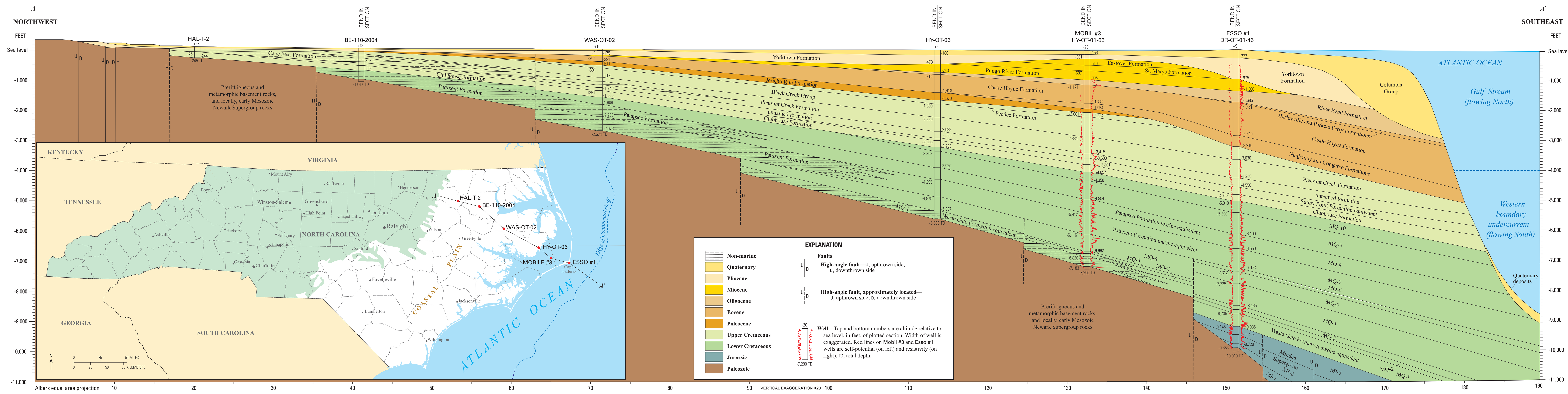

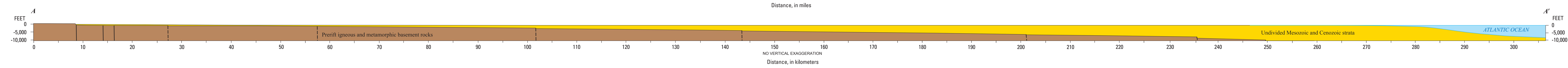

INTRODUCTION

The Atlantic Coastal Plain, the southeasternmost physiographic province in the United States, is underlain by strata that regionally dip gently eastward and gradually thicken toward the Atlantic Ocean basin. These strata, ranging in age from Middle Jurassic to Holocene, accumulated along the eastern margin of North America after the break-up of the supercontinent Pangaea during the Early Jurassic (Manspeizer, 1988). In the east-central United States north of Florida, Cape Hatteras is the point of land that most closely approaches the eastern edge of the Atlantic Continental Shelf of the United States (see inset map). In 1946, Esso (now part of ExxonMobil) drilled a deep oil exploration well to basement rock near the Cape Hatteras lighthouse (figs. 1 and 2). No oil or gas was found there, or in any of the other test wells that were drilled within the onshore North Carolina Coastal Plain. Recent work (Malinconico and Weems, 2010; Reid, 2018) indicates that the top of the oil window lies at 9,000 feet near the base of the Cape Hatteras Esso #1 test well. Therefore, any mature petroleum source rocks that may be present in the North Carolina Coastal Plain are only likely to be found east of the present coastline.

Although the Cape Hatteras test well did not produce oil or gas, it did produce a wealth of stratigraphic information about the outer portion of the onshore Atlantic Continental Shelf (Spangler, 1950). Advances in global stratigraphic correlation, in tandem with our analyses of calcareous nannofossils and dinoflagellate cysts (dinocysts) from the Cape Hatteras test-well spot samples (stored at the North Carolina Geological Survey Coastal Plain Office) have produced significant advances beyond earlier interpretations of this well and other deep test wells inshore of Cape Hatteras (Brown and others, 1972; Zarra, 1989). These results, when coupled with work done offshore of Cape Hatteras (Popenoe, 1985), have allowed us to create a more detailed cross section of the North Carolina Coastal Plain and adjacent continental shelf than previously possible.

Except for the stratigraphy of test-well BE-110-2004, described in detail in Weems and others (2007), the stratigraphic columns of the other wells used to construct cross section *A–A′* have been considerably modified (all from Brown and others, 1972). The detailed stratigraphic columns are shown in figures 8 to 12 (sheet 2) with updated stratigraphic interpretations. Fossil ostracods that were cited as evidence by Maher (1971) and by Brown and others (1972) for the presence of marine Upper Jurassic strata deep in the Cape Hatteras test well (between 8,960 and 9,154 feet depth) have been reassigned as index taxa for basal Cretaceous strata by Crawford and others (2009) and Witrock (2017). Fossil datums from Brown and others (1972) are designated by asterisks on the test-well stratigraphic columns (figs. 8–12) and are identified with their original letter and number designations (starting with letters; for example, LM-1, B-11, ME-8, and so forth). Dinocyst datum levels are indicated by an arrow on the Esso #1 (DR-OT-01-46) test well (fig. 12) and are designated by age names (for example, Albian-Cenomanian, Albian-Campanian, lower Eocene, and so forth); calcareous nannofossil datums are also indicated by arrows on the Esso #1 test well (fig. 12) and designated by nannofossil interval abbreviations starting with CC (Cretaceous), NP (Paleogene), or NN (Neogene) (for example, CC-9a/b, NP17-18, NN-15, and so forth) and are based on the zonations of Martini (1971), Sissingh (1977), and Perch-Nielsen (1985). Detailed results of identified dinocysts and calcareous nannofossil taxa from the Esso #1 test well (fig. 12) from Cape Hatteras are summarized in figures 3 to 6. In the Cape Hatteras test well (Esso #1 [DR-OT-01-46]), the upper Eocene stratigraphy is updated by Weems and others (2016).

STRATIGRAPHY

The cross section *A–A′* is a sequence-stratigraphic model, reflecting the evolutionary development of the North Carolina Coastal Plain in this region. Ideal sequence packages would consist of a lower fining-upward sequence, formed during a transgression across the Coastal Plain, overlain by a coarsening-upward sequence, formed during regression of the sea following transgression. In the Atlantic Coastal Plain, such ideal sequences are rare. Instead, a fining-upward sequence typically is overlain by an unconformity; the associated regressive coarsening-upward cycle either never formed or was stripped away by the next successive transgression (Harris and Self-Trail, 2006). This means that nearly all of the sequence stratigraphic packages recognized here consist of fining-upward sequences capped by unconformities and overlain by the base of the next fining-upward cycle. To adequately reflect the considerable complexity and detail that has been revealed, the primary cross section *A–A′* was compiled with a 20X vertical exaggeration. A simplified cross section without vertical exaggeration, showing the total sediment package (orange-yellow) over basement rocks (brown), is also shown (below *A–A′*) to help the viewer keep the overall spatial geometry in true regional perspective.

Offshore work (Popenoe, 1985) indicates that Atlantic Coastal Plain deposits continue to thicken eastward of our cross section *A–A′*, reaching a maximum thickness of about 30,000 feet slightly east of the east end of cross-section *A–A′*, where water depths are about 9,800 ft. From there, deposits thin southeastward. As there is no stratigraphic control for these outermost-shelf deposits other than seismic reflection data, no effort was made here to portray them. Most or all of these deposits probably belong to the Minden Supergroup (discussed below), which was encountered near the bottom of the Cape Hatteras Esso #1 test well.

The strata of the Atlantic and Gulf of Mexico Coastal Plains are divided into five regionally recognizable supergroups (Weems and others, 2004). These supergroups currently are subdivided only partially into groups, formations, and members based on sub-regional stratigraphic relationships. The oldest supergroup found in the North Carolina Coastal Plain, the Minden Supergroup, is divided here into three informal fining-upward sequences. There are no fossil data known from these strata, so there is no basis for correlating them with any of the Minden Supergroup units named in the Gulf of Mexico Coastal Plain. Lower Cretaceous plus basal Upper Cretaceous (lower Cenomanian) units constitute the Marquesas Supergroup. Its constituent units here in this report are given numeric designations from oldest (1) to youngest (10), each preceded by the letters MQ (units MQ-1 to MQ-10). Unit MQ-1, which is age-equivalent to the Berriasian-Hauterivian(?) Waste Gate Formation of the Delmarva Peninsula (Hansen, 1984), and unit MQ-4 were both encountered as far west as test-well HY-OT-06. Units MQ-2, MQ-3, MQ-5, and MQ-6 are less widespread, being encountered only as far west as test-well Mobil #3 (HY-OT-01-65). In the Cape Hatteras Esso #1 test well, the unpatterned marine strata that comprise units MQ-7 and MQ-8 most readily correlate updip with dash-patterned onshore deltaic strata equivalent to the Lower Cretaceous Patuxent and Patapsco Formations of Maryland and Virginia. If this correlation is correct, then marine microfossils in units MQ-7 and MQ-8 indicate that the Patuxent and Patapsco Formations both belong within the middle to upper part of the Albian stage. This age determination is younger than the Barremian-Aptian age that palynological workers have suggested for the Patuxent Formation (for example, Hochuli and others, 2006). Unit MQ-9 was encountered as far west as test-well WAS-OT-02, and unit MQ-10 pinches out west of test-well HY-OT-06.

Upper Cretaceous (upper Cenomanian through Maastrichtian), Paleocene, and lower Eocene units consist predominantly of marine siliciclastic sediments that constitute the Ancora Supergroup. The middle Eocene through Oligocene units that constitute the Trent Supergroup are predominantly carbonates, unlike other supergroups in the North Carolina Coastal Plain. The Nomini Supergroup, which is predominantly made up of siliciclastic Miocene to recent sediments and rocks, includes the economically important phosphate deposits within the Pungo River Formation.

STRUCTURAL DEVELOPMENT

The developmental history of the Atlantic Coastal Plain includes a number of significant events besides the numerous transgressive and regressive episodes recorded by each sequence package. Early deposition, in the Middle(?) and Upper Jurassic, was confined to the region around and east of Cape Hatteras. These deposits represent early post-rift deposition that occurred shortly after the Mid-Atlantic Ridge fully developed and North America began its westward journey away from the area of the ridge (Manspeizer, 1988). Rifting of North America from Africa initially involved uplift and thinning of the crust immediately above the ridge, followed by parting and downward sinking of the eastern edge of North America as it and the rest of North America moved westward away from the ridge bulge. This spreading event, accompanied by rapid downward subsidence and deposition along the eastern edge of North America, produced the thick Minden Supergroup. Near the beginning of the Cretaceous Period (fig. 7), the eastern margin of North America began to subside across a much wider area, resulting in westward overstepping of the older Minden Supergroup deposits and rapid deposition of shallow marine to continental strata of the lower Marquesas Supergroup (MQ-1 through MQ-6). This interval of rapid deposition was followed by a prolonged interval of non-deposition and (or) erosion during the Barremian through early Albian ages.

Late in the Early Cretaceous, during the middle and late Albian, the rate of deposition in the North Carolina Coastal Plain greatly increased (fig. 7) and sediment of this age concurrently began to accumulate as far west as test-well BE-110-2004, which is far to the west of the region where earlier Cretaceous sediments are preserved. These Albian strata, which are wholly to predominantly nonmarine in the western North Carolina Coastal Plain (dash-pattern on cross section *A–A′*), extend eastward to somewhere slightly east of test-well WAS-OT-02. Still farther east, somewhere between test-wells WAS-OT-02 and HY-OT-06, the nonmarine strata merge seaward into age-equivalent fully marine beds, presumably by intertonguing.

The rate of deposition in the North Carolina Coastal Plain slowed during the Late Cretaceous (Cenomanian through Santonian ages) to a rate similar to that of the early part of the Early Cretaceous (fig. 7). In the late Cenomanian, deposits of the Clubhouse Formation overstepped all older coastal plain deposits toward the northwest as far as the vicinity of test-well HAL-T-2 (Christopher, 1982). The Clubhouse Formation contains calcareous nannofossils and marginal marine dinocysts, indicating that marine conditions also had spread by the late Cenomanian across nearly the entire breadth of the Coastal Plain in northern North Carolina. In the Santonian (fig. 7), a more localized interval of rapid subsidence occurred and Coastal Plain deposition spread sediment southwestward across the Cape Fear arch to the vicinity of Fayetteville. By the end of this event, the modern geometry of the North Carolina Coastal Plain had been established.

Starting in the Late Cretaceous (Campanian age), the rate of deposition in the North Carolina Coastal Plain slowed considerably compared with earlier times (fig. 7). This is best reflected in the Mobil #3 (HY-OT-01-65) test well within cross-section *A–A′*. In the Cape Hatteras area, there is a profound unconformity encompassing latest Cretaceous through early Paleogene (Campanian through early Ypresian) time. As this unconformity is not present to the west, it cannot be attributed to uplift and subaerial erosion, but rather it was most likely caused by submarine current scour. Notching of this magnitude along the eastern margin of the Atlantic Coastal Plain almost certainly was caused by a westward migration of the Gulf Stream path to a position at or near Cape Hatteras (see discussion in Self-Trail and others, 2019). This model is supported by the occurrence of exceptionally warm climates during this stratigraphic gap, both along the northern Atlantic margins (Chandler, 1964; Tiffney, 1999; Weems and Grimsley, 1999) and as far north as Ellesmere Island north of Greenland (Eberle and others, 2009). When the Gulf Stream started to shift back toward the east during the late Ypresian, the area notched out by the Gulf Stream began to fill rapidly with sediment throughout the late-early and middle Eocene. By the late Eocene (Priabonian), this notch had been filled with sediment.

During the late Eocene (Priabonian) through early Miocene, the rates of deposition and subsidence were approximately in equilibrium. The basal coarse beds of successive fining-upward sequences suggest that small unconformities are present throughout this interval, but none are of a magnitude great enough to show as obvious anomalies within the overall succession of sediments. Middle and upper Miocene strata are absent in the Cape Hatteras Esso #1 test well, though they are apparently present to the west in the Mobil #3 test well. This indicates another interval during which the Gulf Stream shifted west of its present position, though apparently not as far west as in the early Eocene. This erosional event occurred at a time when sea levels generally were high across the Atlantic Coastal Plain and the Atlantic Ocean had transgressed far into the Piedmont region (Weems and Edwards, 2007; Edwards and others, 2018). This unconformity also correlates well with an episode of outer-shelf margin erosion that was documented by Popenoe (1985). As in the early Eocene, this scouring event was followed by relatively rapid infilling of the scoured region during early Pliocene (Zanclean). The presence of anomalously old dinocysts in the sample at an altitude of -806 feet (in the Esso #1 test well) probably reflects reworking of scoured older Miocene sediments into basal Pliocene sediment that began filling the region scoured during the Miocene.

The overall rate of subsidence appears to have increased slightly since the middle Miocene (fig. 7). This increased rate of subsidence probably correlates with the uplift and exhumation of the modern Appalachian uplands that began around this time (Huddlestun, 1988; Weems and Edwards, 2007; Edwards and others, 2018).

ACKNOWLEDGMENTS

The authors would like to thank Charles W. Hoffman and the Coastal Plain Office of the North Carolina Geological Survey for making samples from the Cape Hatteras Esso #1 test well available to us for nannofossil and dinocyst analyses. Thanks also go to Gregory S. Gohn and Maryann L. Malinconico for their helpful, constructive, and insightful reviews of the manuscript version of this work, and Matt Smith (U.S. Geological Survey) and Ellen Seefelt (U.S. Geological Survey) for their drafting assistance.

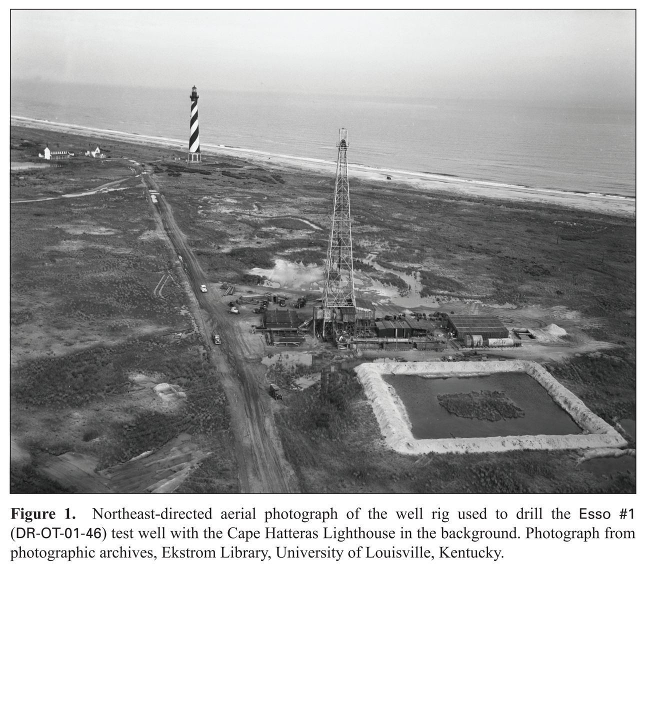

Figure 1. Northeast-directed aerial photograph of the well rig used to drill the Esso #1 (DR-OT-01-46) test well with the Cape Hatteras Lighthouse in the background. Photograph from photographic archives, Ekstrom Library, University of Louisville, Kentucky.

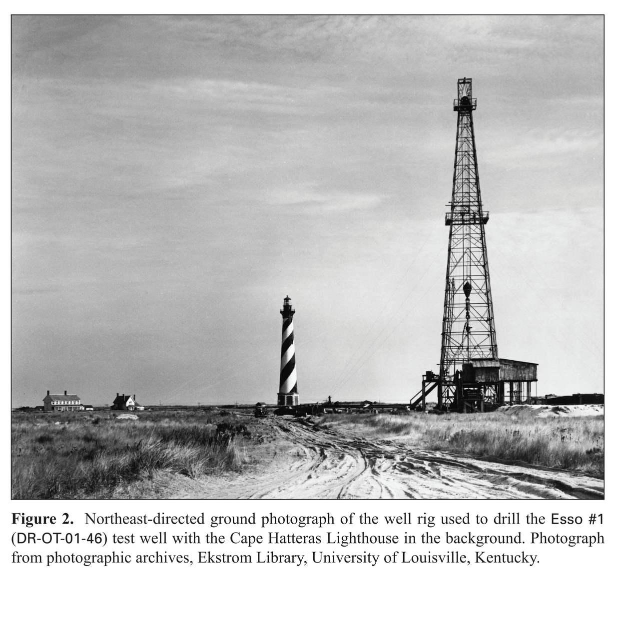

Figure 2. Northeast-directed ground photograph of the well rig used to drill the Esso #1 (DR-OT-01-46) test well with the Cape Hatteras Lighthouse in the background. Photograph from photographic archives, Ekstrom Library, University of Louisville, Kentucky.

USGS paleo-botanical number	Altitude of midpoint of sample interval, in feet	Preser-vation	Diversity	Age range
R6215 Y	-806	P	low	m-l Miocene (reworked)
R6215 V	-2,305	F	mod.	m-l Eocene
R6215 S	-2,893	G	high	e-m Eocene
R6215 BR	-3,156	F-P	mod. high	e Eocene
R6215 BO	-4,381	F	mod.	Cretaceous (Alb.-Camp.)
R6215 BN	-4,591	F	mod.	Cretaceous (Alb.-Camp.)
R6215 BG	-6,538	F-P	mod.	Cretaceous (Alb.-Cenom.)
R6215 BF	-6,558	F-P	low	Cretaceous
R6215 L	-6,730	F-P	mod.	Cretaceous (Alb.-Cenom.)
R6215 G	-7,499	F	mod. high	E. Cretaceous (Barrem.-Apt.?)
R6215 C	-8,913	F-P	mod. high	E. Cretaceous (Berri.?)

Figure 3. Occurrence chart showing the presence of selected dinoflagellate cyst (dinocyst) taxa in samples from the Esso #1 (DR-OT-01-46) test well; Early Cretaceous (Barremian?) through Pliocene stratigraphic interval (altitude -8,913 to -806 feet); sample at -806 feet altitude contains Miocene reworked dinocysts. Symbols for the presence of taxa: X, present; ?, questionably present; a dot (.) means not observed. Abbreviations for preservation quality: P, poor; F, fair; G, good; F-P, fair to poor. Abbreviations for geologic age: E, early; e, early; m, middle; l, late; Alb., Albian; Apt., Aptian; Barrem., Barremian; Berri., Berriasian; Camp., Campanian; Cenom., Cenomanian; ?, age is questionable. Abbreviations for diversity: mod., moderate; mod. high, moderately high. Other abbreviations: feet, ft.

Age	Formation	Calcareous nannofossil zone	Altitude of midpoint of sample interval, in feet	Sample preservation
Pliocene	Yorktown	NN15	-476	G
			-596	M
			-646	M
			-696	M
			-756	M
		NN14-15	-806	M
			-876	M
			-936	M
Oligo-cene	River Bend	NP22	-1,583	M
			-1,646	P
Eocene	Castle Hayne	NP17-18	-1,736	G
			-2,079	P
		NP16	-2,131	P
			-2,253	G
			-2,305	M
			-2,527	M
			-2,649	M
			-2,710	M
			-2,771	M
			-2,831	M
	Congaree	NP14	-2,893	M
		NP14?	-2,946	M
	Nanjemoy	NP13	-3,156	M

Figure 4. Occurrence chart showing the presence of calcareous nannofossil taxa in samples from the Esso #1 (DR-OT-01-46) test well; Eocene through Pliocene stratigraphic interval (altitude -3,156 to -476 feet). Calcareous nannofossil zones are based on the zonation from Martini (1971; NN, Neogene; NP, Paleogene). Abbreviations for abundance of species in sample: A, abundant (1 specimen per field of view); C, common (1 specimen per 10 fields of view); F, frequent (1 specimen per 11–50 fields of view); R, rare (1 specimen per 51–100 fields of view); ?, questionable identification; rw, reworked specimen; a dot (.) means the species was not observed. Abbreviations for "Overall nannofossil abundance in sample": C, common (1–10 specimens per field of view); F, frequent (1 specimen per 1–10 fields of view). Abbreviations for "Sample preservation": G, good; M, moderate; P, poor. The black bar is the first and (or) last occurrences of a marker species.

Age	Formation	Calcareous nannofossil zone	Altitude of midpoint of sample interval, in feet	Overall nannofossil abundance in sample	Sample preservation
Late Cretaceous, Santonian	Shepherd Grove	CC17	-3,376	A	M
	Pleasant Creek	CC16	-4,148	C	G
			-4,163	F	P
Turonian	Unnamed	CC13b	-4,380	C	M
			-4,481	C	M
		CC12	-4,591	C	M
?		?	-4,696	C	M

Figure 5. Occurrence chart showing the presence of calcareous nannofossil taxa in samples from the Esso #1 (DR-OT-01-46) test well; Turonian through Santonian stratigraphic interval (altitude -4,591 to -3,376 feet). Calcareous nannofossil zones from Sissingh (1977) and Perch-Nielsen (1985); CC, Cretaceous. Abbreviations for abundance of species in sample: C, common (1 specimen per 10 fields of view); F, frequent (1 specimen per 11–50 fields of view); R, rare (1 specimen per 51–100 fields of view); ?, questionable identification; ct, contamination; a dot (.) means the species was not observed. Abbreviations for "Overall nannofossil abundance in sample": A, abundant (1 specimen per field of view); C, common (1–10 specimens per field of view); F, frequent (1 specimen per 1–10 fields of view). Abbreviations for "Sample preservation": G, good; M, moderate; P, poor. The black bar is the first and (or) last occurrences of a marker species. The queries (?) at bottom of columns for "Age" and "Calcareous nannofossil zone" mean indeterminate.

Age		Formation or unit	Calcareous nannofossil zone	Altitude of midpoint of sample interval, in feet	Sample preservation
L. Cret.	Ceno-manian	Club-house, MQ-10	CC9c	-4,898	G
				-5,226	P
				-5,250	M
Early Cretaceous	Albian	MQ-9 to MQ-7	CC9a/b	-6,305	M
				-6,483	M
				-6,503	P
				-6,536	M
				-6,558	P
				-7,109	M
				-7,119	M
	u. Berri-asian	MQ-5 to MQ-2	CC2	-7,499	M
				-7,654	P
				-8,759	M
	l. Berr.	MQ-1	CC1b/c?	-8,913	M

Figure 6. Occurrence chart showing the presence of selected calcareous nannofossil taxa in samples from the Esso #1 (DR-OT-01-46) test well; lower Berriasian (l. Berr.) through Cenomanian interval (altitude -8,913 to -4,898 feet). Nannofossil zones from Sissingh (1977) and Perch-Nielsen (1985); CC, Cretaceous. Abbreviations for abundance of species in sample: C, common (1 specimen per 10 fields of view); F, frequent (1 specimen per 11–50 fields of view); R, rare (1 specimen per 51–100 fields of view); ?, questionable identification; ct, contamination; a dot (.) means the species was not observed. Abbreviations for "Overall nannofossil abundance in sample": C, common (1–10 specimens per field of view); F, frequent (1 specimen per 1–10 fields of view). Abbreviations for "Sample preservation": G, good; M, moderate; P, poor. The black bar is the first and (or) last occurrences of a marker species. "CC1b/c?" means age is probable but not certain. Other abbreviations: L. Cret., Lower Cretaceous; u. Berriasian, upper Berriasian.

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Cross Section of the North Carolina Coastal Plain from Enfield through Cape Hatteras

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2019

ISSN 2331-1258 (online)
https://doi.org/10.3133/ofr20191145

Suggested citation: 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, 2 sheets, https://doi.org/10.3133/ofr20191145.