Depositional sequence stratigraphy of Turonian to Santonian sediments, Cape Fear arch, North Carolina Coastal Plain, USA

Wilma B. Alemán González[1], Jean M. Self-Trail[1], W. Burleigh Harris[2, 4], Jessica Pierson Moore[3], and Kathleen M. Farrell[4]

[1]*U.S. Geological Survey, Florence Bascom Geoscience Center, MS: 926-A National Center, Reston VA 20192*
corresponding author email: jstrail@usgs.gov
[2]*Professor Emeritus, Department of Earth and Ocean Sciences, University of North Carolina, Wilmington, NC, 28403*
[3] *West Virginia Geological and Economic Survey, 1 Mont Chateau Road, West Virginia, 26508*
[4]*North Carolina Geological Survey, Raleigh Field Office and Core Storage Facility, MSC 1620, Raleigh, NC 27699-1620*

ABSTRACT: A new sequence stratigraphic framework for Turonian to Santonian (94-84 Ma) sediments is established using data from the USGS Kure Beach and Elizabethtown cores collected from the Atlantic Coastal Plain of North Carolina (NC). These sediments represent some of the oldest marine units deposited on the southeastern Atlantic Coastal Plain and record the early development of a clastic wedge atop crystalline basement. Sediments were deposited as transitional marginal-marine to marine units in a complex interplay of fluvial, estuarine, and shelf environments. Repetitive lithologies and minimal biostratigraphic control requires an integrated analysis of grain-size data, geophysical logs, biostratigraphy, and $^{87}Sr/^{86}Sr$ isotopic data to identify systems tracts and establish a sequence stratigraphic framework. From this integrated approach, three Turonian to Santonian sequences in the Elizabethtown core and six in the Kure Beach core are identified. The new sequences from oldest to youngest are Clubhouse II, Fort Fisher I, Fort Fisher II, Collins Creek I, Collins Creek II, Pleasant Creek I, and Pleasant Creek II.

Sequences from North Carolina document significant shifts of global and regional sea-level during greenhouse conditions in the early Late Cretaceous. Maximum sea-level rise occurred globally during the early Turonian and is documented from the marine sediments of the Clubhouse II sequence. This sequence is unconformably overlain by terrestrial sediments deposited during a major fall in sea level and maximum progradation of the shoreline, as evidenced by the Fort Fisher I sequence. Global sea-level rise in the Coniacian resulted in the deposition of the Fort Fisher II sequence, which is present only in the Kure Beach core. Local marine circulation and erosion on the shelf is suggested by the absence of the Collins Creek I sequence at Kure Beach; this sequence is present only in the up-dip Elizabethtown core. Activation of a possible buried fault structure along the Cape Fear arch resulted in the formation of a regional depocenter during the late Coniacian to early Santonian and is reflected in the unusual thickness of the Collins Creek II and Pleasant Creek I sequences. The return to a more global sea-level influence occurred in the late Santonian with the deposition of the Pleasant Creek II sequence. A comparison of temporal distribution of sequences in the Elizabethtown and Kure Beach cores to corresponding sequences in New Jersey indicates significant differences in erosional and tectonic processes in the Cape Fear region during the Turonian and Santonian.

Key Words: Sequence stratigraphy, Turonian, Santonian, Cape Fear

INTRODUCTION

The Cape Fear River valley in the southern North Carolina Coastal Plain (text-fig. 1) provides some of the best exposures of Cretaceous sediments in the entire southeastern Atlantic Coastal Plain. Many researchers have studied these outcrops since the early 1900's because the strata are well exposed from the Fall Line to the coast. Stephenson (1912, 1923) was the first to examine them in detail and to define the units. He recognized two Cenomanian to Maastrichtian formations, the Black Creek Formation and the Peedee Formation, respectively, but later reassigned their chronostratigraphic position to Turonian through Campanian (Stephenson 1923). Since Stephenson's early work, the areas along the Cape Fear and the Pee Dee rivers in North Carolina and South Carolina, respectively, have been the focus of many lithostratigraphic and biostratigraphic studies of the Cretaceous section. These resulted in the subdivision of the Upper Cretaceous section into several lithostratigraphic units with better defined ages (Brett and Wheeler 1961; Heron and Wheeler 1964; Swift and Heron 1969; Brown et al. 1972; Harris 1978; Sohl and Christopher 1983; and Sohl and Owens 1991). The addition of new coreholes over the last 30 years by the U.S. Geological Survey (USGS) in North Carolina and South Carolina resulted in subsurface studies by Gohn (1992), Self-Trail et al. (2002, 2004b), Farrell et al. (2013) and Balson et al. (2013). These authors used lithostratigraphic, biostratigraphic, geochemical, and well-log methods to interpret the Cretaceous stratigraphy.

With the introduction of sequence stratigraphy (Vail et al. 1977; Haq et al. 1987; and Posamentier et al. 1988), researchers in the Carolinas focused more on placing lithologic units in chronostratigraphic frameworks rather than defining traditional lithostratigraphic units. Although lithologically distinct bodies of rock or sediment form the basis for mapping formations, sequence stratigraphy requires identification of distinct bounding surfaces, and uses an integrated chronostratigraphic approach to subdivide the sedimentary record into distinct depositional packages. These packages are bounded by unconformities or their correlative conformities and are interpreted to represent a cyclic change in sea-level and/or sediment supply (Mitchum et al. 1977). This integrated approach helps correlate marine sedimentary packages with cyclic changes in relative sea-level, accommodation space, and provenance.

Previous early sequence stratigraphic analysis of Late Cretaceous sediments from North Carolina is restricted to the early work of Owens and Gohn (1985), who defined six broad depositional sequences for the Cretaceous of the entire Atlantic Coastal Plain, and Zarra (1989) who focused on the sequence stratigraphy of the Ablemarle and Pamlico sounds, North Carolina. Zarra (1989) utilized cuttings and geophysical data from five wells drilled by Mobil and Esso and 18 seismic lines provided by Cities Service Oil Company to identify seven Late Cretaceous sequences, four of which span the Cenomanian through Santonian. This work provided a solid framework for analysis of sediments of the Cape Fear arch region, where seismic data are not available. However, Zarra (1989) lacked cored material and his extensive use of seismic reflector terminations, coupled with lack of terrigenous biostratigraphy, means that his calculated seismic sequence boundary horizons and well log sequence boundary picks could be off by as much as 100 feet of one another. While not a problem in regions such as the Gulf of Mexico, where sequences are often hundreds of feet thick, this represents a serious problem on the Atlantic Coastal Plain, where sequences rarely attain thicknesses greater than 150 ft.

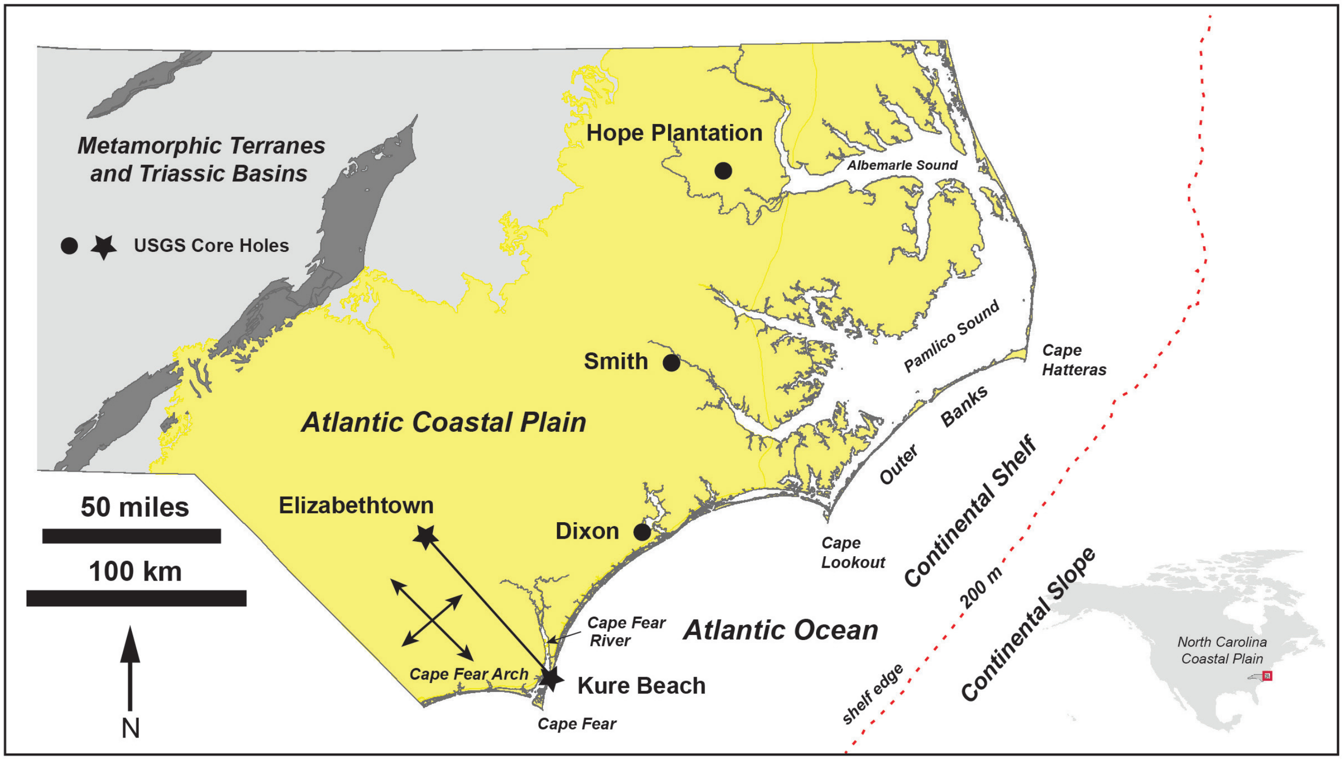
In the Cape Fear region of North Carolina, Pierson (2003) and Harris and Self-Trail (2006) used sequence stratigraphic analysis to define depositional sequences in the Late Cretaceous Campanian-Maastrichtian interval; however, the Turonian-Santonian interval remained undocumented. The Turonian-Santonian interval is important because it corresponds to a period when modern circulation patterns were first established in the Atlantic following the breakup of Pangea (Grow and Sheridan 1988). Peak increase in global warmth is documented across the Cenomanian/Turonian boundary and was associated with increased carbon burial and local organic matter enrichment in the Atlantic Ocean and on the Atlantic continental shelf (Friedrich et al. 2012; Owens et al. 2018). Warming across the Cenomanian/Turonian boundary is largely thought to have been due to emplacement of the Caribbean Large Igneous Province (e.g. Snow et al. 2005). A secondary peak in global warming is inferred during the Santonian-early Campanian (Huber et al. 2018). Changes in global warming and cooling can result in a complex interplay between increased terrigenous flux to the shelf due to changes in the hydrologic cycle, changes in organic carbon burial, and resulting fluctuations in oxygen levels on the shelf. While elevated sea-levels across the Cenomanian/Turonian boundary in the Atlantic Ocean are relatively well understood, questions still remain regarding the global mechanisms and magnitude of sea-level fall during the Turonian and Coniacian (Sugarman et al., in press). Additionally, it is not well understood how local structural features (e.g., movement on faults associated with arches and embayments) affected relative sea-level fluctuations.

Thus, the present study focuses on the sequence stratigraphic framework of the Turonian through Santonian section in two cores, the Kure Beach core and the Elizabethtown core. Both were part of a USGS deep coring program (1999 to 2007) in North Carolina and were collected as part of an effort to better understand and constrain the role that global and local sea-level changes had on shelf sedimentation on the southeastern Atlantic Coastal Plain. Our study has three main objectives: 1) to identify Turonian through Santonian depositional sequences and their bounding surfaces in the Kure Beach and Elizabethtown cores, 2) to determine the ages of the sequences, and 3) to identify the influence of both global and local mechanisms of relative sea-level rise and terrigenous influx on the North Carolina Coastal Plain.

GEOLOGIC SETTING

In North Carolina, the Atlantic Coastal Plain Province is a wedge of sediment that thickens from a featheredge along the Fall Zone (where crystalline Piedmont rocks crop out) to a maximum known onshore thickness of ~3,048 m (10,000 ft) in a well at Cape Hatteras (see cross-section of Weems et al. 2019). Offshore from Hatteras, thicknesses are even greater beneath the contiguous continental shelf. The surface of the emerged Coastal Plain is mostly a relict Pliocene-Pleistocene terrane that is dissected by a number of rivers and valleys, including the incised Cape Fear River valley. The Elizabethtown and Kure Beach coreholes are situated in the Cape Fear River valley but are separated by approximately 60 miles (96.6 km) in the dip direction (text-figs. 1 and 2). The Cenomanian to Santonian section of the southeast Atlantic Coastal Plain is characterized by a succession of interlinked marine, marginal marine and terrestrial depositional systems. Previous studies placed the oldest sediments, herein recognized as the Clubhouse Formation and its associated sequence (Clubhouse II), in the Cenomanian and Turonian stages (Hazel et al. 1977; Hattner and Wise 1980; Valentine 1984; Zarra 1989). Balson et al. (2013) placed the Sunny Point Formation (correlative with the Fort Fisher I sequence) in the Turonian and a previously unnamed unit is identified from the Kure Beach hole that is correlative with the Fort Fisher II sequence. Based on biostratigraphy, it is Turonian to Coniacian in age. Self-Trail et al. (2004a) placed the Collins Creek Formation (correlative herein to the Collins Creek I and basal Collins Creek II sequences) in the Coniacian. The youngest sediments addressed in this study are from the Pleasant Creek Formation (correlative with the Collins Creek II, Pleasant Creek I, and Pleasant Creek II sequences) and are Coniacian to Santonian in age (Self-Trail et al. 2004a).

The Cretaceous section is approximately 236.2 ft (72.0 m) thick at Elizabethtown, thickening to greater than 1230.3 ft (375.0 m) at Kure Beach. The axis of a structural high in the basement rocks, known as the Cape Fear arch, approximately follows the Cape Fear River. Although the arch was recognized as early as the later 1890's (Dall and Harris 1892), Stephenson (1923) is usually given credit for first delineating the structure. The Cape Fear arch formed, along with associated rift basins, in the Early Mesozoic during the opening of the Atlantic Ocean (Klitgord et al. 1988). Variations in composition and thermal conductivity of the basement rocks beneath the Coastal Plain, coupled with plate rotations that affected vertical motion on fault-bounded blocks, are thought to have resulted in movement of the Cape Fear arch through time (Brown et al. 1972; Sheridan 1976; Gohn 1988; LaGesse and Read 2006). Geomorphic and geologic data suggest that uplift occurred as late as the Pliocene and Pleistocene (Markewich 1985), but relative sea-level data from North Carolina and South Carolina suggest that subsidence was also a factor through time (Plassche et al. 2014), as evidenced by the unusual thickness of Santonian age Pleasant Creek I sediments along the cross section (see text-fig. 2).



TEXT-FIGURE 1
Geomorphologic map of the study area showing Elizabethtown and Kure Beach core hole locations (stars) and Smith, Hope Plantation, and Dixon core hole locations (circles). Bold black line connecting Elizabethtown and Kure Beach core holes indicates line of cross section in text-fig. 2.

The Kure Beach corehole (Table 1) was drilled by the USGS to a total depth of 1386.0 ft (422.5 m); basement rocks were not intercepted. The USGS drilled the Elizabethtown 1 and 2 cores to a total depth of 595.0 ft (181.3 m) (Self-Trail et al. 2004b), intercepting weathered basement at 570.6 ft (173.9 m). Both cores obtained sediments of Pleistocene to Turonian age. Natural gamma logs were collected at both drill sites (text-fig. 2). The USGS field lithologic descriptions are available for public use at the USGS headquarters offices in Reston, Virginia.

METHODOLOGY

Depositional sequences and their bounding unconformities were identified in cores using a variety of parameters, including vertical changes in grain size, physical and biological sedimentary structures, presence and type of fossils, biostratigraphy, and correlation with geophysical logs. Percent planktic foraminifera and calcareous nannofossil species richness along with vertical changes in lithology and gamma-ray log response patterns were used to determine patterns of relative sea-level change and to assign system tracts. Calcareous nannofossils, terrestrial palynomorphs, and $^{87}Sr/^{86}Sr$ ratios provided ages for the depositional sequences. Integration of these data was used to develop the sequence stratigraphic framework for the Turonian to Santonian section in the two cores. Concepts of sequence stratigraphic analysis, including determining subaerial unconformities and their marine correlative conformities, were used to delineate sequence boundaries and their internal components following standard sequence stratigraphic models (Haq et al. 1987; Van Wagoner et al. 1988, 1990; Christie-Blick et al. 1990; Hunt and Tucker 1992, 1995; Plint and Nummedal 2000); these are summarized in Catuneanu (2006). The Turonian to Santonian sequences identified in the two cores were correlated to the sediment cyclicity curve of Haq (2014), the transgressive-regressive cycles of Ogg et al. (2004), early sequence work in North Carolina by Zarra (1989), and New Jersey sequences identified by Sugarman et al. (1999), Miller et al. (2004) and Sugarman et al. (in press). These correlations permit the separation of sea-level change from local uplift/subsidence and changes in sediment supply.

Field descriptions of sediments from the Kure Beach and Elizabethtown cores were used to determine the sampling strategy. Samples of core were collected at approximately 5 ft (1.5 m) intervals, except near established lithologic contact zones where a higher concentration of samples was obtained (1.5 ft, 0.5 m) below and above the contact. One hundred and fifteen samples from the Kure Beach core and 53 samples from the Elizabethtown core were examined. Each sample consisted of a quarter round segment of core 0.3 ft (0.09 m) in length. Each was analyzed for grain size, percent calcium carbonate, mineralogy, percent planktic foraminifera, palynology data and calcareous nannofossil data. Strontium dates were mainly determined for the Kure Beach core; however, the Elizabethtown core supplied one viable date. Results of grain size, strontium isotope, calcareous nannofossil, and foraminiferal analyses are available in data tables (Self-Trail et al. 2020) that can be downloaded at https://doi.org/10.5066/P91PG9YC. Calcareous nannofossils and palynomorphs that were particularly useful for determining ages are listed in Appendix 1.

TABLE 1
Identifying information on cores discussed in text.

Common Name	USGS ID	NCGS ID	Latitude	Longitude	Total Depth (m)	Drill Date	Drillers
Kure Beach Core	Kure Beach No. 1	NH-C-1-2001	33.973333N	77.916944W	422.5	2001	USGS
Elizabethtown Core	BL-244	BL-C-1-2003	34.551667N	78.525833W	181.4	2003	USGS
Smith Elementary Core	CR-675	.	35.251667N	77.290278W	323.1	2005	USGS
Dixon Core	Dixon No. 1	.	34.559722N	77.448333W	307.8	2006	USGS

Grain Size Analysis

Grain size analysis was performed using a two-step method modified from Folk (1980) that allowed for separate analyses of sand versus silt/clay; gravel was not present in any of the samples. Each sample was split into two separate samples.

To analyze the sand content, a 0.5% sodium hexametaphosphate solution in water was added to approximately 50 g of dried sediment and set on an orbital shaker for a minimum of 30 minutes in order to disperse the sample. Samples were wet sieved using a U.S. standard sieve #230 (mesh opening 63 µm, 8 inches in diameter) and dried overnight at approximately 40º–50º C. Once samples were dry, they were scanned under a binocular microscope to determine if the sample was free of mud, or had less than 25% mud clumps, and the final weight was noted. The sand-sized fraction was dry sieved at ½ phi intervals, using a Hogentogler Ro-Tap for 15 minutes. The weight of each individual phi size was noted and weight percents were calculated.

To determine the silt and clay content for each sample (Folk 1980), approximately 10 g of sample was air dried, gently disaggregated with a mortar and pestle to break the grain contacts, and dry sieved using a U.S. standard #230 sieve. The mud-sized fraction was dispersed in a 0.25% sodium hexametaphosphate solution in a 1000 ml graduated cylinder and representative samples pipetted at regular, timed intervals. These results were normalized to the sand-sized fraction and weight percent was calculated for the sand, silt, and clay, fractions (see Self-Trail et al. 2020).

Planktic and Benthic Foraminiferal Data

Planktic and benthic foraminiferal data were established for each productive sample by analyzing the >63 µm sand-size fraction. Each sample was split using a microsplitter to obtain 300 to 350 foraminifera per sample. In sparse samples, a minimum of 250 specimens was deemed appropriate (Imbrie and Kipp 1971). After the foraminifera were picked, the percent planktic foraminifera was calculated by dividing the number of planktic foraminifera by the total number of foraminifera picked.

Calcium Carbonate Percent

Ten grams of sediment was dried at 100°C for approximately 12 hours. A 20% HCl solution was poured into the beaker with the sediment, stirred, and allowed to sit overnight. Excess acid was decanted, and the procedure was repeated until the sample no longer effervesced. Once the $CaCO_3$ was digested, the sample was rinsed with deionized water to remove residual acid, allowed to dry overnight and weighed (see Self-Trail et al., 2020).

Mineralogy Estimates

Dry sieved sand-size samples were examined using a Mieji EMZ-8U binocular microscope. Volume percentages of quartz, glauconite, phosphates, mica, iron oxides, heavy minerals, shell fragments, lithoclasts, and organic material were estimated. Estimates were calculated using visual charts representing various percentages; in addition, notes were made on sorting and roundness. Abundances were grouped into the following categories: 0–1 % Trace, 2–15% Rare, 16–25% Common, 26–50% Abundant, 51–75% Very Abundant, and >75% Dominant.

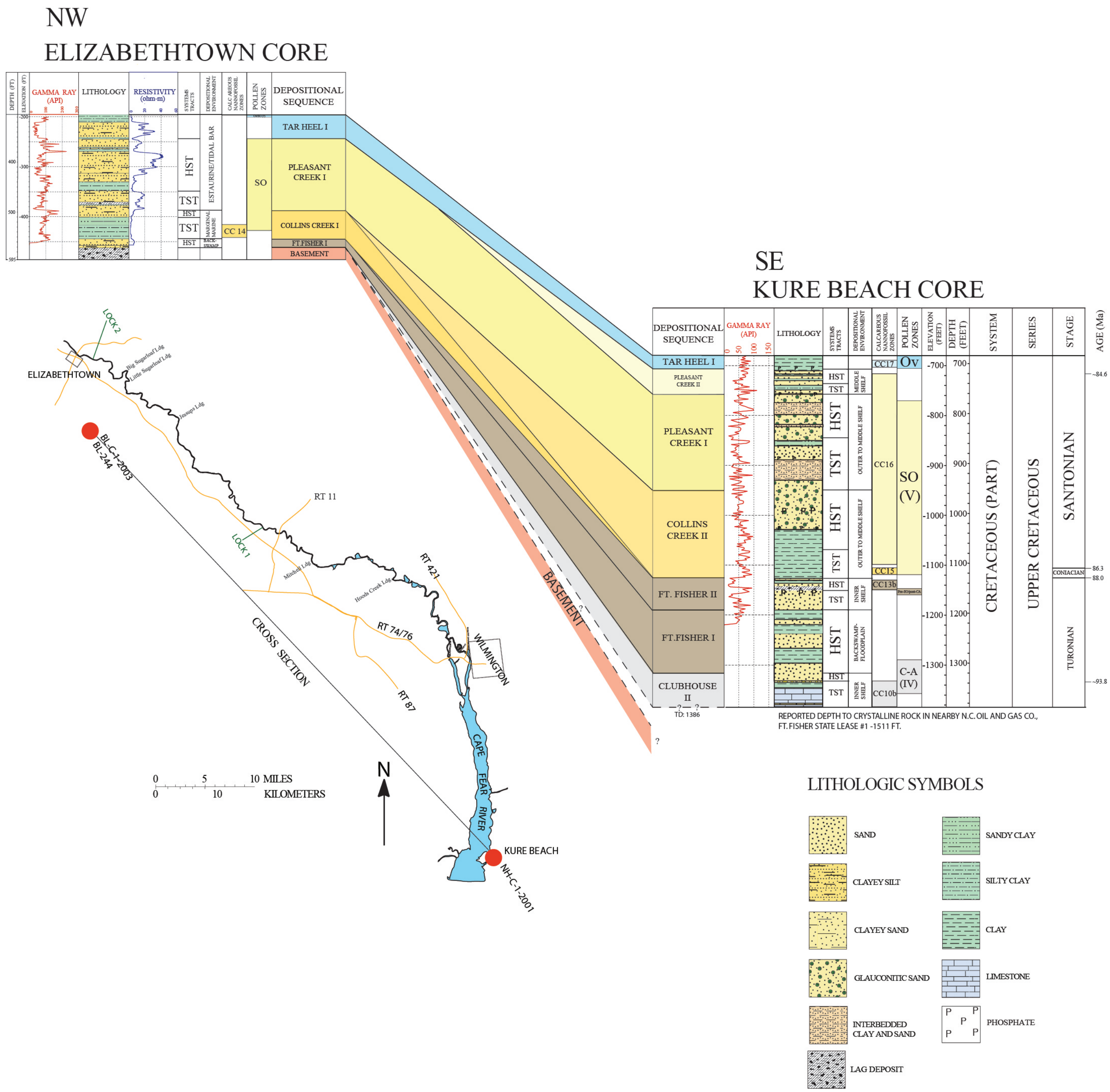
Calcareous Nannofossil Sampling and Methods

Samples examined for calcareous nannofossil content were taken from the center of freshly broken pieces of core in order to avoid contamination by drilling mud. Smear slides were prepared using the double slurry method of Watkins and Bergen (2003) and mounted using Norland Optical Adhesive 61. Slides were scanned using a Zeiss Axioplan 2 light microscope at x1250 magnification under cross-polarized (XPL) light. The zonations of Sissingh (1977 as modified by Perch-Nielsen (1985)) and Burnett (1998) were used for correlation purposes. Calcareous nannofossil data for the Elizabethtown core is available from Self-Trail et al. (2004b) and for the Kure Beach core from Self-Trail et al. (2020).

Sr Bulk Sampling

Samples were collected from a split of the Kure Beach core at regular intervals (every few ft) between 1376.7–690.2 ft (419.6–210.4 m) as samples between 685.0–150.0 ft (208.8–45.7 m) were previously reported on by Pierson (2003) and Harris and Self-Trail (2006). Additional samples were collected near potential sequence boundaries, marine flooding surfaces, closely spaced nannofossil zonal boundaries, or when analyses resulted in questionable results. Samples consisted of about 50 g of material and were used to extract micro- or small megafossils for Sr isotopic analysis. In cases where megafossils were present, only those fossils were collected for Sr analysis. All fossil samples were calcitic and included oysters, other bivalves, crinoid columnals, ostracods and planktic foraminifers. Small megafossils and microfossils were concentrated by screening bulk samples and handpicking. To achieve disaggregation of bulk samples collected for Sr isotopic analyses, they were soaked in demineralized water for several hours. Once disaggregated, the mud fraction was decanted and samples were filtered and dried under a heat lamp. To concentrate the megafossils and microfossils, dried samples were screened into various sand-size fractions using U.S. Standard sieves (between #230 and #10 mesh).

Megafossils and microfossils collected for Sr analyses were washed between 30 and 60 seconds in 0.1 N HCl, rinsed several times in demineralized water, and dried under a heat lamp.



TEXT-FIGURE 2
Cross section showing the sequence relationships between the updip Elizabethtown core and the down-dip Kure Beach core and their relationship to the Cape Fear River. The Tar Heel sequence was documented by Harris and Self-Trail (2006).

Handpicking of impurities provided final purification of the samples. Splits broken from large megafossils, and smaller mega- and microfossils that were best preserved were selected and studied under a binocular microscope to determine degree of preservation. Shell color, opacity, chalkiness, the absence/presence of borings, diagenetic alteration including recrystallization, dissolution, and the presence of secondary carbonate precipitates were determined. Fossil samples that showed extensive weathering and a high degree of diagenetic alteration were excluded from analyses. Shell samples that had minor alteration that could be removed through beneficiation such as scraping, sonification, and acid washing were included for analyses. In one case, crinoid arms were used although they contained secondary calcite in their reticulate structure as previous results using them resulted in viable data (Harris and Self-Trail 2006).

Isotopic Methods

All sample splits were analyzed in the Isotope Geochemistry Laboratory in the Department of Geological Sciences at the

TEXT-FIGURE 3
Sequence boundary and formation contact between the Clubhouse II (Clubhouse Formation) below and the Fort Fisher I (Sunny Point Formation) above in the Kure Beach core.

University of North Carolina at Chapel Hill (UNC-CH). Analytical procedures consisted of placing 2–4 mg quantities of sample in small Savillex PFA vials with 0.5–1 ml of 1.0 M acetic acid (Baker Ultrex II Ultrapure Reagent). Samples were gently heated for about 15 minutes, centrifuged, the solution removed and evaporated to dryness. Sr was separated from the matrix using EiChrom SrSpec resin, a crown-ether Sr-selective resin, following standard chromatographic techniques. Sr was placed on degassed Re filaments and into a VG (MicroMass) Sector 54 thermal ionization mass spectrometer at UNC-CH. Internal precision for Sr carbonate analyses is typically 0.0006 to 0.0009 % standard error, based on 100 dynamic cycles of data collection. Recent analyses of NBS 987 at UNC-CH average 0.710268 (n = 61; two standard deviations = 0.000018). Values for the $^{87}Sr/^{86}Sr$ ratios are reported relative to 0.710250 for standard NBS (SRM) 987 as this is the approximate average obtained by many laboratories worldwide and are available in Self-Trail et al. (2020). Four-to-six splits of NBS (SRM) 987 standard were analyzed with each group of samples and their $^{87}Sr/^{86}Sr$ ratios used to adjust the samples' measured $^{87}Sr/^{86}Sr$ ratios (i.e., if the standards averaged 0.710268, 0.000018 was subtracted from the $^{87}Sr/^{86}Sr$ for each sample).

A Locally-Weighted Regression Scatterplot Smoother (LOWESS) method, involving a point-by-point evaluation of the seawater curve, was used to produce a best-fit model for the $^{87}Sr/^{86}Sr$ curve. Because of the complexity of the method, McArthur et al. (2001) provided a modified look-up table with $^{87}Sr/^{86}Sr$ ratios in 0.000001 increments for age interpolation. Dates were determined using LOWESS (now LOESS) 5 Fit 26 03 13, a preliminary revision of Look Up Table V4B-08/04 (McArthur et al. 2001).

RESULTS – SEQUENCE STRATIGRAPHY

Three new Turonian to Santonian sequences are present in the Elizabethtown core and six in the Kure Beach core (text-fig. 2). The sequences from oldest to youngest are: Clubhouse Crossroads II, Fort Fisher I, Fort Fisher II, Collins Creek I, Collins Creek II, Pleasant Creek I and Pleasant Creek II. The Clubhouse II, Fort Fisher II, Collins Creek II, and Pleasant Creek II sequences are present only in the Kure Beach Core; Collins Creek I occurs only in the Elizabethtown core.

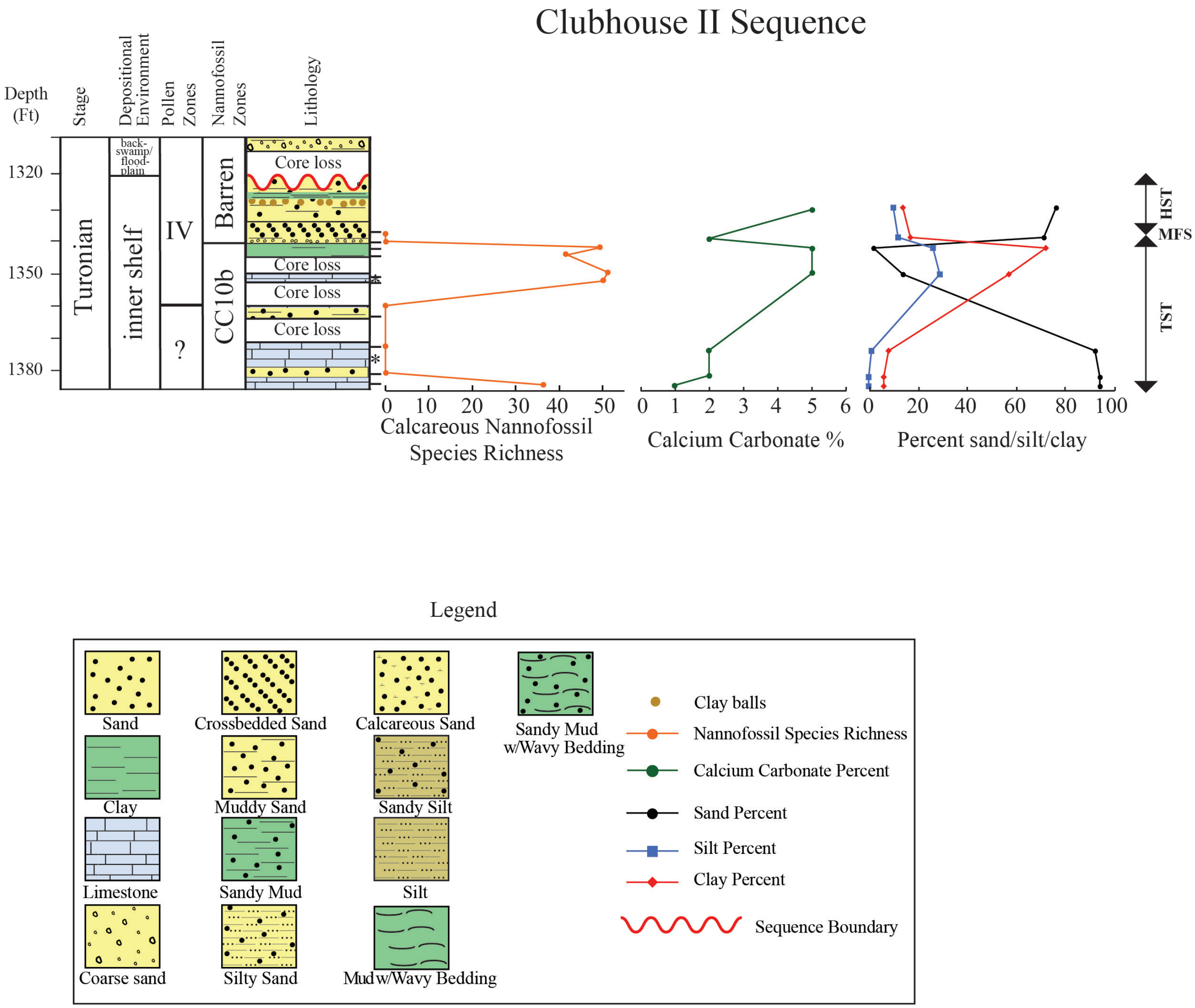
Clubhouse II sequence

The oldest sequence, Clubhouse II, is present from the base of the Kure Beach core at 1386.0 ft (422.5 m) to the overlying sequence boundary at 1320.0 ft (402.3 m) (text-fig. 3). The Clubhouse II sequence is greater than 66 ft thick (20.1 m); its base was not reached during drilling. Data from the USGS Smith Elementary School core (text-fig. 1), indicate that the base of this sequence is Cenomanian in age (Lowery et al. 2019). The Clubhouse II sequence is not present in the Elizabethtown core.

Lithologic description

The Clubhouse II sequence consists of indurated, shelly limestone at its base that is approximately 35.0 ft (10.7 m) thick and is punctuated by muddy sand beds in its lower part. The muddy sand beds are composed of >90% sand and 6 to 8% clay and silt and range in thickness from 0.3 ft (0.1 m) to 6.5 ft (2.0 m). The indurated, shelly limestone layers range in thickness from 0.9 ft (0.3 m) to 3.8 ft (1.2 m). The muddy sand beds are increasingly replaced up-section by clay-silt layers and the indurated shelly limestone is absent above 1350 ft (411.5 m). From about 1350 ft (411.5 m) to a prominent contact at 1339.7 ft (408.3 m), the core is dominated by laminated clay-silt layers. These layers consist of up to 72% clay and range in thickness from 0.5 ft (0.2 m) to 2.6 ft (0.8 m) (Self-Trail et al. 2020). Individual laminae are very thin and vary from < 1 cm to a millimeter in thickness.

The clay-silt interval is capped by a 0.7 ft (0.21 m) thick muddy sand with indurated, rounded intraclasts and small lignite frag-

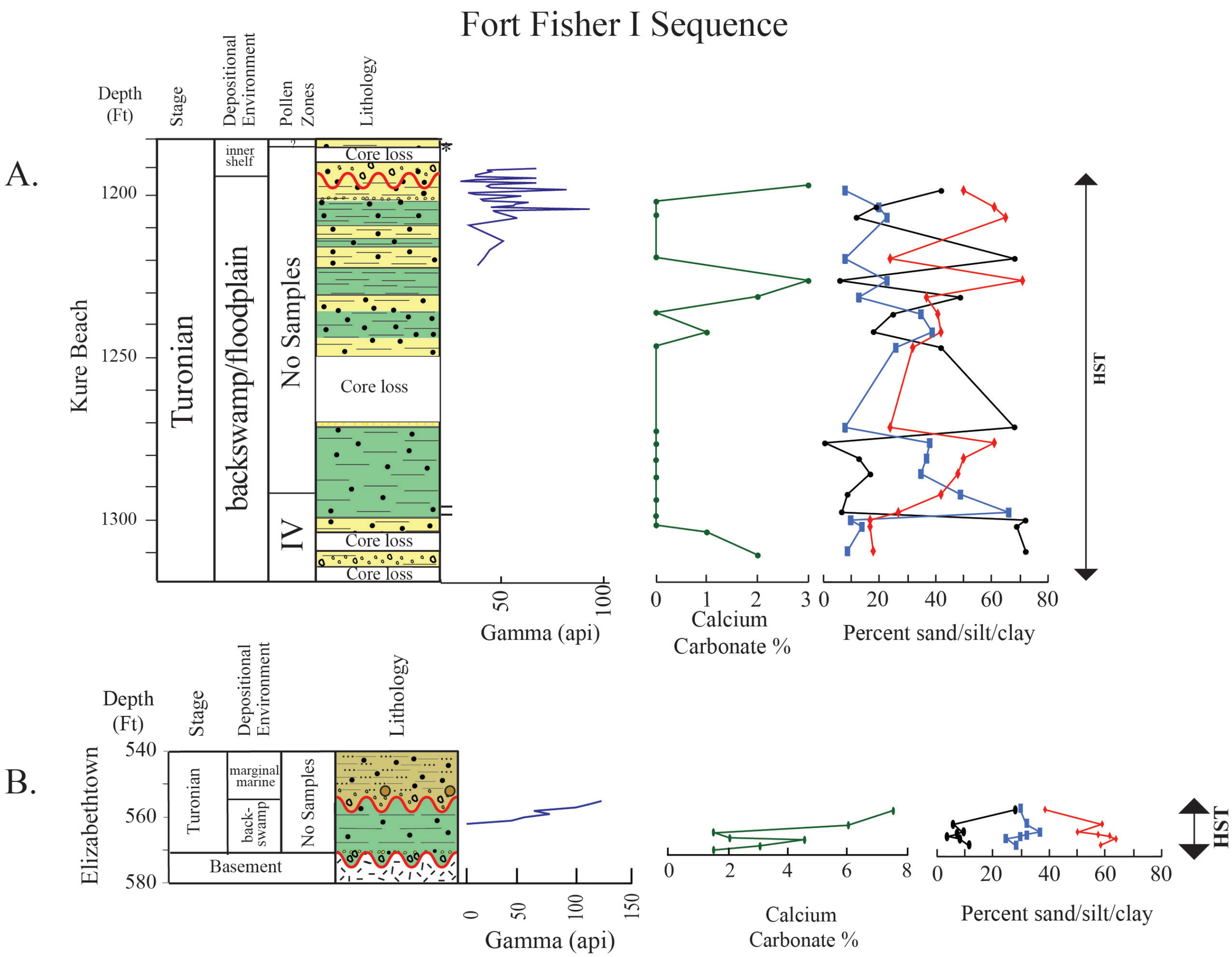


TEXT-FIGURE 4
Correlation of lithologic, biostratigraphic, sequence stratigraphic, and grain-size data for the Clubhouse II sequence, Kure Beach core. Geophysical data was not available for this sequence. TST, transgressive systems tract; MFS, maximum flooding surface; HST, high stand systems tract. Red wavy line indicates a sequence boundary. Asterisk (*) marks location of a Sr isotope sample; tick (-) marks the location of a fossil sample. Legend applies to text-figs. 4-6, 8, 10, 12, 14.

ments in a clayey sand matrix. Glauconite is present throughout in concentrations of ~1%. Sharply overlying the muddy sand is a thick, fine to medium sand (~15.0 ft, 4.8 m) with low angle cross-beds at its base. This unit becomes more massive toward the top and is composed of 72% sand, 10% silt and 18% clay. Scattered clay balls are present from 1326.9 ft (404.4 m) to 1325.9 ft (404.1 m). From 1325.9 ft (404.1 m) to the sequence boundary at 1320.0 ft (402.3 m) is a fine to medium, faintly bedded, micaceous quartz sand that has a 0.3 ft-thick (0.1 m), thinly laminated greasy clay layer in its lower part.

Biostratigraphy and Sr dates

The absence of the calcareous nannofossil marker species *Helenea chiastia*, whose last occurrence marks the top of the Cenomanian, along with the absence of *Quadrum gartneri* and *Eprolithus moratus* and the presence of *Marthasterites simplex,* place these sediments in calcareous nannofossil Zone CC10b of Sissingh (1977) and Zone UC6a of Burnett (1998); these zones are early Turonian in age. The co-occurrence of the palynomorphs *Complexiopollis* spp. and *Atlantopollis verrucosa* indicates that these sediments are within pollen zone IV of Doyle and Robbins (1977) of Cenomanian-Turonian age. Two samples provided strontium isotopic dates of 87.5 Ma and 88.2 Ma, suggesting a late Coniacian age; however, correlation of the calcareous nannofossil and palynomorph data shows this sequence is early Turonian in age. The strontium isotopic data is considered to be too young suggesting that the studied samples have been diagenetically altered.



TEXT-FIGURE 5
Correlation of lithologic, biostratigraphic, sequence stratigraphic, geophysical, and grain size data for the Fort Fisher I sequence. A) Kure Beach core; B) Elizabethtown core. HST, high stand systems tract. Red wavy line indicates a sequence boundary. Asterisk (*) marks location of a Sr isotope sample; tick (-) marks the location of a fossil sample.

Depositional environment

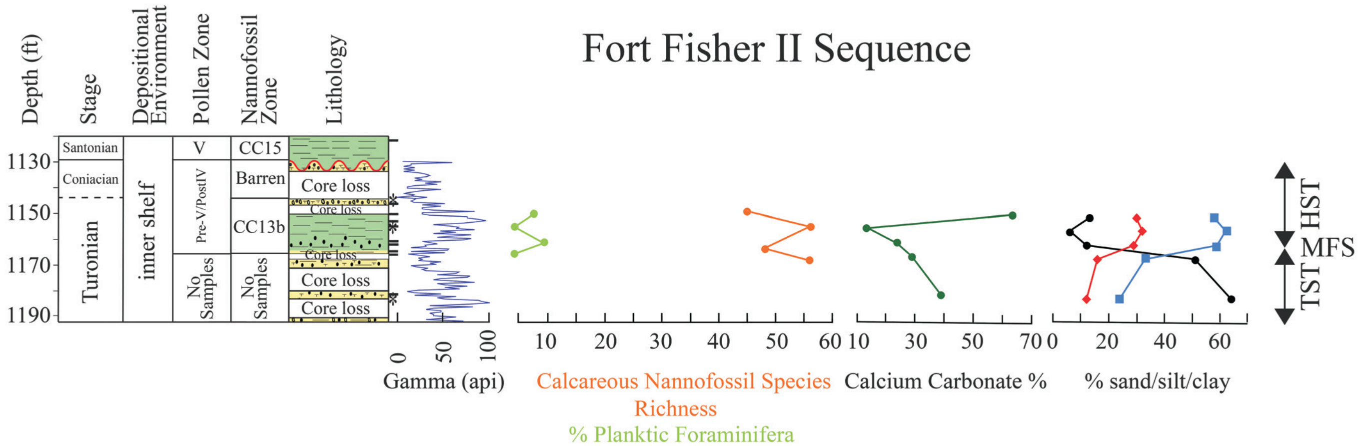
The presence of shelly limestone interbedded with a muddy sand that is capped by a clay suggests that the lower part of the sequence was deposited in a shallow marine environment that was progressively deepening upward to approximately 1350.0 ft (411.5 m). Increasing calcareous nannofossil species richness corroborates this interpretation. Near the top of this sequence, sediments become sandier with decreasing mud, glauconite, and shells and increasing lignite, suggesting deposition in a shelf environment proximal to shore.

Sequence stratigraphy

Lower sediments of the Clubhouse II sequence represent a transgressive systems tract (TST) with a maximum flooding surface (MFS) at 1339.7 ft (408.3 m). The TST is identified by a gradual fining-upward section that changes from interbedded muddy sand and limestone to a well-laminated clay approaching the MFS. The MFS is coincident with an increase in calcareous nannofossil species richness. Above the MFS, the upward decrease in glauconite and mud and the increase of lignite and quartz sand indicate increased sediment input as the highstand systems tract (HST) (text-fig. 4) and its shoreline rapidly prograded seaward.

Fort Fisher I sequence

In the Kure Beach core (text-fig. 5A), the Fort Fisher I sequence extends from its basal boundary at 1320.0 ft (402.3 m) to the base of the Fort Fisher II sequence at 1192.0 ft (363.3 m); it is 128.0 ft (39.0 m) thick (text-fig. 4). The contact between Fort Fisher I and the Clubhouse II sequence below was not recovered in the Kure Beach core; it occurs between 1320.0 ft (402.3 m) and 1310.7 ft (399.5 m) and has been placed at 1320.0 ft (402.3 m) (text-fig. 3). The lack of geophysical data at the bottom of the core and the core loss means this placement is somewhat arbitrary. The presence of coarse quartz pebbles at the top of the



TEXT-FIGURE 6
Correlation of lithologic, biostratigraphic, sequence stratigraphic, geophysical, and grain size data for the Fort Fisher II sequence in the Kure Beach core. TST, transgressive systems tract; MFS, maximum flooding surface; HST, high stand systems tract. Red wavy line indicates a sequence boundary. Asterisk (*) marks location of a Sr isotope sample; tick (-) marks the location of a fossil sample.

coring run suggests that the entire lost interval is a pebble lag at the base of the Fort Fisher I sequence.

In the Elizabethtown core (text-fig. 5B) the Fort Fisher I sequence occurs between 570.6 ft (173.9 m) and 554.0 ft (168.9 m); it is 16.6 ft (5.1 m) thick. Its basal sequence boundary at 570.6 ft (173.9 m) is sharp and nonconformable with basement saprolite below and thick iron-cemented colluvial clay above. The upper boundary with the Collins Creek I sequence at 554.0 ft (168.9 m) is sharp, with rip-up clasts of underlying sediment filling small-scale depressions along the boundary.

Lithologic description

In the Kure Beach core (text-fig. 5A), sediments at the base of the Fort Fisher I sequence consist of fine to coarse, micaceous, faintly laminated sand with scattered rounded quartz pebbles; it is increasingly semi-indurated towards the lower part. This sand fraction fines upward to a thinly and poorly bedded sandy and silty clay (1300.0–1271.5 ft, 396.2–387.6 m) that contains scattered fragments of lignite. Another sand interval that is clayey and heavily oxidized, occurs at 1231.8–1232.0 ft (375.4–375.5 m). In this package, clayey and muddy intervals become thinner and more frequent higher in the section, varying in thickness from 2.0–30.0 ft (0.6–9.1 m). This interval consists of 1–72% sand, 8–66% silt, and 12–71% clay. No calcareous mega- or microfossils are present. At 1203.0 ft (366.7 m), there is a 0.2 ft-thick (0.1 m) thick sandstone with iron cement that contains limonite, goethite and hematite concretions, and root traces (Balson et al. 2013). In the Kure Beach core, sparse traces of horizontal bedding that display high levels of disruption due to root growth occur near the contact with the overlying Fort Fisher II sequence.

In the Elizabethtown core (text-fig. 5B), sediments of the Fort Fisher I sequence consist of a basal massive sandy silty clay with pedogenic structures, common root casts, and sphaerosiderites (Balson et al. 2013). This clay grades upwards into a sandy clay that contains well-sorted, very fine to fine quartz grains. Sand content increases from approximately 15% at the base to about 30% towards the top of the sequence, and sparse, very fine, well-sorted, sub-rounded coarse quartz grains are present (<5 to 7%). No lignite or glauconite is present in this interval. Calcium carbonate percent increases from less than 2% at the base to near 8% at the top. The texture is blocky and fragmented.

Biostratigraphy and Sr dates

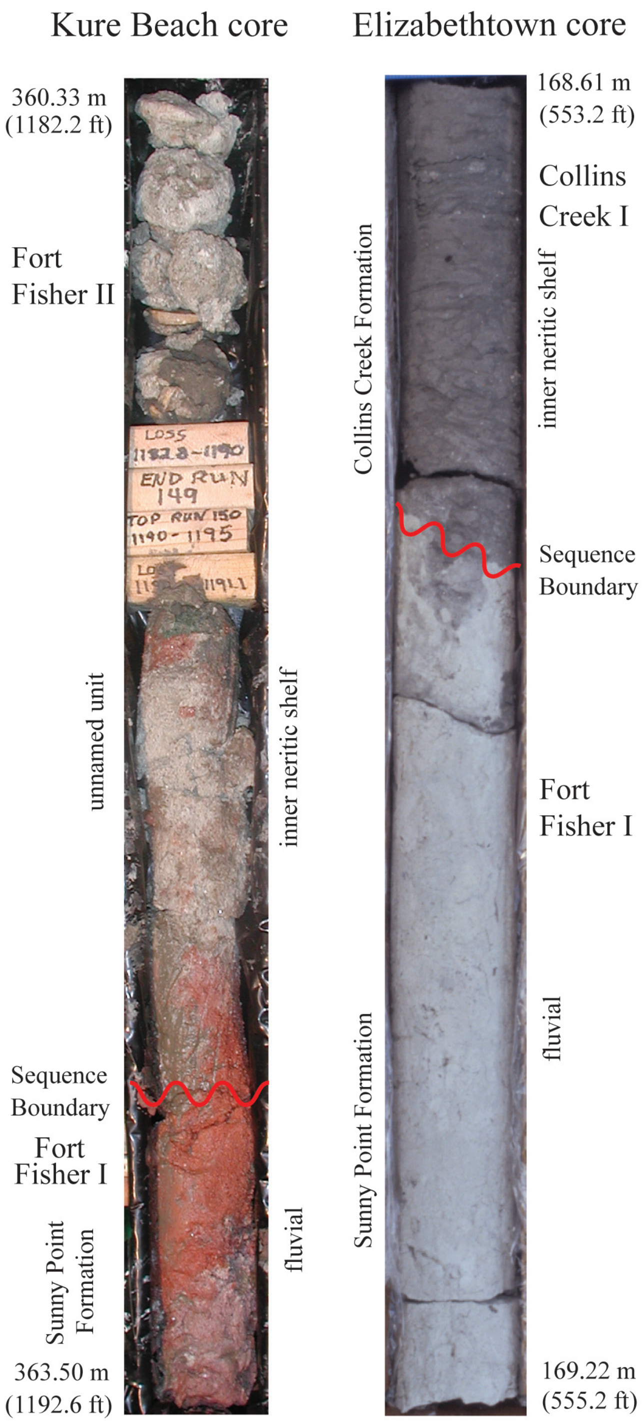
The co-occurrence of palynomorphs of older *Complexiopollis* spp. and *Atlantopollis verrucosa* in two basal samples in the Kure Beach core place these sediments within pollen Zone IV of Doyle (1969) and Doyle and Robbins (1977). Calcareous nannofossils are not present in this sequence in the Kure Beach and Elizabethtown cores. The absence of calcareous material precluded Sr dating. No palynomorph samples were available from the Elizabethtown core. The Fort Fisher I sequence is inferred to be Turonian in age based on the presence of early Turonian calcareous nannofossils and palynomorphs below the sequence boundary and late Turonian microfossils in the Fort Fisher II sequence above in the Kure Beach core. Calcareous nannofossils and pollen from the overlying Collins Creek I sequence in the Elizabethtown core are Coniacian in age.

Depositional environment

In the Kure Beach core, the presence of iron coated sand grains, limonite, goethite, hematite concretions, root traces and the absence of glauconite suggest deposition in a terrestrial environment. Balson et al (2013) noted that the presence of sphaerosiderites, which typically form in reducing environments, suggests deposition in a low energy environment, possibly backswamp or floodplain. In the Elizabethtown core, the lack of glauconite, the absence of marine microfossils, and the presence of terrestrial features such as root traces and pedogenic structures support deposition in a terrestrial environment, possibly backswamp.

Sequence stratigraphy

Fort Fisher I is interpreted to represent deposition in a HST. The presence of thicker sandy and clayey couplets at the base of this section might indicate an early phase of the highstand when the



TEXT-FIGURE 7
Sequence boundary and formation contact between the Fort Fisher I (Sunny Point Formation) and Fort Fisher II (unnamed unit) sequences in the Kure Beach core and the Fort Fisher I (Sunny Point Formation) and Collins Creek I (Collins Creek Formation) sequences in the Elizabethtown core.

rate of base level rise is relatively high and sediment supply was roughly equivalent to this rate. Thus, the normal regression still has a strong aggradational component (Catuneanu 2006). The presence of thinner sandy and clayey packages at the top of this section indicate decreasing accommodation on the shelf, originating from a lower rate of sediment supply relative to sea-level rise, suggesting that progradation was becoming a more dominant factor with time (see text-fig. 4 and grain size data from Self-Trail et al. [2020]). Recent work by Weems et al. (2019) on the Esso #1 core in the Outer Banks of North Carolina establishes that shoreline position was downdip of Kure Beach during the Turonian and supports the interpretation that these sediments represent HST conditions.

In the Elizabethtown core the Fort Fisher I sequence represents progradation of the shoreline during minor relative sea-level fall. This remnant HST has a 0.6 ft (0.2 m) thick colluvium at the base followed by 16.0 ft (4.9 m) of sandy silty clay. The lack of glauconite, shell fragments, and calcareous nannofossils, and the presence of root casts and pedogenic structures is representative of deposition in a fluvial system.

Fort Fisher II Sequence

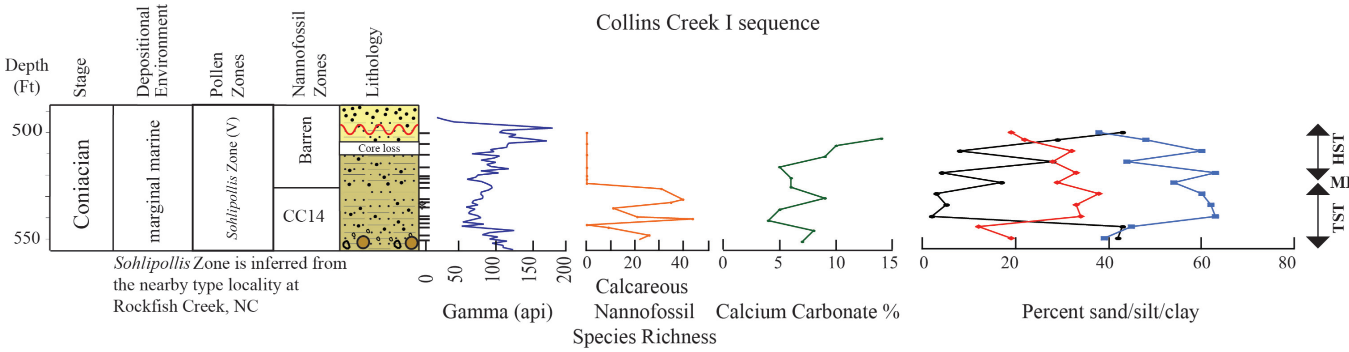
In the Kure Beach core, the Fort Fisher II sequence is designated as the sediments between 1192.0 and 1129.2 ft (363.3–344.2 m), and is 62.8 ft (19.1 m) thick (text-fig. 6). The basal contact with the Fort Fisher I sequence is an irregular but sharp, unconformable surface with small-scale relief observable in the core (up to 0.1 ft (0.03 m)), that separates silty and sandy clay below with poorly sorted clayey sand above (text-fig. 7). Core recovery of sediments in this interval was low (35%), and interpretation relied heavily on the sparse cores and geophysical logs. The Fort Fisher II sequence does not occur in the Elizabethtown corehole.

Lithologic description

The basal part of the Fort Fisher II sequence in the Kure Beach core (1192.0 ft to 1180.5 ft) consists predominately of poorly sorted clayey sand with pebbles to 0.79 inches (2.0 cm) in diameter directly above the lower sequence boundary. The sediments in this basal section are poorly sorted very fine to coarse quartz sand, with coarse grains dominating. Clay and silt make up < 35% of the sedimentary package (text-fig. 6).

From 1180.5 to 1162.0 ft (354.2 m), the sediments consist predominantly of muddy sand interbedded with limey mud that is locally indurated. Core loss throughout this interval was high, and lithologic descriptions are based on a combination of geophysical log interpretations and the sparse core samples. The sand in this section consists of well sorted, fine to medium quartz grains, with trace amounts of pyrite and phosphate. Glauconite, mica, iron oxides, and shell fragments are present throughout in trace amounts. At approximately 1162.0 ft (354.2 m), the mud content sharply increases upwards from 50% to 90%, and the gamma-ray log shows a corresponding sharp deflection to the right, indicating increased radioactivity typical of clays.

A conglomeratic zone containing 1-cm diameter shell fragments and minor amounts of phosphate cemented with calcium carbonate occurs from 1146.2 ft (349.4 m) to 1144.2 ft (348.8 m). Sparse quartz pebbles up to 0.4 inches (1.0 cm) in diameter are present, and lignite and other organic material are absent. The top of the sequence, from 1130.4 ft (344.5 m) to 1129.2 ft (344.2



TEXT-FIGURE 8
Correlation of lithologic, biostratigraphic, sequence stratigraphic, geophysical, and grain size data for the Collins Creek I sequence in the Elizabethtown core. TST, transgressive systems tract; MFS, maximum flooding surface; HST, high stand systems tract. Red wavy line indicates a sequence boundary. Tick (-) marks the location of a fossil sample.

m) contains sandstone consisting of calcite-cemented quartz that is fine to medium and subrounded to rounded. Shells fragments are common.

Biostratigraphy and Sr dates

Balson et al. (2013) noted the presence of pre-zone V/post-zone IV palynomorphs and Zone CC13b calcareous nannofossils from their unnamed unit of the Kure Beach core, which correlates to the base of Fort Fisher II. However, Sr isotopic analysis of three samples (1182.7 ft [360.5 m], 1155.8 ft [352.3 m] and 1145.4 ft [349.1 m]) from the Kure Beach core produced dates of 89.6 Ma, 89.3 Ma, and 87.6 Ma, respectively, suggesting a possible Coniacian age for the sequence. Thus, a late Turonian to early Coniacian age can be assigned to this sequence based on available data.

Depositional environment

In the Kure Beach core, the presence of calcareous nannofossils, planktic and benthic foraminifera, shell fragments, glauconite, and carbonate cemented indurated zones suggest deposition in a shelf environment. The percent of planktic foraminifera is low (<10%), suggesting that deposition occurred in the inner neritic zone in water depths less than 50 m (Leckie and Olson 2003). The presence of terrestrial pollen corroborates the relative proximity of this site to the shoreline at the time of deposition.

Sequence stratigraphy

In the Kure Beach core, the Fort Fisher II sequence represents a TST with a MFS at 1162.0 ft (354.2 m), overlain by an HST (text-fig. 6). The TST consists of poorly sorted very fine to coarse quartz sand and minor poorly sorted pebbly clayey sand at the base. This basal sand gradually becomes more clayey near the MFS, which coincides with a sharp positive deflection on the gamma-ray log. Above the MFS, the presence of horizontal, laminated muds, shell fragments, glauconite and rare ostracods suggests the presence of an early HST, with little sediment input from the shoreline. The gamma ray signature in the Fort Fisher II sequence is characterized by an irregular and serrated pattern above the sequence boundary at 1192.0 ft (363.3 m). Stacking is aggradational, suggesting deposition on a storm-dominated shelf during the TST (Krassay 1998). A transition to deeper water and finer-grained sedimentation is evidenced by a bell-shaped, retrogradational pattern approaching the maximum flooding surface at 1162.0 ft (354.1 m). The HST is characterized by a more funnel-shaped, progradational pattern. Two coarsening-upward packages in the HST are separated by finer-grained material. A sharp upper contact marks the boundary between the Fort Fisher II and overlying Collins Creek II sequences.

A gradual decrease in clay content, coupled with a decrease in species richness, starts at ~1152.0 ft (351.1 m) and is indicative of the development of the late HST. The presence of a conglomeratic zone and interbedded sand and indurated sandstone at the top of the sequence is evidence of continued shoreline progradation. The late HST was deposited when the sedimentation rate outpaced accommodation space in the basin during relative sea-level fall.

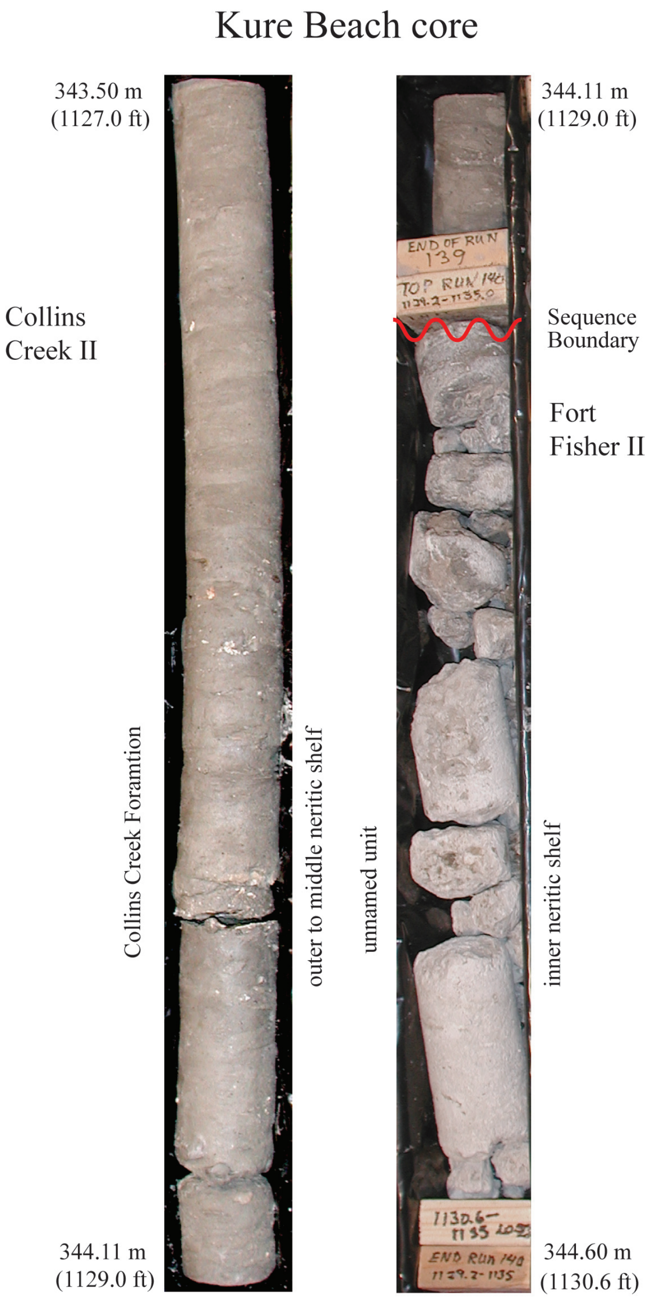
Collins Creek I sequence

The Collins Creek I sequence only occurs in the Elizabethtown core, where it overlies the Fort Fisher I sequence and consists of the sediments between 554.0 ft and 497.8 ft (168.9 m and 151.7 m) (text-fig. 7). The basal sequence boundary is sharp and unconformable and is overlain by coarse sands containing clay balls.

Lithologic description

The basal Collins Creek I sequence from 554.0 ft (168.9 m) to 525.0 ft (160.02 m) contains quartz granules and pebbles to about ~1.3 cm in diameter concentrated just above the sequence boundary (text-fig. 8). Rip-up clasts of underlying sediment, some of which exhibit soft-sediment deformation features, are present just above the contact. Shell fragments are present throughout Collins Creek I but decrease towards the top. Pyritized lignite is present only near the top of the sequence, but mica is abundant throughout. The sand in this sequence rapidly decreases from 43% at the bottom to approximately 5% at 535.0 ft (163.1 m); from there, it increases to 41% at the top. Silt dominates there, constituting up to 65% of the sediments. The silt section is massive, except for scattered small sand lenses. The quartz sand in the lenses is fine to very fine, sub-rounded to rounded, and well-sorted.

From 525.0 ft to 497.8 ft (160.0–151.7 m) the section consists of sandy clayey silt with pyrite nodules scattered throughout. No glauconite is present and trace amounts of organic material are sparse. The sand fraction gradually increases from 20% at the base to 43% at the top. The sand is fine to very fine and well sorted. Clay and silt decrease upward to 28% and 39%, respec-



TEXT-FIGURE 9
Sequence boundary and formation contact between the Fort Fisher II (unnamed unit) and Collins Creek II (Collins Creek Formation) sequences in the Kure Beach core.

tively, at the top of the unit. Shell fragments are present in very thin beds. From 512.5 ft (156.2 m) and upwards, the sediments become poorly sorted, and grain size becomes very coarse. Sparse grains of phosphate and lignite are present. The sediments in this interval coarsen upwards.

Biostratigraphy and Sr dates

The presence of the calcareous nannofossil species *Micula decussata*, the marker species for the base of Zone CC14, and the absence of *Reinhardtites anthophorus*, the marker species for the base of Zone CC15, place sediments of the Collins Creek I sequence in Zone CC14 of Sissingh (1977), which is early Coniacian in age. Pollen data indicates that these sediments are within the *Sohlipollis* taxon range zone of Christopher et al. (1999), which ranges from the Coniacian into the Santonian. Thus, correlation between calcareous nannofossil and pollen data indicate this sequence is Coniacian in age. This sequence provided no shell fragments for Sr dating.

Depositional environment

The presence of glauconite and calcareous nannofossils in the sandy clayey silt at the base indicates a shelf depositional environment. Near the top of the section, the lack of glauconite and calcareous micro- and macrofossils, coupled with an increase in sand, suggests shallowing-upward and deposition in a marginal marine environment.

Sequence stratigraphy

The Collins Creek I sequence is represented by a TST with a MFS at 525.0 ft (160.1 m), overlain by an HST (text-fig. 8). The TST to MFS interval is defined by the gamma ray log as an overall fining upward sequence. Calcareous nannofossils are restricted to the TST. Above the MFS, the percent of sand gradually increases, suggesting that sediment input was slowly outpacing sea-level rise, although increasing calcium carbonate content suggests that the HST was still occurring in a marine environment. The increase in lignite near the top of the HST and the absence of calcareous microfossils is indicative of increased proximity to the shoreline source.

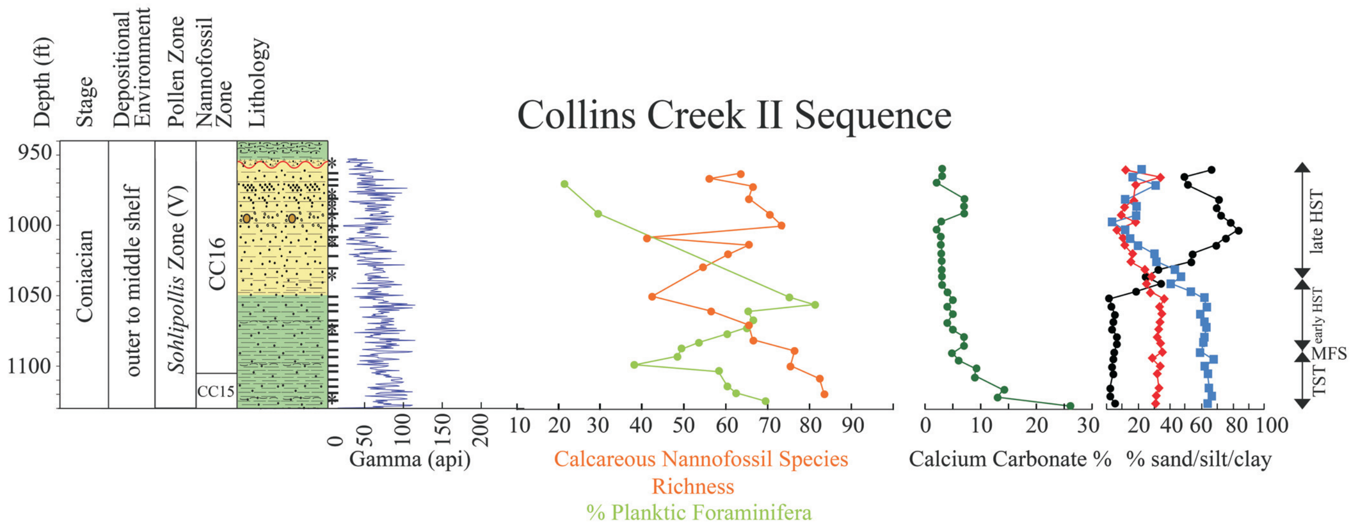
Collins Creek II sequence

In the Kure Beach core, the Collins Creek II sequence occurs between 1129.2 ft and 956.2 ft (344.2 to 291.5 m), a thickness of 173 ft (52.7 m). The boundary between the Collins Creek II and the underlying Fort Fisher II sequence is sharp and unconformable (text-fig. 9). At the sequence boundary, fine to medium, well-sorted glauconitic sand with quartz and phosphate below is overlain by burrowed, silty and glauconitic clay, with very coarse phosphate sand. The Collins Creek II sequence does not occur in the Elizabethtown core.

Lithologic description

In the Kure Beach core, mud dominates from the basal sequence boundary (1129.2 ft, 344.2 m) to about 1050.0 ft (320.0 m), with a maximum thickness of 79.2 ft (24.1 m). Within this interval, the sand content is low (<6%), whereas the silt and clay fractions are 67% and 36%, respectively (text-fig. 10). This muddy interval contains intensely bioturbated beds and sections that contain both wavy and horizontal laminations. It is glauconitic, calcareous, and contains shell fragments that are scattered throughout in small amounts. The burrows are filled with glauconitic sand. The sand in this interval is very fine to medium, well-sorted and angular to sub-rounded. Mica is locally rare to common, iron oxide particles and organic material are both present in small amounts. Phosphate occurs in the basal 1.0 ft (.3 m).

At 1050.0 ft (320.0 m) the percent sand begins to gradually increase from 18% to 83%, and the sediments change from a sandy mud to a glauconitic muddy sand up to 1000.0 ft (304.8 m). The silt and clay content decrease proportionally over this interval. The sand is fine to very fine, well-sorted, angular to sub-rounded and burrowed. Glauconite and mica are common and organic material is present in small amounts. Sporadic clay



TEXT-FIGURE 10
Correlation of lithologic, biostratigraphic, sequence stratigraphic, geophysical, and grain size data for the Collins Creek II sequence in the Kure Beach core. TST, transgressive systems tract; MFS, maximum flooding surface; HST, high stand systems tract. Red wavy line indicates a sequence boundary. Asterisk (*) marks location of a Sr isotope sample; tick (-) marks the location of a fossil sample.

stringers occur as thin to wavy laminations throughout this interval. A coarser interval from 1000.0-990.0 ft (305.4-301.8 m) contains moderately sorted very fine to medium quartz sand with trace amounts of phosphate, clay balls up to 1.5 in (3.8 cm) in diameter, a ray tooth and fish bones. Between 990.0 ft and 956.2 ft (301.8 m and 291.5 m), glauconite becomes sparse and muddy quartz sand is prevalent. Shell fragments are present throughout; lignite, lithoclasts, fish bones, serpulid worm tubes and limonite are sparse, and mica is sparse to common. The sand contains thin discontinuous clay laminae, cross-laminae, and common burrows.

Biostratigraphy and Sr dates

The basal part of the Collins Creek II sequence is placed in calcareous nannofossil Zone CC15 based on the first occurrence of *Reinhardtites anthophorus*, the marker species, at 1121.5 ft (341.8 m) and on the absence of *Lucianorhabdus cayeuxii*, the basal Zone CC16 marker. This zone is relatively thin in the Kure Beach core, as the first occurrence of *L. cayeuxii* occurs at 1100.7 ft (335.5 m). The last occurrence of *Lithastrinus septenarius,* which occurs within Zone CC16, falls within this sequence. Strontium dates from six samples range from 87.5 to 88.6 Ma. Thus, both biostratigraphic and strontium analyses record a late Coniacian age for Collins Creek II.

Depositional environment

The presence of calcareous nannofossils, shell fragments, bioturbation, and a thick succession of mud-dominated sediments at the bottom that coarsen upward to a glauconitic sand all suggest deposition in a shelf environment. From the base of the sequence to ~1050.0 ft (320.0 m), percent planktic foraminifera range between 50–80%, indicating that deposition occurred in outer neritic to possibly upper bathyal conditions. From 1050.0 ft (320.0 m) to the top of the sequence, percent abundance of planktic foraminifera decreases steadily to ~20%, suggesting that water depth was shallowing and deposition occurred in a middle neritic environment.

Sequence stratigraphy

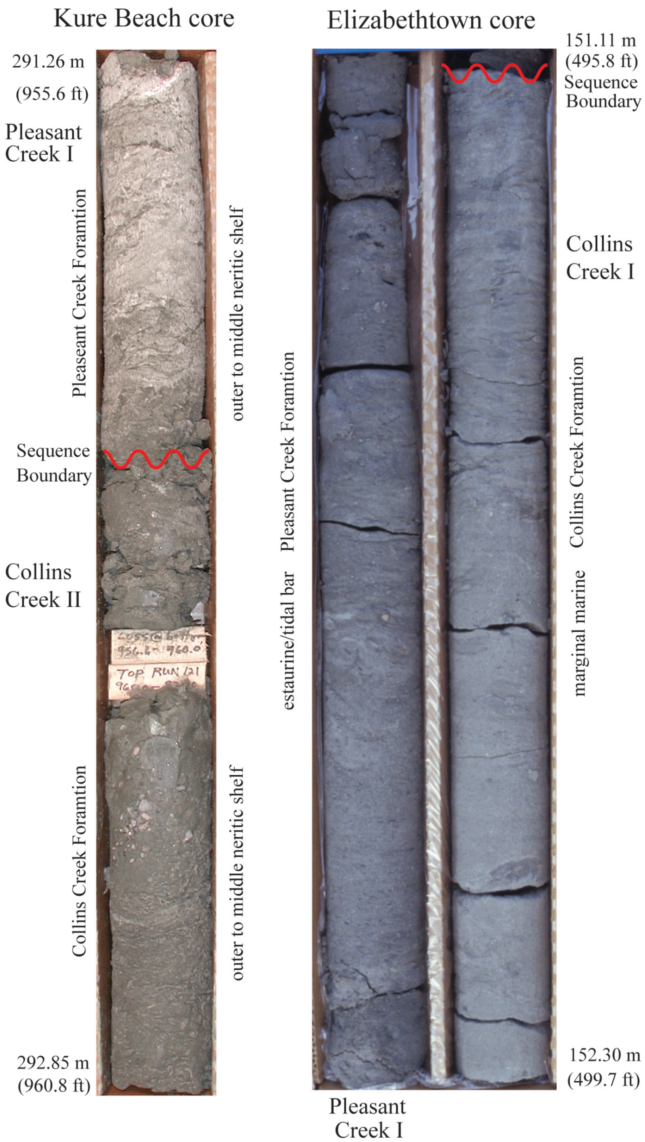
The Collins Creek II sequence consists of a TST from 1129.2 ft to 1090.0 ft (344.2 m to 332.2 m) with the MFS at 1090.0 ft (332.2 m). It is overlain by an early aggradational HST followed by a progradational late HST beginning at 1052.0 ft (320.7 m) (text-fig. 10). The TST is defined in the gamma ray log response pattern by a coarsening upward parasequence that is overlain by muds identified as within the interval of maximum flooding. Within the TST, calcium carbonate percent decreases upward but calcareous nannofossil species richness remains high, as does percent planktic foraminifera. This systems tract formed when a relative rise in sea-level outpaced sediment input from the shoreline, providing accommodation space in the basin.

Above the MFS in the early HST, percent calcium carbonate, sand, silt, and clay remain fairly static throughout, as does the gamma-ray log signature. This is accompanied by a decrease in calcareous nannofossil species richness but an increase in percent planktic foraminifera (text-fig. 10). The static nature of the graphs suggests a balance between sediment input and relative sea-level rise, indicative of the early HST.

Higher in the section above 1052.0 ft (320.7 m), sediment input outpaces sea-level rise, as shown by an increase in percent sand, indicating progradation of the shoreline. Predominance of benthic foraminifera over planktic foraminifera, decreasing calcareous nannofossil species richness, and low percent calcium carbonate higher in the section suggest deposition in a late HST more proximal to the source.

Pleasant Creek I sequence

In the Kure Beach core, the Pleasant Creek I sequence overlies the Collins Creek II sequence between 956.2 ft (291.5 m) and 762.8 ft (232.5 m). The sequence boundary between Pleasant



TEXT-FIGURE 11
Sequence boundary and formation contact between the Collins Creek II (Collins Creek Formation) and Pleasant Creek I (Pleasant Creek Formation) sequences in the Kure Beach core and the Collins Creek I (Collins Creek Formation) and Pleasant Creek I (Pleasant Creek Formation) sequences in the Elizabethtown core.

Creek I and the underlying Collins Creek II sequence is marked by a glauconitic sand below and a calcareous-cemented sandstone above (text-fig. 11).

In the Elizabethtown core, the Pleasant Creek I sequence occurs between 497.8 ft (151.7 m) and 352.3 ft (107.4 m). The sequence boundary at the base of the Pleasant Creek I is sharp and unconformable (text-fig. 11). It is marked by a change from well sorted silty sand below to a 2.0 ft (0.6 m) thick, very fine to very coarse, poorly sorted, clayey quartz sand containing lignite fragments. The Pleasant Creek I sequence ranges in thickness from 193.6 ft (59.0 m) down-dip (Kure Beach) to 145.5 ft (44.35 m) up-dip at Elizabethtown.

Lithologic description

In the Kure Beach core, from its lower boundary at 956.5 ft (291.5 m) to the top of the Pleasant Creek I sequence at 762.8 ft (232.5 m), muddy sand beds predominate, reaching a maximum thickness of 27.0 ft (8.2 m) (text-fig. 12A). Glauconite, shell fragments, and lignite are finely disseminated throughout the muddy sands. Horizontally laminated sandy mud interbedded with muddy sands that are commonly burrowed occur in several intervals; the sandy mud layers are no thicker than 8.0 ft (2.4 m). Lignite (up to 3%), broken fish scales, thin-shelled mollusks, and pyrite nodules are present throughout. From 855.9 ft (260.9 m) to the top of the sequence at 762.8 ft (232.5 m), glauconitic muddy sand is interbedded with sandy mud (text-fig. 12). Volumetric distribution of clay and silt content varies from a few percent to almost 80% in a rhythmic pattern. Percent calcium carbonate and lignite increase towards the upper boundary; glauconite decreases (text-fig. 12).

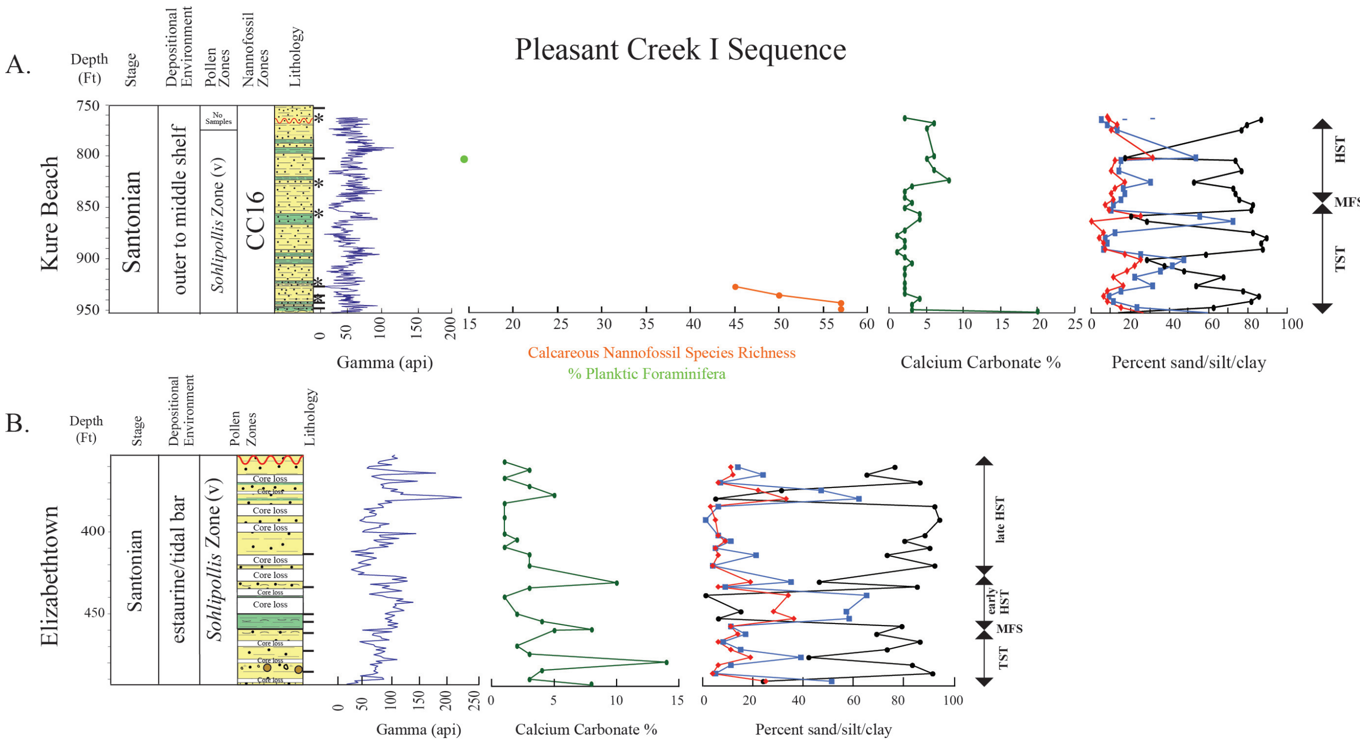
Large unrecovered intervals occur in the Pleasant Creek I sequence in the Elizabethtown core, from its lower boundary at 497.8 ft (151.7 m) to its upper boundary at 352.3 ft (107.4 m). It consists of slightly calcareous muddy sand with trace amounts of glauconite (text-fig. 12B). Complexly interlayered gravel, sands, and muds are common and intraclastic gravels occur near the base. A surface at 484.6 ft (147.7 m) is overlain by clay balls, rip-up clasts, calcite-cemented concretions, lignite, and phosphate granules. Above this to 458.3 ft (139.7 m), sediments consist of fining upward muddy sands. Wavy laminations of discontinuous thin clay are present near the top, locally with silt crossbeds. From 458.3–430.0 ft (139.7–131.1 m), the sediments consist of discontinuous lenses of laminated sandy mud with wavy bedding between intervals of clay laminations. Above this interval to the upper boundary at 352.3 ft (107.4 m), muddy coarse to very coarse sand dominates, and lignitic sands are common. Minor clay layers are present, and near the top of this package two small sandy mud packages contain possible root structures.

Biostratigraphy and Sr dates

In the Kure Beach core, the presence of calcareous nannofossils *R. anthophorus* and *L. cayeuxii*, along with the absence of *L. septenarius* and *Calculites obscurus*, the basal marker species for Zone CC17, places the Pleasant Creek I sequence in the lower part of Zone CC16, and is latest Coniacian to Santonian in age. This is corroborated by pollen data from the Kure Beach and Elizabethtown cores, which suggests placement of the sequence in the *Sohlipollis* taxon range zone of Christopher et al. (1999). Strontium dates from five samples of the Kure Beach core (83.1, 86.2, 87.2, 87.4 and 87.7 Ma) also suggest an age ranging from late Coniacian to Santonian (see Self-Trail et al. 2020). The Elizabethtown core yielded no carbonate material that was suitable for Sr dating.

Depositional environment

In the Kure Beach core, the presence of glauconite, high calcareous nannofossil species richness, terrestrial pollen, and sparse lignite suggests deposition in an outer to middle neritic environment. Near the top of the section, a change to more organic-rich sediments, with wavy laminations, suggests deposition in a more proximal environment. This interpretation is corroborated from one sample at 800.8 ft, which contains 12% planktic foraminifera, suggesting that deposition occurred in inner neritic conditions (Leckie and Olson 2003). In the Elizabethtown core, the complex interplay between gravel, sand, and



TEXT-FIGURE 12
Correlation of lithologic, biostratigraphic, sequence stratigraphic, geophysical, and grain size data for the Pleasant Creek I sequence. A) Kure Beach core; B) Elizabethtown core. No calcareous nannofossils were present in the Elizabethtown core. The gap in the calcareous nannofossil species richness graph represents no samples for that section. TST, transgressive systems tract; MFS, maximum flooding surface; HST, high stand systems tract. Red wavy line indicates a sequence boundary. Asterisk (*) marks location of a Sr isotope sample; tick (-) marks the location of a fossil sample.

mud suggests that deposition occurred in a variable energy environment, possibly estuarine or tidal bar facies; this interpretation is supported by the presence of possible root structures at the top of the sequence.

Sequence stratigraphy

In the Kure Beach core, Pleasant Creek I consists of a TST with a MFS at 855.0 ft (260.6 m), overlain by an HST (text-fig. 12). The TST is defined in the gamma ray log response pattern as a series of stacked, internally coarsening upwards parasequences that show a pattern of retrogradation and fine upward to the clay-rich zone identified as the MFS. Above the MFS, the gamma-ray pattern reflects alternating periods of aggradation and progradation in the HST. The overall pattern on the gamma ray log is one of gradual progradation, also indicated by an increase in lignitic material in the upper part of the HST.

In the Elizabethtown core, the Pleasant Creek I sequence is represented by a series of transgressive lags (parasequences) in the TST and HST (text-fig. 12B). The TST is thin, consisting of muddy sand and trace amounts of glauconite, overlain by a transgressive lag at 484.6 ft (147.7 m) with clay balls, rip-up clasts, pebbles, and phosphate granules. Above this, the gamma-ray log and lithology define a fining upward package of muddy sands associated with the TST and identified as estuarine deposits.

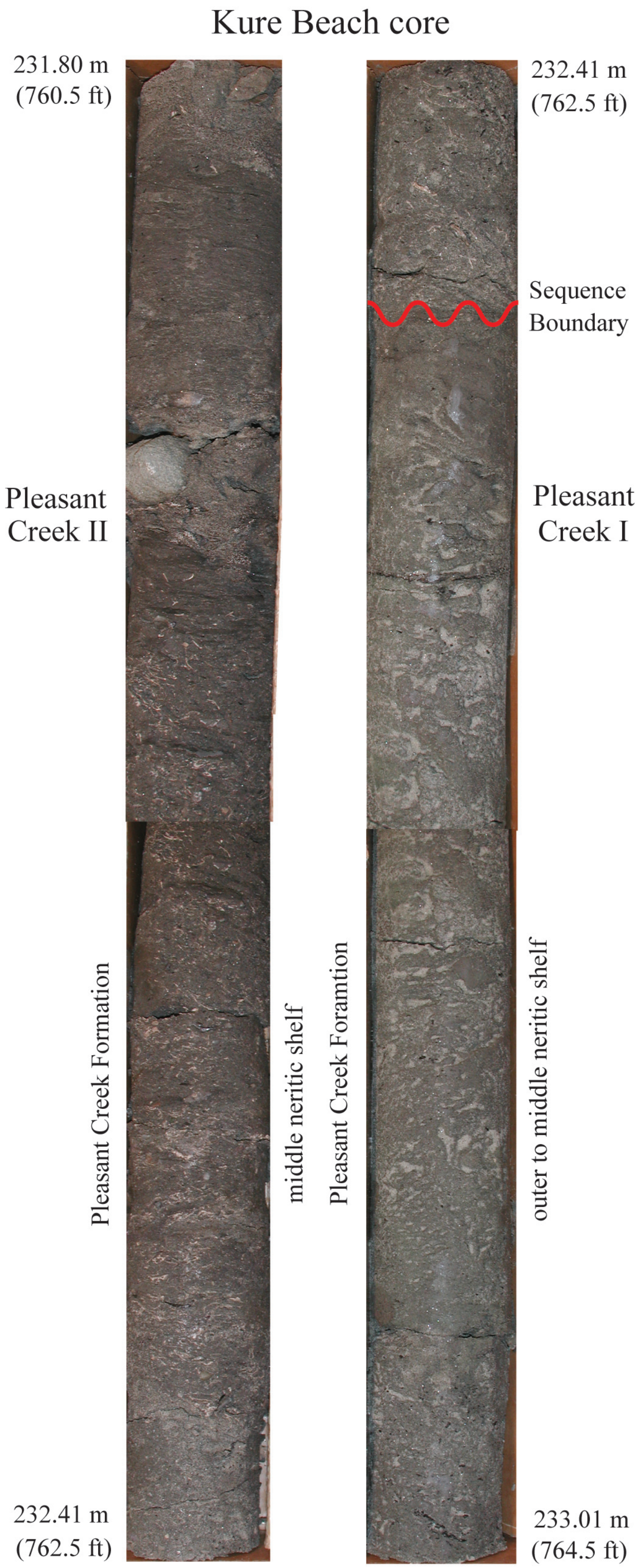
The MFS at 458.3 ft (139.7 m) is marked by a 2.0 in (5.1 cm) piece of lignite; thin lignite layers continue up into the sands in the lower part of the overlying HST. A change in the amount of sediment entering the system is defined by the gamma-ray log response pattern and lithology, which show an increase in the amount of coarse sand, the thicknesses of sand packages, and a decrease in calcium carbonate to less than 1%, all representative of a change from the early to late HST.

Pleasant Creek II Sequence

In the Kure Beach core, the Pleasant Creek II sequence occurs between 762.8 ft (232.5 m) and 710.0 ft (216.4 m), a thickness of 52.8 ft (16.1 m). The boundary between the Pleasant Creek II and the underlying Pleasant Creek I sequence is sharp, separating very fine to fine glauconitic sand below from a lag deposit of fine to very coarse sand containing phosphate and shark teeth above (text-fig. 13). The top of the Pleasant Creek II sequence is marked by a well-developed irregular disconformity that is overlain by the Tar Heel I sequence of Harris and Self-Trail (2006). The lower boundary of the Tar Heel I sequence is herein changed from 681.8 ft (207.8 m), as previously identified by Harris and Self-Trail (2006), to 710.0 ft (216.4 m) (text-fig. 14). The Pleasant Creek II sequence is not identified in the Elizabethtown core.

Lithologic description

The lower section of the Pleasant Creek II sequence is characterized by very coarse to fine sand with sparse shark teeth and phosphate just above the lower boundary. This lithology grades upward into well-sorted, very fine to fine clayey quartz sand with some lignite, phosphate, pyrite nodules, and abundant mica. Shell



TEXT-FIGURE 13
Sequence boundary and formation contact between the Pleasant Creek I (Pleasant Creek Formation) and Pleasant Creek II (Pleasant Creek Formation) sequences in the Kure Beach core.

and coral fragments are common in the upper part. A sharp contact occurs at 753.7 ft (229.7 m) between the underlying sand and an overlying olive-gray to black silty clay. This clay is faintly laminated with a few scattered shell fragments and pyrite nodules; it continues upward to 743.7 ft (226.7 m) where the upper part is intensely burrowed. This clay is overlain by clayey sand that locally contains shell fragments in pockets, glauconite, and small pebbles. From 743.7-716.6 ft (226.7-218.4 m), the sequence consists of interbedded muddy sand and silty clay; the clay typically contains thin lenses of very fine sand. The upper part of the sequence consists of wavy laminated mud with lenses of very fine quartz sand, glauconite, and sparse shell fragments. Percent calcium carbonate in the sequence is cyclic, varying from 1- 5%.

Biostratigraphy and Sr ages

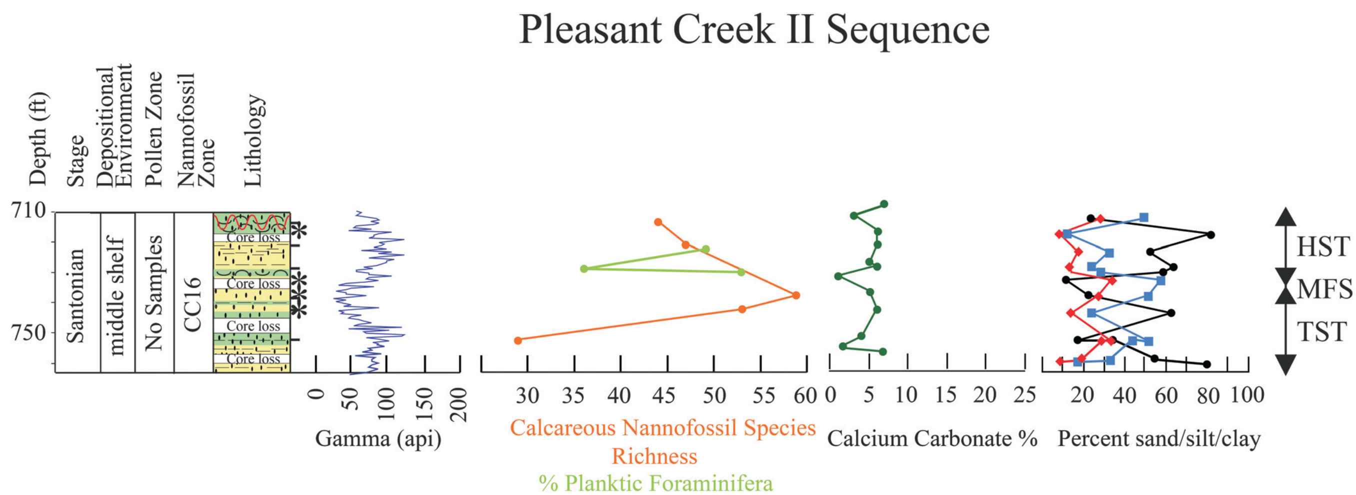
The continued presence of *R. anthophorus* and *L. cayeuxii*, along with the absence of *L. septenarius* and *Calculites obscurus*, places the Pleasant Creek II sequence in the upper part of Zone CC16 of Santonian age. The lowest occurrence of the marker species for the base of Zone CC17, *C. obscurus*, is first recorded at 705.9 ft (215.2 m), about four feet above the boundary between the Pleasant Creek II and Tar Heel I sequence of Harris and Self-Trail (2006). Five strontium dates obtained from three thin-walled pelecypods and two thicker mollusk fragments are between 82.9 and 84.6 Ma (see data tables in Self-Trail et al., 2020). Two samples corroborate a late Santonian age for Pleasant Creek II; however, three samples indicated younger ages.

Depositional environment

The presence of coral fragments, shark teeth, bivalve fragments, calcareous microfossils, and phosphate in the lower quartz sand of the Pleasant Creek II sequence suggests deposition in a marine environment. An increase in calcareous nannofossil species richness from the base of the sequence to ~735 ft (224.0 m), along with an increase in percent planktic foraminifera from 36% to 52% suggest that deposition occurred in middle neritic conditions. Faintly laminated silty clay above the quartz sand contains scattered shell fragments and pyrite nodules suggesting deeper water with possible stratification of the water column near the sediment/water interface. A gradual decrease in calcareous nannofossil richness above 735 ft (224.0 m), along with a change in lithology to interbedded muddy sand and sandy clay suggests a further shallowing of water depth up-section.

Sequence stratigraphy

The Pleasant Creek II sequence consists of a lower, coarsening upwards, transgressive parasequence and an upper HST with the upper part removed by erosion. The lower TST from 762.8–724.0 ft (232.5–220.7 m) consists of a basal, poorly sorted transgressive lag of very coarse to fine sand, that contains shark teeth, shell fragments, minor phosphate, and blue quartz on top of the sharp basal unconformity. The lag deposit grades upwards into very fine to fine clayey sand containing pyrite nodules and lignite. The MFS occurs at 735 ft (224.0 m) just below the level of greatest calcareous nannofossil species richness. From the MFS to the top of the sequence at 710.0 ft (216.4 m) the HST consists of interbedded wavy laminated silty clay and very fine muddy sand. Thicker fossiliferous muddy sand and repetitive beds of wavy laminated clay/very fine sand, which occur to the top of the sequence at 710.0 ft (216.4 m) are interpreted to represent the early HST. Based on the lithology



TEXT-FIGURE 14
Correlation of lithologic, biostratigraphic, sequence stratigraphic, geophysical, and grain size data for the Pleasant Creek II sequence in the Kure Beach core. TST, transgressive systems tract; MFS, maximum flooding surface; HST, high stand systems tract. Red wavy line indicates a sequence boundary. Asterisk (*) marks location of a Sr isotope sample; tick (-) marks the location of a fossil sample.

and gamma-ray log response pattern, the late HST is most likely not present.

DISCUSSION

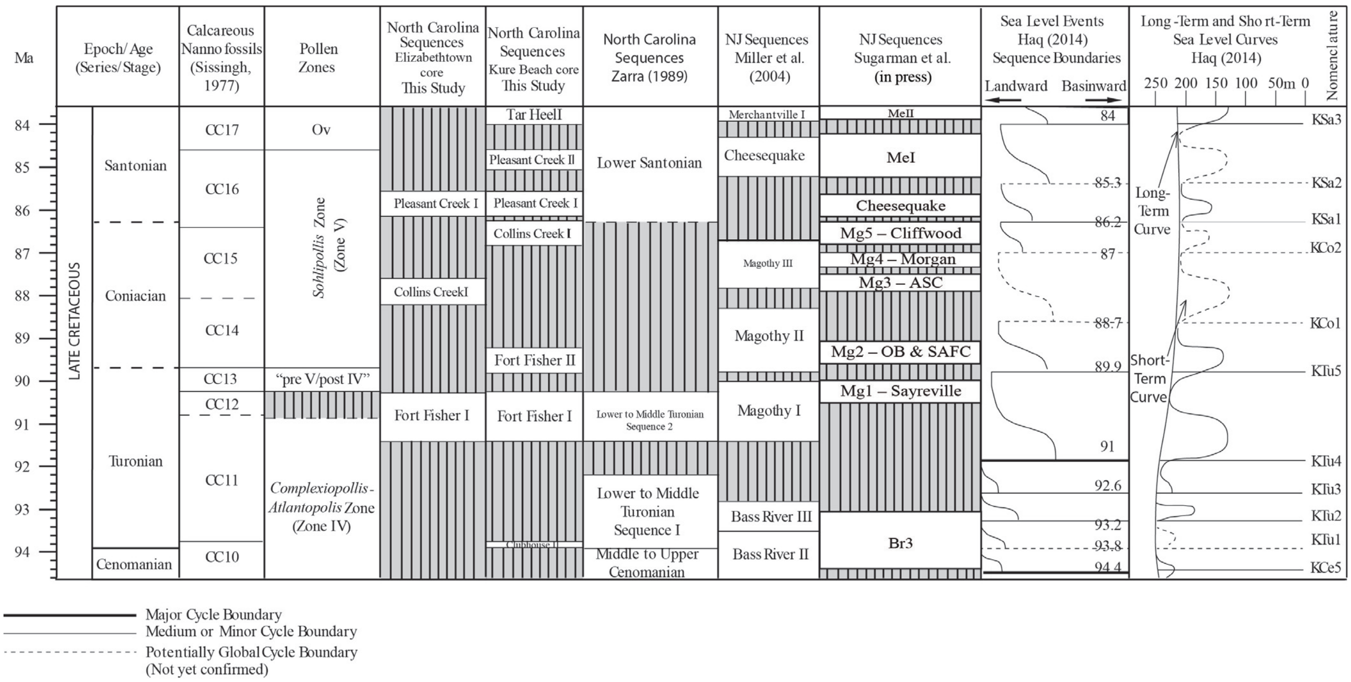
Correlation of the sequences in the Elizabethtown and Kure Beach cores provides insight into the depositional history in the Cape Fear arch area along a cross-sectional sedimentary profile that thickens southeastward. Early work by Owens and Sohl (1969) and Owens and Gohn (1985) argued for a cyclic deltaically influenced shoreline model of deposition for the Upper Cretaceous of the Atlantic Coastal Plain. Here, the systems tracts of Posamentier et al. (1988) are applied to Turonian through Santonian sequences, and it is recognized that shoreline progradation could have occurred via multiple methods, not limited to deltaic formation.

Regional Correlation of Sequences

Sediments consisting of organic-rich black shales and silty clays of late Cenomanian to early Turonian age are found across the margins of the Gulf of Mexico (Denne et al. 2016; Lowery et al. 2017), the southeast Atlantic Coastal Plain (Hattner and Wise 1980; Gohn 1992; Weems et al. 2007, 2019), and the mid-Atlantic Coastal Plain (Petters 1976; Sugarman et al. 1999). Deposition of these sediments was considered to be related to latest Cenomanian/earliest Turonian eustatic rise in sea-level prior to the early Turonian highstand event (Lowery et al. 2017).

The basal Turonian Clubhouse II sequence is representative of this earliest Turonian sea-level rise, as evidenced by a deepening upward succession of limestones capped by calcareous mud in the lower part of the sequence. This sequence is correlated to the middle to upper Cenomanian and lower to middle Turonian sequences of Zarra (1989), the Bass River sequence of Sugarman et al. (1999), and the Bass River III sequence of Sugarman et al. (in press) (text-fig. 15), where a strong biostratigraphic and lithologic similarity to sediments in the Ancora core exists. Deposition most likely occurred in middle to outer neritic water depths and represents a shoaling upward event. The presence of minor crossbedding in the fine sands above the clays of the MFS attest to a progression from deeper to shallower water through time. The Clubhouse II sequence marks the highest Late Cretaceous sea-level event documented on the Atlantic seaboard and is global in nature. Marine sediments of late Cenomanian to early Turonian age are recorded from the subsurface from South Carolina to New Jersey; occasional outcrops of the marine Raritan Formation and fluvial Magothy Formation occur in the updip of central New Jersey (Sugarman et al., in press).

Global base level lowering resulted in the progradation of the western Atlantic and Gulf shorelines during the late Turonian (Zarra 1989; King 1996; Sugarman et al. 1999; Miller et al. 2004). Miller et al. (2004) and Sugarman et al. (in press) documented this trend in the upper part of the Magothy I sequence of NJ, where marginal marine sediments coarsen upward into fluvial sediments of the upper HST and Zarra (1989) noted that the lower to middle Turonian sequence boundary represented a shift from restricted marine clay below to non-marine sandstone above. In Fort Fisher I, the lack of marine microfossils and glauconite, coupled with the presence of lignite, kaolinite-rich clays, iron coated sand grains, pedogenic structures, root casts, and sphaerosiderites (Balson et al., 2013) strongly indicates deposition in a fluvial environment representative of the upper HST. This interpretation is supported by Catuneau (2006) and Abreu et al. (2014), who show that maximum aggradation can result in progradation of the shoreline and that the HST can be fluvial in nature; this process can occur concurrently with sea-level fall. The presence of pollen from the *Complexiopollis- Atlantopolis* Zone (pollen zone IV of Christopher, 1982) in the basal part of Fort Fisher I, suggests that deposition occurred during the middle to late Turonian. Sediments of Fort Fisher I are slightly older than sediments of the Mg1 sequence of Sugarman et al. (in press), which lack *Complexiopollis- Atlantopolis* pollen. Fluvial sediments at the top of the Fort Fisher I sequence in the downdip Kure Beach core places the shoreline east of this core during the late Turonian and represents approximately 150 m of base level lowering. Documentation of fluvial sediments in both North Carolina [lower to



TEXT-FIGURE 15
Correlation of Turonian to Santonian Upper Cretaceous sequences to Zarra (1989; North Carolina), Miller et al. (2004) and Sugarman et al. (in press) from New Jersey, and to the coastal onlap chart of Haq (2014) and the time scale of Ogg et al. (2016). Pollen zones are from Doyle and Robbins (1977), Christopher (1979), Christopher et al. (1999), and Christopher and Prowell (2010).

middle Turonian sequence 2 of Zarra (1989)] and New Jersey suggest that this sea-level fall event was global in nature. The unconformity separating the Fort Fisher I from the Clubhouse II can be correlated with the global mid-Turonian KTu4 sequence boundary of Vail et al. (1977) and Haq (2014).

Sediments of the Fort Fisher II sequence in the Kure Beach core are not correlative with many other published Atlantic Coastal Plain sections, suggesting that uppermost Turonian/lower Coniacian sediments are rarely preserved in the Atlantic Coastal Plain (Valentine 1984); Brown et al. (1972) and Zarra (1989) record a hiatus during this interval. Spangler (1950) and Weems et al. (2019) record the presence of lower Upper Cretaceous marine sediments from the Esso #1 well in North Carolina (equivalent to calcareous nannofossil Zones CC12 and CC13b), and similarly aged sediments are recorded from the Socony Mobil corehole 16 (Dallas, Texas) by Valentine (1984) and Christopher (1982), who noted the presence of "post C-A Zone, pre-Zone V" pollen, an assemblage recorded from the Fort Fisher II sequence (=unnamed unit of Balson et al. 2013). We herein tentatively correlate Fort Fisher II to the Magothy II sequence of Miller et al. (2004) and Sugarman et al. (in press). Maximum transgression for this event in the Cape Fear arch area was limited, as marine sediments of this age are absent from other coreholes updip of Kure Beach (e.g. Dixon, Smith ES, Hope Plantation; see text-fig. 1). The presence of calcareous nannofossils and up to 10% planktic foraminifera suggests deposition in middle to inner neritic water depths (Leckie and Olson, 2003). The sequence boundary that separates Fort Fisher I and Fort Fisher II is correlated to the late Turonian KTu5 sequence boundary of Vail et al. (1977) and Haq (2014). Its identification in both North Carolina and New Jersey suggest this is a global event.

Understanding Coniacian to Santonian sea-level rise and fall in the North Carolina region is difficult due to the limited number of data points. Cores from South Carolina and Georgia (Self-Trail et al. 2004a), as well as North Carolina [Hope Plantation core, Weems et al. (2007); Dixon core, Seefelt et al. (2009)] contain a record of sediments attributable to the Collins Creek and Pleasant Creek formations, and thus to the Collins Creek I, Collins Creek II, Pleasant Creek I and Pleasant Creek II sequences. However, local uplift and faulting on a previously unknown buried Triassic Basin northeast of the Graingers wrench zone, North Carolina (see McLaurin and Harris 2001; Weems et al. 2007), movement along the Cape Fear arch (Plassche et al. 2014), poor biostratigraphic correlation between terrestrial palynomorphs attributable to the chronologically broad *Sohlipollis* Zone (Christopher et al. 1999) and poorly preserved calcareous nannofossil assemblages from the Collins Creek Formation (Self-Trail et al. 2004a) make interpretation difficult.

It is notable that the Collins Creek I sequence is only present in the up-dip Elizabethtown core and is absent from the downdip Kure Beach core. Because of its relative up-dip location, this sequence in the Elizabethtown core records maximum sea-level rise, and subsequent base level lowering, during the middle to late Coniacian. However, the absence of marine sediments attributable to Collins Creek I downdip of Elizabethtown requires explanation. The most likely cause is erosion by ocean currents along the southeastern Atlantic margin and the Cape Fear arch region. Similar erosional events have been documented previously from the late Maastrichtian through the Pliocene of this area (see discussion in Self-Trail et al. 2019). Structural possibilities for the removal of this sequence in Kure Beach are discounted, as uplift of the Cape Fear arch would have resulted in the removal of sediments at Elizabethtown as well. Thus, the Collins Creek I/Fort Fisher I sequence boundary is most likely due to a combination of both local (erosional) and global (sea-level fall) components, and most likely correlates to the KCo1 global boundary.

The Collins Creek II sequence is late Coniacian to earliest Santonian in age and most likely correlates to the Mg5 sequence of Sugarman et al. (in press). The thin TST recorded at Kure Beach is placed in Zone CC15 (late Coniacian) and the MFS corresponds to maximum sea-level rise at 86.6 Ma (Gradstein et al. 2012). Unusually, the early HST in the Collins Creek II sequence is clearly defined and preserved at Kure Beach, and the entire HST of the Collins Creek II is unusually thick (160.0 ft; 48.8 m). This thickness could be a result of tectonic downwarping of the Cape Fear arch resulting in the formation of a local depocenter in this region. As global sea-level dropped and progradation of the shoreline occurred, stripping of sediments during base level lowering most likely resulted in removal of sediments from the up-dip Elizabethtown core while at the same time resulted in deposition of HST sediments in the downdip region. The Collins Creek II/Fort Fisher II basal unconformity most likely correlates to the late Coniacian KCo2 sequence boundary of Vail et al. (1977) and Haq (2014). However, the unusual thickness of this sequence (173 ft; 52.73 m), suggests that local controls also contributed to deposition at this time.

Local controls on sedimentation dominated during deposition of the Pleasant Creek I sequence in the early Santonian. The thickness of this sequence exceeds 150 ft (45.7 m) at Elizabethtown, and two parasequences, and possibly a third, are clearly delineated by the gamma ray signature; these most likely represent 2nd order cycles (text-fig. 12). The presence of abundant calcareous nannofossils, a relatively stable gamma ray signature, and thicknesses of approximately 200 ft (61.0 m) at Kure Beach suggest that deposition occurred in relatively deep water and that sediment input and sea-level rise were in balance at this site. Although Zarra (1989) identified a lower Santonian sequence from the Albemarle and Pamlico sounds, it is unclear as to whether this correlates with Pleasant Creek I or Pleasant Creek II. Correlation with New Jersey is more straightforward, as calcareous nannofossil biostratigraphy of the Cheesequake sequence suggests that it is Coniacian to early Santonian in age (Sugarman et al., in press). Thus, the sequence boundary at the base of the Pleasant Creek I correlates to the KSa1 sequence boundary of Vail et al. (1977) and Haq (2014). However, it is clear that local sedimentation had a greater impact on deposition of this sequence than did global controls. Preservation of the Pleasant Creek I sequence in North Carolina is most likely a result of movement along the faults associated with the Cape Fear arch during the early Santonian, resulting in the formation of a depocenter and resulting increased sediment input.

The Pleasant Creek II in the Kure Beach core is correlated to the Merchantville I sequence of Sugarman et al. (in press) and to the lower Santonian sequence of Zarra (1989). The basal unconformity correlates to the KSa2 sequence boundary of Vail et al. (1977) and Haq (2014).

CONCLUSIONS

Three new Turonian to Santonian sequences in the Elizabethtown core and six in the Kure Beach core are identified. Using integrated grain size analysis, calcareous nannofossil biostratigraphy, palynostratigraphy, and facies interpretations, we produced an improved regional correlation of sediments from the Cape Fear arch region of North Carolina to the Albemarle and Pamlico sounds. These seven new sequences range from upper Turonian to Santonian in age and represent some of the oldest marine units deposited in the southeastern Atlantic Coastal Plain. Development of a sequence stratigraphic framework provides insight into the early development of a clastic wedge atop crystalline basement and the seven identified sequences record significant fluctuations of sea level during Late Cretaceous greenhouse conditions. Correlation of these sedimentary packages to the sequence stratigraphy of New Jersey enables the interpretation of sequence boundaries in the context of global cyclic events of sea-level rise and fall versus regional relative changes in sea level due to erosion and/or movement along buried fault structures of the Cape Fear arch.

The Clubhouse II sequence is definitively associated with global warming and sea-level rise during the late Cenomanian/early Turonian and represents maximum excursion of marine sediments onto the southeastern Atlantic Coastal Plain during the early Late Cretaceous. A major mid-Turonian global sea-level fall (KTu4) is associated with the base of the Fort Fisher I sequence and can be correlated with the Br3/Mg1 sequence boundary of New Jersey (Sugarman et al., in press).

Local factors that influenced sediment deposition and relative sea-level rise and fall are also recognized. Current erosion on the shelf is attributed to the absence of the Collins Creek I sequence in the Kure Beach core and activation of possible buried fault structures along the Cape Fear arch resulted in the formation of a depocenter in this region during the late Coniacian to early Santonian, resulting in thick sedimentary sequences of the Collins Creek II and Pleasant Creek I. Depocenter formation and infilling ceased by the mid- to late Santonian.

Delineation of these seven sequences and correlation to both the global cycle chart and other sediments of the Atlantic Coastal Plain highlights the influence and control that sea-level change has on the deposition of shelf to nearshore sediments. It also shows the role that local controls can have on relative sea-level change, including the role that erosion can play on the shelf edge, how the formation of depocenters can affect local sedimentation, and how re-activation of buried fault structures can produce thickening and thinning of sediment packages over relatively short distances.

ACKNOWLEDGMENTS

The authors thank USGS drillers Eugene Cobbs and Eugene Cobbs Jr. of the Florence Bascom Geoscience Center for their excellent work drilling the Kure Beach and Elizabethtown cores with outstanding core recovery. Ray Christopher (retired, formerly Clemson University) provided the palynology data for the Kure Beach and Elizabethtown cores and Pete McLaughlin (Delaware Geological Survey) kindly provided taxonomic help with palynomorphs. The cores are stored at the North Carolina Geological Survey's Coastal Plain Office and Core Repository. Gregory Gohn (emeritus, USGS) and Marci Robinson (USGS) provided comments on an early draft of this paper and Brett McLaurin and Peter Sugarman provided thorough reviews of the final paper. All comments and suggestions greatly improved the manuscript. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

REFERENCES

ABREU, V., PEDERSON, K., NEAL, J. and BOHACS, K., 2014. A simplified guide for sequence stratigraphy: nomenclature, definitions and method. William Smith Meeting, London, September 2014, *The Future of Sequence Stratigraphy: Evolution or Revolution*: 2 pp.

BALSON, A. E., SELF-TRAIL, J. M. and TERRY, D. O. JR., 2013. The Sunny Point Formation: A new upper Cretaceous sub-surface unit in the Carolina Coastal Plain. *Southeastern Geology*, 50: 1–16.

BRETT, C. E. and WHEELER, W. H., 1961. A biostratigraphic evaluation of the Snow Hill Member, Upper Cretaceous of North Carolina. *Southeastern Geology*, 3: 49–132.

BROWN, P. M., MILLER, J. A. and SWAIN, F. M., 1972. Structural and stratigraphic framework and spatial distribution of permeability of the Atlantic Coastal Plain, North Carolina to New York. *U.S. Geological Survey Professional Paper*, 796: 79.

BURNETT, J. A., 1998. Upper Cretaceous. In: Bown, P. R., Ed., *Calcareous Nannofossil Biostratigraphy*, 132–199. London: Chapman and Hall.

CATUNEANU, O., 2006. *Principles of Sequence Stratigraphy*. Amsterdam: Elsevier, 375 pp.

CHRISTIE-BLICK, N., MOUNTAIN, G. S. and MILLER, K. G., 1990. Seismic stratigraphic record of sea-level change. In: National Research Council, Eds., Sea-level Change, 116–140. Washington D.C.: The National Academies Press.

CHRISTOPHER, R. A., 1979. *Normapolles* and *Triporate* pollen assemblages from the Raritan and Magothy Formations (Upper Cretaceous) of New Jersey. *Palynology*, 3: 73–121.

———, 1982. The occurrence of the *Complexiopollis- Atlantopollis* zone (palynomorphs) in the Eagle Ford Group (Upper Cretaceous) of Texas. *Journal of Paleontology*, 56 (2): 525–541.

CHRISTOPHER, R. A. and PROWELL, D. C., 2010. A palynological biozonation for the uppermost Santonian and Campanian Stages (Upper Cretaceous) of South Carolina, USA. *Cretaceous Research*, 31: 101–129.

CHRISTOPHER, R. A., SELF-TRAIL, J. M., PROWELL, D. C. and GOHN, G. S., 1999. The stratigraphic importance of the Late Cretaceous pollen genus *Sohlipollis* gen. nov. in the coastal plain province. *South Carolina Geology*, 41: 27–44.

DALL, W. H. and HARRIS, G. D., 1892. The Neocene of North Carolina. *U.S. Geologicaly Survey Bulletin,* 84: 1–349.

DENNE, R. A., BREYER, J. A., KOSANKE, T. H., SPAW, J. M., CALLENDER, A. D., HINOTE, R. E., KARIMINIA, M., TUR, N., KITA, Z., LEES, J. A. and ROWE, H., 2016. Biostratigraphic and geochemical constraints on the stratigraphy and depositional environments of the Eagle Ford and Woodbine Groups of Texas (Part 1). In: Breyer, J.A., Ed., *The Eagle Ford Shale: A renaissance in U.S. oil production*. AAPG Memoir 110: 1–86.

DOYLE, J. A., 1969. Cretaceous angiosperm pollen of the Atlantic Coastal Plain and its evolutionary significance. *Arnold Arboretum Journal*, 50: 1–35.

DOYLE, J. A. and ROBBINS, E. I., 1977. Angiosperm pollen zonation of the continental Cretaceous of the Atlantic Coastal Plain and its application to deep wells in the Salisbury Embayment. *Palynology*, 1: 43–78.

FARRELL, K. M., HARRIS, W. B., MALLINSON, D. J., CULVER, S. J., RIGGS, S. R., WEHMILLER, J. F., PIERSON, J., SELF-TRAIL, J. M. and LAUTIER, J., 2013. Graphic logging for interpreting process-generated stratigraphic sequences and aquifer/reservoir potential: with analog shelf to shoreface examples from the Atlantic Coastal Plain Province, U.S.A. *Journal of Sedimentary Research*, 83: 723–745.

FOLK, R. L., 1980. *Petrology of Sedimentary Rocks*. Austin: Hemphill Publishing Company, 182 pp.

FRIEDRICH, O., NORRIS, R. D. and ERBACHER, J., 2012. Evolution of middle to Late Cretaceous oceans-a 55 my record of Earth's temperature and carbon cycle. *Geology*, 40 (2): 107–110.

GOHN, G. S., 1988. Late Mesozoic and early Cenozoic geology of the Atlantic Coastal Plain: North Carolina to Florida. In: Sheridan, R. E., and Grow, J. A., Eds., *The Geology of North America*, *The Atlantic Continental Margin U.S.*, 1-2: 107–130. Boulder: Geological Society of America.

———, 1992. Revised nomenclature, definitions, and correlations for the Cretaceous formations in USGS-Clubhouse Crossroads #1, Dorchester County, South Carolina. *U.S. Geological Survey Professional Paper,*1518: 39.

GROW, J. A. and SHERIDAN, R. E.,1988. U.S. Atlantic Continental Margin: A typical Atlantic-type or passive continental margin. In: Sheridan, R. E., and Grow, J. A., Eds., *The Geology of North America*, *The Atlantic Continental Margin U.S.*, 1-2: 1–8. Boulder: Geological Society of America.

HAQ, B. U., 2014. Cretaceous eustasy revisited. *Global and Planetary Change*, 113: 44–4.5

HAQ, B.U., HARDENBOL, J. and VAIL, P. R., 1987, Chronology of fluctuating sea-levels since the Triassic. *Science*, 235: 1156 – 1166.

HARRIS, W. B., 1978. Stratigraphic and structural framework of the Rocky Point Member of the Cretaceous Peedee Formation, North Carolina. *Southeastern Geology*, 19: 207–229.

HARRIS, W. B. and SELF-TRAIL, J. M., 2006. Late Cretaceous base level lowering in Campanian and Maastrichtian depositional sequences, Kure Beach, North Carolina. *Stratigraphy*, 3: 95–216.

HATTNER, J. G. and WISE, S. W., Jr., 1980. Upper Cretaceous calcareous nannofossil biostratigraphy of South Carolina. *South Carolina Geology*, 24 (2): 41–117.

HERON, S. D., JR. and WHEELER, W. H., 1964. The Cretaceous formations along the Cape Fear River, North Carolina. *Atlantic Coastal Plain Association Field Guide, Fifth Annual Field Excursion*. October, 1964: 55pp.

HUBER, B. T., MACLEOD, K. G., WATKINS, D. K. and COFFIN, M. F., 2018. The rise and fall of the Cretaceous Hot Greenhouse climate. *Global and Planetary Change*, 167: 1–23.

HUNT, D. and TUCKER, M. E., 1992. Stranded parasequences and the forced regressive wedge systems tract: deposition during base-level fall. *Sedimentary Geology*, 81: 1–9.

———1995. Stranded parasequences and the force regressive wedge systems tract: deposition during base-level fall – reply. *Sedimentary Geology*, 95: 147–160.

IMBRIE, J. and KIPP, N. G., 1971. *A new micropaleontological method for quantitative paleoclimatology; application to a late Pleistocene Caribbean core: The late Cenozoic glacial ages.* New Haven: Yale University Press, 71–147.

KING, D. T., 1996. Sequence stratigraphy of Upper Cretaceous alluvial plain facies Tuscaloosa Formation, eastern Alabama. *Gulf Coast Association of Geological Societies Transactions,* 46: 469–470.

KLITGORD, K. D., HUTCHINSON, D. R. and SCHOUTEN, H., 1988. Atlantic continental margin; structural and tectonic framework. In: Sheridan, R. E. and Grow, J. A., Eds., *The Geology of North America*, *The Atlantic Continental Margin U.S.*, 1-2: 19–55. Boulder: Geological Society of America.

KRASSAY, A. A., 1998. Outcrop and drill core gamma ray logging integrated with sequence stratigraphy: examples from Proterozoic sedimentary succession of northern Australia. *AGSO Journal of Australian Geology and Geophysics,* 17(4): 285–299.

LAGESSE, J. and READ, J. F., 2006. Updip sequence development on a wave- and current-dominated mixed carbonate-siliciclastic continental shelf; Paleogene, North Carolina, eastern U.S.A. *Sedimentary Geology*, 184: 155–182.

LECKIE, R. M. and OLSON, H. C., 2003. Foraminifera as proxies for sea-level change on siliciclastic margins. In: Olson, H. C. and Leckie, R. M., Eds., *Micropaleontologic Proxies for Sea-Level Change and Stratigraphic Discontinuities*, 5-19. Broken Arrow: SEPM Special Publication 75.

LOWERY, C. M., CUNNINGHAM, R., BARRIE, C. D., BRALOWER, T. and SNEDDIN, J. W., 2017. The northern Gulf of Mexico during OAE2 and the relationship between water depth and black shale development. *Paleoceanography*, 32: 1316–1335. https://doi.org/10.1002/2017PA003180.

LOWERY, C. M., SELF-TRAIL, J. M. GILBREATH, K. and YAGODINZSKI, L., 2019. Expression of Cenomanian-Turonian OAE2 on the East Coast of North America. AGU meeting, San Francisco, Dec. 2019, abstract.

MANIVIT, H., PERCH-NIELSEN, K., PRINS, B. and VERBEEK, J. W., 1977. Mid Cretaceous calcareous nannofossil biostratigraphy. *Koninklijke Nederlandsd Akademie van Wetenschappen*, B80 (3): 169–181.

MARKEWICH, H. W., 1985. Geomorphic evidence for Pliocene-Pleistocene uplift in the area of the Cape Fear Arch, North Carolina. In: Morisawa, M. and Hack, J. T., Eds., *Tectonic Geomorphology*, 279–297. Boston: Allen and Unwin.

MCARTHUR, J. M., HOWARTH, R. J. and BAILEY, T. R., 2001. Strontium isotopic stratigraphy: LOWESS version 3: Best fit to the marine Sr-isotopic curve for 0-509 Ma and accompanying Look-up table for deriving numerical age. *The Journal of Geology*, 109: 155–170.

McLAURIN, B. T. and HARRIS, W. B., 2001. Paleocene faulting within the Beaufort Group, Atlantic Coastal Plain, North Carolina. *GSA Bulletin*, 113 (5): 591–603.

MILLER, K. G., SUGARMAN, P. J., BROWNING, J. V., KOMINZ, M. A., OLSSON, R. K., FEIGENSON, M. D. and HERNANDEZ, J. C., 2004. Upper Cretaceous sequences and sea-level history, New Jersey Coastal Plain. *GSA Bulletin*, 116: 368–393.

MITCHUM, R. M., VAIL, P. R. and THOMPSON, III, S., 1977. The depositional sequence as a basic unit of stratigraphic analysis. In: Payton, C.E. Ed., *Seismic stratigraphy-applications hydrocarbon exploration*, 53–62. Tulsa: American Association of Petroleum Geologists.

OGG, J. G., AGTERBERG, F. P. and GRADSTEIN, F. M., 2004. The Cretaceous Period. In: Gradstein, F., Ogg, J. and Smith, A., Eds., *A Geologic Time Scale 2004*: 344–383. Cambridge: Cambridge University Press.

OGG, J. G., OGG, G. M. and GRADSTEIN, F. M., 2016. *A Concise Geologic Time Scale 2016*. Amsterdam: Elsevier, 234 pp.

OLSSON, R. K., 1991. Cretaceous to Eocene sea-level fluctuations on the New Jersey margin. *Sedimentary Geology*, 70: 195–208.

OWENS, J. D., LYONS, T. W., and LOWERY, C. M., 2018. Quantifying the missing sink for global organic carbon burial during a Cretaceous oceanic anoxic event. *Earth and Planetary Science Letters*, 499: 83–94.

OWENS, J. P. and GOHN, G. S. 1985. Depositional history of the Cretaceous Series in the U.S. Atlantic Coastal Plain: Stratigraphy, paleoenvironments, and tectonic controls of sedimentation. In: Poag, C.W., Ed., *Geologic evolution of the United States Atlantic Margin*, 25–86. New York: Van Nostrand Reinhold.

OWENS, J. P. and SOHL, N. F., 1969. Shelf and deltaic paleoenvironments in the Cretaceous-Tertiary formations of the New Jersey Coastal Plain. In: Subitzky, S., Ed., *Geology of selected areas in New Jersey and eastern Pennsylvania and guidebook of excursions*, 235–278. New Brunswick: Rutgers University Press.

PERCH-NIELSEN, K., 1985. Mesozoic calcareous nannofossils. In: Bolli, H. M., Saunders, J. B. and Perch-Nielsen, K., Eds., *Plankton Stratigraphy*, 329–426. Cambridge: Cambridge University Press.

PETTERS, S. W., 1976. Upper Cretaceous subsurface stratigraphy of Atlantic Coastal Plain of New Jersey. *AAPG Bulletin*, 60 (1): 87–107.

PIERSON, J. A., 2003. Late Cretaceous (Campanian and Maastrichtian) sequence stratigraphy, Southeastern North Carolina, USA. Unpublished M.S. thesis, University of North Carolina, Wilmington, 78 pp.

PLASSCHE, O. VAN DE., WRIGHT, A. J., HORTON, B. P., KEMP, A. C., MALLINSON, D. and KOPP, R. E., 2014. Estimating tectonic uplift of the Cape Fear Arch (south-eastern United States) using reconstructions of Holocene sea-level. *Journal of Quaternary Science*, 29(8): 749–759.

PLINT, A. G. and NUMMEDAL, D., 2000. The falling stage systems tract: recognition and importance in sequence stratigraphic analysis. In: Hunt, D. and Gawthorpe, R.L., Eds., *Sedimentary Response to Forced Regression*, 172: 1–17. London: Geological Society of London Special Publication.

POSAMENTIER, H. W., JERVEY, M. T. and VAIL, P. R., 1988. Eustatic controls on clastic deposition I–conceptual model. In: Wilgus C. K., et al., Eds., *Sea-level Changes*: *an integrated approach*, 42: 9–124. Tulsa: SEPM Special Publication 42.

SEEFELT, E. L., ALEMAN GONZALES, W. B., SELF-TRAIL, J. M., WEEMS, R. E., EDWARDS, L. E., PIERCE, H. A. and DURAND, C. T., 2009. Preliminary physical stratigraphy and geophysical data from the USGS Dixon core, Onslow County, North Carolina. *U.S. Geological Survey Open-File Report* 2009-1194: 140pp.

SELF-TRAIL, J. M., ALEMAN GONZALEZ, W. B. and HARRIS, W. B., 2020. Grain size, microfossil, and strontium data for the Kure Beach and Elizabethtown cores, North Carolina. *U.S. Geological Survey Data Release,* https://doi.org/10.5066/P91PG9YC.

SELF-TRAIL, J. M., CHRISTOPHER, R. A. and PROWELL, D. S., 2002. Evidence for large scale reworking of Campanian sediments into the upper Maastrichtian Peedee Formation, Burches Ferry, South Carolina. *Southeastern Geology*, 41: 145–158.

SELF-TRAIL, J. M., PARKER, M., HAYNES, J. T., SCHULTZ, A. P. and HUDDLESTUN, P.F., 2019. Geology and biostratigraphy of the Upper Floridan aquifer in the greater Savannah region, Georgia and South Carolina. *Stratigraphy*, 16 (1): 41–62.

SELF-TRAIL, J. M., PROWELL, D. C. and CHRISTOPHER, R. A., 2004a. The Collins Creek and Pleasant Creek Formations: two new Upper Cretaceous subsurface units in the Carolina/Georgia Coastal Plain. *Southeastern Geology*, 42: 237–252.

SELF-TRAIL, J. M., WREGE, B. M., PROWELL, D. C., SEEFELT, E. L. and WEEMS, R. E., 2004b. Preliminary physical stratigraphy and geophysical data of the USGS Elizabethtown Core (BL-244/BL-C-1-2003), Bladen County, North Carolina. *U.S. Geological Survey Open-File Report* 2004-1301, 1–297.

SHERIDAN, R. E., 1976. Sedimentary basins of the Atlantic margin of North America. *Tectonophysics*, 36 (1-3): 113–132.

SISSINGH, W., 1977. Biostratigraphy of Cretaceous calcareous nannoplankton. *Geologie en Mijnbouw*, 56: 37–65.

SNOW, L. J., DUNCAN, R. A. and BRALOWER, T. J., 2005. Trace element abundances in the Rock Canyon Anticline, Pueblo, Colorado, marine sedimentary section and their relationship to Caribbean Plateau construction and oxygen anoxic event 2. *Paleoceanography*, 20 (3): PA3005, doi.10.1029/2004PA001093

SOHL, N. F. and CHRISTOPHER, R. A., 1983. The Black Creek-Peedee formational contact (Upper Cretaceous) in the Cape Fear region of North Carolina. *U.S. Geological Survey Professional Paper* 1285: 37pp.

SOHL, N. F. and OWENS, J. P., 1991. Cretaceous Stratigraphy of the Carolina Coastal Plain. In: Horton, J.W., Jr. and Zullo, V.A., Eds., *The Geology of the Carolinas: 50th Anniversary volume*,191–220. Raleigh: Carolina Geological Society.

SPANGLER, W. B., 1950. Subsurface geology of the Atlantic Coastal Plain of North Carolina. *AAPG Bulletin*, 34: 100–132.

STEPHENSON, L. W., 1912. The Cretaceous formations. In: Clark, W. B., Miller, B. L., Stephenson, L. W., Johnson, B. L. and Parker, H. N, Eds., *The coastal plain of North Carolina*, 3: 73–171. Raleigh: North Carolina Geologic and Economic Survey.

STEPHENSON, L. W., 1923. The Cretaceous Formations of North Carolina: *North Carolina Geologic and Economic Survey*, 5: 604pp.

SUGARMAN, P. J., MILLER, K. G., BROWNING, J. V., MCLAUGHLIN, P. J. and KULHANEK, D. K., in press. Late Cretaceous (Turonian-Coniacian) sequence stratigraphy, sea-level, and deltaic facies, Magothy Formation, U.S. Middle Atlantic Coastal Plain. *Stratigraphy*, 18.

SUGARMAN, P. J., MILLER, K. G., OLSSON, R. K., BROWING, J. V., WRIGHT, J. D., DE ROMERO, L. M., WHITE, T. S., MULLER, F. L. and UPTEGROVE, J., 1999. The Cenomanian/Turonian carbon burial event, Bass River, NJ, USA: geochemical, paleoecological, and sea-level changes. *Journal of Foraminiferal Research*, 29 (4): 438–452.

SWIFT, D. J. P. and HERON JR., D. S., 1969. Tidal Deposits in the Cretaceous of the Carolina Coastal Plain. *Sedimentary Geology*, 1: 259–282.

VAIL, P. R., MITCHUM, R. M., JR., TODD, R. G., WIDMIER, J. M., THOMPSON, S., III, SANGREE, J. B., BUBB, J. N. and HATLELID, W. G., 1977. Seismic stratigraphy and global changes in sea-level. *American Association of Petroleum Geologists Memoir 26*: 49–212.

VALENTINE, P. C., 1984. Turonian (*Eaglefordian*) stratigraphy of the Atlantic Coastal Plain and Texas. *U.S. Geological Survey Professional Paper* 1315: 21pp.

VAN WAGONER, J. C., POSAMENTIER, H. W., MITCHUM, R. M., VAIL, P. R., SARG, J. F., LOUTIT, T. S. and HARDENBOL, J., 1988. An overview of the fundamentals of sequence stratigraphy and key definitions. In: Wilgus, C.K., et al., Eds., *Sea-level changes: an integrated approach*, 42: 39–45. Tulsa: Society of Economic Paleontologists and Mineralogists.

VAN WAGONER, J. C., MITCHUM, R. M., CAMPION, K. M. and RAHMANIAN, V. D., 1990. Siliciclastic sequence stratigraphy in well logs, core, and outcrops: concepts for high-resolution correlation of time and facies. *American Association of Petroleum Geologists Methods in Exploration Series 7*: 55pp.

WATKINS, D. K. and BERGEN, J. A., 2003. Late Albian adaptive radiation in the calcareous nannofossil genus *Eiffellithus*. *Micropaleontology*, 49: 231–251.

WEEMS, R. E., SEEFELT, E. L., WREGE, B. M., SELF-TRAIL, J. M., PROWELL, D. C., DURAND, C., COBBS III, E. F., and MCKINNY, K. C., 2007. Preliminary physical stratigraphy and geophysical data of the USGS Hope Plantation Core (BE-110), Bertie County, North Carolina. *U.S. Geological Survey Open-File Report* 2007-1251: 163pp.

WEEMS, R. E., SELF-TRAIL, J. M. and EDWARDS, L. E., 2019. Cross-section of the North Carolina Coastal Plain from Enfield through Cape Hatteras. *U.S. Geological Survey Open-File Report* 2019-1145: 2pp.

ZARRA, L., 1989. Sequence stratigraphy and foraminiferal biostratigraphy for selected wells in the Albemarle Embayment, North Carolina. *North Carolina Geological Survey Open-File Report* 89-5: 1–48.

APPENDIX 1

Calcareous Nannofossils

Calculites obscurus (Deflandre 1959) Prins and Sissingh *in* Sissingh 1977
Eprolithus moratus (Stover 1966) Burnett 1998
Helenea chiastia Worsley 1971
Lithastrinus septenarius Forchheimer 1972
Lucianorhabdus cayeuxii Deflandre 1959
Marthasterites simplex (Bukry 1969) Burnett 1997
Micula decussata Vekshina 1959
Quadrum gartneri Prins and Perch-Nielsen *in* Manivit et al. 1977
Reinhardtites anthophorous (Deflandre 1959) Perch-Nielsen 1968

Palynomorphs

Atlantopollis verrucosa (Groot and Groot 1962) Góczán et al. 1967