were concentrated using sodium polytungstate (Munsterman and Kerstholt, 1996). Where possible, 100 to 300 foraminifera were picked at random from aliquots or, when rare, from the entire >63 micron portion of each sample. Twenty-five samples were barren of foraminifera. Foraminifera were compared with illustrations in the published literature (e.g., Culver and Buzas, 1980, and included references) and identifications were confirmed by reference to type material housed in the Cushman Room, Smithsonian Institution, Washington, D.C. and the Heron-Allen Room, The Natural History Museum, London.

Following Culver et al. (2008, 2011), recognition of patterns in the benthic foraminiferal data was aided by cluster analysis (Mello and Buzas, 1968) (SYSTAT, Ward's linkage method and Euclidian distances) utilizing normalized abundance data of all taxa (66) constituting 2% or

more of the assemblage in any sample. The species composition of each cluster group was examined via the following simple metrics (Hazel, 1977); occurrence (O; the number of times a species occurred in a cluster group), constancy (C; the percentage of samples in which the species occurred in each cluster group), and biofacies fidelity (BF; a measure of species faithfulness to a cluster group). A second cluster analysis was performed including data from OBX-17 (Fig. 1) to facilitate correlation with cores (OBX-10, 11, 12, 13, 17) documented in Culver et al. (2011).

3.2 Diatoms

Five samples from OBX-14, processed followed the methodology of Zong and Horton (1998), contained diatoms. Samples from OBX-15 and 16 were barren of diatoms. Valves were identified by reference to van de Werff and Huls (1958-1966) and Hartley (1996) and their ecological classification (polyhalobous, fully marine; mesohalobous, brackish water; oligohalobous-halophilous, brackish-fresh; oligohalobous indifferent, fresh-brackish; halophobous, fresh water) was based on Denys (1991, 1992) and Vos and de Wolf (1993).

3.3 Pollen

Pollen was isolated from 23 samples taken from cores OBX-14, 15, 16 and MLD-2 using standard palynological techniques (Traverse, 1988; Willard et al., 2003); at least 300 pollen grains per sample were counted when possible. Pollen data (lodged in the Neotoma Paleoecology Database: <http://www.neotomadb.org/about/category/database>) were compared to a modern pollen database from the Mississippi Sound (Edwards and Willard, 2001), Chesapeake Bay (Willard et al., 2003), the western Atlantic Ocean (Litwin and Andrie, 1992; Willard et al., 2005), and the eastern Canada Shelf (Mudie, 1980, 1982) to determine paleoenvironmental conditions. Using the modern analogue technique and squared chord distance (SCD) measure

(Overpeck et al., 1985), core samples were considered to be analogous to modern samples when they had SCD values ≤ 0.15 . Pollen data were also used to constrain the age of sediments.

3.4. Amino Acid Racemization Age Estimates

Seventy-seven mollusc samples, representing either whole shells or shell fragments (*Mercenaria*, *Mulinia*, *Spisula*, and *Crassostrea*) (Table 2), were analyzed for amino acid racemization (AAR) using gas chromatographic (GC) methods outlined in Wehmiller and Miller (2000) or reverse phase liquid chromatographic (RPLC) methods described in Kaufman and Manley (1998). Eight statistically distinct, *Mercenaria*-based aminozones are recognized in the region (Wehmiller et al., 2010): AZ2, AZ2+, AZ3-, AZ3+, AZ3.5, AZ4-, AZ4, AZ4+ (Table 3), although not all are recognized in the cores discussed here. The age estimates for these regional aminozones (Table 3) are derived from a non-linear kinetic model calibrated with $^{87}\text{Sr}/^{86}\text{Sr}$ analyses (Wehmiller et al., 2010; Wehmiller et al., 2012). *Mulinia*-based subgroups A1, A2, B1, B2, B3, and C1 and C2 (Table 3) were also used to estimate ages of sedimentary units (Wehmiller et al., 2010). Some foraminifera were also dated using $^{87}\text{Sr}/^{86}\text{Sr}$ values (Mallinson et al., 2010). Age estimates assigned to stratigraphic units are based on AAR results in combination with other taphonomic and lithostratigraphic information.

3.5. Radiocarbon Age Estimates

Radiocarbon age estimates were obtained for 21 samples of plant fragments (wood, stems, leaves, bark), and several mollusks (Table 4). Organic carbon samples were washed in distilled water and treated with acid-base-acid leaches to remove inorganic carbon and mobile humic/fluvi phases. Inorganic carbon samples were treated with phosphoric acid. Radiocarbon ages, analyzed at the National Ocean Sciences Accelerator Mass Spectrometry (NOSAMS)

facility, were calibrated using the IntCal09 dataset for plant material and, with no local reservoir correction (following Culver et al., 2008, 2011), the Marine 09 dataset for shells (Reimer et al., 2009).

4. Results and Paleoenvironmental Interpretations

The general patterns of foraminifera in the four rotasonic cores (Figs. 2–5) are described, followed by discussion of the results of the cluster analysis. Paleoenvironmental change through time for each core is then described from northeast to southwest (OBX-15, OBX-16, OBX-14, MLD-02).

4.1. Foraminiferal Patterns

Foraminifera were not recorded from the uppermost ca. 6 m of MLD-2 and the lowermost part of OBX-14 and 15. Within the foraminifera-bearing sections, all cores exhibited one or more barren zones of varying thickness (Figs. 2–5). The calculated number of foraminiferal tests per 100 g dry weight of sediment is variable, ranging from less than 10 specimens to more than 2.5 million specimens (e.g., OBX-15; Fig. 2). Samples from the Holocene are characterized by fewer foraminifera compared to the Pleistocene. Species richness (number of species in a sample), although affected by number of specimens picked per sample, mimics this pattern (e.g., MLD-02; Fig. 5). Percent planktonic foraminifera in each sample also increases where species number of specimens and number of species is high (e.g., OBX-15; Fig. 2). The maximum value of 10% is reached in the sample with the greatest number of specimens per sample (OBX-15; Fig. 2).

Cluster analysis of benthic foraminiferal data defined four groups (biofacies A to D). Group membership of each sample containing foraminifera is indicated on the core logs (Figs. 2–

5). A northeast-southwest geologic section was constructed to show correlations between cores based on lithology, seismic data, microfossils and paleoenvironmental interpretations determined from these data (Fig. 6). Group A samples consistently have a greater number of species per sample than groups B, C and D. Group B has the lowest number of species per sample but these values are low due to the low number of specimens per sample available to be picked. The number of specimens picked per sample is generally the same in groups C and D but group D samples consistently exhibit higher species richness (Figs. 2–5).

Occurrence, constancy and biofacies fidelity were calculated to determine the species responsible for the clustering of samples (Table 6). Forty-nine taxa are unique to a group (BF = 10); of these 39 taxa are restricted to group A, three to group C and seven to group D. All of these 49 taxa have very low occurrences (occur in few samples). Few species have both high BF and C values; those taxa with both BF and C values of 4 or more per group were arbitrarily defined as “characteristic” of that group (Table 6). *Elphidium excavatum* occurs in all samples in this study (C = 10 in every group) and, therefore, has low BF scores; thus it is not “characteristic” of any group. Group B has relatively low species richness (it contains 33 taxa) (Table 6). In contrast, group A has very high species richness with 110 taxa, many of which are rare (O of 1, C of 1 and BF of 10). Cluster group B has high dominance (only one characteristic species (*Elphidium galvestonense*) whereas cluster groups A and D have 14 and 19 characteristic species respectively and, thus, exhibit less dominance (Table 6). The number of species composing the four groups is 110, 69, 59 and 33 (Table 6). In the central Albemarle Embayment, four groups contained 55, 50, 42 and 14 species (Culver et al., 2011). In the northern Albemarle Embayment, six groups contained 35, 35, 34, 31, 4 and 1 species (Culver et al., 2008). This indicates that the major modern biogeographic boundary at Cape Hatteras, that separates lower

diversity assemblages to the north and higher diversity assemblages to the south (Culver and Buzas, 1980; Buzas and Culver, 1981), existed throughout the Pleistocene.

4.2. *Paleoenvironmental Interpretations of Foraminiferal Assemblages*

Paleoenvironmental interpretations of foraminiferal assemblages are based on modern foraminiferal distributional data (in particular, Grossman and Benson, 1967; Schnitker, 1971; Ellison and Nichols, 1976; Culver and Buzas, 1980, and included references; Scott and Medioli, 1980; Poag et al., 1980; Workman, 1981; Culver and Snedden, 1996; Culver et al., 1996; Woo et al., 1997; Culver et al., 2006; Vance et al., 2006; Abbene et al., 2006; Horton and Culver, 2008; Pruitt et al., 2010). Environments defined from foraminiferal assemblages often include the term “shelf” more broadly than that defined sedimentologically in facies models (see Farrell et al., 2013). Here, the definition of “Undifferentiated Shelf” palaeoenvironments (both Pleistocene and Pliocene) in Figure 6 includes a broad range of intertidal to subtidal deposits of normal marine salinity (e.g.: shoreface (upper and lower), ebb-tidal delta, bona-fide shelf). Included as “Undifferentiated Shelf”, for example, are all five (shelf to shoreface), sedimentologically and geomorphically-defined facies associations depicted in Farrell et al. (2013, their fig. 14). To date, a discrete shoreface environment has not been identified using microfossil assemblages. This non-specificity with respect to differentiating oceanside environments is currently the subject of new research.

The foraminiferal assemblages of group A have high species richness, relatively low dominance, abundant small (<100 microns) specimens, many relatively rare taxa and high percentage of planktonics. Samples characterized by this assemblage generally occur in fine sand and mud in all four cores (Figs. 2–5). This assemblage is also restricted to Pleistocene sediments except for two sandy samples in OBX-16 (Fig. 3). *Elphidium excavatum* occurs in all samples,

but fourteen additional taxa are characteristic of group A (Table 6). Several of these (e.g., *Bolivina lowmani*, *Bolivina variabilis* and *Fursenkoina fusiformis*) are generally infaunal (Corliss and Chen, 1988) and commonly occur in reduced oxygen environments (Poag, 1985; Snyder et al., 1988; Sen Gupta and Machain-Castillo, 1993); they are generally found today at mid-shelf depths off the mid-Atlantic coast of North America (Culver and Buzas, 1980; Poag et al., 1980; Culver and Snedden, 1996). Relatively abundant planktonic foraminifera (Figs. 2–5) also indicate inner to middle shelf environments (Grimsdale and Morkhoven, 1955; Murray, 1976). In summary, most samples containing group A foraminiferal assemblages accumulated in relatively low energy conditions, at times with reduced oxygen conditions, at inner to mid-shelf depths. These assemblages are equivalent to those of group C in the central Albemarle Embayment (Culver et al., 2011) and group Bm in the north-central Albemarle Embayment (Culver et al., 2008). However, several epifaunal (Corliss and Chen, 1988) species typical of inner shelf, well oxygenated environments (Grossman and Benson, 1967; Schnitker, 1971, Culver and Buzas, 1980) also occur in less muddy group A samples (*Cibicides fletcheri*, *Cibicides* sp., *Quinqueloculina recta*, *Quinqueloculina seminula*, *Quinqueloculina* sp., and *Textularia* cf. *T. gramen*). These assemblages are comparable to those of group Bs in the north-central Albemarle Embayment (Culver et al., 2008).

High dominance, low species richness group B is generally restricted to Holocene clean sand (Figs. 2–5). *Elphidium excavatum* dominates (Table 5) and planktonic foraminifera are rare. *Elphidium galvestonense* is the sole characteristic species of this assemblage (Table 6). This species can occur commonly in high salinity estuaries/lagoons (e.g., Pruitt et al., 2010) but it can also occur on the shallow inner shelf south of Cape Hatteras (Abbene et al., 2006). Other relatively common taxa in group B (e.g., *Ammonia parkinsoniana*, *Cibicides lobatulus*,

Elphidium gunteri, *Elphidium mexicanum*, *Hanzawaia strattoni* and *Quinqueloculina seminula*) are typical on the modern inner shelf off North Carolina (Schnitker, 1971; Workman, 1981; Stanton, 2008). This shallow inner shelf assemblage is comparable to that of group D in the north-central Albemarle Embayment (Culver et al., 2008) and group B in the central Albemarle Embayment (Culver et al., 2011).

Samples containing group C assemblages are generally from both Holocene and Pleistocene clean sand (Figs. 2–5). *Elphidium excavatum* and *Ammonia parkinsoniana* dominate moderately diverse assemblages (Table 5) and two additional species, *Elphidium mexicanum* and *Elphidium subarcticum*, both common on the inner shelf (e.g., Schnitker, 1971; Workman, 1981; Culver and Snedden, 1996), are characteristic of group C (Table 6). Planktonic foraminifera, indicating open marine inner shelf waters (Grimsdale and Morkhoven, 1955; Murray, 1976), occur in group C (Figs. 2–5) but are generally less abundant than in group A. Thus, the assemblages composing group C, like those of group B, are typical of normal salinity environments that characterize the inner shelf off North Carolina at the present time (Schnitker, 1971). Group C of this study is comparable to group D in the north-central Albemarle Embayment OBX cores (Culver et al., 2008) and group D of the central Albemarle Embayment (Culver et al., 2011).

Group D assemblages occur mainly, but not exclusively, in Pleistocene sediments of varying grain size (Figs. 2–5). *Elphidium excavatum* comprises 42% of assemblages (Table 5) but the 14 characteristic species (several in common with the characteristic species of group A) (Table 6) reflect the relatively high species richness of group D assemblages. Group D and group A assemblages have three of the four most dominant species in common (Table 5). Group D assemblages, like those of group A, are also generally characterized by high specimen abundance

and relatively high percentages of planktonic foraminifera (Figs. 2–5). The reason samples characterized by group D assemblages cluster with group C assemblages rather than group A assemblages is probably due to the high number of relatively rare taxa in the latter. The environment of deposition indicated by group D assemblages, therefore, is more similar to that of group A than of group C; that is an inner to mid-shelf, sometimes low energy, sometimes reduced oxygen environment.

4.3. Age Estimates

None of the planktonic foraminifera were useful for distinguishing Pliocene from Pleistocene sediments. However, macrofossils (bivalve, echinoid) from the basal carbonate in OBX-14 suggest recovery of late Pliocene to early Quaternary sediments (P. Weaver, personal communication; Mallinson et al., 2010). Five samples of carbonate sediment from basal units in OBX-14, OBX-16 and MLD-02 were investigated for calcareous nannofossils but they are barren (J. Self-Trail, personal communication). The AAR and Sr-isotope estimates indicate that the cored sediments are Quaternary with a Sr-isotope maximum age of 2.4 Ma, and AAR maximum age of 1.84 Ma (Mallinson et al., 2010; Wehmiller et al., 2010; 2012). AAR data indicate eight possible chronostratigraphic units (Tables 2, 3) comprising the various seismically and lithologically defined depositional sequences. These are further discussed below with respect to each site and the overall stratigraphic framework.

4.4 OBX-15

4.4.1. Age Estimates

Geophysical data indicate that Pliocene deposits are approximately 10 m below the base of this core (Fig. 6; Mallinson et al., 2010). Pollen analysis was attempted on three samples from 39.97, 42.42 and 44.44 m. The lower two were barren and the shallowest did not contain age-

diagnostic taxa. From 39.73 m to 31.1 m, several *Mercenaria* (aminozone AZ4) and *Mulinia* (Group C1)-based age estimates range from 1450 to 960 ka. (Tables 2, 3; Fig. 2). A *Mulinia* group age estimate from 27.83 m is 770 to 530 ka (B3). A *Mercenaria mercenaria* valve from 22.65 m has an age range of 36,681 to 36,121 cal yr B.P.; AAR data from the same depth assign a *Mercenaria* valve to aminozone AZ2 (80 ka). A *Mulinia* age estimate from slightly shallower (22.56 m) is 125 to 160 ka (A2). Reworking of shell material from older deposits is also indicated by a *Mercenaria* from 22.38 m that belongs to aminozone 3+ (290 to 430 ka; Table 3). A *Mercenaria* from 15.67 m belongs to aminozone AZ2, with an age estimate of 80 ka (Tables 2, 3; Wehmiller et al., 2010; Wehmiller et al., 2012).

Holocene age estimates are at 13.66 m core depth. A *Chione cancellata* valve has a 2-sigma age range of 7443 to 7204 cal yr B.P. (Table 4) and AAR data also assign it to the Holocene (Fig. 2); woody plant fragments from the same depth have a slightly older 2-sigma age range of 8413 to 8310 cal yr B.P. (Table 4; Fig.2), suggesting reworking of this sample.

4.4.2. Paleoenvironmental Interpretations

The lower ca. 6 m of OBX-15, barren of foraminifera and pollen (Fig. 2), is generally sandy with burrows and traces of horizontal laminations. This section does not contain clean, coarse sand and gravel typical of fluvial deposits elsewhere in the Albemarle Embayment (e.g., OBX-02, 03 and 05 in the paleo-Roanoke River valley; Culver et al., 2008), and is interpreted as marine (inner shelf) in origin (Fig. 6), possibly leached of carbonate, including foraminifera. The overlying ca. 1.5 m of fine sand and mud is also barren of foraminifera but contains a *Quercus* and *Pinus* dominated pollen assemblage. No modern analogs were identified for this assemblage, however the common occurrence of *Carya*, *Ostrya/Carpinus*, *Fagus* and *Poaceae* suggest

deposition under a cooler than modern climate. A freshwater wetland environment is tentatively suggested for this unit (Fig. 6).

From ca. 39 to 18 m alternating sand and mud layers contain foraminifera (assemblage A followed up-core by assemblage D) (Fig. 2) indicative of low oxygen, low energy inner to mid shelf environments becoming more oxygenated and higher energy up-core. This trend is probably related to up-core shallowing as indicated by the decrease in specimen numbers per 100 g of sediment and in the decreasing percent of planktonic specimens up-core (Fig. 2). The 39 to 18 m section of core, however, contains three major seismic reflectors (Q30, Q30b and Q50) associated with coarser lag deposits, and represent at least three depositional sequences (Fig. 6). Seismic correlations here are projected laterally approximately 5 km (Mallinson et al., 2010).

From 18 m to 14 m, Pleistocene sand is barren of foraminifera. Holocene sand above reflector Q99, which marks the Pleistocene/Holocene boundary (Fig. 2, 6), is characterized by shallow inner shelf foraminiferal assemblages B and C (Fig. 2). The lowermost 2 m of the Holocene section is muddy and rich in plant material and is interpreted as estuarine or back-barrier in origin. Above this is shoreface sand overlain by a barrier island complex, which could include inlet, beach, overwash, and dune sands.

4.5. OBX-16

4.5.1. Age estimates

The lowermost 30 cm of this core are composed of bioclastic hash. Planktonic foraminifera are not age-diagnostic but seismic data correlation to OBX-14 suggest that this section is Pliocene in age (Fig. 7; Mallinson et al., 2010). Amino acid racemization age estimates from both *Mercenaria* and *Mulinia* between 52.9 m and 26.5 core depth indicate that the latest Pleistocene is not present and that the Pleistocene section of this core was deposited from 1840

to 660 ka (Tables 2, 3; Fig. 3). A peat-rich sand from 23.93 m core depth was radiocarbon dead (Table 4; Fig. 3). A single fragment of *Mercenaria* from 8.9 m was originally interpreted as AZ2 (80 ka) (Fig. 3; Wehmiller et al., 2010); however, the D/L values in this sample fall in the range of both AZ2 and mid-Holocene ¹⁴C-dated beach shells (Wehmiller et al., 2010). Thus, this sample could be either reworked Pleistocene or Holocene in age because the Pleistocene/Holocene boundary is at ca. 22.32 m core depth based on geophysical data, sedimentology in OBX-16, and correlation to cores to the northeast and southwest (Fig. 6).

4.5.2. *Paleoenvironmental interpretations*

The 30 cm of probable Pliocene carbonate at the base of OBX-16 (Fig. 3) is of shallow, high energy shelf origin. It is a hash composed of barnacle plates, echinoid spines and test fragments, bryozoan fragments, and ostracods. Foraminifera are abundant and the assemblage is dominated by typical shallow shelf taxa (*Textularia*, *Quinqueloculina* with *Amphistegina*). The sample from this unit was not included in the cluster analysis because many specimens of foraminifera were embedded in bioclastic limestone fragments and counts of individual species were not possible. The unit's top is marked by an erosional surface that corresponds to Q30, which has truncated the basal Pleistocene reflector Q0 (Fig. 6). For mapping purposes, the two reflectors (Q30 and Q0) coincide at this locality.

Above Q30 are two sand units interpreted as non-marine valley-fill. The lower unit is a mottled quartzose sand (3m thick) crosscut by large root traces or burrows that are partly impregnated with soft carbonate (mobilized from underlying unit). This unit is iron-stained/cemented at its base and includes humates (dark brown organic-rich stains). Near its top a few foraminifera belonging to shallow shelf assemblage C are present. These specimens are, however, recrystallized and clearly reworked from the underlying Pliocene shell hash. This unit

is interpreted as a terrestrial, perhaps wetland forest or bog deposit that was established on top of fluvial channel sands.

A sharp facies contact at ca. 50 m core depth separates the lower carbonate-impregnated sand from an overlying loose, gravelly sand unit. Above the contact is a ca. 6 m thick (50.58–45.03 m), fining upwards, gravelly sand barren of foraminifera and interpreted as fluvial in origin (Figs. 3, 6). Pollen isolated from the upper part of this unit is dominated strongly by *Pinus*; *Quercus*, *Fagus*, *Tsuga*, and *Carya* are common elements of this no-analog assemblage. The common occurrence of *Fagus* (6%) and *Tsuga* (4%) suggest deposition in a cooler than modern climate. Above this, from 45.03 m to 31.77 m (the approximate level of reflector Q30b) is a marine sand sequence, in part barren of foraminifera, but characterized by shallow shelf foraminiferal assemblage C. Pollen was isolated from four samples within this interval; all were dominated by *Pinus* and *Quercus*, with varying abundances of *Carya*, *Liquidambar*, *Tsuga*, and *Fagus*. There are no modern analogs for these samples, but the common occurrence of *Fagus* and *Tsuga* (each comprising 2-7% of assemblages) suggests deposition in cooler than modern climates. From 31.77 m to 27.10 m is a generally fining upwards sequence of sand and mud characterized by inner to mid-shelf, foraminiferal assemblage A. The percent planktonic foraminifera reaches 6% (Fig. 3). Pollen assemblages in this interval are dominated strongly by *Pinus* (70-88%), and *Quercus* pollen is subdominant. Modern analogs for the samples include pine-oak forests that range from the North Carolina coast through Florida and the Gulf Coast.

From 27.10 to 24.75 m is another fining upwards sequence characterized by relatively low diversity inner shelf assemblage C in coarse sand overlain by higher diversity assemblage D (high number of specimens per 100g of sediment) in fine sand. A fining upwards peaty sand, lacking fossil fragments, from 24.75 to 24.00 m is interpreted as fluvial in origin; this is overlain

by estuarine deposits from 24.00 to 23.20 m. The fluvial and estuarine facies represent a remnant of a valley-fill that is truncated by a transgressive ravinement surface corresponding to seismic reflector Q50 (Mallinson et al., 2010).

The ca. 1 m of core (23.20–22.32 m) (Figs. 3, 6) above the transgressive ravinement surface (Q50) is characterized by several thin coarse-grained muddy, gravelly sand units, burrowed, with evidence of subaerial exposure, and containing foraminiferal assemblages B and C. The sample with assemblage B is tentatively interpreted as estuarine in origin. The sample with assemblage C (Fig. 3) has relatively high species richness, abundant specimens, 3 % planktonic foraminifera, and contains two taxa (*Bolivina lowmani* and *Rosalina* sp. A) that are typical of inner to mid-shelf assemblage D. The Pleistocene Holocene boundary is at 22.32 m core depth coinciding with Q99.

The top 22.32 m of core OBX-16 is composed of 2 to 3 m thick sand units characterized mainly by inner shelf foraminiferal assemblage B; two samples contain higher diversity foraminiferal assemblage A, indicating increased influence of offshore waters (e.g., see Grand Pre et al., 2011). This Holocene sand is interpreted as representing shoreface sand overlain by modern barrier island sand of Ocracoke Island.

4.6. OBX-14

4.6.1. Age estimates

Correlation of cores in the northern Albemarle Embayment with geophysical data (Mallinson et al., 2010) indicates that the lower part of OBX-14 (below 36.30 m) is Pliocene in age (Figs. 4, 6). This is supported by the presence of the mollusc *Carolinapecten eboreus* and the echinoid *Mellita* (P. Weaver, personal communication) in these basal carbonate sediments but, given the stratigraphic ranges of these taxa, not demonstrated conclusively. In Lee Creek mine

(on the southern shore of the Pamlico River; Fig. 1A), *C. eboreus* is common in the mid-Pliocene upper Yorktown Formation equivalent to Mansfield's (1944) Zone 2 and the mid-Pliocene Duplin Formation of southern North Carolina (Gibson, 1987), although it does range up into the early Pleistocene James City Formation of North Carolina (Ward and Blackwelder, 1987). Several species of *Mellita* have been recorded in the Yorktown Formation and Croatan Formation (James City Formation equivalent) of North Carolina (Kier, 1983). Planktonic foraminifera are not age-diagnostic.

Thirteen 2-sigma radiocarbon age estimates on plant material and shells of several bivalve species, from 22.43 m to 20.03 core depth, range from 6714–6400 to 7689–7587 cal yr B.P. (Table 4; Fig. 4). AAR data from the same interval confirm a Holocene age (Table 2, Fig. 4).

Three pollen samples from 25.06 m to 22.95 m are dominated by *Pinus*; relatively abundant *Picea* pollen (2-6%) suggests deposition during cooler than modern conditions, but the exact time during the Pleistocene cannot be determined with the pollen. Samples from 22.59 m and 21.76 m are dominated by *Quercus*, and *Pinus* pollen is subdominant. *Picea* pollen is absent to rare, and *Liquidambar*, *Nyssa*, and *Fagus* pollen is more common than in lower samples in this core. Dominance of *Quercus* pollen in these two samples is consistent with early Holocene records from the Atlantic Coastal Plain (Watts, 1979; Willard et al., 2005) and the early Holocene age estimates in this section of OBX-14. A sample from 20.36 m is dominated by *Pinus* pollen (68%), and *Quercus* pollen is subdominant (15%); the dominance of *Pinus* pollen suggests a late Holocene age (<5 ka) based on comparison with well-dated Holocene records from the Atlantic Coastal Plain although radiocarbon age estimates suggest a slightly older age at this depth (Fig. 4).

4.6.2. *Paleoenvironmental interpretations*

The bottom 11 m of OBX-14 is composed of several carbonate facies of probable mid-Pliocene age (Figs. 4, 6). The uppermost 4 m of this unit contains inner to mid-shelf, high species richness foraminiferal assemblage A. Specimens are recrystallized and include many *Amphistegina* and thus these assemblages are distinct from assemblage A from known Pleistocene sediments. This assemblage likely characterizes the entire carbonate sequence but foraminifera are embedded in limestone fragments and, thus, the lowermost four samples were not included in the cluster analysis. Reflector Q0, which represents the Pliocene/Pleistocene boundary, is at the top of this carbonate section at 36.30 m (Fig. 6). Above Q0, is a 0.48 m thick gravelly sand with shell hash and foraminiferal assemblage A, both reworked.

Identifying the position of reflector Q30b in this core is difficult because of disruption from coring, bioturbation, and lithologically similar sand facies above and below the boundary. Q30b is placed at a core depth of 29.72 m; here a contact separates better-stratified, better sorted medium quartz sands below from overlying unconsolidated, coarser, more poorly-sorted sands with mollusk hash and poorly preserved primary stratification. Below Q30b (29.72 m) sands within the interval 35.82 m to 29.72 m are barren of foraminifera (Fig. 4). In the basal sand above Q30b, the sample from 29.66 m is characterized by foraminiferal assemblage C, indicating shallow inner shelf conditions. Above this, a barren sand occurs at core depth 28.11 m. This fines upward into a sandy mud barren of foraminifera at 27.20, but containing a *Pinus*-dominated pollen assemblage at 27.13 m. Pollen of *Picea*, *Quercus*, *Poaceae*, and other herbaceous taxa is also common in this sample but fern spores are abundant (22% of the assemblage). No modern analogs were identified for this assemblage but the abundance of fern spores and pollen of herbaceous plants could result from deposition close to shore or perhaps during an interval of

increased fluvial discharge. The barren mud that contains pollen is separated from an overlying well-stratified marine mud by a poorly-sorted bioturbated sand (at core depth 25.91–26.18 m) with a fabric caused by large, sand-filled burrows (at 25.91–26.43 m) that cross-cut the underlying mud, creating a brecciated appearance. Burrows that originate in this bioturbated sand, interpreted as an erosional lag bed, are infilled with coarse quartz and mollusk hash, and extend downward into underlying units (to a depth of 28.35 m).

The boundary at the top of the bioturbated sand (25.91 m) is a flooding surface that is overlain by well-stratified marine mud (core depth 25.91–22.93 m). Sandy mud at 25.00 m core depth contains shallow shelf foraminiferal assemblage B; mud at the top of the sequence contains foraminiferal assemblage D with high numbers of specimens and species and increased percent planktonic foraminifera (Fig. 4). Above the base of this mud unit (core depth 25.91 m), this sequence exhibits an increasing offshore marine influence (likely a deepening) up-core to 22.93 m, the level of seismic reflector Q99 which represents the Pleistocene/Holocene boundary. Three pollen samples from the muddy upper part of this sequence are dominated by *Pinus* pollen (49–61%) with lower percentages of *Quercus* (4–15%) and *Picea* (2–6%) pollen. Fern spores also are common, comprising 7% of assemblages. These assemblages are analogous to those of modern offshore samples collected near southeastern pine forests of the Gulf Coastal Plain (Mississippi) and Atlantic Coastal Plain (Florida northward to Virginia).

Immediately above the Pleistocene/Holocene boundary is a 3 m thick unit of heterolithic strata containing abundant shell and plant material (Fig. 4). A sample near its base contains shallow shelf foraminiferal assemblage C but two samples near the top of this unit are barren of foraminifera. Diatom assemblages from five samples in this unit are also variable in character. The deepest sample (22.65 m) contains 65% polyhalabous taxa and 26% mesohalobous taxa;

dominated by *Cocconeis scutellum* (19%), suggesting a fully marine environment. Evidence for an increased brackish influence is preserved at 21.79 m where polyhalobous diatoms decrease to 52%; *Cocconeis scutellum* decreases to 4% of the assemblage and the marine/brackish epipsammous *Opephora marina* and *Achanthes delicatula* comprise 19% and 9% of the assemblage, respectively. Increased brackish influence continues to 21.25 m where polyhalobous taxa decrease to 19% of the assemblage and mesohalobous (brackish) taxa increase to 50%. *Cocconeis scutellum* comprises only 2% of the assemblage, *Achanthes delicatula* comprises 39% and the oligohalobous indifferent, freshwater epiphyte *Nitzschia amphibia* comprises 8% of the assemblage. Samples from 20.76 m and 20.42 m preserve evidence of a return to fully marine conditions with 55% and 70% polyhalobous species, respectively. *Cocconeis scutellum* is abundant (18% and 24%, respectively) whereas *Achanthes delicatula* is rare; the marine taxa *Dimeregramma minor* (7% and 6%, respectively) and *Grammatophora oceanica* (5% and 6%, respectively) are also important components of assemblages.

Pollen assemblages from the lower part of this unit (22.59 m and 21.76 m) are dominated by *Quercus* (45-53%), and *Pinus* pollen is subdominant (30-40%). *Picea* pollen is absent to rare, and *Liquidambar*, *Nyssa*, and *Fagus* pollen is more common than in pollen assemblages from the underlying Pleistocene unit. Dominance of *Quercus* is consistent with early Holocene records from the Atlantic Coastal Plain (Watts, 1979; Willard et al., 2005). These assemblages are analogous to those from the modern Chesapeake Bay, where proximity to oak-hickory-pine forests is reflected by greater abundance of *Quercus* pollen. A sample from near the top of this heterolithic unit (20.36 m) (where fully marine conditions are indicated by diatoms) is dominated by *Pinus* pollen (68%) and *Quercus* pollen is subdominant (15%). This assemblage is analogous to those of modern offshore samples collected near southeastern pine forests of the Gulf Coastal

Plain and southeastern Atlantic Coastal Plain. This 3 m thick unit is interpreted as estuarine in origin (Fig. 6) and represents fill of the last glacial maximum Pamlico Creek (Fig. 6), which drained what is now Pamlico Sound (Mallinson et al., 2010; Grand Pre et al., 2011). The Holocene sea-level curve for North Carolina (Horton et al., 2009) indicates sea level reached ca. 20 m below present sea level between 9500 and 10,000 cal yr B.P.; age estimates for the estuarine deposits are between 6500 and 7000 cal yr B.P. (Fig. 4).

The top 20 m of core OBX-14 is composed of several medium to coarse sand and sandy gravel units characterized (with one exception) by shallow inner shelf foraminiferal assemblage B (few species and few specimens) (Fig. 4). With one exception, planktonic foraminifera are absent. This sand sequence is interpreted as representing shoreface sand (see Farrell et al., 2013, fig. 14) overlain by modern barrier island sand. The uppermost sample, characterized by foraminiferal assemblage D, was taken from probable fill material.

4.7. MLD-02

4.7.1. Age estimates

Geophysical data (Mallinson et al., 2010) suggest the Pliocene/Pleistocene boundary is at 21.19 m at a lithologic change from cemented moldic bioclastic (or biofragmental) limestone (rudstone/packstone) to shell-rich sandy gravel (Figs. 5, 6). Planktonic foraminiferal assemblages from either side of the boundary are not age-diagnostic but middle Pleistocene Duplin Formation sediments have been recorded at a similar elevation (ca. 20 m below sea level) in two cores 50 km west of MLD-02 along the axis of the Cape Lookout High (Katrosh and Snyder, 1982). Pollen analysis on five samples higher in the core, between 9.91 m and 14.54 m, did not reveal age-diagnostic taxa or assemblages.

All radiocarbon and AAR data from MLD-02 indicate Pleistocene ages (Tables 2, 4; Fig. 5). From 6.48 m to 10.12 m, the indicated age ranges from 80 ka to ca. 430 ka, although the assignment of several *Mulinia* specimens to B2 (340–430 ka) at 7.89 m may indicate reworking. *Mercenaria* valves from 14.36 m and 20.61 m yield AAR age estimates of 960–1840 ka (aminozones AZ4/4+).

4.7.2. *Paleoenvironmental interpretations*

The lowermost 4.73 m of core MLD-02 is a light grey quartz-rich, bivalve moldic limestone, with echinoid spines and bryozoan fragments, of probable mid-Pliocene age. Foraminifera were difficult to extract but a sample at the base of this section clustered within shallow inner shelf assemblage C (Fig. 5). A sample near the top was unique in that it was dominated by *Cassidulina norvangi*; it also clustered within shallow shelf assemblage C.

The Pliocene/Pleistocene boundary, equivalent to seismic reflector Q0, is located between the limestone and overlying shelly sandy gravel at 21.19 m core depth (Figs. 5, 6). This basal gravel and the overlying coarsening upwards sandy sequence is characterized by high species richness, inner to mid-shelf foraminiferal assemblages A and D (Fig. 5). Percent planktonic foraminifera and number of specimens per 100 g of sediment decrease towards the top of this unit suggesting shallowing upwards. Many foraminifera in the highest sample in this section were strongly iron-stained (orange/brown).

A fining upwards sequence of mostly quartzose gravelly sand commences at 14.45 m core depth (Fig. 5); reworked shell gravel occurs at base. Foraminifera are absent from sand samples from the lower half of this sequence. A sample from the uppermost muddy unit contains a few foraminifera that are classified as assemblage B. Pollen assemblages from five samples between 9.88 m and 13.93 m core depth are dominated strongly by *Pinus* (50–78%) with fern

spores, primarily those of *Osmunda*, subdominant (7–23%). In the basal sample at 13.93 m, *Picea* and Ericaceae pollen are more abundant (each comprising 5% of assemblages) than in the other samples; this sample has no modern analogs. Analogs for the upper four samples include modern sites offshore of southeast Atlantic and Gulf Coastal Plain pine forests. The sandy lower part of this sequence is interpreted as fluvial and the uppermost muddy section containing foraminifera as high brackish estuarine. The top of the fluvial-estuarine sequence at 10.24 m is equivalent to seismic reflector Q50 (Figs. 5, 6).

Almost 3 m of coarse sandy, mixed siliciclastic/bioclastic shell-bed gravel overlie the estuarine unit. Three samples from this unit are characterized by shallow inner shelf foraminiferal assemblage C. Moderately high species richness is accompanied by relatively high numbers of specimens per 100 g of sediment. Similar shell beds occur at the same stratigraphic level across the entire Albemarle Embayment (Culver et al., 2008, 2011; Mallinson et al., 2010). Foraminiferal assemblage C also characterizes overlying muddy sand up to 6.04 m core depth, the Pleistocene/Holocene boundary, equivalent to seismic reflector Q99 (Figs. 5, 6). The Holocene section is composed of estuarine barrier island sand and is barren of foraminifera (Fig. 5).

5. Nature and Timing of Paleoenvironmental Change

A generally northeast-southwest geologic section along the modern southern Outer Banks (Fig. 6) is used to interpret the geometry and age of Quaternary deposits filling the southern Albemarle Embayment. Seismic stratigraphic units (SSUs) and the major, high amplitude, regionally continuous acoustic reflections (Q0, Q10, Q30, Q30b, Q50 and Q99) that

define them are modified from Mallinson (2010) and summarized in Table 7. AAR data (Tables 2, 3; Fig. 6) constrain the age of SSUs.

Q0, a regionally continuous reflection that marks the contact between Pleistocene and Pliocene units (Mallinson et al., 2010), shallows towards the southwest of the section as Cape Lookout High is approached (Fig. 6). Q0 was penetrated in OBX-07 in the north-central Albemarle Embayment (Culver et al., 2008) but not in the deeper central Albemarle Embayment, although geophysical and pollen data from shelf sediments suggest Pliocene deposits were close to the base (within 10 m) of core OBX-10 (Culver et al., 2011). In OBX-7, sediments beneath the level of Q0 yielded Pliocene planktonic foraminifera (Culver et al., 2008). In the southern Albemarle Embayment, based on the interpreted level of Q0, Pliocene strata were reached in OBX-16, OBX-14 and MLD-02, in the latter core at ca. 20 m below modern sea level (NAVD 88; Fig. 6). Macrofossils in the shallow shelf carbonate strata beneath the level of Q0 suggest mid-Pliocene to early Pleistocene ages, however these carbonates are assigned to the Pliocene based on seismic correlation. They may represent carbonate shoal facies in the clastic-dominated, fossiliferous middle Pliocene Duplin Formation of southern North Carolina and South Carolina (Rhodes and Conrad, 1985; Dowsett and Cronin, 1990; Ward et al., 1991). In contrast, in OBX-07, in the north-central Albemarle Embayment, correlative Pliocene strata, based on their planktonic and benthic foraminiferal assemblages, consist of low energy, reduced oxygen, mid-shelf muds, and likely belong to the Yorktown Formation (Culver et al., 2008).

Reflections Q0 and Q30/Q30b constrain SSU I-III (Table 7). These early Pleistocene subhorizontal inner to mid-shelf marine units are present in all four cores of this study (Fig. 6). They contain aminozones AZ4+ and AZ4 and *Mulinia* subgroup C1, indicating deposition between 960 to 1840 ka BP (Table 3). In OBX-16, fluvial deposits, beneath Q30, are preserved

in a valley-like depression (Fig. 6A). Pollen data from immediately above Q30 in OBX-15 indicate a cooler than modern climate (Fig. 6B).

The middle Pleistocene record (SSU IV) in the study area is bounded by Q30b and Q50 (Table 7; Fig. 6), although Q50 is eroded in OBX-14 (Fig. 6). Similar to early Pleistocene units, inner to mid-shelf deposits are represented (OBX-14, 15, 16). These strata were deposited across the early/mid-Pleistocene boundary (781 ka) from 980 to 660 ka BP based on the presence of AZ4- and *Mulinia* group B3 (Table 3). However, in central Albemarle Embayment cores, mid-Pleistocene strata are much younger age estimates ranging from 430 to 170 ka BP (Culver et al., 2011; 430–150 ka based on Table 3 of this work). Reworking of older material into mid-Pleistocene units of the southern Albemarle Embayment may explain the large difference in ages, however AAR age estimates are based on whole, yet fragile, *Mulinia* valves. In MLD-02, undated but likely mid-Pleistocene fluvial and estuarine deposits directly underlie Q50 (Fig. 6); pollen assemblages indicate a climate similar to that of today. Thin fluvial and estuarine deposits have a similar stratigraphic position in OBX-16 (Fig. 6). Pollen assemblages (27.13–22.95 m) in OBX-14 above Q30b (at 29.72 m) are interpreted to be from mid-Pleistocene SSU IV due to the presence of mid-shelf foraminiferal assemblages in muds which are typical of the early and mid-Pleistocene but not yet demonstrated to occur in late Pleistocene deposits of the Albemarle Embayment (Culver et al., 2008, 2011, this paper).

Seismic reflection Q50, corresponding to a marine transgressive ravinement surface associated with shelly lag deposits, is continuous in the central Albemarle Embayment (Culver et al., 2011) and occurs in OBX-15, OBX-16 and MLD-2 in the southern Albemarle Embayment (Fig. 6). It is not present in OBX-14 due to fluvial dissection during the last glacial maximum (Mallinson et al., 2010). Q50 (Table 7) likely represents the MIS 6 to 5 (Termination 2)

transgressive ravinement surface (Mallinson et al., 2010; Culver et al., 2011) and overlying shelly lag deposits, and thus indicates the mid-/late Pleistocene boundary. Inner shelf marine sands (transgressive shoreface/foreshore deposits in figure 14 of Farrell et al., 2013) overlying the Q50 transgressive lag, are MIS 5a to 5e deposits (Mallinson et al., 2008). This is generally confirmed by 80 ka age estimates (AZ2) in OBX-15 and *Mulinia* group B2 and A1 age estimates from 430 to 80 ka in MLD-02.

Reflection Q99 (Table 7) occurs in Pamlico Sound and is an amalgamated surface, representing the LGM paleolandscape surface and paleodrainage pattern that was subsequently modified by bay ravinement during Holocene transgression (Mallinson et al., 2010; Zaremba et al., in press). Beneath the barrier islands, however, the Holocene/Pleistocene boundary is defined by a transgressive marine ravinement surface associated with a mid-Holocene shoreline position that was landward of the present shoreline. This surface is herein referred to as Q99b (Fig. 7). Shoreface and barrier islands sands above this surface represent late Holocene shoreline progradation in the study area (Peek et al., 2013; Mallinson et al., 2014). This progradational phase of the North Carolina shoreline began at ca. 4500 cal y BP and is also seen along northern portions of the state (Mallinson et al., 2008; Moran et al., 2014) and south of Cape Lookout (Timmons et al., 2010). In the southern Albemarle Embayment, Q99 defines a paleovalley at OBX-14 (Pamlico Creek) and underneath the modern Pamlico Sound (paleo-Neuse and paleo-Tar rivers) (Mallinson et al., 2010) (Fig. 6). Basal valley-fill deposits comprise estuarine sediments in OBX-14 where pollen assemblages indicate climatic conditions similar to today (Fig. 6B). Thin (2 m) estuarine deposits at the base of the Holocene section in OBX-15 (Fig. 6) are Holocene transgressive deposits that were not fully removed by shoreface ravinement. Estuarine muddy sands (Fig. 6) above Q99 represent the initial marine flooding of the last glacial

drainage system in the early Holocene. Based on the North Carolina Holocene sea-level curve (Horton et al., 2009) flooding occurred in the paleo-Neuse/Tar drainage ca. 9000 cal yr BP (Grand Pre et al., 2011) and a little later in Pamlico Creek (7000 cal yr BP; Grand Pre et al., 2011). The latter is in agreement with the depth below sea level of estuarine sediments in OBX-14.

Most of the up to 20 m thick Holocene sequence beneath the Outer Banks barrier islands is composed of sand units deposited in subtidal shoreface to supratidal barrier island environments (Fig. 6). Surficial sands are reworked by aeolian and overwash processes (Culver et al., 2006). Similar processes, but on a smaller scale have formed and continue to modify the estuarine barrier island on Cedar Island where MLD-02 was cored (Figs. 1, 6).

Culver et al. (2011) noted the shallowing of the Albemarle depositional basin over a series of transgressive-regressive cycles throughout the Quaternary. When the data from this study are included, inner to mid-shelf early Pleistocene deposits, representing transgressive to highstand systems tracts (TST to HST) are overlain by similar mid-Pleistocene deposits in the southern and central Albemarle Embayment and by inner shelf deposits in the north-central embayment. Late Pleistocene marine sediments were deposited in inner shelf settings across the Albemarle Embayment but these are poorly preserved on the northern flank of the Cape Lookout High. Thin lowstand deposits (lowstand systems tract – LST), are indicated by basal fluvial deposits, and are preserved in remnants of incised valleys beneath several TST-HST cycles except in the south-central Albemarle Embayment; this area was generally an interfluvium throughout the Pleistocene with major drainages to the north and the south. This inherited geometry continues today (Fig. 1) with antecedent topography controlling development of younger drainages.

6. Conclusions

Micropaleontological, sedimentological, seismic and chronostratigraphic data from the southern Albemarle Embayment, North Carolina, USA, provide an increased understanding of the pattern and process of basin infilling and environmental change in passive margin shelf basins during frequent high amplitude sea-level fluctuations. These data provide information on the paleoenvironmental and paleoclimatic evolution of this specific region throughout the late Pliocene and Quaternary.

The Pliocene “basement” in this region shallows towards the depositional Cape Lookout High. Pliocene carbonate sediments and fossils reflect a subtropical marine climate and contrast with clastic Pliocene sediments in the northern embayment. Foraminiferal assemblages throughout the Pleistocene exhibit a similar contrast; assemblages have significantly higher diversity in the southern embayment indicating that the location of the modern major biogeographic provincial boundary for shelf organisms at Cape Hatteras remained essentially unchanged over the past 2 million years.

Considered together with similar data from the central and north-central Albemarle Embayment, the geometry of the basin has remained similar throughout the Quaternary. The northern and southern portions were characterized by lowstand fluvial dissection of highstand mid- to inner shelf marine sands and muds. The location of valleys, filled with fluvial, estuarine and shallow shelf deposits is generally inherited from antecedent topography. The south-central part of the embayment was an interfluvial during lowstands. Highstand deposits forming across interfluvial were open inner to mid-shelf sands and muds during the early and mid-Pleistocene and inner shelf sands during the late Pleistocene. Thus the Albemarle Embayment shallowed

through time as the continental shelf prograded eastwards. Preservation of the stratigraphic record during transgressive-regressive cycles was incomplete. In the southern Albemarle Embayment, the late Pleistocene record is limited. Due to the proximity of the Cape Lookout High, there was less accommodation space compared to the central and northern Albemarle Embayment and early to mid-Holocene units had essentially filled the available space.

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TABLE CAPTIONS

TABLE 1 – Depth, elevation and location data for rotasonic cores. Depth is from land surface.

TABLE 2 –Amino acid racemization data for rotasonic OBX and MLD cores. Aminozones (AZ2, AZ2+, etc.) are based on VL values in *Mercenaria*. VL is the average of valine and leucine D/L values. Groups (A, A1, A2, etc.) are based on AG values in *Mulinia* (Wehmiller, 2010). AG is the average of aspartic acid and glutamic acid D/L values. In a few cases, aminozones or groups are assigned based on results for taxa other than *Mercenaria* or *Mulinia*. Age estimates for aminozones are given in Table 3.

TABLE 3 — Summary of *Mercenaria* leucine age estimates for AAR zones derived from alternative kinetic models, and corresponding *Mulinia* subgroups (modified from Wehmiller et al., 2010). Age ranges quoted for each aminozone or subgroup are derived from the extrapolated range of D/L values for calibration samples.

TABLE 4 –AMS ^{14}C age estimates for OBX cores calibrated using IntCal09 and Marine 09 (Reimer et al., 2009). Median probability age estimates are plotted on the figures. NAVD88 is ~15 cm above mean sea level in the study area.

TABLE 5 – Dominant species in cluster groups A to D indicating mean percent of the four most dominant species in all samples of each group.

TABLE 6 – Occurrence (O), constancy (C) and biofacies fidelity (BF) for each foraminiferal species for the groups A to D recognized by cluster analysis. Fidelity and constancy are expressed in tens rounded to the nearest whole number. Large rectangles indicate characteristic foraminiferal species for each cluster group (arbitrarily defined as those taxa with C and BF values of 4 or more). Small rectangles indicate non-characteristic taxa (i.e., low BF values) that occur in most samples in a biofacies (C of 7 or greater). See text for further explanation.

TABLE 7 – Seismic reflection and seismic stratigraphic unit (SSU) summary (modified from Mallinson et al., 2010a) for the Albemarle Embayment. Age estimates based on AAR data from Wehmiller et al. (2010) and strontium isotope data from Mallinson et al. (2010). MIS = Marine Isotope Stage. HST, LST and FSST = highstand, lowstand and falling stage systems tracts, respectively.

FIGURE CAPTIONS

FIG. 1 – Location of study area, the Albemarle Embayment, in the context of the modern shoreline and structure contours showing the depth to the Q0 reflection, interpreted as the top of the Pliocene (Mallinson et al., 2010). A, Satellite image of eastern North Carolina. The location of Figures 1B, 1C and 1D are indicated. NA = Norfolk Arch, CLH = Cape Lookout High. B, Location of four rotasonic drillholes in the southern Albemarle Embayment. A'' – A''' indicates the location of the section in Figure 6. C, Location of rotasonic drillholes and section A–A' in

the northern Albemarle Embayment (Culver et al., 2008). D, Location of rotasonic drillholes, split-spoon cores and section A'-A'' in the central Albemarle Embayment (Culver et al., 2011).

FIG. 2 – Lithologic log of core OBX-15 indicating sample depths, number of benthic foraminiferal species per sample, number of specimens picked per sample, percent planktonics, calculated number of specimens in 100 g dry weight of sediment, depth of pollen samples. b, barren of foraminifera. Horizontal fine dashed lines indicate level of AAR and median probability ^{14}C age estimates (the two lowermost estimates are minimum ages). Shading indicates the Holocene section. See Figure 5 for key to symbols.

FIG. 3 – Lithologic log of core OBX-16 indicating sample depths, number of benthic foraminiferal species per sample, number of specimens picked per sample, percent planktonics, calculated number of specimens in 100 g dry weight of sediment. b, barren of foraminifera. Horizontal fine dashed lines indicate level of AAR and median probability ^{14}C age estimates. Shading indicates the Holocene section. See Figure 5 for key to symbols.

FIG. 4 – Lithologic log of core OBX-14 indicating sample depths, number of benthic foraminiferal species per sample, number of specimens picked per sample, percent planktonics, calculated number of specimens in 100 g dry weight of sediment, and depth of diatom and pollen samples. b, barren of foraminifera. Horizontal fine dashed lines indicate level of AAR and median probability ^{14}C age estimates. Shading indicates the Holocene section. See Figure 5 for key to symbols.

FIG. 5 – Lithologic log of core MLD-2 indicating sample depths, number of benthic foraminiferal species per sample, number of specimens picked per sample, percent planktonics, calculated number of specimens in 100 g dry weight of sediment, depth of pollen samples. b, barren of foraminifera. Horizontal fine dashed lines indicate level of AAR and median probability ^{14}C age estimates (minimum ages). Shading indicates the Holocene section.

FIG. 6 – A, Summary interpretive cross section along the Outer Banks showing paleoenvironments and correlations from OBX-17 (northeast) to MLD-02 (southwest) based on seismic data, lithology, foraminifera, pollen, diatoms, and age indicators (AAR age ranges, median probability ^{14}C age estimates). B, Summary cross section indicating details of paleoenvironmental interpretations. Core OBX-17 (data are presented in Culver et al., 2011) is included on these sections to illustrate the correlation between the central Albemarle embayment (Culver et al., 2011) and the southern Albemarle embayment (this paper).

Figure 1

-46 -150

Figure 3

[illegible]

Figure 5

Key to Symbols (from Farrell et al., 2013)

6 let
A

borehole

Legend for B

Paleoenvironmental trends within a unit

↑ S Shallowing/closer to shore
D Deepening/further from shore

bi	barrier island complex	msh	middle shelf
e	estuarine	if	inlet fill
fl	fluvial	w	freshwater wetland
ish	inner shelf	sf	shoreface

Table 1

Core No.	Latitude (N)	Longitude (W)	Core Depth (m)	Elevation (NAVD 88) (m)
OBX-14	35.11510365	75.98772009	47.2	0.93
OBX-15	35.18939361	75.77922646	47.2	1.01
OBX-16	35.16143795	75.83651149	53.3	1.67
MLD-02	35.01840379	76.31260951	25.9	1.22

Table 2

Locality ID	Sampled interval, feet	Interval top, meters	SampleID	SubSampleID	SampleType	A-Zone (Merc VL)	A-Group (Mul AG)	Notes
MLD-02	21.25	6.48	JW2004-122-001	2007451	<i>Mulinia</i>		A1	¹⁴ C also: OS 67733 (Table 4)
MLD-02	21.25	6.48	JW2004-122-002	2007452	<i>Mulinia</i>		A1	
MLD-02	21.25	6.48	JW2004-122-003	2007453	<i>Mulinia</i>		A1	
MLD-02	21.25	6.48	JW2004-122-004	2007454	<i>Mulinia</i>		A1	
MLD-02	23.5	7.16	JW2004-123-001	2007455	<i>Mulinia</i>		A1	
MLD-02	23.5	7.16	JW2004-123-002	2007456	<i>Mulinia</i>		A1	¹⁴ C also: OS 67833 (Table 4)
MLD-02	23.5	7.16	JW2004-123-003	2007457	<i>Mulinia</i>		A1	
MLD-02	25.9-26.1	7.89	JW2004-124-001	2007461	<i>Mulinia</i>		B2	
MLD-02	25.9-26.1	7.89	JW2004-124-002	2007462	<i>Mulinia</i>		B2	
MLD-02	25.9-26.1	7.89	JW2004-124-003	2007463	<i>Mulinia</i>		B2	
MLD-02	27.45	8.37	JW2004-125-001	2004196	<i>Mercenaria</i>	AZ2		¹⁴ C also: OS 63815 (Table 4)
MLD-02	33.2	10.12	JW2004-128-001	2007430	<i>Mulinia</i>		B1?	
MLD-02	33.2	10.12	JW2004-128-002	2007431	<i>Mulinia</i> or <i>Spisula</i>		B1?	
MLD-02	47.1	14.36	JW2004-129-001	2004153	<i>Mercenaria</i>	AZ4/4+		
MLD-02	67.6	20.61	JW2004-133-001	2004208	<i>Mercenaria</i>	AZ4/4+		
OBX-14	73.2	22.32	JW2004-112	2004151	<i>Mercenaria</i>	H		1; ¹⁴ C also: OS 45330 (Table 4)
OBX-14	73.2	22.32	JW2004-112	2005349	<i>Mercenaria</i>	H		1a
OBX-14	73.6	22.44	JW2004-113	2004193	<i>Mercenaria</i>	H		1a; ¹⁴ C also: OS 45331 (Table 4)
OBX-14	117.5	35.82	JW2004-115-002	2005493	<i>Mercenaria</i>	AZ4+		
OBX-14	117.5	35.82	JW2004-115-003	2005494	<i>Mercenaria</i>	AZ4+		
OBX-15	51.4	15.67	JW2004-064	2006006	<i>Mercenaria</i>	AZ2		
OBX-15	73.4	22.38	JW2004-066	2006007	<i>Mercenaria</i>	AZ3+		
OBX-15	73.8	22.56	JW2004-068-001	2007379	<i>Mulinia</i>		A2	
OBX-15	73.8	22.56	JW2004-068-002	2007380	<i>Mulinia</i>		A2	
OBX-15	73.8	22.56	JW2004-068-003	2007381	<i>Mulinia</i>		A2	
OBX-15	74.3	22.65	JW2004-067-001	2004195	<i>Mercenaria</i>	AZ2		¹⁴ C also: OS 50448 (Table 4)
OBX-15	74.3	22.65	JW2004-067-001a	2005525	<i>Mercenaria</i>	AZ2		
OBX-15	74.3	22.65	JW2004-067-001b	2005526	<i>Mercenaria</i>	AZ2		
OBX-15	74.3	22.65	JW2004-067-002-1	2005346	<i>Mercenaria</i>	[AZ3.5]		2
OBX-15	74.3	22.65	JW2004-067-002-1a	2006008	<i>Mercenaria</i>	[AZ3.5]		2
			JW2004-067-002inner	2005527	<i>Mercenaria</i>	[AZ3.5]		2
OBX-15	74.3	22.65	JW2004-067-002-o	2005345	<i>Mercenaria</i>	[AZ3.5]		2
			JW2004-067-002outer	2005528	<i>Mercenaria</i>	[AZ3.5]		2
OBX-15	74.3	22.65	JW2004-067-003	2005529	<i>Mercenaria</i>	[AZ3.5]		2
OBX-15	74.3	22.65	JW2004-067-004	2006009	<i>Mercenaria</i>	[AZ3.5]		2
OBX-15	74.3	22.65	JW2004-067-005	2006010	<i>Mercenaria</i>	[AZ3.5]		2
OBX-15	91.3	27.83	JW2004-069-001	2007382	<i>Mulinia</i>		B3	
OBX-15	91.3	27.83	JW2004-069-002	2007383	<i>Mulinia</i>		B3	
OBX-15	91.3	27.83	JW2004-069-003	2007384	<i>Mulinia</i>		B3	
OBX-15	102	31.1	JW2004-072	2006011	<i>Mercenaria</i>	AZ4		
OBX-15	103.35	31.51	JW2004-073	2004206	<i>Mercenaria</i>	AZ4		
OBX-15	103.35	31.51	JW2004-073	2005347	<i>Mercenaria</i>	AZ4		
OBX-15	102	31.1	JW2004-072	2006011	<i>Mercenaria</i>	AZ4		
OBX-15	103.35	31.51	JW2004-073	2005347	<i>Mercenaria</i>	AZ4		
OBX-15	108.8	33.17	JW2004-075	2005348	<i>Mercenaria</i> or <i>Spisula</i>	AZ4		
OBX-15	109.6	33.41	JW2004-076-001	2007393	<i>Mulinia</i>		C1	
OBX-15	109.6	33.41	JW2004-076-002	2007394	<i>Mulinia</i>		C1	
OBX-15	109.6	33.41	JW2004-076-003	2007395	<i>Mulinia</i>		C1	
OBX-15	111.7	34.05	JW2004-077-001	2007399	<i>Mulinia</i>		C1	
OBX-15	111.7	34.05	JW2004-077-002	2007400	<i>Mulinia</i>		C1	
OBX-15	111.7	34.05	JW2004-077-003	2007401	<i>Mulinia</i>		C1	
OBX-15	123.55	37.66	JW2004-079-001	2007407	<i>Mulinia</i>		C1	
OBX-15	123.55	37.66	JW2004-079-002	2007408	<i>Mulinia</i>		C1	
OBX-15	123.55	37.66	JW2004-079-003	2007409	<i>Mulinia</i>		C1	
OBX-15	128.4	39.14	JW2004-080	2007410	<i>Mercenaria</i>	AZ4		
OBX-15	129.8	39.56	JW2004-081	2007411	<i>Mercenaria</i>	AZ4		
OBX-15	130.35	39.73	JW2004-082	2007412	<i>Mercenaria</i>	AZ4		
OBX-16	29.2	8.9	JW2004-090	2005491	<i>Mercenaria</i>	AZ2		
OBX-16	86.9	26.5	JW2004-096-001	2007415	<i>Mulinia</i>		B3	
OBX-16	86.9	26.5	JW2004-096-002	2007416	<i>Mulinia</i>		B3	
OBX-16	86.9	26.5	JW2004-096-003	2007417	<i>Mulinia</i>		B3	
OBX-16	91.25	27.81	JW2004-097-001	2007419	<i>Mulinia</i>		B3	
OBX-16	91.25	27.81	JW2004-097-002	2007420	<i>Mulinia</i>		B3	
OBX-16	91.25	27.81	JW2004-097-003	2007421	<i>Mulinia</i>		B3	
OBX-16	99.55	30.34	JW2004-098-001	2007422	<i>Mulinia</i>		B3	
OBX-16	99.55	30.34	JW2004-098-002	2007423	<i>Mulinia</i>		B3	
OBX-16	99.55	30.34	JW2004-098-003	2007424	<i>Mulinia</i>		B3	
OBX-16	99.55	30.34	JW2004-098-004	2007425	<i>Mulinia</i>		B3	
OBX-16	100.25	30.56	JW2004-100-001	2006028	<i>Mercenaria</i> hinge?	AZ4-		
OBX-16	100.25	30.56	JW2004-100-002	2006029	<i>Spisula</i> hinge?	AZ4		3
OBX-16	101	30.79	JW2004-101-002	2005492	<i>Spisula</i> ?	AZ3?		3,4
OBX-16	101	30.79	JW2004-101-1	2005478	<i>Spisula</i>	AZ4		3
OBX-16	148.1	45.1	JW2004-103-001	2007426	<i>Mulinia</i>		C1	
OBX-16	148.1	45.1	JW2004-103-002	2007427	<i>Mulinia</i>		C1	
OBX-16	148.1	45.1	JW2004-103-003	2007428	<i>Mulinia</i>		C	5
OBX-16	148.1	45.1	JW2004-103-004	2007428a	<i>Mulinia</i>		C	5
OBX-16	173.5	52.9	JW2004-104	2007429	<i>Mulinia</i>		C	5
Notes								
1	Sample dated by ¹⁴ C; AAR analysis yielded D/L values indicating Holocene age							
1a	Multiple subsample identification indicates repeat analysis of shell							
2	Italicized samples represent multiple fragments, possibly from same reworked shell at this depth							
3	AZ4 assigned based on known intergeneric relations between <i>Spisula</i> and <i>Mercenaria</i>							
3, 4	Sample has low D/L values - likely altered							
5	D/L values lower than others from this depth range - samples likely altered; aminogroup uncertain							

Table 3

Age Range, ka (rounded to nearest 10 ka)				
Aminozone (<i>Mercenaria</i>)		Non-Linear model age		<i>Mulinia</i> subgroup ^c
AZ2	AZ2	80 ka ^a	A1	A
AZ2+		125-160 ka ^b	A2	
AZ3-	AZ3	150-220 ka ^{a,d}	B1/B2	B
AZ3+		290-430 ka ^e	B2	
AZ3.5		530-770 ka ^e	B2/B3	
AZ4-	AZ4	660-980 ka ^d	B3/C1	C
AZ4		960-1450 ka ^e	C1	
AZ4+		1220-1840 ka ^e	C2	

a) AZ2 assigned an age of 80 ka based on local U-Th calibration; AZ3- assigned an age of ~ 190 ka based on local calibration.

b) AZ2+ appears to be early MIS5 based on AZ2 calibration and local stratigraphic relations.

c) Corresponding *Mulinia* subgroups based on intergeneric relations (see Wehmiller et al., 2010).

d) Non-linear model ages are based on Fig. 13 and Table 8 in Wehmiller et al., 2010.

e) Non-linear model ages are consistent with Sr isotope ages in Fig. 2 and Table 2 of Wehmiller et al., 2012.

Table 4

Sample ID	Lab Number	Material	Depth (m) in Core	Depth (m) NAVD88	Age (14C yr BP)	Error (yr)	d13C	2-s Age Range	Relative Probability	Median Age (yr)	Calibration Data
MLD-02 21.25	OS-67833	<i>Mulinia lateralis</i>	-6.48	-5.26	33600	200	-0.1	36985 38587	1	37821	Reimer et al. 2009
MLD-02 23.5	OS-67733	<i>Mulinia lateralis</i>	-7.16	-5.94	30800	640	-0.3	33455 36364	1	34908	Reimer et al. 2009
MLD-02 27.45-27.6	OS-63815	<i>Mercenaria mercenaria</i>	-8.39	-7.17	38900	490	0.9	42019 43595	1	42788	Reimer et al. 2009
OBX-14 65.7	OS-45437	plant fragments	-20.03	-19.10	5830	25	-28	6561 6594	0.15	6649	Reimer et al. 2009
								6596 6679	0.72		
								6681 6728	0.13		
OBX-14 66.6	OS-45438	plant fragments	-20.30	-19.37	5950	30	-25	6678 6708	0.06	6775	Reimer et al. 2009
								6712 6808	0.71		
								6811 6859	0.21		
								6871 6880	0.01		
OBX-14 67.4	OS-45310	plant fragments	-20.54	-19.61	5750	30	-28	6467 6639	1	6549	Reimer et al. 2009
OBX-14 67.7a	OS-45308	<i>Sassafras albidum</i> root	-20.63	-19.70	5920	30	-28	6667 6798	0.98	6740	Reimer et al. 2009
								6819 6830	0.02		
								6840 6840	0.00		
OBX-14 67.7b	OS-45322	<i>Crassostrea virginica</i>	-20.63	-19.70	6240	40	-2.1	6417 6734	1	6579	Reimer et al. 2009
OBX-14 70.6	OS-45329	<i>Crassostrea virginica</i>	-21.52	-20.59	6230	30	-1.2	6420 6716	1	6568	Reimer et al. 2009
OBX-14 71.5	OS-45439	plant fragments	-21.79	-20.86	5900	35	-26	6645 6647	0.003	6719	Reimer et al. 2009
								6651 6795	0.997		
OBX-14 71.8	OS-45323	<i>Nassarius obsoleta</i>	-21.88	-20.95	6220	40	-1	6400 6714	1	6558	Reimer et al. 2009
OBX-14 71.8CV	OS-45328	<i>Crassostrea virginica</i>	-21.88	-20.95	6290	35	-1.6	6470 6791	1	6638	Reimer et al. 2009
OBX-14 72.0	OS-45332	<i>Crassostrea virginica</i>	-21.95	-21.02	6290	40	-2.4	6463 6798	1	6638	Reimer et al. 2009
OBX-14 72.3	OS-45309	plant fragments	-22.04	-21.11	6810	35	-27	7587 7689	1	7644	Reimer et al. 2009
OBX-14 73.2	OS-45330	<i>Mercenaria mercenaria</i>	-22.31	-21.38	6330	40	-0.5	6512 6856	1	6687	Reimer et al. 2009
OBX-14 73.6	OS-45331	<i>Mercenaria mercenaria</i>	-22.43	-21.50	6340	30	-0.4	6540 6858	1	6698	Reimer et al. 2009
OBX-15 44.8	OS-45440	woody plant fragments	-13.66	-12.65	7540	35	-27	8220 8236	0.02	8368	Reimer et al. 2009
								8310 8413	0.98		
OBX-15 44.8CC	OS-45333	<i>Chione cancellata</i>	-13.66	-12.65	6900	35	0.83	7204 7443	1	7332	Reimer et al. 2009
OBX-15 51.4-51.7	OS-64287	<i>M. mercenaria</i> or <i>S. solidissima</i>	-15.71	-14.70	29700	200	-0.3	33275 34543	1	33886	Reimer et al. 2009
OBX-15 74.3	OS-50448	<i>Mercenaria mercenaria</i>	-22.65	-21.64	32200	190	1.37	35376 36008	0.41	36270	Reimer et al. 2009
								36121 36681	0.59		
OBX-16 78.5	OS-45441	peaty sand	-23.93	-22.26	>48000		-27	- -	-		

Table 5

Group A	mean %	Group B	mean %	Group C	mean %	Group D	mean %
<i>Elphidium excavatum</i>	32.7	<i>Elphidium excavatum</i>	75.6	<i>Elphidium excavatum</i>	51	<i>Elphidium excavatum</i>	42.3
<i>Rosalina</i> sp. A	11.3	<i>Hanzawaia strattoni</i>	4.4	<i>Ammonia parkinsoniana</i>	20.1	<i>Rosalina</i> sp. A	9.4
<i>Bolivina lowmani</i>	5.7	<i>Quinqueloculina seminula</i>	2	<i>Elphidium gunteri</i>	3.2	<i>Epistominella</i> cf. <i>E. sandiegoensis</i>	5.1
<i>Epistominella</i> cf. <i>E. sandiegoensis</i>	5.3	<i>Elphidium mexicanum</i>	1.6	<i>Rosalina</i> sp. A	3.1	<i>Cibicides lobatulus</i>	5

Table 6

	A			B			C			D		
	O	C	BF	O	C	BF	O	C	BF	O	C	BF
<i>Ammodiscus</i> sp.	1	x	10	0	0	0	0	0	0	0	0	0
<i>Ammonia becarrii</i>	0	0	0	0	0	0	0	0	0	1	x	10
<i>Ammonia parkinsoniana</i>	10	7	3	9	4	1	15	8	3	8	7	3
<i>Ammonia tepida</i>	0	0	0	0	0	0	1	x	10	0	0	0
<i>Amphistegina</i> sp.	5	3	6	0	0	0	3	2	2	1	x	2
<i>Astacolus</i> sp. A	1	x	10	0	0	0	0	0	0	0	0	0
<i>Asterigerina carinata</i>	9	6	5	2	x	1	6	3	3	1	x	1
<i>Asterigerinata</i> cf. <i>A. mamilla</i>	1	x	2	0	0	0	2	1	3	2	2	5
<i>Asterigerinata</i> sp. A	4	3	7	0	0	0	0	0	0	1	x	3
<i>Bolivina lowmani</i>	12	8	4	1	x	x	9	5	2	9	8	4
<i>Bolivina semipunctata</i>	1	x	10	0	0	0	0	0	0	0	0	0
<i>Bolivina</i> sp.	5	3	6	0	0	0	1	x	1	2	2	3
<i>Bolivina spathulata</i>	1	x	10	0	0	0	0	0	0	0	0	0
<i>Bolivina variabilis</i>	6	4	5	0	0	0	1	x	x	4	4	4
<i>Buccella depressa</i>	4	3	5	0	0	0	0	0	0	3	3	5
<i>Buccella frigida</i>	2	1	3	1	x	2	0	0	0	2	2	5
<i>Buccella inusitata</i>	7	5	3	4	2	1	6	3	2	6	5	4
<i>Buccella</i> sp.	1	x	3	0	0	0	2	1	3	1	x	3
<i>Bulimina elegans</i>	1	x	10	0	0	0	0	0	0	0	0	0
<i>Bulimina elongata</i>	2	1	4	0	0	0	1	x	1	2	2	5
<i>Bulimina marginata</i>	1	x	4	0	0	0	0	0	0	1	x	6
<i>Bulimina</i> sp.	2	1	6	0	0	0	0	0	0	1	x	4
<i>Bulimina</i> sp. A	1	x	10	0	0	0	0	0	0	0	0	0
<i>Buliminella elegantissima</i>	7	5	3	0	0	0	7	4	3	6	5	4
<i>Cancris sagra</i>	1	x	4	0	0	0	0	0	0	1	x	6
<i>Cassidulina carinata</i>	1	x	4	0	0	0	0	0	0	1	x	6
<i>Cassidulina laevigata</i>	2	1	10	0	0	0	0	0	0	0	0	0
<i>Cassidulina norvangi</i>	3	2	3	0	0	0	0	0	0	5	5	7
<i>Cassidulina reniforme</i>	11	7	5	0	0	0	5	3	1	6	5	4
<i>Cassidulina</i> sp.	0	0	0	0	0	0	0	0	0	2	2	10
<i>Cibicides fletcheri</i>	8	5	4	0	0	0	3	2	1	8	7	5
<i>Cibicides lobatulus</i>	10	7	3	9	4	2	11	6	2	9	8	3
<i>Cibicides refulgens</i>	1	x	2	1	x	1	1	x	1	3	3	6
<i>Cibicides</i> sp.	6	4	6	2	x	1	2	1	1	1	x	1
<i>Cyclogyra</i> sp. A	1	x	5	0	0	0	1	x	5	0	0	0
<i>Dyocibicides</i> sp.	2	1	10	0	0	0	0	0	0	0	0	0
elphidiid	4	3	6	0	0	0	1	x	2	1	x	2
<i>Elphidium</i> cf. <i>E. poeyanum</i>	1	x	10	0	0	0	0	0	0	0	0	0
<i>Elphidium</i> cf. <i>E. craticulum</i>	2	1	7	0	0	0	1	x	3	0	0	0
<i>Elphidium discoideale</i>	3	2	5	0	0	0	3	2	5	0	0	0
<i>Elphidium excavatum</i>	15	10	3	20	10	2	18	10	3	11	10	3
<i>Elphidium galvestonense</i>	1	x	1	8	4	5	3	2	3	1	x	1
<i>Elphidium gunteri</i>	7	5	2	10	5	2	13	7	3	8	7	3

Table 7

North Central				Central				South			
Reflection	SSU	Age	Interpretation	Reflection	SSU	Age	Interpretation	Reflection	SSU	Age	Interpretation
Q100		Holocene	Modern sediment/water interface	Q100		Holocene	Modern sediment/water interface	Q100		Holocene	Modern sediment/water interface
		Holocene	Transgressive marine ravinement surface	Q99b		Holocene	Transgressive marine ravinement surface	Q99b		Holocene	Transgressive marine ravinement surface
	VI	Latest Pleistocene/Holocene	Fluvial, estuarine, sand shoal, barrier island deposits	VI		Latest Pleistocene/Holocene	Fluvial, estuarine, barrier island and shallow open shelf sediments	VI		Latest Pleistocene/Holocene	Fluvial, estuarine, barrier island and shallow open shelf (including shoreface) sediments
Q99		Late Pleistocene	Last glacial maximum subaerial unconformity; incised valleys	Q99		Late Pleistocene	Last glacial maximum subaerial unconformity	Q99		Late Pleistocene	Last glacial maximum subaerial unconformity; incised valleys
	V	Late Pleistocene MIS 5	Multiple inner shelf depositional sequences	V		Late Pleistocene MIS 5	Multiple inner shelf depositional sequences with extensive estuarine, shelf, and fluvial valley-fill	V		Late Pleistocene MIS 5	Multiple inner shelf depositional sequences
Q50		Late Pleistocene	Transgressive ravinement surface associated with MIS6/5 sea-level rise	Q50		Late Pleistocene	Transgressive ravinement surface associated with MIS6/5 sea-level rise	Q50		Late Pleistocene	Transgressive ravinement surface associated with MIS6/5 sea-level rise
	IV	Early to mid-Pleistocene MIS 7-13?	Multiple inner depositional sequences; wetland deposits	IV		Early to mid-Pleistocene MIS 7-13?	Multiple inner to mid-shelf depositional sequences; FSST and TST; multiple incised valleys	IV		Early to mid-Pleistocene MIS 7-13?	Multiple inner to mid-shelf depositional sequences; FSST and TST; fluvial/wetland incised valley-fill
Q30		Early to mid-Pleistocene	Subaerial unconformity	Q30		Early to mid-Pleistocene	Subaerial unconformity	Q30, 30b		Early to mid-Pleistocene	Subaerial unconformity; incised valley
	III	Early Pleistocene	Multiple inner to mid-shelf depositional sequences	III		Early Pleistocene	Multiple inner to mid-shelf depositional sequences	III		Early Pleistocene	Multiple inner to mid-shelf depositional sequences
				Q20		Early Pleistocene	Subaerial to shallow marine unconformity; defines lowstand shelf				
				II		Early Pleistocene	Multiple depositional sequences exhibiting LST, TST and HST				
				Q10		Early Pleistocene	Unconformity - minimal subaerial exposure				
				I		Early Pleistocene	Mid to outer shelf				
Q0		Pliocene/Pleistocene boundary	Submarine unconformity	Q0		Pliocene/Pleistocene boundary	Submarine unconformity	Q0		Pliocene/Pleistocene boundary	Submarine unconformity
		Mid-Pliocene	Muddy sand and mud facies of Yorktown Formation (?)			Mid-Pliocene	Sandy mud facies of Yorktown Formation (?)			Mid-Pliocene	Carbonate facies of Duplin Formation (?)