Updip Sequence Development on a Mixed Carbonate-Siliciclastic Continental Shelf, Paleogene, North Carolina, Eastern U.S.A.

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Thesis submitted to the Faculty of the Virginia Polytechnic Institute and State University

in partial fulfillment of the requirements for the degree of

Master of Science

in

Geological Sciences

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August 28, 2003

Blacksburg, Virginia

Keywords: Paleogene, sequence development, nontropical, mixed carbonate-siliciclastic, swell-dominated shelf, North Carolina

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ABSTRACT:

Cores, quarry exposures, and exploratory wells in the Paleogene Albemarle Basin, North Carolina sample the transition between the southern carbonate and northern siliciclastic provinces of the eastern U.S. continental shelf succession. The study area includes the relatively positive Cape Fear Arch on the Onslow Block to the south, and the slowly subsiding (1.5 cm/ky) Albemarle Block to the north.

The Paleogene supersequence set boundary is a hardground on Cretaceous shoreface/shallow-shelf mollusk facies. It is overlain by a thin Paleocene sequence of deeper offshore, glauconitic fine sands to deep marine silt-shale. Five regionally mappable, vertically stacked Eocene sequences are 0 to 30 m thick and contain coastal sands, shoreface sandy-mollusk rudstones, offshore bryozoan grainstone-packstones and subwave base fine wackestone-packstone and marl. The Eocene sequences commonly are bounded by hardgrounds, overlain by thin local lowstand sands and consist of a thin transgressive unit (commonly absent), overlain by an upward shallowing highstand marine succession. On the arch, lowstand and transgressive units may be condensed into lags. The Lower Oligocene succession on the arch has a single marl to fine foram sand dominated sequence whereas downdip, two to three sequences are developed, capped by nearshore sandy molluscan facies. The Upper Oligocene is dominated by possibly three sequences composed of basal, thin sands up into variably sandy mollusk rudstone.

Sequence development was influenced by differential movement of the basement blocks, coupled with increasing 3rd order eustatic sea level changes during global cooling. This was coupled with swell-wave and current sweeping of the shelf that effectively decreased available accommodation by 20 to 30 m, and generated the distinctive hardgrounds on sequence boundaries, and variable development of lowstand and transgressive system tracts. The well developed highstands reflect maximum accommodation allowing deposition of an upward shallowing succession that terminated at the depth of wave abrasion on the open shelf. The sequence stratigraphic development contrasts markedly with that from tropical shelves.

ACKNOWLEDGEMENTS

This project would not have been possible without the support of friends, colleagues, and family. I thank Fred Read for the opportunity to learn about carbonate systems, for years of valuable suggestions, guidance, and conversation. Members of the graduate committee, Kenneth Eriksson, and Michal Kowalewski are also thanked for their valuable input and instruction. The office staff has also been indispensable to everyday life, and is thanked for their assistance. This work has benefited from the North Carolina Graduate Student Research Fund. Special thanks to Kathleen Farrell at the North Carolina Geological Survey for her time and guidance, and to the personnel at the North Carolina Geologic Survey for providing access to data and materials.

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INTRODUCTION

Present sequence stratigraphic models have mainly been based on tropical ramps and rimmed shelves. However, more recently, attempts have been made to define sequence stratigraphic models for non-tropical successions (James and Clarke 1997). A major difference between tropical and temperate settings is the lack of a rim to the shelf, which is open to wave and boundary current sweeping in these typically swell-wave dominated settings. Such open shelves are rarely aggraded to sea level because of low sedimentation rates and the depth of wave abrasion, which can extend down to water depths of 20 to 60 meters or more (Collins 1988; James 1997; Pekar and Kominz 2003). This in effect limits available accommodation, which is essentially the distance between the sea floor and the depth of wave abrasion, rather than sea level (Fig. 1; Osleger 1991). Once the shelf reaches the wave abrasion zone, it becomes a bypass surface (Pekar and Kominz 2003), resulting in coincidence of a hardground with the sequence boundary and a derth of nearshore facies.

In order to better understand sequence development in this setting, three cores from the Paleogene of North Carolina were logged, the facies studied using plastic impregnated thin-sections. The cores were tied into quarry sections with age control, and wells to provide a local sequence stratigraphic framework. The study shows the profound influence that the open shelf setting, with its wave sweeping and boundary current scour had on sequence development, which was also influenced by significant 3rd order glacio-eustatic sea level changes from the Paleogene greenhouse to icehouse transition, and differential movement of basement blocks of the basin.

METHODS

Three cores from the North Carolina Geological Survey were used in this study, including the Beaufort County core (BF-C-1-68), the Onslow County core (ON-C-1-94), and the U.S.G.S. Kure Beach core drilled during the summer of 2001. The cores were logged in terms of color, quartz grain size, composition (sand, shale, and limestone), Dunham rock groups, biotic make-up, and sedimentary structures. Representative lithologies from the three cores were studied in plastic-impregnated thin sections stained

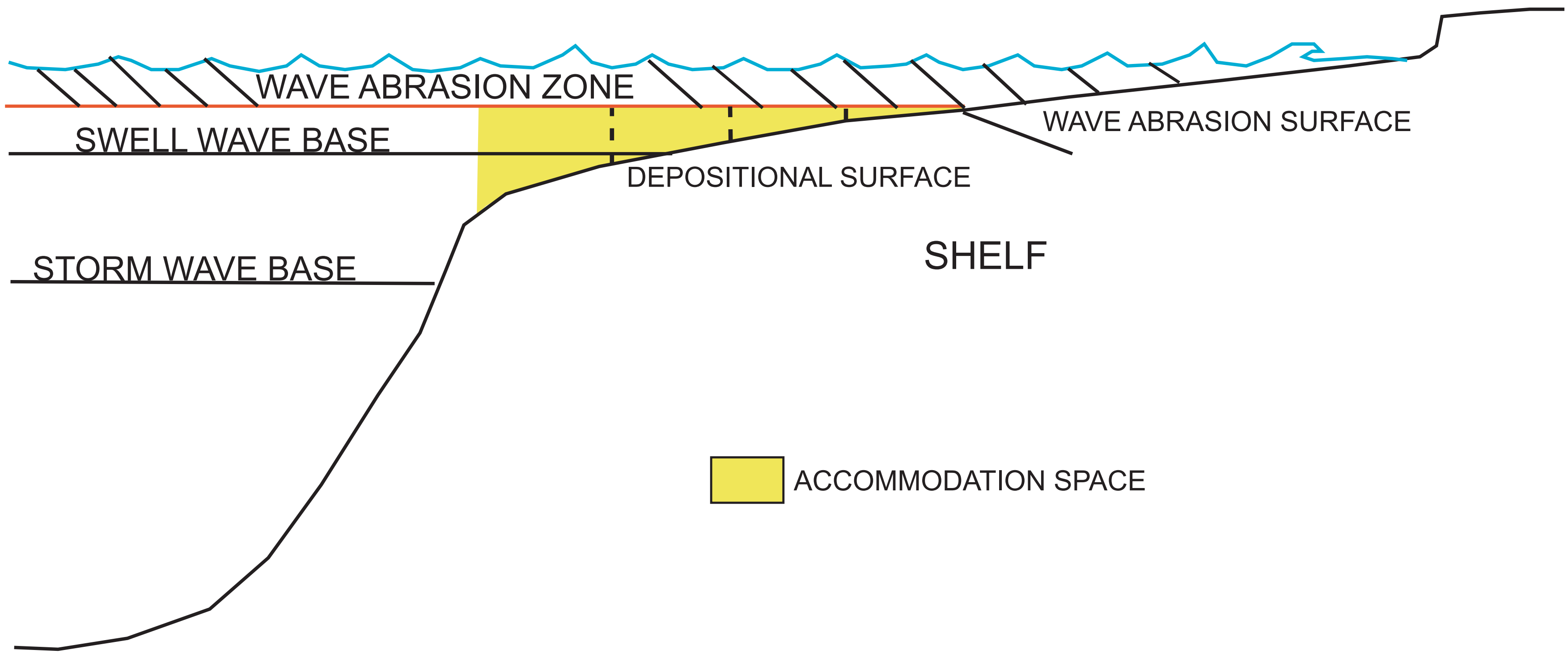


Figure 1: Schematic diagram showing open shelf wave climate. Accommodation is the space from the surface of the shelf to the wave abrasion depth, 30 to 60 meters or more. The wave abrasion zone prevents sediment deposition on the shallow shelf. (Modified from James 1997).

with Dickson's (1965) solution. Cores were incorporated into regional cross sections based on cores logged by Harris et al. (2000), published quarry data, and in downdip areas, several oil and gas exploratory wells that had been subjected to thin sectioned cuttings analysis by Coffey (2000). The relatively sparse biostratigraphic and Sr isotope age data was incorporated, and sequence boundaries, flooding surfaces, and systems tracts were picked on the cross sections.

STRUCTURAL SETTING

The study area is in the Albemarle Basin of coastal North Carolina on the southern part of the Onslow Block and the northern part of the Albemarle Block. The Onslow Block is bounded on the southwest by the Cape Fear Arch, to the north by the Neuse Hinge, which separates it from the Albemarle Block, bounded to the north by the Norfolk Arch (Fig. 2). The Cape Fear and Norfolk Arches may have formed by lithospheric flexure in response to sediment loading offshore throughout the Mesozoic and Cenozoic (Gardner 1989; Popenoe 1985; Gohn 1988). During this period, the Onslow and Albemarle Blocks also underwent episodic periods of differential uplift and subsidence that has been attributed to variations in sediment loading (Harris and Laws 1997). At present the Albemarle Block is down relative to the Onslow Block (Harris and Laws 1997). Other Cenozoic faults such as those in the Grainger Wrench Zone, include reverse-, wrench-, and strike-slip faults that may have been caused by compressional stress fields (Gardner 1989; Gohn 1988; McLaurin and Harris 2001).

Accommodation rates on the passive margin in North Carolina are estimated at less than 1.7 cm/ky (Coffey 2002). Accommodation was created by thermal subsidence after Jurassic continental rifting, and by subsidence due to sediment loading in offshore basins and troughs (Steckler and Watts 1978; Popenoe 1985). Accommodation space could also have been created intermittently by local gyres and larger contour currents such as the ancestral Gulf Stream, which scoured and incised large areas of the shelf and Blake Plateau (Popenoe 1985; Popenoe et al. 1987). Throughout much of the Cenozoic, the North Carolina shelf had a distinct depositional profile of inner shelf, inner shelf

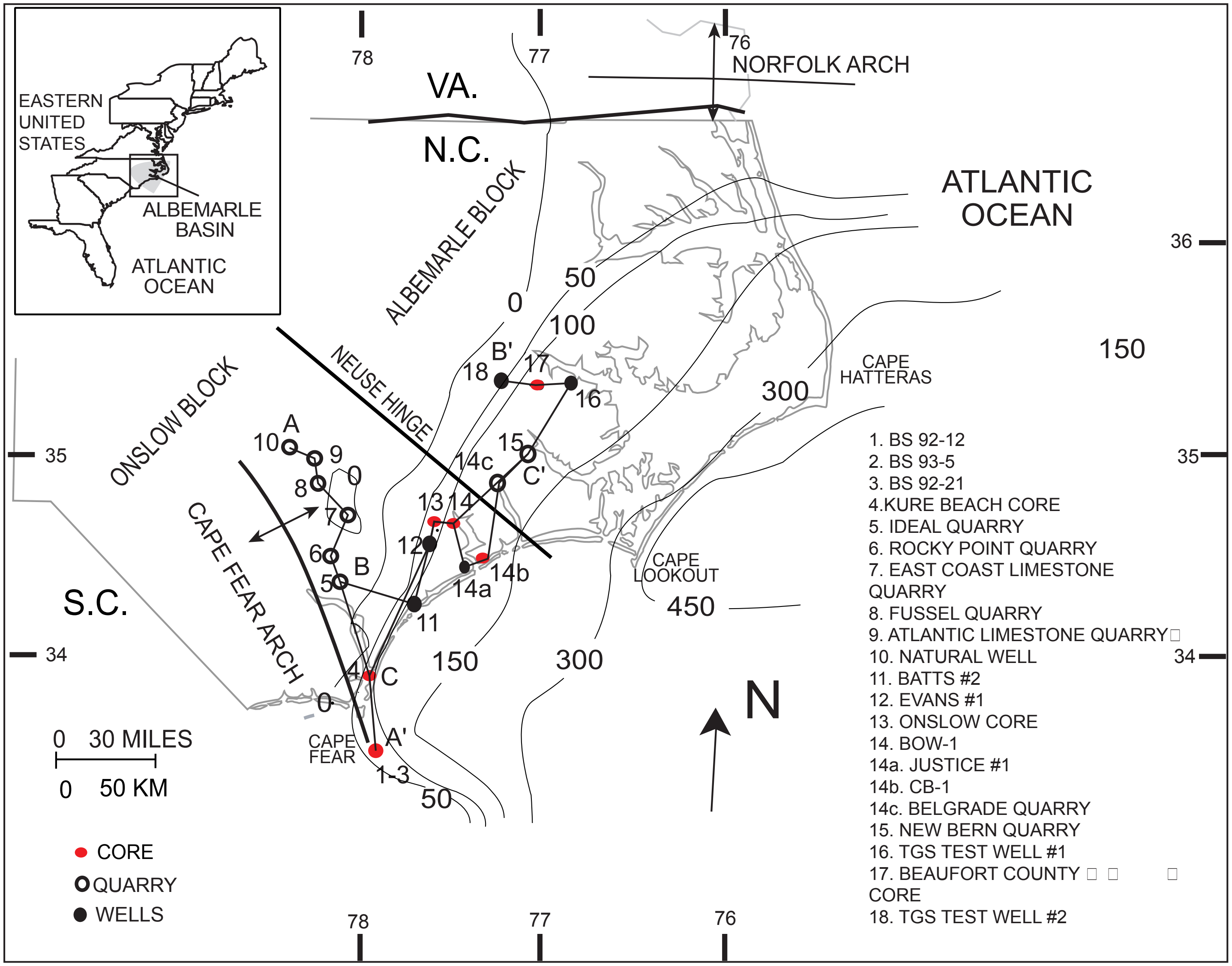


Figure 2: Regional base map showing major structural controls, Paleogene isopach thickness (in meters), location of core, quarry, and well sections used, and cross-section transects. (Modified from Coffey, 2000).

break, deep shelf (ancestral Blake Plateau), and continental slope (Coffey 2000), a profile that also characterized the New Jersey margin (Miller et al. 1997).

STRATIGRAPHIC FRAMEWORK

The Paleogene sediments in the Albemarle Basin are from 0 m to over 500 m thick, thickening offshore in the easterly-dipping Mesozoic and Cenozoic sedimentary wedge (Brown et al. 1972). The stratigraphic framework of the North Carolina Paleogene, based on limited outcrops and quarry exposures, offshore logs of exploratory wells, sequence stratigraphic analysis of thin sectioned well cuttings, and regional biostratigraphic studies, along with offshore seismic data (Fig. 3) (Thayer and Textoris 1972; Baum et al. 1978; Ward et al. 1978; Otte 1981; Popenoe 1985; Zullo and Harris 1987; Coffey 2000). The Paleocene sediments (Beaufort Formation) unconformably overlie Upper Cretaceous sediments, the contact being disconformable and marked by thick, phosphatized hardgrounds, and are mapped as the Beaufort Formation (Baum et al. 1978). The Paleocene units include a Lower Paleocene (Danian) sequence of fine quartz sands (Yaupon Beach Member) and a sequence of siliceous mudstones (Jericho Run Member), and an Upper Paleocene (Thanetian) sequence of sandy molluscan limestones (Mosley Creek Member; Harris and Laws 1993).

Eocene sediments disconformably overlie Paleocene units in the subsurface updip or unconformably overlie Cretaceous strata where the Paleocene is absent. The Eocene sediments are bryozoan-echinoderm limestones, and are referred to as the Castle Hayne Limestone (Middle Eocene, Lutetian and Bartonian) which was subdivided into the New Hanover and Comfort Members (Ward et al. 1978). The overlying mollusk-rich Eocene unit is mapped as New Bern Formation, it is considered to be early Late Eocene (Priabonian) by Baum et al. (1978), but was included in the Spring Garden Member, considered to be latest Middle Eocene by Ward et al. (1978). Five Eocene depositional sequences labeled 0 to 4 were recognized by Zullo and Harris (1987).

The Lower Oligocene (Rupelian) strata have been named Trent Formation (Baum et al. 1978) and the upper Oligocene (Chattian) units named Belgrade/Silverdale

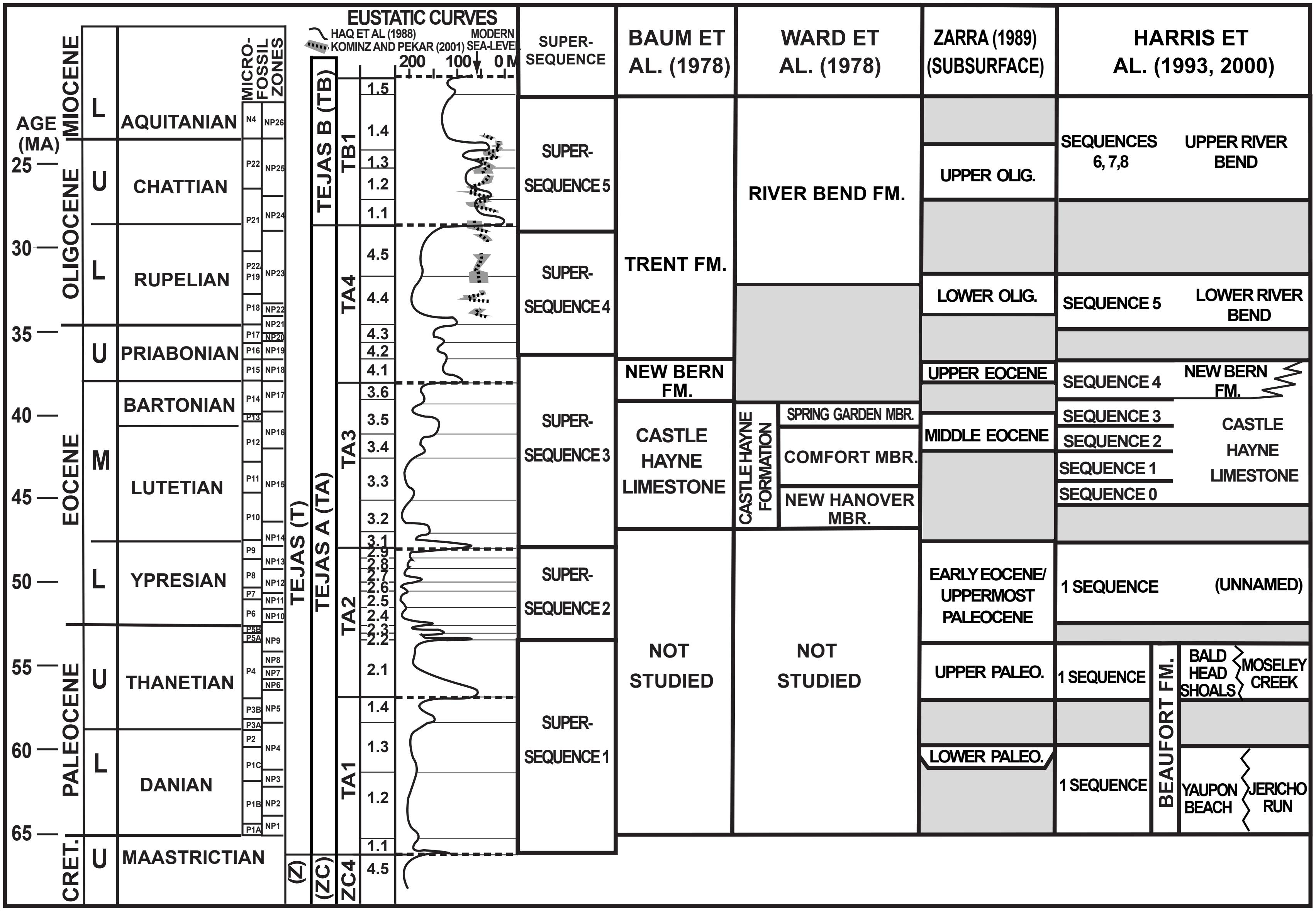


Figure 3: Regional stratigraphic framework for the Paleogene of the North Carolina coastal plain (Modified from Coffey 2000). Paleogene global and regional eustatic curves of Haq et al. (1988) and Kominz and Pekar (2001) are included. Biostratigraphic zonations and radiometric time scale are from Berggren et al. (1995).

formations (Zullo and Harris 1987). They are now all included in the River Bend Formation (Ward et al. 1978; Harris et al. 2000). The Lower River Bend consist of marls, fine sands, and sandy molluscan limestones, whereas they upper River Bend consists of silty-sandy molluscan limestones. A single depositional sequence was recognized in the Lower Oligocene and three sequences noted in the Upper Oligocene (Zullo and Harris 1987). The Oligocene units are unconformably overlain by Lower Miocene to Pliocene units (Baum et al. 1978).

Coffey (2000) did a regional study of thin-sectioned well cuttings from 23 wells throughout the onshore basin (Fig. 4). He mapped several major facies on a regional dip and a strike cross-section through the subsurface, and tied these into the offshore seismic. The study provided a regional supersequence scale framework, but because of the limited age control, 3rd order sequences although evident on the cross-sections, were not tied to those defined in the outcrop belt by Zullo and Harris (1987) and Harris and Laws (1997).

FACIES AND DEPOSITIONAL ENVIRONMENTS

The following are modified from Coffey (2000) and supplemented by information from the present study. The schematic facies profile modified from Coffey (2000) is shown in Figure 5a and water depths of facies in Figure 5b, and in Tables 1a and 1b. Distribution of the facies in the cross-sections and cores are shown in Figures 6 to 10.

Quartz sands

Fine to medium grained quartz sands (described in Table 2) formed in shallow high energy settings on the shore face to inner shelf in water depths of less than 40 m, determined by comparison with similar facies on modern continental shelves (Pekar and Kominz 2001). The lack of interstitial mud, nearshore molluscan skeletal components, and the position of this facies near the bases of upward-deepening units and tops of upward-shallowing successions supports this high energy setting. This facies is generally poorly cemented. Some cemented quartz sands were reworked into lithoclasts during

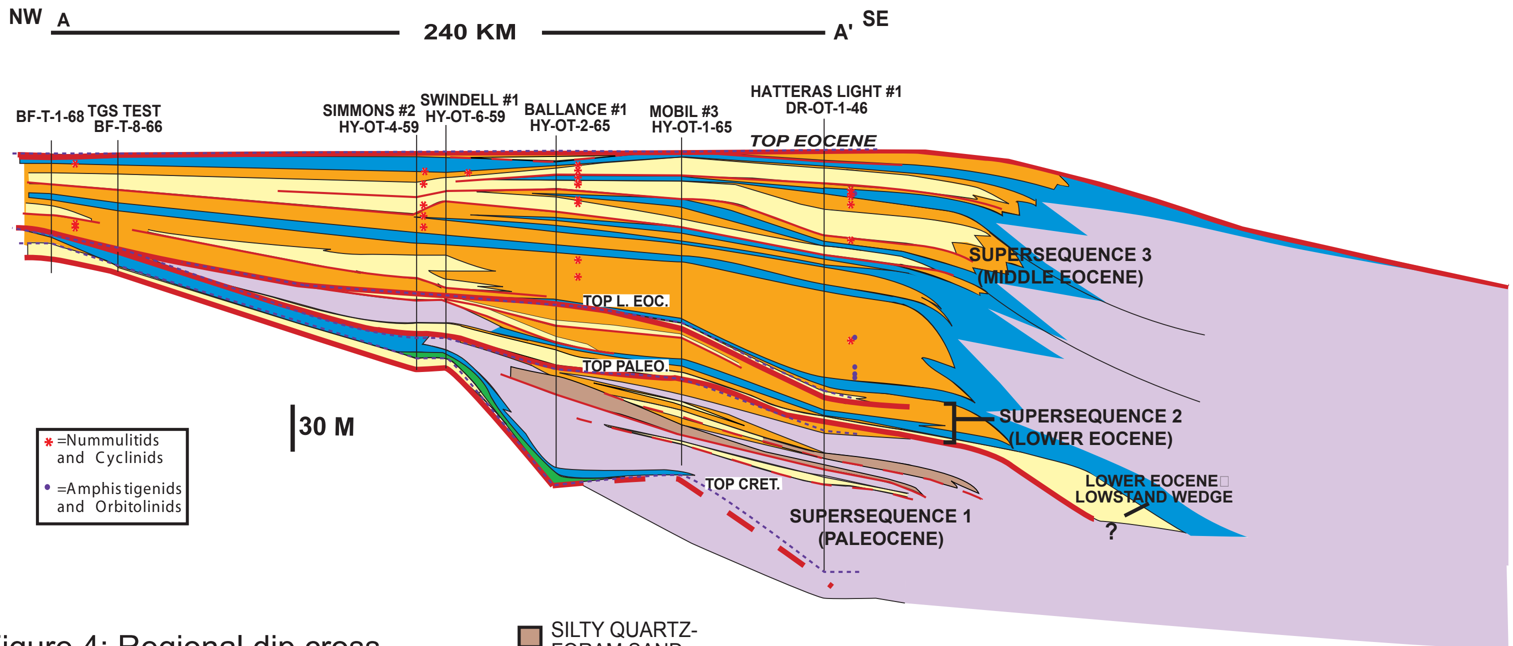
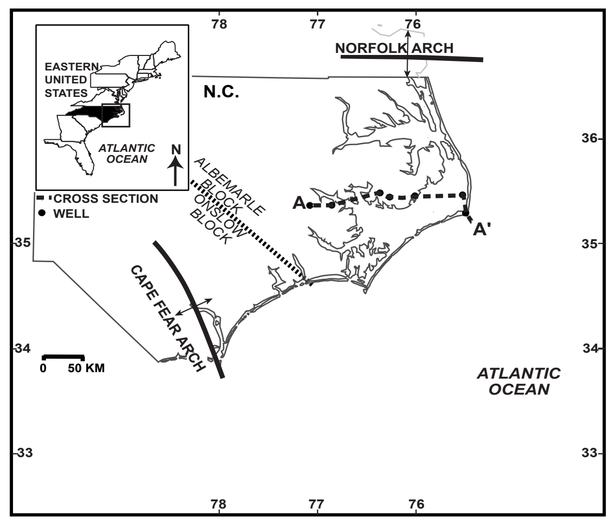


Figure 4: Regional dip cross-section of Paleocene-Eocene from Coffey and Read (in press) showing dominant lithologies, sequence boundaries, and supersequence stacking patterns. Correlations are constrained by biostratigraphic control and seismic data. The study area for this paper is located in the furthest landward region of the cross-section. Note Lower Eocene seismically defined lowstand wedge.

- SILTY QUARTZ-FORAM SAND
- QUARTZ SAND/MOLLUSK GRAINSTONE/PACKSTONE
- PHOSPHATIC SAND AND HARDGROUND
- SKELETAL GRAINSTONE/PACKSTONE
- SKELETAL PACKSTONE/WACKESTONE
- SILTY MARL
- SANDY MOLLUSK GRAINSTONE/PACKSTONE (Differentiated only on Oligocene)
- AGE BOUNDARY
- SUPERSEQUENCE BOUNDARY
- SEQUENCE BOUNDARY



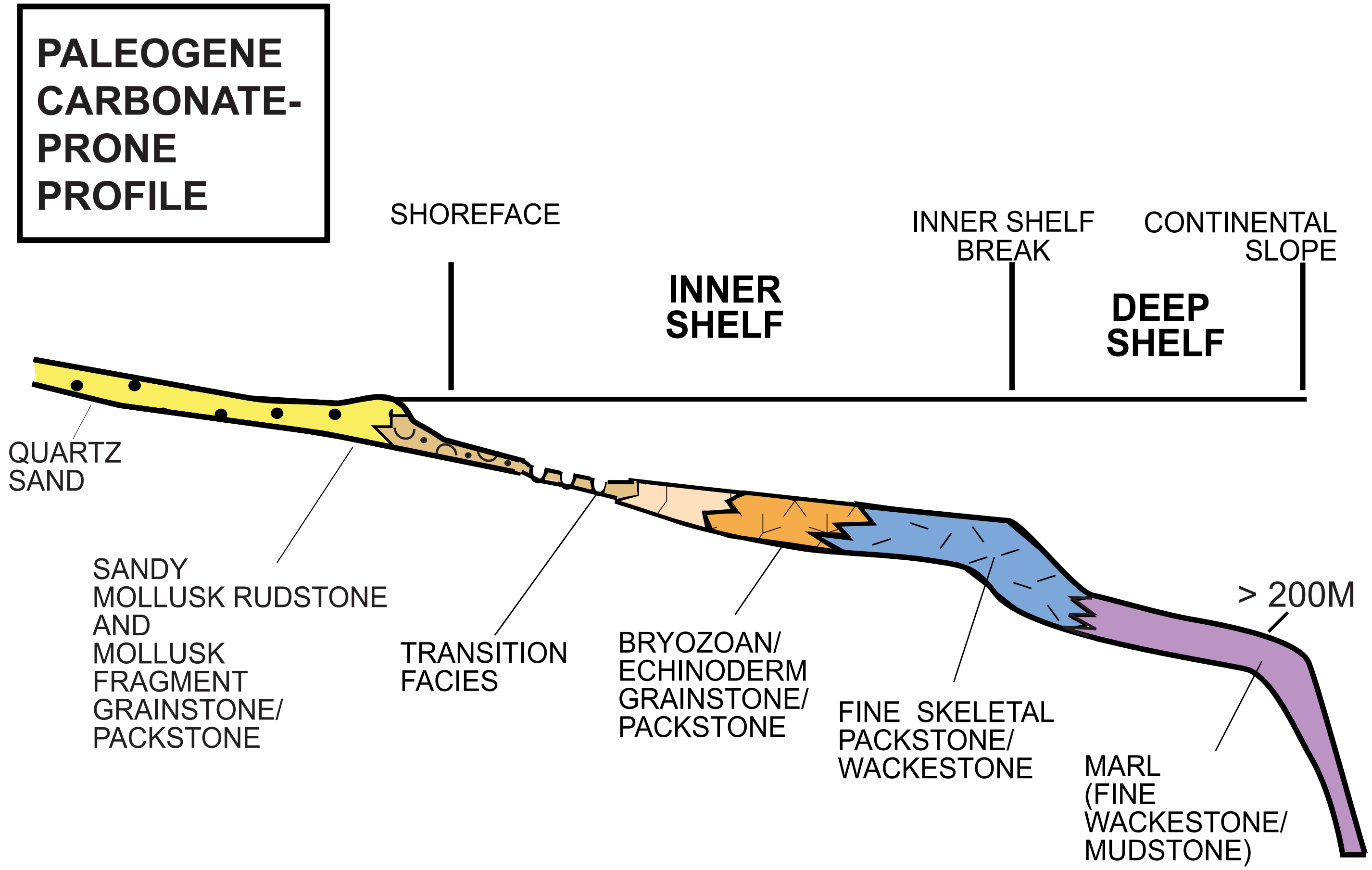


Figure 5a: Generalized carbonate facies distribution across the Paleogene shelf. Hardground formation occurs at 20-60 meters water depth, where there is no net accumulation of sediments. Modified from Coffey 2000.

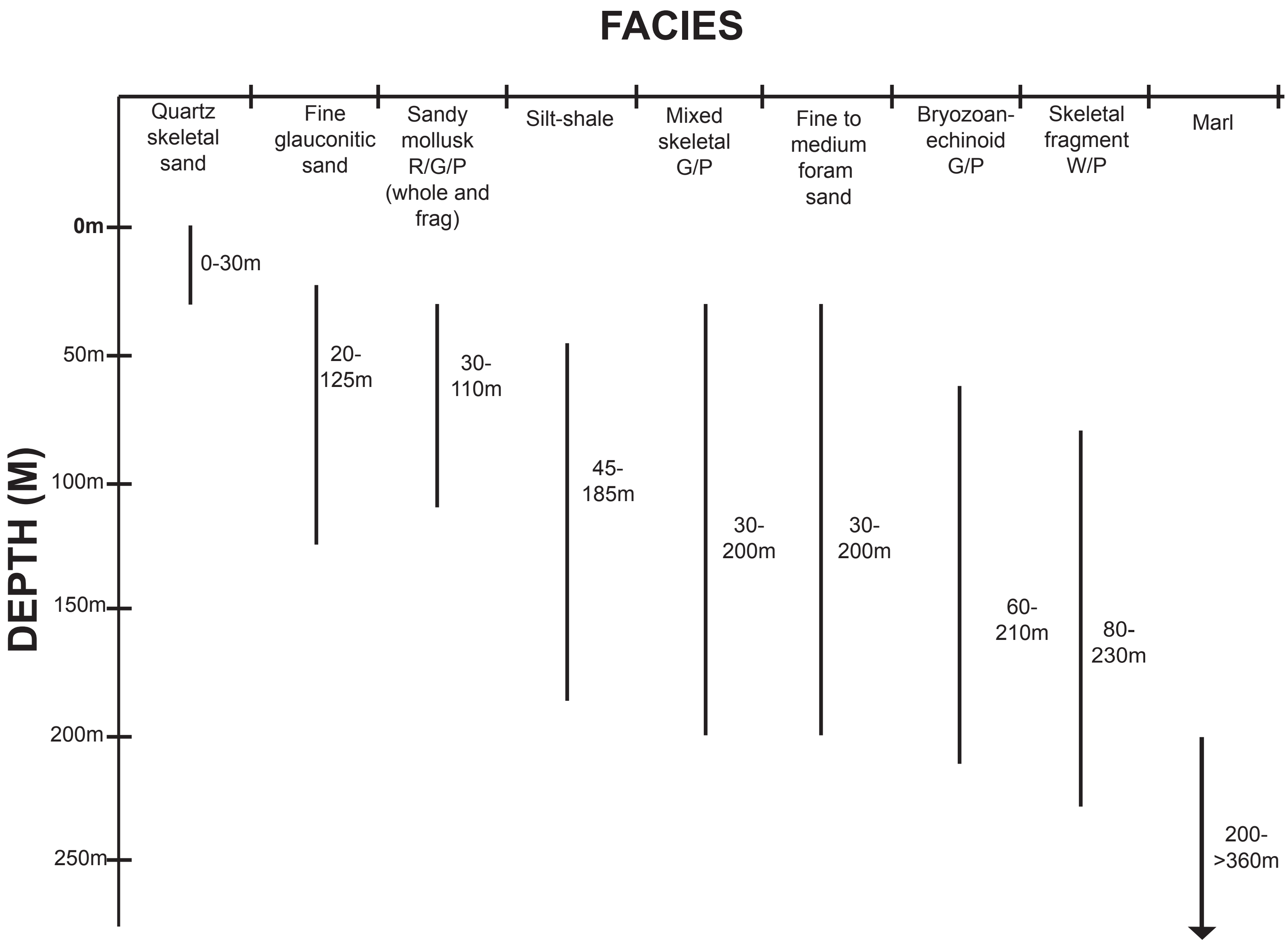


Figure 5b: Compiled depth of facies analogs. Compled from: Rao 1964; Jones 1983; Collins 1988; Browning et al 1997; James et al. 1997; James et al. 1999; Pekar and Kominz 2000; Pekar and Kominz 2001; and Pekar et al. 2003.

FACIES	LOCATION	**DEPTHS***	**COMPILED DEPTH**
Quartz sand	Inner neritic	0-15 m [2], <30m [8], 10-30m [1]	0-30m
Fine glauconitic sand	Inner neritic	20-50m [8], 20-125m [4], 25-75m [9]	20-125m
Sandy mollusk rudstone/grainstone/ packstone	Inner to middle neritic	30-85m [9], 30-110m [5,8], 35-50m [6]	30-110m
Silt-shale	Middle to outer neritic	45-90m[8], 60-185m[4]	45-185m
Mixed-skeletal grainstone/packstone	Middle to outer neritic	30-90m [5], 80-125 [7], 120-200m [6]	30-200m
Fine foram sand	Middle to outer neritic	30-70m [8], 120-200m [6], 145-185m [1]	30-200m
Bryozoan-echinoid grainstone/packstone	Middle to outer neritic	60-210 [7], 80-140m [5], 90-170m [3]	60-210m
Skeletal fragment packstone/wackestone	Outer neritic	80-200m [7], 150-200m [6], 170-230m [3]	80-230m
Marl	Outer neritic to slope	200->300m [6], 210->300m [7]	200- >360m

Table 1a: Estimated water depths for North Carolina Paleogene facies. Depths are compiled from similar environments of the New Jersey Oligocene and the modern Australian shelf.
*From: [1] Rao, 1964, [2] Jones 1983, [3] Collins 1988, [4] Browning et al 1997, [5] James et al 1997, [6] James et al 1999, [7] James et al 2001, [8] Pekar and Kominz 2001, and [9] Pekar et al. 2003.

	Inner Neritic	**Middle Neritic**	**Mid-Outer Neritic**	**Outer Neritic**
Jones 1983	0-15m	15-50m	-	50-100m
Browning 1997	0-30m	30-100m	-	100-200m
Boreen et al 1993		30- 130m		130- 180m
Pekar and Kominz 2001	0-40m	10-110m	30-130m	70-145m
James et al 2001	0-50m	50-120m	-	120-160m
Collins 1998	0-60m	60-100m	-	100-170m

Table 1b: Water depths of inner, middle, mid-outer, and outer neritic shelf environments are compliled from similar environments of the New Jersey Oligocene, modern Australian shelf, and North Carolina Eocene.

	Quartz sands	Glauconitic sands	Sandy whole mollusk rudstone/ grainstone/ packstone	Sandy, mollusk-fragment grainstone/ packstone and sand-lean mollusk fragment grainstone/packstone	Silt-shale	Mixed skeletal fragment grainstone/ packstone	Fine grained skeletal fragment/foram sands	Bryozoan-echinoid grainstone/ packstone	Fine skeletal fragment packstone wackestone/ mudstone	Marl/lime wackestone to mudstone	Hardgrounds
Stratigraphic Occurrence	Units 0.3m or less; may be reworked as lithoclasts into overlying limestone units	Units up to 2m thick in Paleocene, Kure Beach core	0.3 to 3m thick units in Cretaceous to Oligocene.	Units 1.5 to 3m thick in Cretaceous to Oligocene. Commonly interbedded with sandy whole mollusk beds	Units up to 7m thick in Paleocene, Kure Beach core.	Units 0.3 to 6m thick; common to dominant facies in the Middle Eocene.	10 to 30m in thick in Oligocene.	Units 0.3 to 4.6m thick, in Eocene; interbedded with mollusk fragment/skeletal fragment grainstone/packstone and fine skeletal fragment wackestone/mudston e	Units 0.3 to 3m thick in Eocene. Interbedded with bryozoan-echinoid beds.	Units 0.3 to 10.7m thick in Eocene and Oligocene.	Glauconitic/ phosphatic bored surfaces capping carbonate and cemented sands.
Color	Gray-tan	Brown-gray	White-gray	Gray, tan-gray	Brown-black	Gray, tan-gray	Gray-tan	Gray/tan-gray	Gray, brown-gray	Light gray, gray-tan	Gray-black, green
Bedding/ Sedimentary Structures	Structureless	Structureless and massively bedded, rarely flaser bedded	Structureless to faintly bedded	Massively bedded, with rare crossbeds, geopetal fills in leached moldic pores, commonly capped by hardgrounds	Massively bedded, some burrows and flaser bedding	Massively bedded, commonly capped by hardgrounds with bored surfaces.	Abundant burrows, common mud layers in sands	Massively bedded with rare mud layers	Massively bedded, burrowed	Heavily burrowed	Surfaces have cm-size borings and phosphatic/ glauconitic crusts
Depositional Texture and Constituents	Clean sands composed of poorly sorted subangular to rounded fine to coarse quartz sand with rare very coarse skeletal fragments. Rare to common very fine to medium glauconite and phosphate.	Muddy sands composed of well sorted subrounded very fine to fine quartz sand, rare skeletal fragments, very fine to granule sized glauconite and fine to medium phosphate.	Mud-lean to mud-rich poorly sorted rudstone, grainstone, and packstone composed of abundant to common gravel sized whole mollusks, common to abundant subangular fine to coarse quartz, common to rare benthic forams, and rare oyster and pectin.	Poorly sorted grainstones and muddy packstones composed of abundant to common coarse-grained mollusk fragments, common to abundant pectin fragments, common silt-sand sized benthic forams, oyster and gastropod fragments, common fine to coarse subangular to rounded quartz, rare ostracods, bryozoans, echinoids, and barnacles; rare carbonate and sandstone lithoclasts, rare fine to medium glauconite and fine phosphate.	Well sorted silt-shale composed of abundant silt to very fine to fine subrounded quartz sand, rare to common fine to very fine sand size mica, glauconite and phosphate.	Mud-lean to mud-rich, poorly sorted grainstones and packstones composed of whole and fragmented, common mollusks, bryozoans, echinoids, gastropods, ostracods, barnacles, pectins, forams, rare to common crustaceans, rare brachiopods and oysters, and rare to common very fine to coarse, subrounded quartz. Rare sandstone lithoclasts and clasts of hardgrounds; rare very fine to medium glauconite and phosphate.	Muddy fine sands composed of well sorted very fine to medium quartz sand, abundant benthic and planktic forams, rare to common ostracods and indeterminate skeletal fragments, rare delicate bryozoans, and rare very fine glauconite and phosphate; some interstitial carbonate and clay mud matrix.	Mud-lean to mud-rich poorly sorted grainstones and packstones composed of abundant to common whole and fragmented bryozoans, echinoids, forams, common ostracods, rare to common crustaceans, rare brachiopods, mollusks and oysters, rare very fine to coarse angular to rounded quartz, rare limestone and phosphate lithoclasts, and very fine to fine glauconite and phosphate and a lime mud matrix.	Fine grained packstones, wackestones, and mudstones composed of common to abundant indeterminate skeletal fragments, common to abundant bryozoan and echinoid fragments and forams, rare oysters, pectins and barnacles, rare to common very fine to medium subrounded quartz. Rare fine to medium glauconite and phosphate, rare sandstone lithoclasts and phosphate clasts, and a lime mud matrix.	Fine mud-rich wackestone/ lime mudstone with common to abundant sand-silt size benthic and planktic forams, common to rare bryozoan and indeterminate skeletal fragments, common silt, to very fine to medium quartz sand. Rare clasts of phosphate and lime mudstone, rare very fine to fine glauconite and phosphate grains, and common to rare chert nodules.	Multiply indurated irregular to planar surfaces, commonly encrusted by benthic forams and bryozoans. Common fine to medium glauconite and phosphate. Developed on carbonates and sandstones. Overlying beds may contain reworked hardground clasts.
Interpreted Environment	Inner neritic 0-37m	Inner neritic 20-125m	Inner to middle neritic 30-110m	Inner to middle neritic 30-110m	Middle to outer neritic 45-185m	Middle to outer neritic 30-210m	Middle to Outer neritic 30-200m	Middle to outer neritic 80-210m	Outer neritic 120-200m	Outer neritic-slope 200->360m	Zone of wave sweeping 40-60m, and Gulf Stream abrasion from middle neritic to slope.

Table 2: Mixed carbonate-siliciclastic facies descriptions and interpreted environments.

transgression and redeposited into adjacent facies. Cements in this facies are generally rare.

Glauconitic sands

Fine to very fine grained glauconitic sands with abraded glauconite grains and minor skeletal material (described in Table 2) are similar to Oligocene glauconitic sands from New Jersey that are located at depths of 20 m to 125 m (Browning et al. 1997a, Pekar and Kominz 2001, and Pekar et al. 2003). The glauconite is interpreted to form in quiet, middle neritic and deeper low-oxygen settings (McRae 1972). Glauconite associated with fine to coarse sands with shallow fauna is interpreted to be recycled, evidenced by abraded and cracked grains, and a mixture of green and weathered brown grains (Pekar et al. 1997). No cements were observed in this facies.

Sandy whole mollusk rudstone/grainstone/packstone

Sandy coarse grained whole mollusk rudstones, grainstones, and packstones (described in Table 2) are associated with the nearshore quartz sand and fragmented mollusk facies. They formed in inner to middle neritic (30 m to 85 m water depths) environments on the New Jersey Oligocene shelf (Pekar et al. 2003), and modern southern Australian shelves in depths of 30 m to 110m (Jones 1983, James et al. 1997, and James et al. 1999). Preservation of whole shells in this relatively high-energy setting was assisted by the robust character of the mollusk fauna and the relatively rapid sedimentation rates, which in areas bare of grass/algal cover formed winnowed rudstones and grainstones. However, in areas beneath possible seagrass or macro-algae cover (James et al. 1997), interstitial lime mud in packstones produced by physical and biological disintegration of skeletal material, was deposited during low energy periods.

Cements common in this facies are pink fine- to very fine equant cements within Eocene sediments, and bladed pink and purple staining high-Mg calcite with fine rhombohedral blue dolomite matrix in the underlying Cretaceous units.

Sandy fragmented mollusk grainstone/packstone and sand-lean fragmented mollusk grainstone/packstone

Sandy and sand-lean coarse grained fragmented mollusk grainstones and packstones (described in Table 2) are similar to those associated with nearshore quartz sand and sandy whole mollusk facies as on the southwest Australian shelf, where they occupy inner to middle neritic settings in water depths of 30 m to 110 m (James et al. 1997, James et al. 1999), depths that are similar to those of the Oligocene, New Jersey (Pekar et al. 2003). This facies formed by physical and biological fragmentation of shells produced by mollusk dominated assemblages. The thin, delicate nature of these mollusk valves noted by Ward (1978) in the Upper Castle Hayne Limestone may have contributed to the abundant fragmentation of the shells in this high-energy environment. The grainstones formed in areas of bare mobile substrates, subjected to winnowing by waves and currents. Disintegration of shells or weakly calcified organisms may have formed the muddy packstones that could have formed under local seagrass cover (Davies 1970, James 1997). Cements in the Eocene units consist of abundant to common pink, purple, and blue staining bladed marine high-Mg calcite, and later pink and purple staining fine and coarse equant calcite with syntaxial cements on echinoids. In the underlying Cretaceous, this facies contains bladed pink, and purple former high-Mg calcite cements, and blue stained euhedral dolomite.

Silt-shale

Very fine to fine grained silty quartz sands, described in Table 2, formed in low to moderate energy settings in middle to outer neritic settings similar to the Oligocene of offshore New Jersey (Pekar and Kominz 2001). Estimated water depths for this facies in New Jersey are from 45 m to 185 m based on paleoslope modeling and associated foraminifera from modern analogs on the New Jersey continental shelf (Pekar and Kominz 2001; and Browning et al., 1997). Fines were carried out onto the shelf as muddy plumes emanating from rivers in flood, and transported by longshore currents. There facies are rarely cemented.

Mixed skeletal fragment grainstone/packstone

Fragmented mixed skeletal grainstones and packstones, described in Table 2, formed in inner and middle neritic settings. The mollusk-bearing, bryozoan-echinoid-barnacle assemblages are transitional into middle and outer neritic bryozoan-echinoid assemblages. Modern analogs of this facies in Australia form on wave-swept sandy and rocky seafloor from depths of 30 m to 200 m (James et al. 2001, James et al. 1999, and James 1997). In the wave-swept middle neritic setting, sediments are usually a thin veneer over the indurated sea floor and skeletal material is abraded and/or the finer material swept away to deeper water (James 1997). The hard substrates are populated by benthic mollusks, echinoids, crustaceans, epibenthic bryozoans and barnacles, and are surrounded by sandy substrates that support isolated bryozoans (James et al. 1999, James et al. 2001). The sediments locally were infiltrated by lime mud during quiet periods to form packstones. Hardgrounds, and sandstone and limestone lithoclasts indicate that this facies experienced reworking and incision from wave sweeping and by boundary currents. Cements are primarily composed of abundant to common pink bladed high-Mg calcite, common pink rim, common fine and coarse pink equant cements, and rare purple and blue fine equant cements.

Bryozoan-echinoid grainstone/packstone

Whole and fragmented bryozoan and echinoid skeletal grainstones and packstones, described in Table 2, commonly are interbedded with mollusk fragment and mixed skeletal fragment grainstone/packstone facies. Similar facies on modern open shelves of Australia formed in water depths from 60 m to 210 m on rippled sand and rocky substrates of the moderate-energy middle to outer neritic parts of the shelf (James et al. 2001, and Collins 1988). Here, hard substrates support prolific growth of sponges, encrusting bivalves, and abundant bryozoa, which also are attached to sponges; the bryozoans decrease in diversity and abundance down dip as sponges increase. The meter scale interbedding of mud-lean bryozoan grainstones and mud-rich packstones, as noted by Coffey (2000) may be related to parasequence-scale changes in intensity of wave reworking of the shelf, perhaps related to changes in water depth or storm intensity. Some packstones formed by mud infiltration into earlier deposited grainstone beds (some of which are cross-bedded, megarippled), that were lightly cemented by former high-Mg calcite prior to mud deposition. Local hardgrounds, and reworked sandstone and limestone lithoclasts may be due to periods of wave sweeping or Gulf Stream boundary current erosion. This facies contains common pink high-Mg calcite bladed cements, pink rim and pink fine and coarse equant calcite, and rare purple and blue equant calcite.

Fine grained, foram quartz sands

Fine to medium grained foraminiferal quartz sands, described in Table 2, were formed in low-energy settings with gentle winnowing by low energy waves and currents. Similar southern Australian outer neritic facies are forming in water depths of 120 m to 200 m (James et al. 1999), and at depths of 30 m to 70 m in New Jersey Oligocene sediments (Pekar and Kominz 2001), by accumulation of fine to medium quartz sand carried across the shelf along with benthic and planktonic forams, ostracods, and fine sand- and silt-size skeletal debris. Much biogenic reworking homogenized the sediments. This facies contains common to rare pink rim and pink fine equant calcite cements.

Fine skeletal fragment packstone/wackestone/mudstone

Fine grained skeletal packstones and wackestones, described in Table 2, are similar to modern southern Australian analogs forming in low-energy outer neritic settings (80 m to 230 m water depth) that are rarely influenced by storm waves (James et al. 2001, Collins 1988, and James et al. 1999). Much of the fine carbonate is winnowed from updip to accumulate along with indigenous biotic components such as echinoid, delicate bryozoa, and benthic and planktic foraminifera (James et al. 2001, James et al. 1999, and Collins 1988). In the modern, sponges are locally conspicuous in this facies, becoming more numerous towards the shelf edge in 200 m water depth. Pink staining high-Mg bladed, fine equant, and rim cements are common.

Marl/lime wackestone to mudstone

Fine grained skeletal wackestone and lime mudstone, described in Table 2, formed in low-energy outer neritic and upper slope settings below swell-wave base favoring accumulation of fine sediment. On the southern Australian shelf these form in water depths of 200 m or more (James et al. 1999, James et al. 2001), but depths could have been less (100 m to 150 m; Browning et al. 1997b), on lower energy Atlantic and Carolinas margins. The fine mud winnowed from updip accumulated along with planktic and benthic forams, and other fine skeletal debris, together with storm transported terrigenous silt and minor fine to medium sand. This facies contains rare to common fine pink equant cements.

Hardgrounds

Multiple glauconitic and phosphatic, indurated and bored surfaces (hardgrounds), described in Table 2, occur on calcite cemented quartz sands, sandy molluscan grainstone and packstones, and within various carbonate facies. Some hardgrounds have a lag of sandstone and limestone clasts on the hardground surface, suggesting that they formed in the zone of intense swell-wave sweeping and bioerosion on the shelf in water depths of perhaps 40 m to 60 m, as on the modern Australian shelf (James et al. 1994). Pekar et al. (2003) suggest that the Oligocene New Jersey shelf became a bypass surface once it shoaled above 90 m water depth, with much of the sediments then accumulating seaward of the rollover. Hardgrounds could also be the result of incision and reworking by the ancestral Gulf Stream that migrated up the slope and onto the deep shelf during high sea level (Pinet and Popenoe 1985, Popenoe 1985). A similar boundary current (the Leeuwin Current) runs along the southwestern and southern Australian shelf (Collins 1988, James et al. 1994). Hardgrounds formation was favored by low sedimentation rates and bottom currents (Tucker and Wright 1990, p. 329).

SEQUENCE STRATIGRAPHY

Supersequence 1 (Paleocene)

Age and Regional Development:

Supersequence 1 is Paleocene (Danian and Thanetian) and unconformably overlies Cretaceous units (Harris and Laws 1997; Coffey 2000). In the Kure Beach core, Paleocene units are Danian in age (L. Edwards 2002, personal communication). The supsersequence is thin to absent on the updip Onslow Block, but thickens to over 100 m offshore and downdip onto the Albemarle Block (Harris and Laws 1996). The supersequence boundary is at the base of a widespread basal sand that dies out downdip (Fig. 4) (Coffey 2002). This is overlain by fine skeletal wackestone-packstones, grading downdip into thick marls. The Paleocene succession contains two quartz sand units within the carbonate-prone shelf succession, suggesting that three sequences may be present (Coffey in press).

Sequence Development in Study Area:

Downdip on the Cape Fear Arch, the basal boundary of Supersequence 1 is present in the Kure Beach core where it is a hardground overlain by a thin (1 m) sandy mollusk limestone (section 4, Fig. 6). The sequence boundary is also present in section 12 (Fig. 7), where it is overlain by a lowstand systems tract of quartz sand to sandy mollusk limestone.

The Paleocene transgressive systems tract in the Kure Beach core (Fig. 8) deepens upward from fine glauconitic sand to the basal one meter of a burrowed silt-shale in which the sand content decreases upward. The maximum flooding surface is at the base of the overlying laminated silt-shale. Downdip, the fine glauconitic sand thickens to 10 m in a local lobe (sections 1 to 4, Fig. 6).

The highstand systems tract in the Kure Beach core consists of 8 m of dark gray laminated silt-shales that grade up into a burrowed and cross-laminated silt-shale in which the sand content increases upwards (Fig. 8). Downdip, the succession grades into fine skeletal wackestone-packstones (sections 1 to 4, Fig. 6). On the Albemarle Block, possible Paleocene highstand facies include 7 m of fine skeletal wackestone-packstone (section 16, Fig. 7).

Supersequences 2 and 3 (Eocene)

Age and Regional Development:

The Eocene contains two supersequences. Supersequence 2 is Early Eocene (Ypresian), and Supersequence 3 is Middle to Late Eocene (Lutetian-Priabonian; Harris

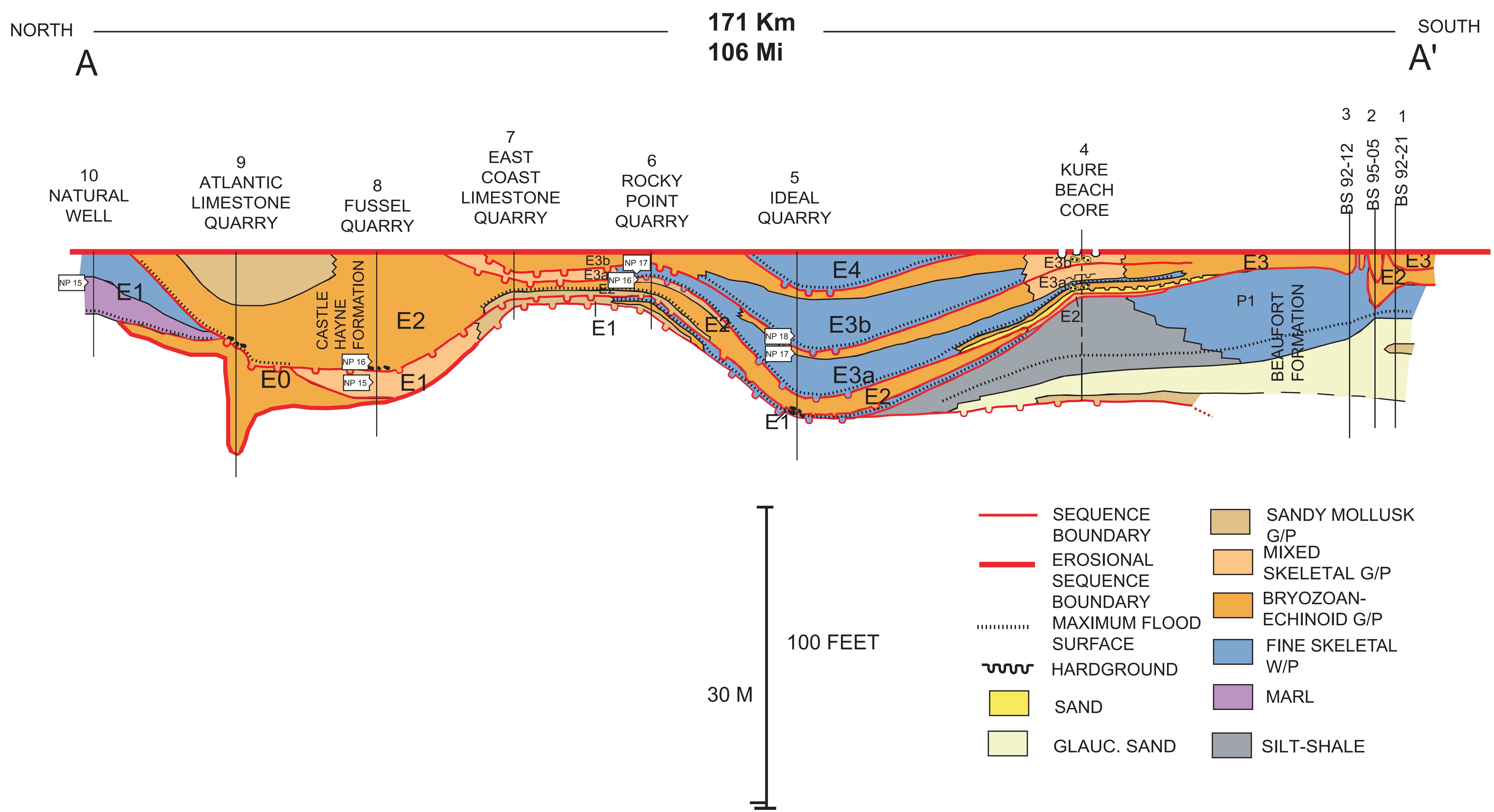


Figure 6: Interpretive dip cross-section A-A' of Paleocene to Eocene succession. Section line shown on Figure 1, runs parallel to Cape Fear Arch along Onslow Block. Sections are thin and condensed and thickness changes may reflect structure. Nannoplankton dates from Worsley and Laws, 1986. Published quarry data from Zullo and Harris 1987.

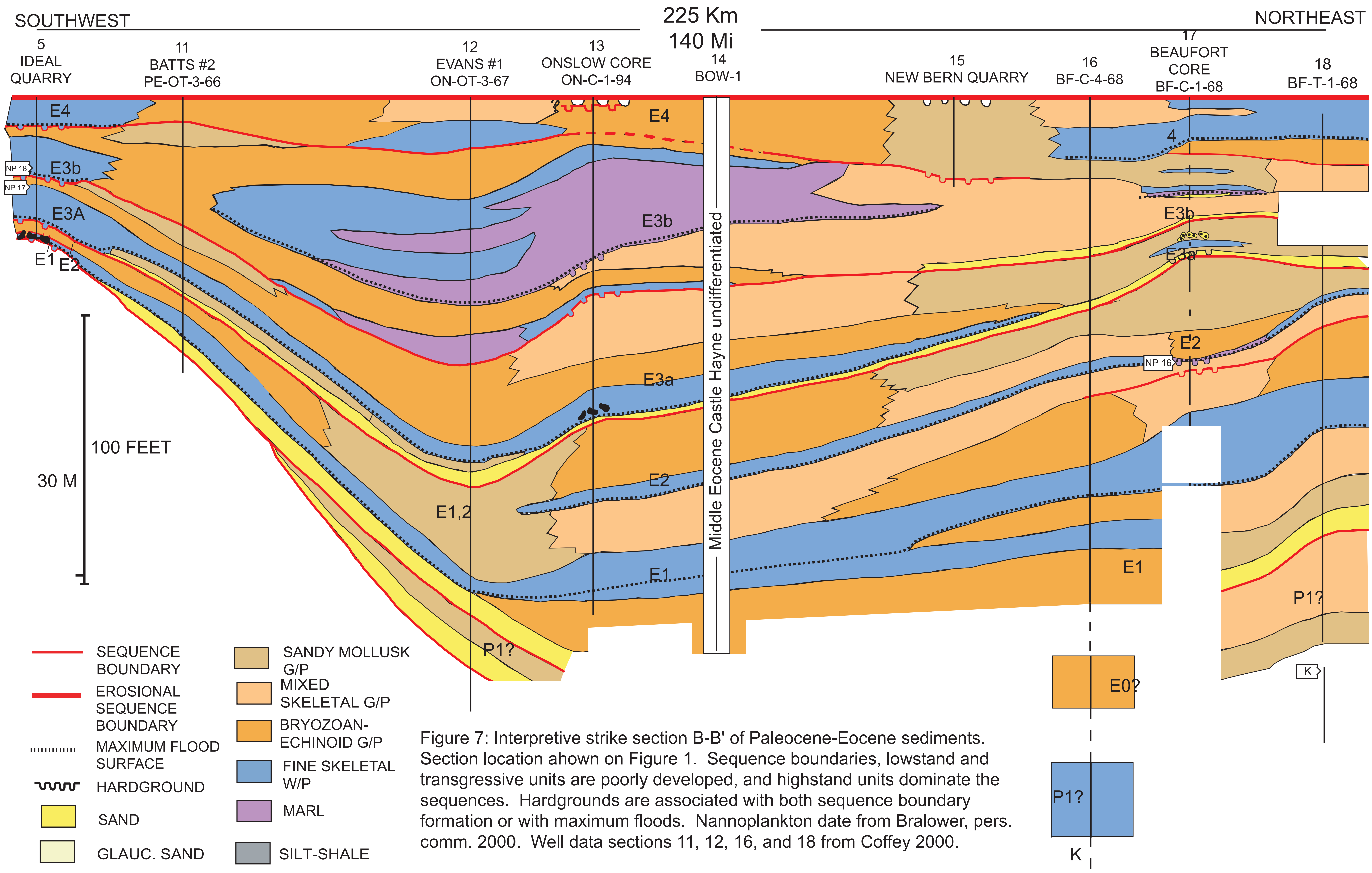


Figure 7: Interpretive strike section B-B' of Paleocene-Eocene sediments. Section location ahown on Figure 1. Sequence boundaries, lowstand and transgressive units are poorly developed, and highstand units dominate the sequences. Hardgrounds are associated with both sequence boundary formation or with maximum floods. Nannoplankton date from Bralower, pers. comm. 2000. Well data sections 11, 12, 16, and 18 from Coffey 2000.

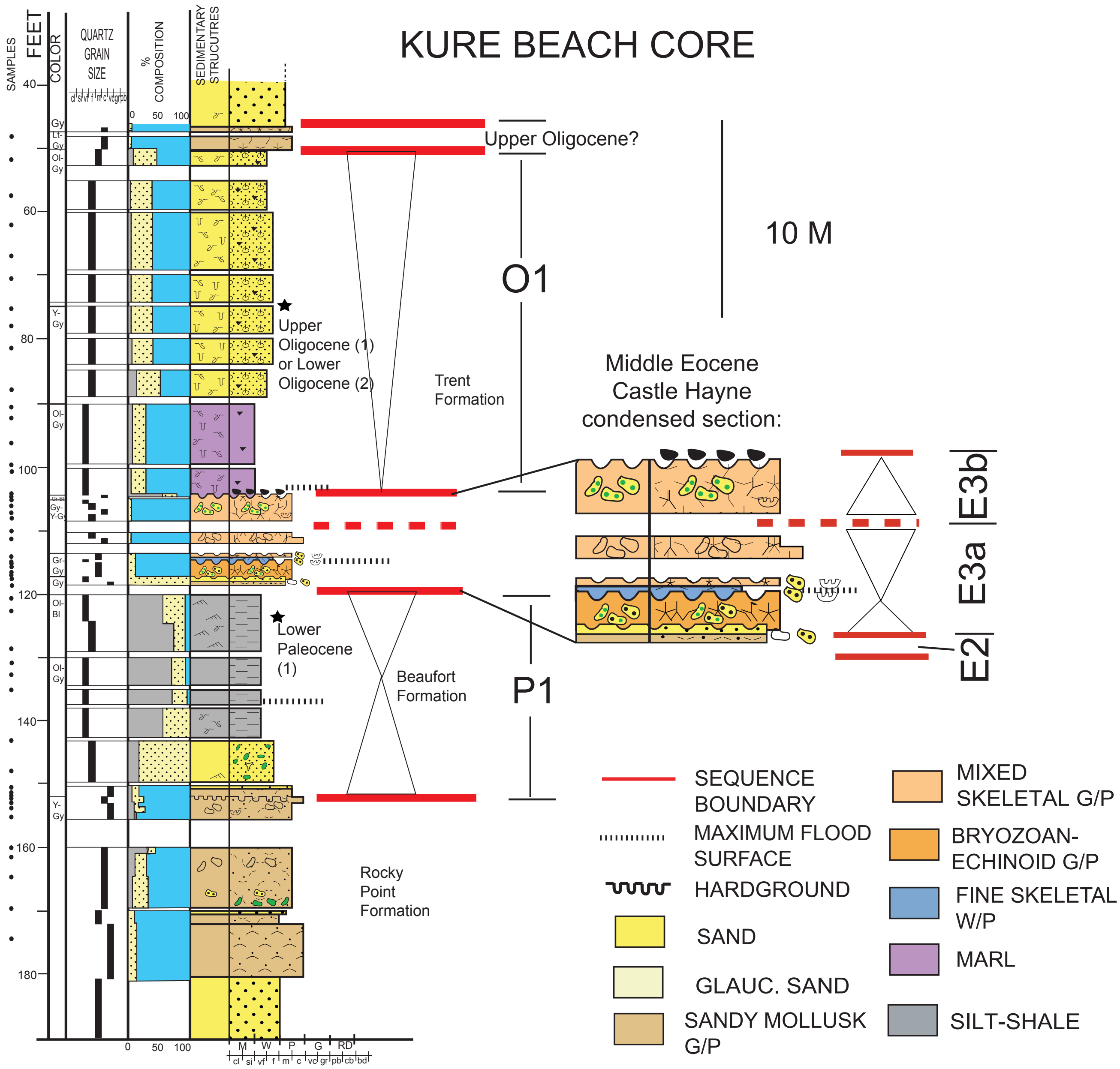


Figure 8. Lithologic log of USGS Kure Beach core. The core penetrates Paleocene sitting unconformably on Cretaceous mollusk limestones. The Paleocene has a weakly developed lowstand followed by transgressive flauconitic sand and a thick silt-shale highstand. The Middle Eocene is highsly condensed and contains 2 sequences. Lowstands are a thin sandy veneer (E3a) or sandstone clasts that are reworked into the overlying highstand bryozoan limestones (E3b). Hardgrounds are associated with sequence boundaries and the maximum flooding surface. Condensed transgressive and highstand bryozoan limestones dominate the sequences. The Early Oligocene is a thick marl and fine foram sand highstand with a condensed transgressive phophate lag at the base. It is capped by a Late Oligocene molluscan limestone unit. Age picks provided by L. Edwards pers. comm.,(1), and Harris and Laws 1997 (2).

and Laws 1997; Coffey 2000). Supersequence 3 contains 5 sequences, dated in terms of nannoplankton (NP) zones. Sequences 0 and 1 is NP 15 age; Sequence 2 is NP 16 age; Sequence 3a spans NP 16 and NP 17; Sequence 3b is NP 18 age; and Sequence 4 spans NP 19 and 20 (Zullo and Harris 1987; Harris et al. 1993; Harris and Laws 1994).

Early Eocene Supersequence 2 is up to 40 m thick and is confined to the subsurface of the Albemarle Block (Coffey 2000). The base of Supersequence 2 is placed beneath a regional basal sand on the shelf, and beneath a seismically defined lowstand sand wedge downdip (Coffey 2000) (Fig. 4). Early Eocene transgressive units consist of mollusk sands and thin bryozoan limestones (Coffey 2000). The Supersequence 2 maximum flooding surface is placed at the base of a 30 m thick marl unit that extends up to 160 km updip of the modern shoreline (Fig. 4) (Coffey 2000). Early Eocene highstand systems tract is an upward shallowing succession of marls to wackestone-mudstones to bryozoan limestones capped by a thin quartz sandstone (Coffey 2000).

Middle to Late (?) Eocene Supersequence 3 is the most regionally extensive Paleogene unit of the North Carolina coastal plain (Harris and Laws 1997). Supersequence 3 is up to 200 m thick and is dominated by bryozoan limestones with thin quartz sands and thin deeper water wackestones (Coffey 2000) (Fig. 4). Updip, the base of Supersequence 3 is an erosional unconformity between Middle Eocene units and underlying Cretaceous strata. Downdip, Supersequence 3 unconformably overlies Lower Paleocene sediments in the deeper parts of the Albemarle Basin, but a lowstand wedge is absent (Coffey 2000). The transgressive systems tract consists of a thick (up to 100 m) buildup of bryozoan limestones beneath Cape Hatteras that thins to the southwest on the updip Onslow Block and Cape Fear Arch to a condensed marl (Coffey 2000). The Middle Eocene maximum flooding surface is at the base of a regional wackestone-mudstone (Fig. 4). Highstand systems tract units consist of upward shallowing sequences of skeletal packstone-wackestones to bryozoan packstone-grainstones to quartz-mollusk sands (Coffey 2000). The highstand has clinoformed reflectors near the inner shelf break downdip, and updip occurs as erosional outliers (Coffey 2000). Clinoforming is also evident on the shelf associated with the major buildup along the margin (Coffey 2000).

Sequence Development in Study Area:

There is a Lower Eocene Ypresian thin basal sand overlain by silty clay on the seaward edge of the Albemarle Block (Zarra 1989), but Early Eocene Supersequence 2 units were not evident in most of the study area. Supersequence 3 (Middle to Late Eocene) strata on both the Onslow and the Albemarle Blocks in the study area unconformably overlie either Paleocene or Upper Cretaceous beds. Five depositional sequences labeled 0 to 4 within Supersequence 3 can be traced throughout the study area of the Onlsow and Albemarle Blocks where they have an aggregate thickness up to 77 m thick (Zullo and Harris 1987). Bryozoan limestone punctuated by thin sandy units and deeper water wackestone-packstone dominate the sequences. Updip sequences on the Onlsow Block are highly condensed, contain several regional hardgrounds, and have an erosional updip limit (Harris and Laws 1997). Downdip on the Albemarle Block, sequences are better developed and also show some parasequence scale units (Fig. 7). The Eocene units are unconformably overlain by Oligocene, Pliocene, and Pleistocene strata.

Sequence E0: Sequence E0 has patchy distribution and typically occurs as isolated, single facies for which no systems tract can be identified. The basal boundary of sequence 0 is only observed updip along the arch in quarry sections 8 and 9, where sequence 0 units disconformably overlie Cretaceous strata (Fig. 6). No lowstand systems tract is observed.

Sequence E0 is localized in erosional depressions along the arch, and consists of 14 m of a bryozoan-echinoid grainstone-packstone that thins rapidly to 0 m within 5 miles (sections 8 and 9, Fig. 6). Downdip in well section 16, sequence 0 is 6 m of bryozoan-echinoid grainstone-packstone (Fig. 7). Its systems tracts are not identified.

Sequence E1: On the Cape Fear Arch (Fig. 6), sequence 1 is 0 to 8 m thick. On the strike line, boundaries between sequences E1 and E2 cannot be determined, and together the sequences thicken to an aggregate thickness of 37 m (Fig. 7).

The base of sequence E1 over the local high on the arch (sections 5 to 7, Fig. 6) is a hardground overlain by shallow water sandy mollusk facies. Downdip in sections 11 and 12, the base of sequence E1 is placed beneath a 3 m lowstand quartz sand that is seen again updip on the Albemarle Block at section 18 (Fig. 7).

On a local high in section 6 (Fig. 6), the transgressive systems tract is a very thin (0.5 m) succession of sandy mollusk limestone to bryozoan-echinoid grainstone-packstone. The transgressive systems tract is not evident elsewhere updip (Fig. 6), and is absent from sections 11 and 12 on the strike section (Fig. 7). Transgressive units on the Albemarle Block likely consist of a bryozoan-echinoid grainstone-packstone capped by a flooding surface in sections 13 to 16 (Fig. 7, Fig. 9) that grade updip into a 9 m succession of sandy mollusk limestone to mixed skeletal grainstone-packstone (section 18, Fig. 7).

The highstand systems tract for sequence E1 on the arch is a 6.5 m succession of marl to fine skeletal wackestone-packstone with an NP 15 age pick (Worsley and Laws 1986) in the updip section 10 (Fig. 6). Further downdip, the highstand systems tract reappears as a very thin (less than 0.5 m) fine skeletal wackestone-packstone that pinches out within 5 miles (sections 5 and 6, Fig. 6). The highstand systems tract in the strike section consists of a shallowing upward succession of fine skeletal wackestone-packstone to mixed skeletal grainstone-packstone and bryozoan-echinoid grainstone-packstone with an undefined top (sections 11 to 18, Fig. 7). The flooding unit is split at section 16 by a bryozoan limestone (Fig. 7).

Sequence E2: The sequence E2 boundary on the arch is a regional hardground (sections 5 to 9, Fig. 6) overlain by a thin (1 m) sandy mollusk limestone at sections 6 and 7. Updip on the Albemarle Block in the Beaufort core (section 17, Fig. 7; Fig. 10), the

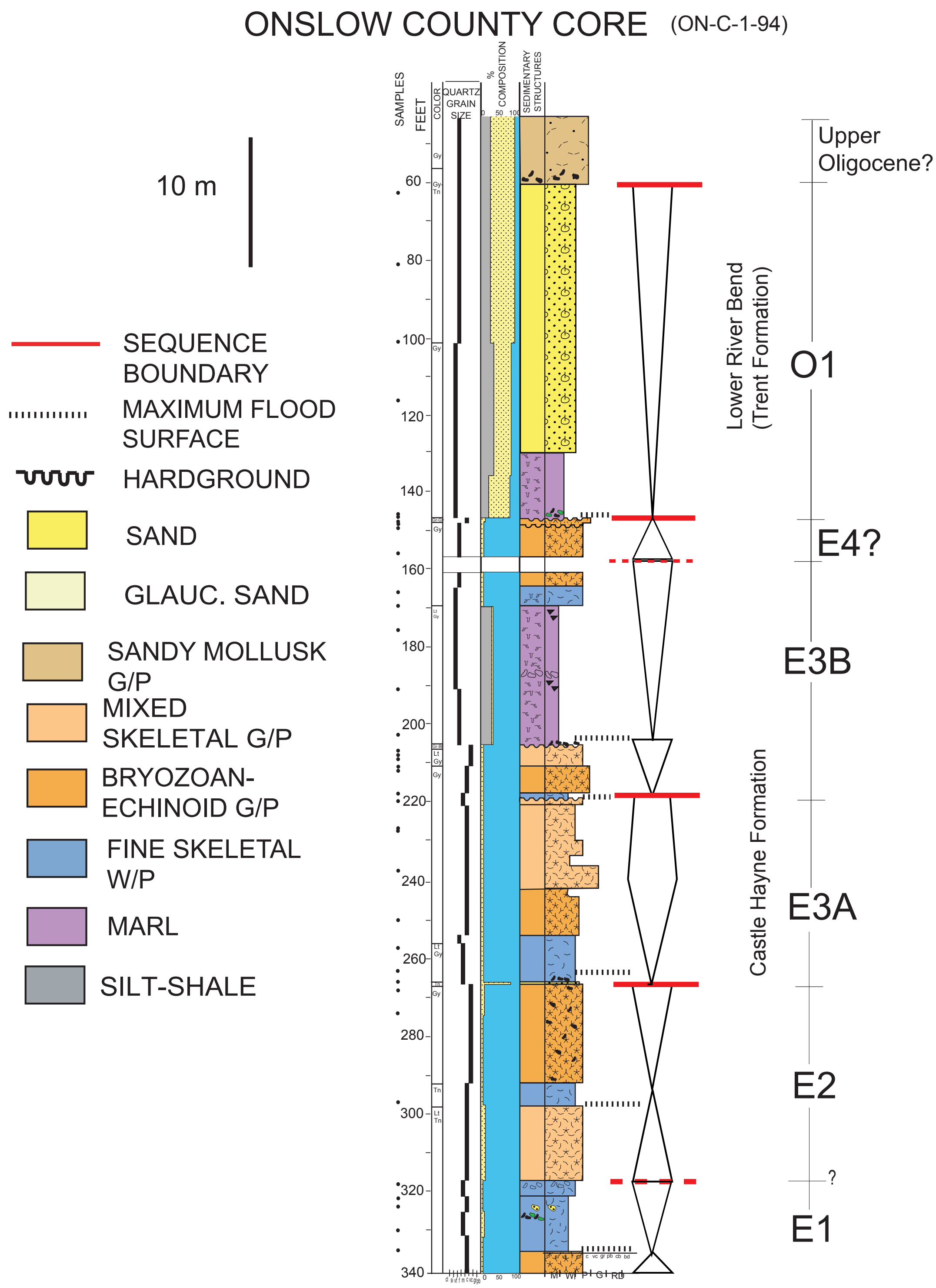


Figure 9: Lithologic log of Onslow County Core. Middle Eocene section contains at least 4 sequences, and 2 sequences occur in the Oligocene. Lowstand units are absent or very thin, and sequences are dominated by thick highstand units (E2, E3a, E3b). Transgressive units are present either as shallowing upwards parasequences (E3b) or thin phosphatic lags (E3a). In this downdip core, hardgrounds are coincident with sequence boundaries or maximum flooding surfaces. However some sequence boundaries are relatively conformable (E2, E3a).

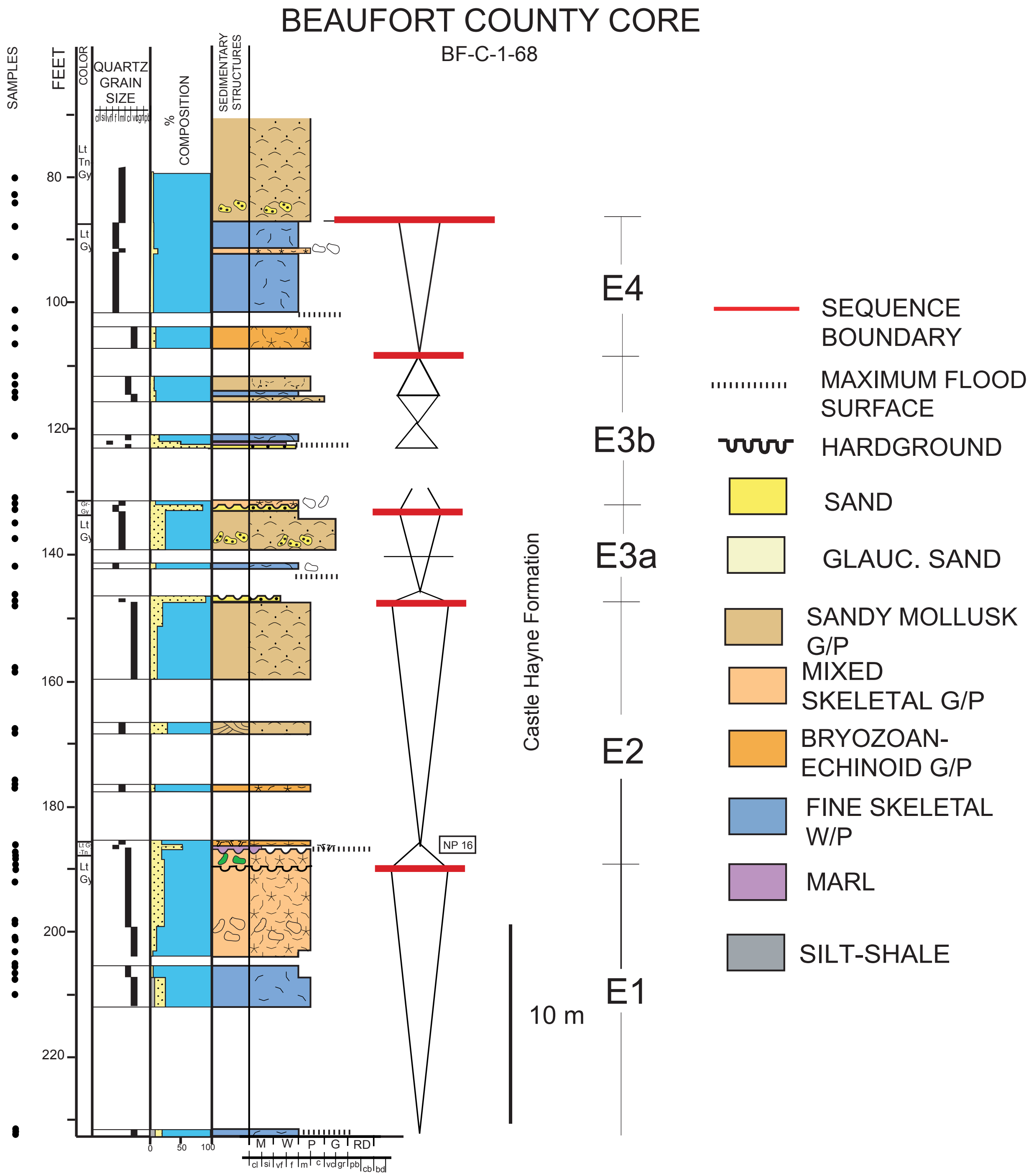


Figure 10: LIthologic log of Beaufort County Core. The Middle Eocene section is composed of at least 4 depositional sequences. Sequences E1 and E2 show no lowstand development, a deep water maximum flood, and a shallowing upward highstand. Sequences E3a and E3b have poorly developed lowstand units associated with hardgrounds, and contain parasequences in the highstand. Sequence E4 consists of a minor transgressive bryozoan limestone followed by a thicker highstand unit.

sequence boundary is placed at a hardground, beneath which sand content in the underlying bryozoan limestone increases upwards.

The sequence E2 transgressive systems tract is a phosphate pebble lag (and possibly the overlying bryozoan-echinoid grainstone-packstone) that are localized in a broad depression at section 8 on the arch; it thins downdip and has an NP 16 age pick (Worsley and Laws 1986). Transgressive units may be present in the Kure Beach core (section 4, Fig. 6; Fig. 10), as a very thin (0.5 m), sandy mollusk limestone, and offshore as thin bryozoan grainstone-packstones (sections 1 to 3, Fig. 6). On the strike line, the transgressive units of sequence E2 cannot be defined, but likely are within the 7 m mixed skeletal grainstone-packstone and bryozoan-echinoid grainstone-packstone units beneath a major flooding unit (sections 13-18, Fig. 7). The transgressive systems tract may also be present at section 11 as a 2 m bryozoan-echinoid grainstone-packstone.

The sequence E2 highstand systems tract on the arch is a local 6 m sandy mollusk limestone at section 9. Downdip, the highstand systems tract is a 2 m upward shallowing succession of bryozoan-echinoid grainstone-packstone to molluscan limestone at sections 6 and 7 (section 6 contains an NP 16 age pick by Worsley and Laws 1986), and may be a very thin (0.5 m) molluscan limestone in the Kure Beach core (section 4, Fig. 6; Fig. 8). Basinward on the Onslow Block, the highstand units consist of shallowing upwards succession of fine skeletal wackestone-packstone to bryozoan-echinoid grainstone-packstone (sections 13 to 16, Fig. 7). In the Onslow core, the highstand is a shallowing upwards succession of fine skeletal wackestone-packstone to bryozoan-echinoid grainstone-packstone is accompanied by an increase in sand content (section 13, Fig. 7; Fig. 9). Updip on the Albemarle Block the highstand shallows upwards from fine skeletal wackestone-packstone and marl dated as NP 16 (Bralower 2000), to bryozoan limestones that are capped by sandy mollusk limestones (section 17, Fig. 7; Fig. 10).

<u>Sequence E3</u>: Sequence E3 consists of two minor sequences 3a and 3b. Sequence E3 is 0 to 12 m thick along the Cape Fear Arch (Fig. 6), thickening to 47 m basinward on the Albemarle Block (Fig. 7).

Sequence E3a: Along the Cape Fear Arch, the basal boundary of sequence E3a is a hardground on the local high (sections 5 to 7, Fig. 6). In the Kure Beach core, the sequence E3a basal boundary is placed beneath a thin, (less than 1 m) local sand that contains sandstone rip-up clasts and is capped by a hardground (section 4, Fig. 6; Fig. 8). In the strike section (Fig. 7), the basal boundary is beneath a laterally extensive 1 m thick lowstand quartz sand (sections 11 to 18), as in the Onslow and Beaufort cores (sections 13 and 17, Fig. 7; Figs. 9 and 10). In the Beaufort core, the lowstand sand is capped by a hardground.

The transgressive systems tract of sequence E3a updip on the arch (section 4, Fig. 6; Fig. 8) is a local, thin (1 m) bryozoan-echinoid grainstone-packstone unit that contains sandstone rip-up clasts, and is capped by a hardground. Further downdip, transgressive units are developed at sections 11 and 12 (Fig. 7) as a 3 m thick sandy mollusk limestone, and may be present in the Onslow core (section 13, Fig. 7; Fig. 9) as a very thin phosphate pebble lag. Elsewhere along strike, the transgressive systems tract cannot be differentiated from the highstand except in the Beaufort core (section 17, Fig. 7; Fig. 10) where it is a transgressive sandy mollusk limestone beneath highstand fine skeletal wackestone-packstone.

Where it forms a distinct unit along the arch, the highstand systems tract of sequence E3a is a thin upward-shallowing succession of fine skeletal wackestone-packstone to bryozoan grainstone-packstone (section 5, Fig. 6), or mixed skeletal limestone (section 4, Fig. 6; Fig. 8). The sequence boundary on the top of the highstand systems tract was not recovered in the Kure Beach core. Along the strike line, the highstand systems tract is a slightly thicker succession of fine skeletal wackestone-packstone to bryozoan-echinoid grainstone-packstone, (sections 11 to 14, Fig. 7), locally capped by sandy mollusk limestone (section 11, Fig. 7) or mixed skeletal limestone (sections 13,14, Fig. 7). Updip on the Albemarle Block, the sequence 3a undifferentiated transgressive and highstand systems tract are not differentiated and is a molluscan limestone unit only recovered in cuttings in section 16 (Fig. 7). In the Beaufort core (section 17, Fig. 7; Fig. 10), only a portion of the upper highstand was recovered where it consists of a shallowing upwards succession of fine skeletal wackestone-packstone to sandy mollusk limestone containing sandstone rip-up clasts at the base, with an upward increase in sand content. This flooding unit is stratigraphically higher than that in adjacent sections 11 to 14, implying that it is a different flooding event (parasequence scale?) or that the underlying transgressive unit is locally thickened.

Sequence E3b: Along the arch, the sequence E3b basal boundary is a hardground at sections 5 and 6 (Fig. 6). In the Kure Beach core (section 4, Fig. 6; Fig. 8), the sequence boundary probably lies within a zone of no recovery directly beneath a mixed skeletal limestone that contains sandstone rip-up clasts possibly reworked from a lowstand sand. Further downdip (sections 1 to 3, Fig. 6), sequence E3b cannot be differentiated from sequence E3a.

Along strike at section 11, the sequence E3b boundary is placed above shallow water units with an upward increase in sand content, and beneath a fine skeletal wackestone-packstone (Fig. 7). In sections 12 and 13, the sequence 3b boundary is placed beneath a deep water facies and in the Onslow Core (section 13), it is a hardground overlain by deep water facies (Fig. 7, Fig. 9). On the Albemarle Block in sections 16 and 17, the sequence boundary is placed beneath a thin (less than 0.5 m) lowstand sand (Fig. 7).

The sequence E3b transgressive systems tract in sections 1 to 7 (Fig. 6) cannot be separated from the highstand systems tract within the bryozoan limestone unit. Along strike in section 11 (Fig. 7), the sequence 3b transgressive systems tract is a 8 m bryozoan-echinoid grainstone-packstone that changes laterally in sections 12 to 14 to an upward shallowing succession (5 m) of marl/fine skeletal wackestone-packstone to bryozoan grainstone-packstone to mixed skeletal grainstone-packstone (Fig. 6). In section 16 (Fig. 7) the transgressive systems tract is a mixed skeletal grainstone-packstone with an undefined top that extends into section 17 (Fig. 7; Fig. 10) where it shallows upward into a very thin (less than 0.5 m) parasequence-scale quartz sand overlain by deeper water units.

The sequence E3b highstand systems tract along the arch at section 5 (Fig. 6) is a 7 m fine skeletal wackestone-packstone with an NP 18 age pick (Worsley and Laws 1986), that shallows up to a bryozoan-echinoid grainstone packstone. The systems tracts are not separable in the thin bryozoan limestones in sections 6 and 7 (Fig. 6).

In the strike line (section 11, Fig. 7), the highstand systems tract consists of 5 m of shallowing upward fine skeletal wackestone-packstone to sandy mollusk limestone. The highstand thickens to 20 m in adjacent well section 12 (Fig. 7) where it consists of marl and interbedded fine skeletal wackestone-packstone. In the Onslow core (section 9, Fig. 7; Fig. 9), the highstand systems tract thins slightly and consists of marl to fine skeletal wackestone-packstone to a bryozoan-echinoid grainstone-packstone possibly capped with a hardground. The sequence E3b highstand systems tract continues to thin to the east and at section 15 (Fig. 7) consists of mixed skeletal grainstone-packstone that is capped by a sandy mollusk limestone at section 16 (Fig 7). In the Beaufort core (section 17, Fig. 7; Fig. 10), the highstand consists of two shallowing upwards parasequences, the lower one capped by a very thin (less than 1 m) unit of marl to fine skeletal wackestone-packstone to sandy mollusk limestone and the upper one of very thin fine skeletal wackestone-packstone and capped by sandy mollusk limestone. The sandy mollusk facies makes up the highstand at (Fig. 7).

<u>Sequence E4:</u> Sequence E4 is either latest Middle Eocene or early Late Eocene (Priabonian) (Ward et al. 1978; Zullo and Harris 1987). It has patchy distribution along the Cape Fear Arch and is locally capped by Oligocene, Pliocene, or Pleistocene units. It commonly is a single facies, making systems tract identification difficult. The sequence 4 boundary is only evident along the arch at section 5 (Fig. 6), where it is a hardground.

In the strike section, the sequence E4 boundary is a hardground at quarry section 15 (Fig. 7). Elsewhere along strike, the sequence boundary was difficult to define and was arbitrarily placed above sandy mollusk limestones and beneath bryozoan-echinoid grainstone-packstones (sections 11, 17 and 18), or above fine skeletal wackestone-packstones and beneath bryozoan limestones (section 12, Fig. 7). In core section 13 (Fig.

7; Fig. 9), there is no obvious basal sequence boundary. There is a hardground within bryozoan limestones, although this hardground appears to be far too high stratigraphically to be the basal sequence E4 boundary.

The sequence E4 transgressive systems tract was not recognizable along the arch. It is recognizable in sections 17 and 18 (Fig. 7), as a 1 m bryozoan-echinoid grainstone-packstone (Fig. 10).

The sequence E4 highstand systems tract at section 5 (Fig. 6) is a localized 4 m thick fine skeletal wackestone-packstone that pinches out laterally. The sequence 4 highstand is only recognizable on the strike section (Fig. 7) at sections 17 and 18 where it consists of fine skeletal wackestone-packstone interbedded with mixed skeletal grainstone-packstone. In the Onslow core (section 13, Fig. 7; Fig. 9), the highstand systems tract may be the thin (less than 1 m) bryozoan limestones which have an upward increase in sand content toward the top of the unit. Elsewhere the sequence E4 transgressive and highstand tracts are not able to be differentiated and include sandy mollusk limestone, fine skeletal wackestone-packstone and mixed skeletal grainstone-packstone (sections 15 to 18, Fig. 7).

Supersequences 4 and 5 (Oligocene)

Age and Regional Development:

The Oligocene contains two supersequences. Supersequence 4 is Lower Oligocene (Rupelian) in age, and Supersequence 5 is Upper Oligocene (Chattian). Defining third-order sequences in these successions is difficult given the mixed data set of core, well, and quarry exposures, and the poor time control on individual units. Ages shown in Figure 7 include $Sr^{87/86}$ dates (Denison et al. 1993; Harris et al. 2000) and biostratigraphic ages (Ward et al. 1978). Nannofossil ages in cores have given younger ages than the $Sr^{87/86}$ ages (Harris et al. 2000) which could be due to infiltration of nannofossils down section during drilling.

Seismically the supersequences show flat-lying reflectors onshore. Immediately offshore, the supersequences show clinoformed reflectors along the paleo-inner shelf edge, with two seismically defined lowstand wedges (Coffey 2002). Supersequence 4 contains up to 3 sequences that are recognizable in offshore seismic profiles (Snyder et al. 1994) and in cuttings from a few onshore wells (Coffey 2000), but are difficult to identify onshore. Supersequence 5 contains at least 3 sequences that can be recognized from offshore seismic data (Snyder 1982), and in some wells (Coffey 2000).

Sequence Development in Study Area:

Supersequence 4 (Rupelian): The updip pinchout of Supersequence 4 is further downdip than the underlying Upper Eocene pinchout. The depositional edge is relatively close to the present shoreline in the south, and steps over 50 km inland further to the north. Sequence O1: Given the $Sr^{87/86}$ age ranges in section 14 (Harris et al 2000) (Fig. 11) and the absence of any breaks within the Kure Beach core (section 4, Fig. 11), the southern part of the study area is interpreted as a single sequence informally labeled O1. It is approximately 15 m in the Kure Beach core to 30 m in section 14 (Fig. 11). Sequence O1 thins to 13 m in section 14A (Fig. 11), beyond which it cannot be traced with any surety. It may continue updip into sections 14B and 14C, but there is little age control.

The basal sequence boundary of Sequence O1 is a hardground in core sections. No lowstand systems tract or transgressive systems tract can be recognized, and the maximum flooding surface is coincident with the sequence boundary. The highstand systems tract consists of a lower unit of marl 5 m to 10 m thick, overlain by 14 m to 30 m of fine foram sand.

Sequence O2a: Given the age control in section 14B and the sand bodies in section 14A (Fig. 11), it is inferred that Sequence O1 is overlain by Sequences O2a and O2b downdip. Updip to the north in section 14C (Fig. 11), the O2 silty sand may pass into undifferentiated shell beds given the $Sr^{87/86}$ age picks in the Belgrade Quarry. The basal sequence boundary of O2a in section 14A (Fig. 11) is placed beneath a local lowstand to

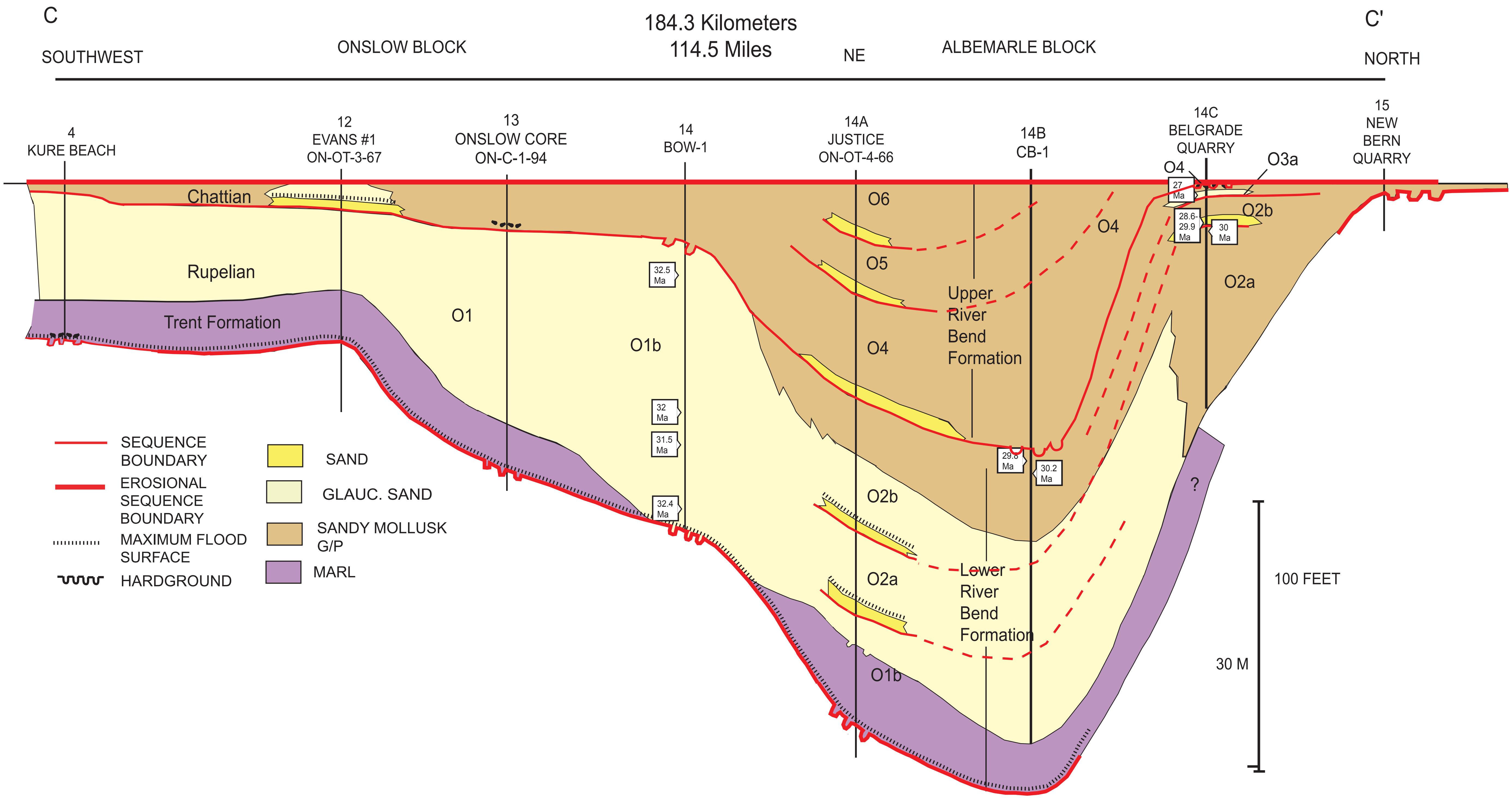


Figure 11: Interpretive Oligocene cross-section C-C' from the Onslow Block to the Albemarle Block, location shown in Figure 1. Oligocene sequences unconformably overlie Eocene carbonates. Succession is broadly upward shallowing, with deeper water marl overlain by thick fine foram sands, overlain by sandy mollusk carbonates. The two supersequences are Lower Oligocene (Rupelian) and Upper Oligocene (Chattian). Note that updip there are only one or two sequences, wheras downdip there are several possible sequences.Interpretation constrained by biostratigraphic ages and Sr 87/86 dating (Ward et al. 1978; Denison et al. 1993; and Harris et al. 2000).

early transgressive coarse sand body. The sand unit is overlain by 10 m of transgressive/highstand systems tract fine foram sand.

Sequence O2b: The sequence boundary for Sequence O2b in section 14A (Fig. 11) is placed beneath a local lowstand to early transgressive coarse sandy zone. This sand reappears to the north in section 14C (Fig. 11) and is dated at 30 Ma (Harris et al. 2000). The highstand systems tract consists of an upward shallowing succession of 10 m to 20 m of fine foram sand overlain by 15 m of sandy mollusk limestone that thins to the northeast to 2 m in section 14C (Fig. 11). Sequence O2b is preserved only in the basin, as it appears to pinch out to the southwest and northeast.

Sequence O3: A third locally preserved sequence tentatively labeled O3 is recognized in section 14C (Fig. 11). It is bracketed by $Sr^{87/86}$ age dates of 27 Ma above and 29 Ma below (Denison et al. 1993). The O3 sequence boundary is placed beneath the local lowstand to early transgressive sand, and the highstand systems tract consists of 2 m of sandy mollusk limestone (section 14C, Fig. 11).

<u>Supersequence 5 (Chattian):</u> Supersequence 5 ranges in thickness from 2 m in the south at section 4 (Fig. 11), slightly thickening to 8 m in section 14, and then undergoes rapid thickening into the basin (sections 14A and 14B, Fig. 11). It then thins to a thin veneer updip to the north (section 14C and 15, Fig. 11). Age control is limited.

Sequences O4, O5, O6: The supersequence boundary on the Onslow Block is placed at the base of either lowstand to early transgressive local coarse sands (sections 12 and 14A, Fig. 11) or where these are absent, at the base of sandy mollusk limestone units that are locally marked by phosphatized pebbles (sections 13 and 14C, Fig. 11). In the basin at section 14A (Fig. 11), there is a weak suggestion that three sequences may be developed (Sequences O4, O5, and O6) based on slight increases in sand in the well cuttings at the presumed bases of the sequences. The remainder of the sequences are comprised of sandy mollusk limestones. Sequence O4 appears to extend out of the basin to the north into section 14C and 15 (Fig. 11) based on $Sr^{87/86}$ ages at 14C (Denison et al. 1993). On the Onslow Block, although only one sequence appears to be developed, it is unclear if it is Sequence O4 or O5. The top of Supersequence 5 is placed above lithified sandy mollusk limestones and beneath unlithified Miocene and younger sandy beds.

DISCUSSION AND INTERPRETATION

Controls

Subsidence Rates: Subsidence rates for onshore Paleogene units average 1.4 cm/ky (Coffey 2002), but in the study area, probably were below 0.5 cm/ky. Elsewhere along the east coast subsidence rates, especially in more offshore areas, were higher (up to 4 cm/ky) (Steckler and Watts 1978). Abrupt changes in sediment thickness in onshore sections (e.g. Fig. 6) have been attributed to numerous faults evident on seismic data with localized thickenings in small graben-like depressions (Baum 1977; McLaurin and Harris 2001). Areas of low subsidence rates generally were sites of shallow water sedimentation and local preservation of thin deeper water units, while widespread deeper water units were only preserved in more rapidly subsiding areas.

Eustasy: Eustatic sea level changes have been cited as the major influence on the timing of supersequence and sequence development in the Paleogene of North Carolina and New Jersey (Harris et al. 1993; Harris and Laws 1997; Miller et al. 1998). This is indicated by the correspondence of unconformities and maximum flooding surfaces in New Jersey and along the Atlantic margin to the Haq et al. (1988) sea level record, (Browning et al. 1997a; Miller et al. 1997). Paleocene eustatic sea level rise of at least 100 m, evidenced by near-shore Upper Cretaceous facies overlain by deep-water marls, is associated with the transition into global greenhouse climate following late Cretaceous cooling (Coffey 2002). Delta O^{18} values of foraminifera of New Jersey indicate that greenhouse conditions continued into the Early Eocene (Miller et al. 1987), but show a cooling trend in the Middle to Late Eocene into a transitional period of "doubthouse" before passing into the icehouse of the Oligocene (Miller et al. 1991). In the study area, widespread erosion at the Eocene-Oligocene boundary and the transition from Eocene subtropical bryozoan limestone facies to siliciclastic-dominated facies deposited in the Oligocene icehouse (Figs. 6, 7, and 11) reflect significant climate cooling and subsequent progressively lower sea levels (Coffey and Read in press).

Wave Climate: The open shelf environment of the Paleogene Atlantic margin was subject to intense wave sweeping generated by storms in the "roaring forties," as it was positioned north of 30 degrees latitude (Scotese 1997) as well as swells generated from tropical storms to the southwest. Swell waves created a zone of abrasion that caused continuous scouring of the shallow shelf, as on the present southwestern Australian shelf (Collins 1988; James et al. 1997; and Osleger 1991). However, because of the less energetic setting of the Paleogene Atlantic margin, the sub-environments likely occurred at shallower depths than their modern southern Australian counterparts (Collins 1988; James et al. 1997; James et al. 1999; and James et al. 2001) and New Jersey to North Carolina margin (Jones 1983; Browning et al. 1997a; Pekar and Kominz 2001; and Pekar et al. 2003) (Table 1a, 1b). This was because the Paleogene Atlantic Ocean was closed, shallow to the north, and relatively narrow, limiting the distances that the swell waves traveled prior to reaching the shelf (Scotese 1991). The Albemarle Embayment also would have been somewhat protected from swell and storm waves by the bordering Norfolk and Cape Fear arches, and the offshore Hatteras buildup noted by (Coffey and Read 2002).

The ancestral Gulf Stream current began its circulation across the Blake Plateau during the Late Paleocene and the Early Eocene, migrating onto the shelf during highstands of sea level, in depths as shallow as 200 m (Pinet and Popenoe 1985, Popenoe et al. 1987) and perhaps even shallower over the arches. Gulf Stream erosion produced gullies, pits, and "scour bands" in Paleogene strata across the Blake Plateau seaward of the study area (Pinet and Popenoe 1985; Popenoe et al. 1987), and possibly hardground surfaces in outer neritic facies in the study area. The southwestern coast of Australia experiences similar effects from the warm Leeuwin Current (James et al. 1994; James et al. 1999). The influence of the Gulf Stream is reflected within the study area where hardgrounds are present in outer neritic facies (Figs. 9, 10), and where ripped-up, reworked limestone clasts lie within middle to outer neritic facies (Fig. 8).

Paleocene Supersequence 1 Controls: Upper Cretaceous sediments probably were exposed on the arch as latest Cretaceous glaciation (Barrera et al. 1987) lowered sea level. Supersequence 1 deposition was initiated when relative sea level rose over 100 m to flood the shelf (Haq et al. 1988; Frakes et al. 1994). This allowed deposition of Lower Paleocene deeper water facies in the downdip portion of the study area, under wet-temperate to subtropical climate (Nystrom et al. 1991) that promoted deposition of fine siliciclastics, grading seaward into carbonates.

Possible differential uplift of the Onslow Block along with the smaller Late Paleocene sea level rise (Haq et al. 1988) prevented accumulation (or preservation) of a subsequent Late Paleocene succession in the study area, and may have allowed erosion of any earlier deposited, updip shallow water Lower Paleocene units from the region. The area appears to have remained above sea level throughout the Early Eocene during which the Supersequence 2 accumulated in the basin downdip from the study area (Coffey 2000), and which was a time of global cooling that continued into the Middle Eocene (McGowran et al. 1997).

Eocene Supersequence 3 Controls: Widespread deposition of bryozoan carbonates of Supersequence 3 was initiated by major sea level rise in the Middle Eocene, during NP 14 and 15 time, aided by subsidence of the Onslow and Albemarle Blocks that shifted the updip depositional limit 175 to 200 kms updip of the earlier depositional edge (Harris and Laws 1997). At least 5 sea level cycles in the Middle to Late Eocene generated the sequences under warm, marginally subtropical conditions (Harris et al. 1993; Coffey 2000). Low subsidence rates over the arch and corresponding low accommodation generated thin sequences with basal phosphate lags; these sequences double or triple in thickness into the more rapidly subsiding basin. Regional sand influx at the base of sequence 3a may be due to late Middle Eocene cooling, aridification, and relatively prolonged sea level fall (Miller et al. 1987). Flooding possibly associated with late Middle Eocene warming (McGowran et al., 1997) was followed by a latest Middle Eocene sea level fall of 20 m (Miller et al. 1998) to 100 m (Haq et al. 1988), and deposition of the basal sequence 3b sand. Upper Eocene sea level rises reached substantially lower positions than earlier (Harris et al. 1997), although this is not reflected in the sequences, which locally accumulated deeper water muddy carbonates in more rapidly subsiding areas both on the arch and in the basin.

Oligocene Supersequences 4 and 5 Controls: The basal boundary of Supersequence 4 formed during major global cooling in the Late Eocene, culminating in onset of Oligocene icehouse and sea level lowstand (Miller et al. 1997; Coffey and Read in press). The cooler climate, increased aridity, and overall lower Oligocene sea levels promoted siliciclastic deposition in the area. Sea level lowstand was followed by at least 50 m (Miller et al. 1998), and up to 100 m sea level rise (Haq et al. 1988) that drowned the shelf, depositing widespread basal Oligocene marls. Accommodation during drowning was aided by space created by continued subsidence during prior emergence, coupled with subsequent water loading. Oligocene sequence 1 appears to have filled in much of the accommodation on the arch with fine foram sands. The remaining accommodation in the basin was filled by 3 or more Early Oligocene sequences that finally shallowed up into shell beds associated with sea level changes in excess of 50 m (Kominz and Pekar 2001). These sequences did not extend onto the arch, according to the $Sr^{87/86}$ age constraints (Harris et al. 2000).

Middle Oligocene global cooling and sea level fall is marked by a regional hiatus on the arch between Lower Oligocene (Rupelian) and Upper Oligocene (Chattian) units, around 28.5 m.y. (Berggren et al. 1995). The subsequent sea level rises of 50 m or so (Kominz and Pekar 2001) flooded the shelf, leaving little accommodation remaining over the arch where a single Upper Oligocene sequence dominated by molluscan limestones was deposited. Downdip however, greater subsidence allowed 3 or more shallow water shell-bed dominated sequences to accumulate, possibly in response to late Oligocene glacio-eustasy (Kominz and Pekar 2001). Although these Late Oligocene sea level changes may have been 50 to 60 m (Kominz and Pekar 2001), the shelf probably was never flooded to more than a few tens of meters, evidenced by the development of only inner neritic sand and molluscan limestones, and the lack of deeper water facies.

Systems Tract Development of Sequences

Sequence Boundaries and Hardgrounds: In the study area, two-thirds of sequences have recognizable sequence boundaries, and of these, almost half are hardgrounds (Fig. 12A). The coincidence of sequence boundary and hardground is related to the wave swept character of the shelf during low sea level (Fig. 13). During the fall of relative sea level, unfilled accommodation from the previous highstand kept the inner shelf within the zone of abrasion in a few tens of meters water depth (Fig. 13). Continuous wave sweeping and low sedimentation rates generated the sequence boundary and hardgrounds (Collins 1988; Tucker and Wright 1990, p. 329; Boreen et al. 1993; Riggs et al. 1998). As waves abraded the shelf, the sediment stayed at the sediment-water interface with little new sediment deposited, and constant wave current agitation provided a continuous source of $CaCO_3$ that promoted rapid cementation (Tucker and Wright 1990, p. 325). This formed the indurated, bored and abraded hardgrounds in core sections. Their phosphatic and glauconitic composition reflects the low sedimentation rates associated with hardground formation (McRae 1972; Moran 1989).

There is little evidence for exposure of the shelf during Paleogene sequence boundary development in the study area, except for the Cretaceous-Tertiary contact, below which there is a negative shift in C and O isotope values in the heavily cemented molluscan limestone (Baum and Vail 1988); others have suggested that Middle Eocene hardground formation required exposure (Moran 1989), but this is difficult to prove given the relative scarcity of undoubted subaerial fabrics beneath sequence boundaries.

In the Middle Eocene updip sections, most sequences have identifiable sequence boundaries, and most of these are also hardgrounds (Fig. 12B). By comparison, just over half of downdip sequences have sequence boundaries and only a few of these are hardgrounds (Fig. 12C). The higher number of recognized sequence boundaries and coincident hardgrounds in updip sections indicates that the further landward sections experienced intense wave sweeping during lowstand or transgression, preventing

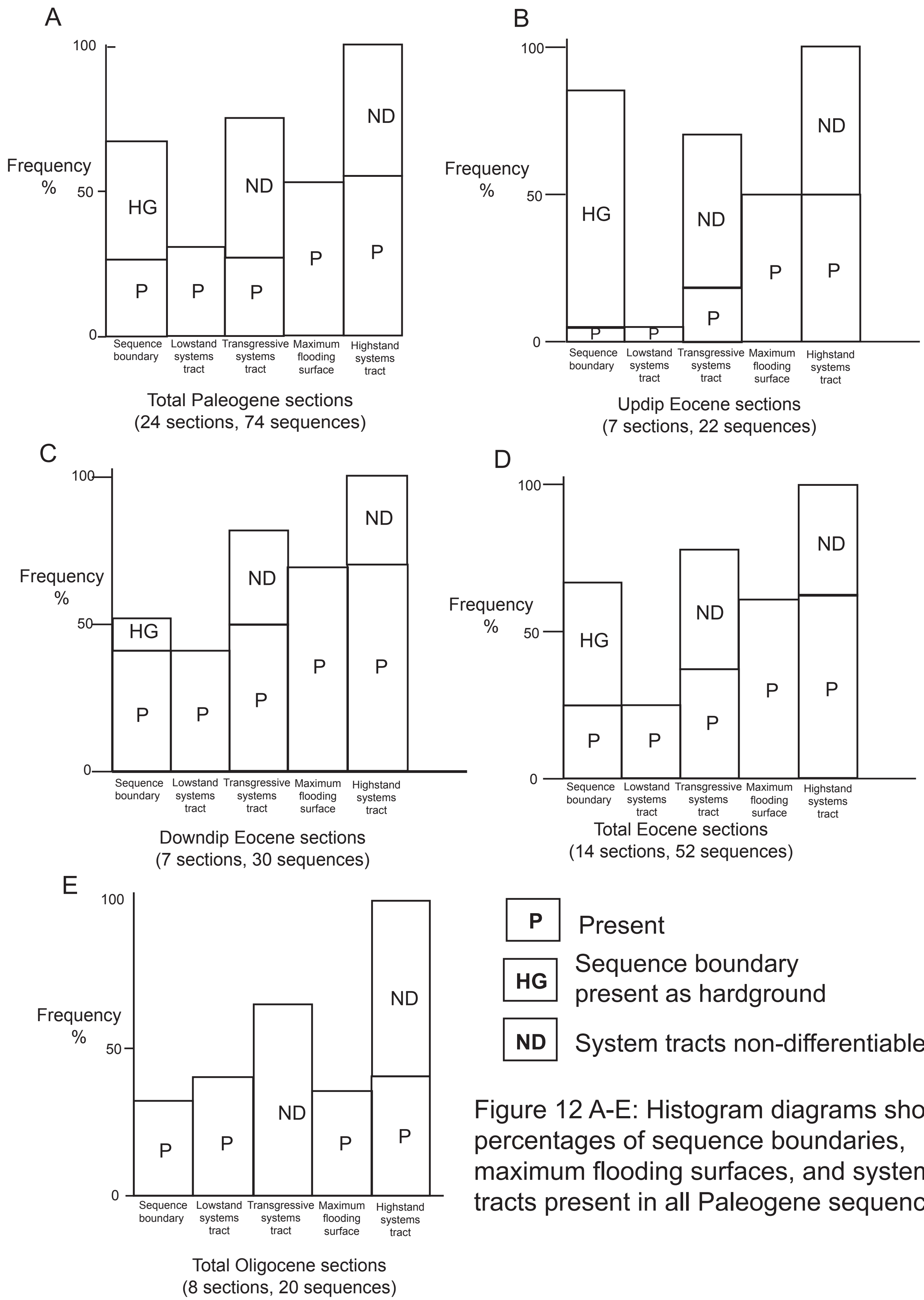


Figure 12 A-E: Histogram diagrams showing percentages of sequence boundaries, maximum flooding surfaces, and systems tracts present in all Paleogene sequences.

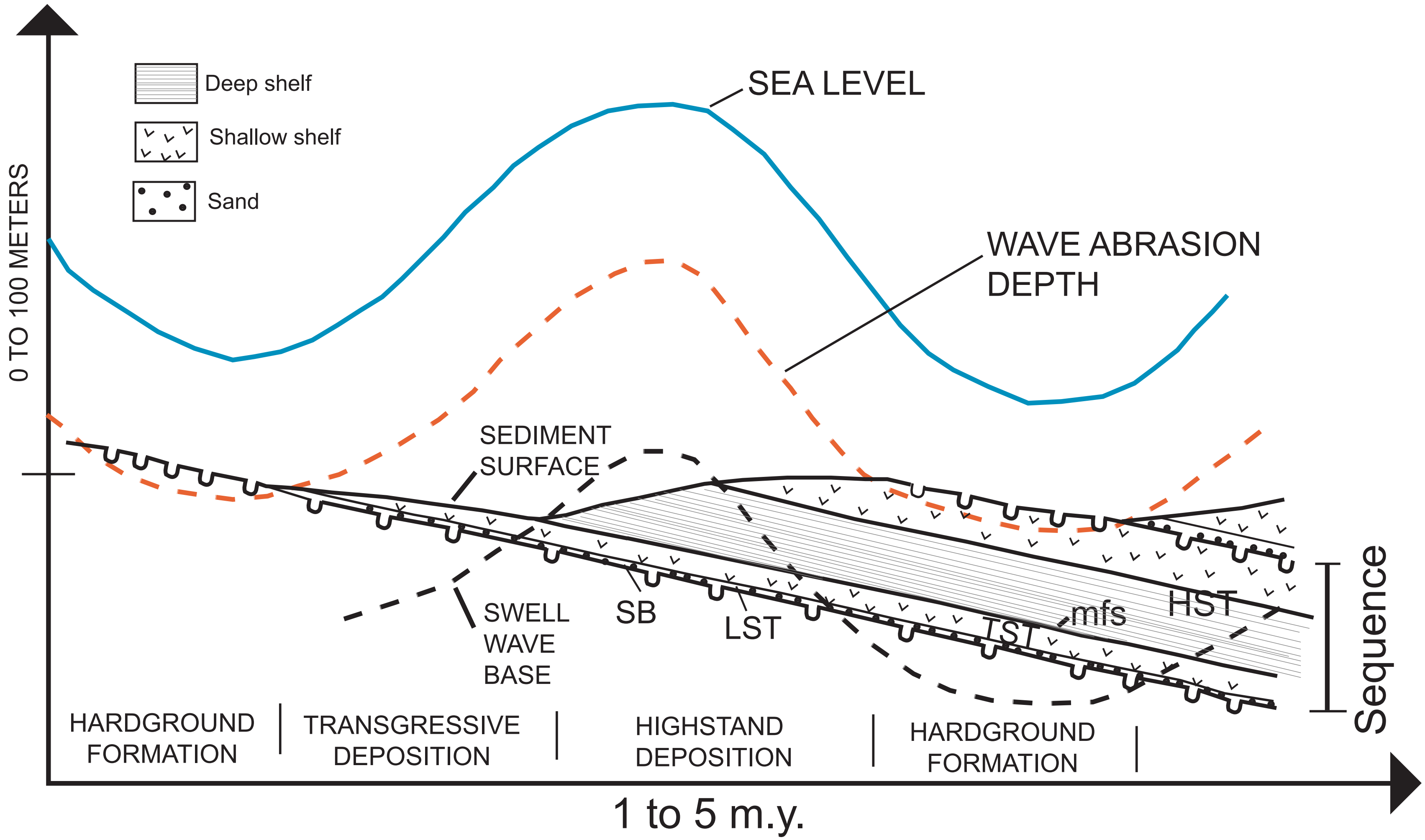


Figure 13: Schematic diagram showing systems tract development on a swell wave dominated shelf during a sea level cycle and uniform subsidence. During low sea level, the sediment surface is in the zone of wave sweeping which causes hardground formation at the sequence boundary. There is little accommodation space for sandy lowstand units to form. During sea level rise thin, open shelf transgressive units may be deposited under low sedimentation rates. After maximum flooding, accommodation favors deposition of a highstand upward shallowing succession. Sea level fall causes the shelf to re-enter the zone of wave sweeping, preventing sediments building to sea level.

deposition of significant transgressive deposits. However, the lower number of coincident sequence boundaries and hardgrounds in downdip sections also may have been underestimated due to poor resolution of well cuttings data, as hardgrounds were best recognized in quarry or core sections.

Although sequences are difficult to trace in the Oligocene, two-thirds have recognizable sequence boundaries, and about one-third are also hardgrounds, the remainder underlie quartz sands (Fig. 12E). As in the Middle Eocene, the number of sequence boundaries developed as hardgrounds in the Oligocene may have been underestimated in sections with only well cuttings data.

<u>Lowstand Systems Tract:</u> Lowstand wedges are only developed at the supersequence scale in the Paleogene of North Carolina. They are evident in offshore seismic sections at the base of the Lower Paleocene, Lower Eocene, Early Oligocene, and Upper Oligocene sections (Coffey 2002). These wedges lie offshore from the study area, and onlap the inner shelf margin updip and downlap onto the inner shelf slope and deep shelf downdip (Coffey 2002). In the present study area, recognizable lowstand deposits are shelf margin wedges located on the downdip part of the inner shelf. These lowstand shelf margin wedges are developed in one-third of Paleogene sequences, suggesting that sediment was rarely deposited or preserved on the hardground-dominated surfaces within the zone of wave sweeping during lowered sea level (Fig. 13).

In the Paleocene study area, the only evidence of lowstand deposits is a thin sandy zone in one well (section 12, Fig. 7). In the Middle Eocene, updip sections had lowstand deposits in only one sequence of a single section (Fig. 8), but downdip sections had lowstand sands in two-fifths of sequences. Similarly, Oligocene sequences also have thin lowstand sands in at least two-fifths of sequences, but the data is poor.

The thin sands suggest that during lowered sea levels, local thin veneers and sand waves formed on the sediment starved, swell-wave swept shelf, similar to modern Australian "shaved shelves" where there is negligible net accumulation of quartz sands on the inner shelf (James et al. 1994; James et al. 2001). Some of these thin sand units that had become calcite-cemented (either in the intertidal zone or on the shallow shelf) were reworked during transgression into sandstone lithoclast lags (section 4, Fig. 6; section 17, Fig. 7). If these sands are the distal edge of shoreface sands, then transgression may have stranded them on the shelf, shutting off sediment supply, allowing them to cement, and then be bioeroded and physically reworked by swell waves.

Transgressive Systems Tract: Transgressive systems tracts are recognizable in only about one-third of the Paleogene sequences; they may be present but undifferentiated from highstand systems tract in about half of sequences lacking a distinct maximum flooding surface (Fig. 12A).

The Paleocene transgressive systems tract in the study area is a locally developed deepening-up succession of nearshore shelly limestones to offshore marine glauconitic sandstones, with the maximum flooding surface at the base of burrowed, deeper water shales (Fig. 6, Fig. 8). This succession reflects increasing accommodation relative to sedimentation rates.

In the Middle Eocene sections, the transgressive systems tract is absent from four-fifths of updip sections and half of downdip sections. The transgressive systems tract is recognized in only one-fifth of sequences updip (Fig. 12D) where it is either a thin veneer of more offshore facies on the underlying sequence boundary of lowstand tract (sections 6, 7, Fig. 6), or a phosphatic pebble lag (sections 5, 8, 9 Fig. 6). The poor development or lack of a transgressive systems tract was probably due to wave/current sweeping preventing deposition of sediments during transgression (Fig. 13), as well as the carbonate factory backstepping. In some cases, earlier deposited sediments were reworked by wave and boundary current winnowing, to form a phosphatic gravel lag condensed zone.

Half of the downdip Eocene sections appear to have a recognizable transgressive systems tract. This reflects greater accommodation downdip associated with the higher subsidence, so that with eustatic rise, a transgressive unit was able to accumulate as wave-sweeping progressively decreased with deepening. Some transgressive tracts in downdip sections are an upwards-shallowing parasequence capped by the maximum flooding surface although these are not able to be traced regionally, due to the quality of the well data (sections 12, 13, 17 Fig. 7). Such transgressive tract parasequences may be aborted maximum floods caused by 4th order sea level fluctuations superimposed on the 3rd order sea cycle, or they may be due to local high sedimentation rates exceeding accommodation. Where the sequences are dominated by a single shallow water lithology and lack a deeper water unit and associated maximum flooding surface, the transgressive and highstand system tracts cannot be separated, as in about half of updip Middle Eocene sections and one-third of downdip sections (Fig. 12B, 12C.)

Maximum Flooding Surface: A maximum flooding surface is recognized in about half of Paleogene sequences (Fig. 12A), where its presence makes differentiation between transgressive and highstand units possible. The maximum flooding surface of Supersequence 1 is in the Lower Paleocene of the study area, with the Upper Paleocene missing at least from the arch. This greater flooding in the Lower Paleocene compared to the Upper Paleocene is compatible with the Haq et al. (1988) chart. However, the regional distribution of the Paleocene throughout the basin suggests syndepositional differential uplift of the Onslow Block and subsidence of the Albemarle Block which caused the Upper Paleocene to onlap farther than the Lower Paleocene units (Harris and Laws 1997; Coffey and Read in press).

The maximum flooding surface of the Middle to Late Eocene (?) Supersequence 3 appears to be in sequence 1 (NP 15 age; Harris and Laws 1986; Zullo and Harris 1987) beneath locally preserved marls updip (section 10, Fig. 6), and regional deeper water fine skeletal wackestone-packstones in the basin (Fig. 7). This is compatible with the regional subsurface data of Coffey (2000) who showed downlap onto a maximum flooding surface in roughly this stratigraphic position adjacent to the Hatteras buildup.

In the third-order sequences, the maximum flooding surface is present in half of updip Middle Eocene sequences, and in two-thirds of downdip sequences (Fig. 12B, 12C). The coincidence of the maximum flooding surface with a hardground at the sequence boundary (sections 4 to 6, 9, Fig. 6), or with phosphatic pebble lags reflect wave swept conditions during lowstand and transgression that inhibited sediment deposition. Limited core data downdip suggests that some maximum flooding surfaces on transgressive units are hardgrounds (Figs. 7, 9, 10), and mark a period of non-deposition prior to highstand aggradation. Scour may have been caused by Gulf Stream currents which migrated onto the shelf during high sea levels (Popenoe et al. 1987).

Maximum flooding surfaces for Oligocene Supersequence 4 at the base of the regional Trent Marl (Fig. 11) formed following 50 to 100 m of sea level rise (Kominz et al. 1998; Haq et al. 1988). This resulted in regional drowning of the shelf (Coffey and Read in press). Third-order maximum flooding surfaces were difficult to define for Oligocene units.

<u>Highstand Systems Tract:</u> In the Paleogene of the study area, highstand systems tracts are recognized in about half of the sequences and they comprise the bulk of the sequences (Fig. 12A).

For the locally developed Paleocene on the arch, the highstand unit does not shallow up out of the deep-water facies of the maximum flooding unit (sections 1-4), suggesting that deposition of Paleocene shallow water facies during the late highstand may have been inhibited by wave-sweeping or removed by subsequent erosion, as indicated by incision on the Paleocene downdip (Fig. 6). Coffey (2000) shows that further basinward, the thick Paleocene supersequence highstand is a complex upward shallowing succession, reflecting increased accommodation downdip.

In the study area, most Eocene sequences show well developed highstands that make up much of the sequences. Many consist of an upward shallowing succession from deeper water muddy carbonates up into more shallow, grainy facies. This reflects some shallowing due to aggradation (typically less than 15 m), but with considerable shallowing due to sea level fall, with deposition continuing up to the depth of vigorous wave sweeping (a few tens of meters). In more downdip or more rapidly subsiding areas, shallowing reached depths for deposition of bryozoan limestone, mixed skeletal limestone, and mollusk facies in more updip areas. A few highstand units that lack deeper water facies are dominated by a single shallow water facies, which filled the small amount of available accommodation. There is little evidence for regional parasequence development, the highstand parasequences being only mappable locally. This may be due to low accommodation or to higher frequency sea level oscillations either being absent or of low amplitude such that they were too small to affect the surface of the shelf, lying at depths of tens of meters.

CONCLUSIONS:

The Paleogene of southern North Carolina was selected for the study of sequence development of open shelf carbonates in a low accommodation, swell-wave setting using cores that were then tied into previously studied quarries, and exploratory wells.

Tectonics of the study area played an important role in the development of sequences by maintaining a positive arch to the south (Cape Fear Arch) and a slowly subsiding basinal block to the north (Albemarle Block). This influenced relative sea level changes and accommodation space on the shelf. The Cape Fear Arch also interacted with the Gulf Stream, resulting in phosphatic erosional lags on some sequence boundaries.

In the study area, Paleocene sequences were dominated by thin, sandy molluscan facies, glauconitic sands, and offshore silt-shales and marls. Middle Eocene sequences were characterized by molluscan limestone, bryozoan-echinoid grainstone-packstone, and deep water fine skeletal wackestone-packstone and marl. Middle Eocene sequences generally were better developed downdip than along the updip Cape Fear Arch. Early Oligocene sequences are dominated by localized sand units, deep-water foram sands and marls. Late Oligocene sequences are typically molluscan limestones with local sandy units.

Rather than subaerial surfaces, most sequence boundaries in the Paleogene study area are marine hardgrounds that formed as sediment-starved wave abrasion surfaces during lowered sea levels. Lowstand sands were thin and patchily developed on the shelf. Transgressive units are also commonly thin and variably developed, and may even be condensed into phosphate lags, due to sediment-starvation, wave sweeping, sediment bypassing, and backstepping of sediment sources. Rare transgressive units are a single upward shallowing parasequence. Highstand units make up the bulk of sequences and consist of a single shallowing-up unit that generally lacks parasequences. Sea level rise and flooding of the shelf formed relatively regional, deeper water carbonates above the maximum flooding surface in areas of regional subsidence. However on the arch, these deeper water units commonly are discontinuous and confined to local areas (grabens?) with higher subsidence. The highstand shallowed up to inner shelf facies, but there is little evidence that these were ever prograded by coastal shoreface units that filled the accommodation, due to low sedimentation rates on the shelf, wave sweeping, and sediment bypassing.

Sequence development in the study area is distinctive, with its hardground-sequence boundaries, limited lowstand and transgressive systems tract development, and dominance of highstands with unfilled accommodation. This contrasts markedly with tropical shelves with their multiple parasequences, inboard peritidal cycles, and well developed subaerial sequence boundaries.

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APPENDIX A: CORE AND WELL SECTION LOCATIONS

County	NCGS Well code	Well name	Lat.	Long.
Beaufort	BF-C-1-68	Beaufort Core #17	35˚ 22' 30''	76˚ 58' 30''
	BF-C-4-68	TGS Test #16	35˚ 21' 28.8''	76˚ 55' 29.9''
	BF-T-1-68	TSG Test #18	35˚ 22' 30''	77˚ 4' 44.4''
New Hanover	N/A	Kure Beach #4	(approx.) 34˚ 00' 00''	77˚ 50' 00''
Onslow	ON-OT-3-67	Evans 1 #12	34˚ 41' 31.2''	77˚ 30' 28.8''
	ON-OT-4-66	Justice 1 #14a	34˚ 32' 59.9''	77˚ 22' 30''
	ON-C-1-94	Onslow Core #13	34˚ 41' 45.6''	77˚ 27' 54''
	N/A	BOW-1 # 14	34˚ 42' 00''	77˚ 26' 00''
	N/A	CB-1 #14b	34˚ 35' 40''	77˚ 18' 00''
Pender	PE-OT-3-66	Batts 2 #11	34˚ 13' 15.6''	77˚ 49' 30''
Offshore	N/A	BS 92-21 #1	33˚ 28' 48''	78˚ 2' 24''
	N/A	BS 95-05 #2	33˚ 29' 24''	78˚ 1' 48''
	N/A	BS 92-12 #3	33˚ 30' 0''	78˚ 1' 12''

APPENDIX B: LOCATIONS OF QUARRIES

Craven County

Martin-Marietta New Bern Quarry: 1km east of the intersection of SR 55W and Route 1402 in New Bern, NC (now flooded)

Duplin County:

Fussell Quarry: 1.1km west of the intersection of US 117 and SR 1148, on the south side of SR 1148

Natural Well: East side of NC State Road 1003 in the Rose Hill 15-minute quadrangle.

New Hanover County:

Martin-Marietta Ideal Quarry: 3.2km east of the intersection of US 117 and SR 1002, on the north side of SR 1002

Onslow County:

Martin-Marietta Belgrade Quarry: East of the White Oak River, east of US 17 at

Belgrade, NC

Pender County:

Martin-Marietta Rocky Point Quarry: 2km southeast of Rocky Point, NC on the east side of Interstate 40.

East Coast Limestone Quarry: 4km northwest of Maple Hill, NC on the north side of SR 53 (now flooded)

BF-C-1-68	Footage	Facies	Rock Description	Color	Sed Structures
BF 6A	82.5'	Sandy moll frag g/p	Leached frag mollusk w/qtz pkst	gray	geopetal
BF 16A	86'	Mixed skeletal frag g/p	Muddy leached frag bry-mollusk with variable qtz pkst	brown-gray	geopetal
BF 24A	101.5'	Mixed skeletal frag g/p	Fine muddy bry-ech-moll skel frag pkst w/microspar matrix	gray	-
BF 28A	104'	Sandy moll frag g/p	Leached frag mollusk and bry pkst	gray	-
BF 31A	113'	Sandy moll frag g/p	Leached whole and frag mollusk skel frag w/minor qtz pkst	gray	-
BF 11B	123'	Hardground	Mdst unerlain by glauc hardground underlain by skel frag wkst	gray-tan	hardground
BF 15B	132'	Hardground	Leached moll/bry frag pkst underlain by hardground, underlain by f-m qtz w/minor skel frag sst	gray/white	hardground
BF 22B	135'	Sandy whole mollusk r/g/p	Qtz leached whole mollusk grst/sst	white-gray	-
BF 16C	148'	Sandy whole mollusk r/g/p	Leached whole mollusk f-m qtz sst/pkst	white-gray	-
BF 24C	158.5'	Sandy moll frag g/p	Leached frag mollusk and bry skel frag w/vf-vc qtz sst/pkst (shell grit?)	gray	-
BF 1D	167.5'	Sandy moll frag g/p	Leached mollusk frag wf-m qtz pkst	gray-d. gray	geopetal
BF 5D	176.5'	Bry-ech g/p	Muddy foram-ech-moll frag w/minor qtz pkst	gray-d. gray	-
BF 14D	187'	Mixed skeletal frag g/p	Muddy vf-c qtz moll-bry skel frag pkst w/ carb silt matrix	gray-brown	-
BF 17D	189'	Mixed skeletal frag g/p	Leached mollusk-bry skel frag w/qtz pkst	gray-brown	-
BF 23D	198'	Mixed skeletal frag g/p	Leached mollusk-bry skel frag pkst	gray-brown	-
BF 4E	201'	Mixed skeletal frag g/p	Leached mollusk-bry skel frag pkst w/minor qtz	gray-brown	-
BF 9E	203'	Mixed skeletal frag g/p	Muddy foram-moll-bry skel wkst/pkst	muddy gray	-
BF 19E	207.5'	Fine skel frag p/w/m	Muddy fine skel frag wkst/pkst	muddy gray	-
BF 28E	232'	Fine skel frag p/w/m	Skel frag w/minor qtz pkst	brown/gray/green	-

APPENDIX C: Beaufort County Core thin section analysis.

Carbonate grain size	Silic grain size/%	Carbonate grain shape	Siliciclastic grain shape	Well/poorly washed	Mollusk	Gastropod	Oyster	Pectin	Byozoan
vc skel frags 45%	f-m 5-7%	round	subangular	well	A	C	-	C	R
f-vc skel frag 45-50%	f-c 5%	round	subangular	poor	A	-	-	C	C
vf-vc skel frag 40%	f 1-2%	subround-subangular	subangular	poor	C	-	-	C	C-A
vf-vc skel frag 50%	f-c 5%	subround	subround	well	A	C-R	-	C	R-C
c-vc skel frag 50%	m-vc 5-7%	round	subround-round	well	A	R	-	-	C
vf 50%/f-c 1%skel frag	vf/f-m 7-10%	subround/subround	angular/subround	poor/poor	-/R	-/-	-/-	-/R	-/C
c-vc 45%/f-m 10% skel frag	f-m 1%/f 45%	round/round	subround/subangular	poor/well	A/R	-/-	-/-	-/R	C-A/-
f-vc skel frag 35%	f-m 25%	round	subangular	poor	A-C	-	-	C	R
m-vc skel frag 50%	f-m 15-20%	subround	subangular	well to poor	A-C	-	-	C	R
f-vc skel frag 35-40%	vf-vc 10%	round	subangular	well	A	A	-	A	R
m-vc skel frag 35%	f-m 20-25%	round	subangular	well to poor	A	C	-	A	R
vf-c skel frag 35-40%	vf-m 1-2%	subround	subround	poor	R	-	-	R	C
f-vc skel, fine microspar 30%	vf-c 15%	subround	angular-subangular	poor	C	-	-	C	C-R
f-vc skel frag 25-30%	vf-c 15-20%	subround	angular	poor	A	-	R	R	C-R
f-vc skel frag 40%	vf-c 25%	subround	subround	well	A	-	-	-	C
vf-vc skel frag 40-45%	vf-vc 10-15%	subround	subangular	well	A	-	-	-	C
f-c skel frag 25%	vf-m 5-7%	subround	subangular	poor	C	-	-	-	C-A
f-vc skel frag 35-40%	vf-m 5-7%	subround-round	subround	poor	C-R	-	-	C-R	C-A
f-vc skel frag 40%	vf-vc 5%	subround-round	subround	poor	R?	-	-	R	R

APPENDIX C: Beaufort County Core thin section analysis.

Echinoderms	**Forams**	**Brachiopods**	**Coral**	**Sponge**	**Crustaceans**	**Ostracod**	**Barnacle**
-	A	-	-	-	-	R	R
C	C	R	-	-	R	R	A-C
C	C	R	-	-	-	-	-
R	C	R	-	-	-	-	-
-	C	R	-	-	-	-	-
-/C-R	-/C	-/R	-/-	-/-	-/-	-/-	-/-
R/R	C/R	-/-	-/-	-/-	R/-	-/-	-/-
-	C	-	-	-	-	-	-
-	C-R	-	-	-	-	-	-
R	-	-	-	-	-	-	-
-	C	R	-	-	R	C	-
A	A	A	-	-	C	C	-
C	C	A	-	-	R	R	-
C	C	A	-	-	-	-	-
C	C	C-R	-	-	R	-	-
C-A	C-R	A	-	-	R	-	-
R--	A	C-R	-	-	C	R	-
A	C-A	C	-	-	R	-	C-R
C-R	A	R	-	-	C	-	-

APPENDIX C: Beaufort County Core thin section analysis

Indet. skel grains	Lime clasts	Matrix	Glauconite%	Phosphate %	Quartz	Other grains
C-A	-	Lime mud dominant	R f 1%	R f 1%	f-m 5-7%	crystal silt
C-R	-	Lime mud dominant	R f-m 1-2%	R f 1%	f-c 5%	detrital skel frags
A	-	Lime mud dominant	R f-m 2%	R vf-f 1%	f 1-2%	A vf microspar
A	-	Lime mud dominant	R f-m 5-7%	R vf-f 1-2%	f-c 5%	-
C-A rounded	-	Lime mud dominant	R f-m 3-5%	R vf-f 2%	m-vc 5-7%	-
C-A/C-A	-/-	Terrigenous silt/clay dominant	R/f-m 1-2%	R/f 1-2%	vf/f-m 7-10%	-/intraclasts
R/C	-/-	Lime mud/Terrigenous silt clay dominant	R f-m 1%/-	R f 1%/f 1%	no detrital/1%	-/-
C	-	Lime mud dominant	R, f, <1%	R vf-f 1-2%	vf <1%	detrital skel frags
C-A	-	Lime mud dominant	R vf-f 1%	R vf-f 1%	vf 2%	detrital skel frags
C-A	-	Lime mud dominant	R vf <1%	R vf-f <1%	vf <1%	crystal silt
C-A	-	Lime mud dominant	R vf-f <1%	R vf-f 1%	<1%	crystal silt
C-A	-	Lime mud dominant	R f 1-2%	R vf 1-2%	vf-m 1-2%	-
C-A	-	Lime mud dominant	R f 3%	R vf 1-2%	vf-c 1%	-
C	-	Lime mud dominant	R vf-f 1%	R vf-f 1%	vf-c 1%	-
C	C-R	Lime mud dominant	R vf-f 1%	R vf <1%	vf-c 1%	detrital skel frags
C	C	Lime mud dominant	R vf-f 1%	R vf-f 1-2%	vf-vc 10-15%	-
C	A	Lime mud dominant	R vf-f 1%	R vf-f 1%	vf-m 5-7%	-
C	-	Mixed	R f-m 3%	R f-m 3%	vf-m 5-7%	-
C-A	-	Mixed	R f-vc 5-7%	R f-m 1%	vf-vc 5%	-

APPENDIX C: Beaufort County Core thin section analysis

Phosphate impreg.	Glauconite impreg	Calcite cements	Dolomitization	Porosity Type
R	C	C fine equant	-	MO 50%
C	R	A pink fine bladed, rim, fine equant R blue and purple fine equant	-	MO, IP 20-25%
-	R	Microspar, C-A pink fine and coarse equant, purple fine and coarse equant	-	IP, BP 3-4%
R	C-A	A pink rim, bladed, fine equant	-	MO 40%
C-A	C-A	A pink rim, fine equant	-	MO, IP 25-30%
-/C	-/C	-/C pink fine equant	-/-	-/minor BP
-/-	-/-	R-C pink rim/-	-/-	MO 30%/BP 20%
-	-	C pink vf equant	tiny rhombs?	MO, BP 30-35%
-	-	C-A pink fine equant	-	MO 30%
-	R in molds	C pink vf equant, coarse equant	tiny rhombs	MO IP BP 35%
-	-	C pink f equant, R pink coarse equant	-	MO 35-40%
-	C	C pink c equant, bladed, rim, C purple f and c equant, bladed, R blue c equant, rim	-	BP 10%
in glauc	R-C	C pink f equant, R purple-blue equant	-	MO BP 20-25%
-	C-R	A pink f equant, R pink bladed	-	MO BP 30%
C	C-R	A pink bladed, rim, f and c equant, R purple and blue	-	MO IP BP 35%
C	C	A pink rim, bladed, fine equant	-	MO 45%
C	C-A	A pink f equant, R pink c equant	-	MO BP 15-20%
C	C-A	C-A pink f equant, bladed, c equant	-	BP IP 20-25%
R	C-A	C pink c bladed rim, R purple	-	BP IP 40-45%

APPENDIX C: Beaufort County Core thin section analysis

Kure Beach	Footage	Facies	Rock Name KB	Color
KB 2	48'	Fine skel frag p/w	Brach-ech frag f-m qtz skel frag pkst	gray
KB 3	51.5'	Skel frag qtz sand	F-vf skel frag qzt sst	gray
KB 4	57.2'	Fine foram sand	Vf-f skel frag qtz sst w/marl matrix	gray-tan
KB 5	62'	Fine foram sand	Vf-m skel frag vf-f qtz sst w/marl matrix	gray-d. gray
KB 6	67'	Fine foram sand	Vf-f skel frag qtz sst w/marl matrix	gray-d. gray
KB 7	70.9'	Fine foram sand	F skel frag qtz sst w/marl matrix	gray-tan
KB 8	75.1'	Fine foram sand	F skel frag qtz sst w/marl matrix	gray-tan
KB 9	78'	Fine foram sand	F skel frag qtz sst w/marl matrix	gray
KB 10	81.4'	Fine foram sand	Vf-m skel frag vf-f qtz sst w/marl matrix	gray
KB 11	87.1'	Fine foram sand	Vf-m lime muddy skel frag sand	gray
KB 12	90.3'	Marl	Vf-f qtz w/vf-f minor skel frag marl/sand	gray
KB 13	92'	Marl	Vf qtz w/vf-m minor skel frag marl	gray
KB 14	96'	Marl	Vf qtz and minor vf-f skel frag qtz sand	gray
KB 15	99.4'	Marl	Vf qtz w/vf-f skel frag marl	tan
KB 16	100.5'	Marl	Vf qtz w/vf-f skel frag marl	tan-gray
KB 17	104.4'	Phosphatic siltstone	Phosphatic vf-c qtz w/ vf-m skel frag siltstone	tan-gray
KB 18i	104.5'	Hardground	Phosphatic hdgd underlain by bry-ech foram pkst	d gray
KB 18ii	104.5'	Mixed skel frag g/p	Bry-ech-moll-foram skel frag pkst	d-lt gray
KB 19	105'	Bry-ech g/p	Bry-ech--foram skel frag pkst	gray
KB 20	106'	Bry-ech g/p	Bry-ech-foram skel frag pkst	gray
KB 21	107'	Bry-ech g/p	Vf-vc ech-foram-bry skel frag pkst	gray
KB 22	108'	Bry-ech g/p	Bry-foram skel frag pkst	gray
KB 23	110'	Mixed skel frag g/p	Vf-vc bry-ech-moll foram skel frag pkst	brown-gray
KB 24	111.2'	Bry-ech g/p	Skel frag pkst host w/pkst/wkst clasts, variable qtz	tan-gray
KB 24a	114'	Mixed skel frag g/p	Bry-moll skel frag pkst	d gray-tan
KB 25	114.9'	Hardground	Vf-vc skel frag wkst underlain by hrgd, underlain by vf-vc skel frag pkst: (above/below):	gray/gray
KB 26i	115'	Bry-ech g/p	Vc bry skel frag pkst host with bored glauconitic f sst lithoclasts	gray
KB 26ii	115'	Mixed skel frag g/p	Vf-vc bry-moll skel frag pkst w/vf qtz lithoclasts	gray
KB 26iii	115'	Mixed skel frag g/p	Vf-vc bry-moll skel frag pkst	gray
KB 27	115.5'	Bry-ech g/p	Vf-vc bry-ech skel frag pkst w/vf-f qtz glauc coated sst lithoclasts	d gray
KB 28	116.8'	Hardground	Bry skel frag pkst w/qtz underlain by hdgrd underlain by vf-vc foram skel frag pkst w/vf-m qtz, glauc/phos coated	d gray
KB 29	117'	Hardground	Vf-vc skel frag grst w/sst and glauc clasts underlain by hdgd, underlain by vf qtz sst w/minor skel frags	gray/gray
KB 30	117.6'	Qtz sand w/minor skel frag	Vf qtz sst w vf/f minor skel frag (host) w/ vf-vc skel frag grst/pkst in cavities/borings	d. gray
KB 31	118.4'	Fine skel frag p/w	Vf-vc skel frag pkst w/vf-c qtz	gray
KB 32	120.1'	Sandy shale	Vf qtz sandy shale	brown
KB 33	122.4'	Silt-shale	Silty, muddy vf-f qtz sandy shale	brown-black
KB 34	128.2'	Shale	Dolomitic shale w/vf-f qtz	brown
KB 35i	132.5'	Silt-shale	Shale w/vf qtz (dolo?)	brown
KB 36	135'	Silt-shale	Vf qtz shale w/dolo rhombs	brown-black
KB 38	143'	Glauc qtz sand	F glauc/phos sst w/minor mud	brown-cream
KB 39	147.8'	Glauc qtz sand	F glauc/phos sst	lt gray
KB 40	150.6'	Sandy whole moll r/g/p	Leached whole moll muddy pkst w/qtz (dolomitic)	d gray

APPENDIX D: Kure Beach Core thin section analysis, samples 1-40.

Sed Structures	Carbonate grain size	Carbonate grain shape	Silic grain size/%	Siliciclastic grain shape	Well/poorly washed
-	m-vc skel frags 35-40%	subangular	f-m 5-7%	subround	poor
-	f skel frag 10-15%	subangular	vf-f 30-35%	subround	poor
R muddy lenses	vf-f skel frag 20-25%	round	vf-f 45%	subangular-subround	poor
mud lenses	vf-m skel frag 25%	round	vf-f 45%	subangular-subround	poor
uncont. mud layers	vf-m skel frag 25-30%	round	vf-f 30%	subround	poor
muddy layers	f-m skel frag 25-30%	subangular-subround	f 25-30%	subround	poor
uncont. mud layers	f-m skel frag 25-30%	subround	f 30%	subround	poor
uncont. mud layers	vf-f skel frag 25%	subangular-subround	f 30%	round	poor
muddy layers	vf-m skel frag 25%	subround	f 30%	subround	poor
-	vf-m skel frag 30%	subround	vf-f 35%	subround	poor
-	vf-f skel frag 20-25%	subangular-subround	vf 30%	subangular-subround	poor
-	vf-m skel frag 20%	subround	vf 25%	subangular	poor
-	vf-f 15-20%	subround	vf 20-25%	subangular	poor
-	vf-f skel frag 30%	subround	vf 25%	subround	poor
-	vf-f skel frag R 25-30%	subround-round	vf 35%	subangular-angular	poor
-	vf-m 15-20%	subround	vf-c 20-25%	subangular-subround	poor
hardground	vf-vc 40-50%	subangular-subround	vf-f 1%	subangular	poor
-	vf->vc skel frag 35%	varied	vf <1%	subround	poor
variable muddiness	vf->vc skel frag 30-35%	varied	vf-f R < 1%	subangular	poor
-	vf->vc 40-45%	subangular-round	vf-f 1%	angular-subangular	poor
-	vf-vc skel frag 40%	varied	vf-c 1-2%	subround-round	poor
-	vf-vc skel fra 30-40%	angular-round	vf-f <1%	subround	poor
geopetal	vf-vc skel frag 15-20%	angular-round	vf-f <1%	subround	poor
mud layers	vf-vc skel frag/whole 15-25%	angular-round	vf-c 1-3%	subangular	poor (varies)
-	vf-vc skel frag/whole 35%	varied	vf-m 3-4%	subangular-subround	poor
hardground	vf-vc10%/vf-vc 30% skel frag	varied/varied	vf-m 5%/vf 5%	subround/subround	poor/poor
borings in clasts	vf-vc skel frag 20-25%	varied	f-c 10%	angular	variable
-	vf-vc skel frag 25%	varied	m-c 10%	subangular	poor
-	vf-vc skel frag/whole 25%	round	vf-m 1-3%	subround	poor
-	vf-vc skel frag 30%	varied	vf-c 1-3%	subangular	poor
hardground	f-vc 30%/ f-vc 30-35%	angular-round/angular-round	f-m 7%/ f-m 3-5%	subangular/subround	poor/poor
hardground	vf-vc 35%/vf-f 3-5% skel frags	varied	f-m 1%/vf >50%	subround/subang-angular	well
scour cavities	vf-f skel frag 15%	round	vf 35%	subangular	well
-	vf-vc skel frag 30-35%	round	vf-c 15-20%	subangular-subround	poor
-	little-absent	-	vf 45-50%	angular	poor
-	vf <1%	-	vf-f 50%	subangular-subround	poor
-	little-absent	-	vf-f 15%	subround	poor
muddy layers	little-absent	-	vf 30-35%	subangular-round	poor
muddy layers	little-absent	-	vf 25%	subangular	poor
-	little-absent	-	f >50%	subround	well-poor
-	-	-	f >50%	subround	well
-	f-vc 30%	varied	f-c 7-10%	angular-subangular	poor

APPENDIX D: Kure Beach Core thin section analysis, samples 1-40.

Mollusk	Gastropod	Oyster	Pectin	Byozoan	Echinoderms	Forams	Brachiopods	Coral	Sponge	Crustaceans	Ostracod	Barnacle
R	-	-	-	R	C	A	A	-	-	C	-	-
R	-	-	-	R	R	C-A	-	-	-	-	-	-
R	-	-	-	R	R	A	-	-	-	-	-	-
R	-	-	-	R	R	A-C	R	-	-	-	-	-
R	-	-	-	R	R	R	-	-	spicules?	-	-	-
R	-	-	-	R	R	A-C	-	-	-	-	-	-
R-absent	R	-	-	R	R	A	-	-	-	C	C	-
-	-	-	-	R	R	A	-	-	-	C	C	-
R-absent	-	-	-	C-R	R	C-A	?	-	-	R	C	-
R-absent	R	-	-	-	-	C-A	R	-	spicules?	-	-	-
R-absent	-	-	-	R	-	C-A	?	-	spicules?	-	-	-
R-absent	-	-	-	R	R	A-C	?	-	-	-	-	-
-	-	-	-	R-absent	R-absent	A	?	-	-	-	-	-
?	-	-	-	?	?	C	?	?	-	-	-	-
R-absent	-	-	-	R-absent	R-absent	C	R	-	-	-	-	-
R-absent	-	-	-	R-absent	R-absent	C	?	-	-	-	-	-
R	-	-	R	A	C-A	A	C-A	-	-	C-R	C	-
C	C	-	C	A	-	C-A	C-R	-	-	C	C-A	-
R	-	-	-	A	-	A	-	-	-	C	C	R
C-R	R	R	R	A	A	A	-	-	-	C	C	-
R	-	-	R	R	C	A	-	-	-	C-A	C-A	-
R-absent	-	-	-	C-A	C	A	-	-	-	C	C	-
C-R	-	-	-	C	C	A	C	-	-	C	C	-
R	-	R	-	C	C	A	C	-	-	C	C	-
C	C	-	C	C-A	C-R	A	C	-	R	C	-	-
R/R	-	-	-	R/C	-	A/A	-	-	-	R/R	R/R	-/-
R	R	-	-	C-R	-	A	R	-	-	R	-	-
C-R	-	-	-	C	R	A	R	-	-	C-R	C-R	-
C-R	-	-	-	A	C	A	R	-	-	R-C	-	-
-	-	-	-	A	C-R	A	R	-	-	C-R	-	-
R/R	-/-	R/-	-/R	A/C	C/C	A/A	-/R	-	-	R/R-C	-/R-C	-
R/-	-/-	-/-	R/-	C/-	R/-	A/R	R/-	-	-	R/-	-	-
?	-	-	-	?	?	C	?	-	-	-	-	-
-	-	-	-	C	C	C	C-R	-	-	R	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-
C-A	-	R	-	-	-	R	-	-	-	-	-	-

APPENDIX D: Kure Beach Core thin section analysis, samples 1-40.

Indet. skel grains	Lime clasts	Matrix	Glauconite%	Phosphate %	Quartz	Other grains	Micritization
A	-	Dominant lime mud	-	R f <1%	f-m 5-7%	-	C-A
A	-	Mixed	R vf <1%	R vf-f <1%	-	iron hydroxides	C-A
A	-	Mixed	R vf <1%	R vf 3%	-	-	A
A	-	Mixed	-	R vf-f 10%	-	-	C-R
A	-	Dominant terrigenous silt/clay	R vf <1%	R vf-f <1%	-	-	A
A	-	Mixed	R vf-f <1%	-	-	-	A
A	-	Mixed	R vf <1%	R f-m 1%	-	-	C
A	-	Dominant terrigenous silt/clay	-	R vf-f	-	-	C
A	-	Dominant terrigenous silt/clay	R vf <1%	R f <1%	-	-	-
A	-	Dominant terrigenous silt/clay	R f <1%	R vf-f <1%	-	-	C-A
A	-	Dominant terrigenous silt/clay	R vf 1%	R vf-f 3%	-	-	C-A
A	-	Dominant terrigenous silt/clay	R vf <1%	R vf 1-2%	-	-	C-A
A	-	Dominant terrigenous silt/clay	R vf-f 2%	R vf-f 3%	-	-	C-A
A	-	Dominant terrigenous silt/clay	R vf 1%	R vf-f 2-3%	-	-	C
A	-	Dominant terrigenous silt/clay	R vf 1-2% R m	R vf-f 3-5%	-	-	C
A	-	Dominant terrigenous silt/clay	R f-vc 5-7% pebbles	R vf-vc 3-5%	-	-	-
C	-	Dominant lime mud	R vf-f 3-5%	R f 3%	vf-f 1%	framboidal pyrite	C-A
C	-	Dominant lime mud	R vf-f <1%	R vf <1%	vf <1%	chalcedony?	C
C-A	-	Dominant lime mud	R vf-f <1%	R vf-f 1%	vf-f R	hrgd ripup clast	C
C	-	Dominant lime mud	R vf <1%	R vf <1%	vf-f 1%	lime clasts	C
C	c-vc clasts	Dominant lime mud	R vf-c	R vf-c	vf-c 1-2%	phosphatized wkst ripup clasts	C
C	-	Dominant lime mud	R vf-m <1%	R vf-f <1%	vf-f 1%	-	C
C	-	Dominant lime mud	R vf-f <1%	R f 1%	R vf-f <1%	detrital skel frags in molds	C
C-A	C	Dominant lime mud	R f-c	R f-m 1%	vf-c 1-3%	lime intraclasts, phosphate clast	C-A
A	?	Dominant lime mud	R f-m 3%	R vf-f 3-4%	R vf-m	qtz lithoclasts	C-A
C-A/C-A	-	Dominant lime mud	R vf-m 1%/	C-A vf/	vf-m/vf	abundant glauc/phos @ hdgd	-
C-A	-	Dominant lime mud	R f	R vf 3%	f	sst rip up clasts	-
A	C	Dominant lime mud	R f-c 1-2%	R f 1%	vf	sst rip up clasts	C
A	-	Dominant lime mud	R f-m 1-2%	R vf-m 1-5%	vf-m 1-3%	-	A
A	C	Dominant lime mud	R vf-c 1%	R f 1%	vf-c 13%	glauc-coated mud/silt lithoclasts	C
C/C	-	Dominant lime mud	R f 3%/ f-m 2%	R f 1%/vf-f 1%	f-m 7%/f-m 3%	-	A/A
C/C	-	Dominant lime mud	R m-c 1%/	R f 1%/R f 1%	f-m/vf	sst clasts/detrital skel frags	C/C
A	-	Dominant lime mud	R vf<1%	R vf-f <1%	no detrital	skel frag infill	-
C	C	Dominant lime mud	R f-m 3-4%	R vf-m 2-3%	vf-c 15-20%	R vc glauc/phos pebbles	A
-	-	Dominant terrigenous silt/clay	R	C vf-f 7%	no detrital	Micas	-
-	-	Dominant terrigenous silt/clay	R vf-f 1-2%	R vf-f 2%	no detrital	f-spar?	-
-	-	Dominant terrigenous silt/clay	R vf-f 1%	R vf-f 5-7%	no detrital	-	-
-	-	Dominant terrigenous silt/clay	R vf <1%	R vf 5%	no detrital	-	-
-	-	Dominant terrigenous silt/clay	R vf 1-2%	R vf-f 4%	no detrital	micas	-
-	-	Dominant terrigenous silt/clay	R vf-m 3%	R vf-f 4-5%	no detrital	-	-
-	-	Dominant terrigenous silt/clay	R f-vc 5%	R vf-f 5%	no detrital	-	-
R	-	Dominant terrigenous silt/clay	R f 1%	R f 1%	no detrital	-	C

APPENDIX D: Kure Beach Core thin section analysis, samples 1-40

Phosphate impreg.	Glauconite impreg	Calcite cements	Dolomitization	Porosity Type	NOTES
-	-	A pink bladed, rim, f/c equant	-	no estimate	
-	-	C-R pink f equant	floating rhombs	no estimate	
-	-	C-R pink f equant	floating rhombs	<5%	
-	-	R pink rim	floating rhombs	BP IP varies	
-	-	R pink rim	floating rhombs	<5%	
-	-	C pink rim	floating rhombs	BP 15%	
-	-	R pink fine bladed, rim	floating rhombs	BP 5%	
-	-	R pink	floating rhombs	BP IP 20-25%	
-	-	R-C pink fine rim	-	BP 10%	
-	-	C pink rim	rhombs	IP, BP 5%	
-	-	C pink f equant	-	MO BP fracture 1-2%	
-	-	C-R pink rim	-	<1-2%	
-	-	C-R pink f equant	-	BP MO 3%	
-	-	R pink f equant	rhombs	fracture 1%	thin slide, skel frags plucked
C (in glauc)	-	R pink f equant	-	no estimate <1%	
C (in glauc)	minor	R pink fine bladed	rhombs in matrix	no estimate <1%	
C-A	C-A	C-A pink f/c equant, bladed	-	little/none	
C	C-A	C-A pink f/c equant, bladed	-	little/none	
C	A-C	C pink f equant, bladed	-	little/none	
-	minor	R-C pink f/c equant, bladed, rim	-	MO BP localized 10%	
C-A	-	R pink f equant, bladed	-	MO BP IP sol'n enlarged, 10-15%	
R	R	R pink f equant, bladed	-	MO BP 15%	
-	C-R in molds	R f equant f bladed	-	MO IP BP 7-15%	
C (in glauc)	C-R	C pink f/c equant, bladed, rim	-	BP MO 15%	plucking
C (in glauc)	R	C-R pink f/c equant	-	MO IP 15-25% variable	
R/R	R/R	none/A-R pink c equant, bladed	-	<1%/ MO IP 15%	
in glauc	-	R pink f equant in matrix	-	low	
C	C	C-R pink f equant, bladed	-	MO BP ?	plucking
C	C-A	C pink f equant, bladed	-	MO 7-19%	plucking
C	R	R pink f equant, bladed	-	BP 1-3%	
A/A	A/A	R-C pink c equant/R f equant	-	MO IP 15%/ MO BP 5%	
A/C	A/C	A-C pink f/c equant, bladed/none	-	BP 5%/BP 1%	
-	-	R pink f equant	-	v low	skel frags too small to ID
C	C	C pink f/c equant, bladed, rim	-	v low BP <5%	
-	-	-	-	v low/none	
-	-	-	-	v low/none	
-	-	-	rhombs	v low/none	
-	-	-	rhombs 20-30%	fracture, v low 5%	
-	-	-	rhombs 30%	fracture, v low	
-	-	-	vf, r rhombs	BP 15-20%	
R (in glauc)	-	-	-	BP no estimate	
-	-	C pink c equant, pink-purple	rhombs 40%	MO 10-15%	

APPENDIX D: Kure Beach Core thin section analysis, samples 1-40.

Kure Beach	Footage	Facies	Rock Name KB	Color
KB 41i	151.8'	Sandy frag moll g/p	Leached frag moll grst/pkst with variable vf-m qtz	tan-gray
KB 41ii	151.8'	Sandy frag moll g/p	Moll skel frag qtz pkst	gray-tan
KB 42	152'	Hardground	Whole leached moll pkst w/qtz underlain by hrdgd underlain by moll-bry skel frag pkst w/less qtz	tan
KB 43	152.1'	Sandy frag moll g/p	Leached moll qtz pkst	gray
KB 44i	152.8'	Sandy frag moll g/p	Moll-skel frag qtz pkst	gray
KB 44ii	152.8'	Sandy frag moll g/p	Moll skel frag pkst w/minor qtz	gray
KB 45	153.7'	Sandy frag moll g/p	Leached moll-skel frag qtz pkst	gray
KB 46	155'	Sandy frag moll g/p	Leached moll qtz pkst	tan-gray
KB 47	160'	Sandy frag moll g/p	Silty qtz leached moll-bry pkst	tan-gray
KB 48	161.3'	Sandy frag moll g/p	Leached moll skel frag qtz pkst	gray
KB 49	164.8'	Sandy frag moll g/p	Vc leached whole/frag moll skel frag qtz pkst	gray-tan
KB 50	169.8'	Sandy frag moll g/p	Leached moll skel frag f-m qtz pkst	gray
KB 51	174.2'	Sandy whole moll r/g/p	Leached whole moll skel frag qtz grst/pkst	brown-gray

APPENDIX D: Kure Beach Core thin section analysis, samples 41i-51.

Sed Structures	Carbonate grain size	Carbonate grain shape	Silic grain size/%	Siliciclastic grain shape	Well/poorly washed
-	f-vc 30%	varied	vf-m 15%	subround	?
-	c-vc skel frags/whole 30%	subangular	f-m 25%	subangular	well
hardground	c-vc 30%/c-vc 45% skel frag	angular-round/angular-round	f-m 3%/ f-vc 3%	subangular/subround	poor/poor
-	vc skel frags/whole 40%	subangular	m-c 20-25%	round	poor-well
-	m-vc skel frag/whole 30%	varied	f-vc 10%	subround	poor
geopetal	f-vc skel frag/whole 35-40%	varied	f-c 3-5%	subround	poor
-	f-vc skel frag/whole 15-20%	varied	f-vc 7-20%	subround	poor
-	c-vc 20%	varied	f-vc 5%	subangular-subround	well
gradational terrig-neomorphic matrix	f-vc 15-20%	varied	f-c 15%	subround	poor
mud/silt layers	f-vc 15-20%	round	f-c 20%	subround	poor
-	f-vc 7-10%	varied	f-c 15-20%	subround	poor
more mud at top of slide	f-vc 25-30%	round	f-c 5-25%	subangular-subround	variable
-	f-vc 7-10%	varied	f-vc 10-15%	subround	well

APPENDIX D: Kure Beach Core thin section analysis, samples 41i-51

Mollusk	Gastropod	Oyster	Pectin	Byozoan	Echinoderms	Forams	Brachiopods	Coral	Sponge	Crustaceans	Ostracod	Barnacle
A	-	C-R	-	R	C	R	C	-	-	R	R	-
C	-	-	-	-	-	R-C	C-A	-	-	-	-	-
C/A	-	-	-/C	-/C-R	-/C-R	-	-	-	-	R/C	R/-	-
C-R	-	-	R	-	-	-	-	-	-	-	-	-
A	-	A	A	R	R	?	-	-	-	R	-	-
A	-	C	A	-	-	R	-	-	-	R	-	-
C-A	-	A	A	-	-	R	-	-	-	R	-	-
A	-	-	A	-	-	R	-	-	-	-	-	-
A-C	-	-	R-C	R	C-R	R	-	-	-	-	-	-
A	-	-	R	-	R	-	-	-	-	-	-	-
A	-	-	?	-	R	-	-	-	-	-	-	-
A	-	-	R	-	R	-	-	-	-	R	-	-
A	-	-	C	R	C	-	-	-	-	-	-	-

APPENDIX D: Kure Beach Core thin section analysis, samples 41i-51

Indet. skel grains	Lime clasts	Matrix	Glauconite%	Phosphate %	Quartz	Other grains	Micritization
C	-	little mud	R f 1%	R f 1%	no detrital	-	A
R	-	little mud	R vf <1%	R f 1-2%	f-m 25%	-	A
C/R	-	lime mud/terrigenous silt/clay	R m <1%/m <1%	R f <%/f <1%	f-m 3%/f-vc 3%	-	A/C
R	-	little/no mud	R f <1%	R f 1%	m-c 20-25%	-	A
R	-	Dominant lime mud	R f <1%	R f 1-2%	f-vc 10%	pebble- silic mdst clast	C
C	-	Dominant lime mud	R f <1%	R vf-f 3-7%	f-c 3-5%	pebble-silic mdst clast	C
C	-	Dominant lime mud	R vf-f <1%	R vf-f 5-7%	f-vc 7-20%	-	C-A
C-A	-	Dominant lime mud	none	R vf-f 5-7%	f-vc 5%	-	A
A	-	Dominant terrigenous silt/clay	R vf <1%	R f 2-3%	f-c 15%	detrital glauc mud, lithoclast	A
A	-	Dominant lime mud	R f <1%	R vf-f 3-5%	f-c 20%	-	A
A-C	-	Dominant lime mud	R f-c <1%	R vf-f 1-2%	f-c 15-20%	terrig mud pebbles	A
A	-	Dominant lime mud	none	R vf 2%	f-c 5-27%	micas?	A
C-A	-	Dominant lime mud	none	R vf-f 1-2%	f-vc 10-15%	limonite	A

APPENDIX D: Kure Beach Core thin section analysis, samples 41i-51

Phosphate impreg.	Glauconite impreg	Calcite cements	Dolomitization	Porosity Type
R	R	C purple, blue bladed, f/c equant 40%	R rhombs	MO no estimate
R	R	C-A pink, purple, blue bladed, rim, f equant	-	MO BP no estimate
-/R	-	C pink-blue rim/ A pink-purple, blue rim, bladed, f/c equant	-	MO 40%/little-none
R	-	C pink-purple-blue f/c equant, bladed 40%	-	no estimate
C	R-none	C pink-blue bladed, f equant, fibrous	-	MO no estimate
C-A	-	C pink-purple f/c equant, bladed	-	MO BP no estimate
C-A	R-none	C pink-purple f/c equant, bladed	-	MO 15-20%
C-A	-	C pink-blue rim f/c equant, bladed	-	MO 30-40%
C	-	A blue matrix, pink-purple-blue equant, bladed	dolo neomorphosed matrix	MO 40%
C	R-none	A blue matrix, pink-purple-blue equant, bladed	dolo neomorphosed matrix	MO BP 40%
C	-	A blue matrix, pink-purple-blue equant, bladed	dolo neomorphosed matrix	MO 30%
A	R	A blue matrix, pink-purple-blue equant, bladed	dolo neomorphosed matrix	MO 25-30%
A-C	R-C	A blue matrix, pink-purple-blue equant, bladed	dolo neomorphosed matrix	MO 40%

APPENDIX D: Kure Beach Core thin section analysis, samples 41i-51

ON-C-1-94	Footage	Facies	Rock Description	Color	Sed Structures	Carbonate grain size	Silic grain size/%
ON 13A	146'	Skel frag qtz sand	f-vf qtz skel frag muddy (terrig clay) sst	brown-gray	thin mud layers	f skel frag 5%	vf-f 20-25%
ON 21A	147.5'	Skel frag qtz sand	f qtz skel frag muddy sst/siltst	gray-brown	-	f skel frag 15%	f gradational <1-25%
ON 23A	148.5'	Bry-ech g/p	c bry-ech pkst	gray-brown	-	f-vc skel frag/whole 30%	c <10%
ON 26 A	148.7'	Mixed skel frag g/p	Poorly sorted bry-ech-moll pkst	gray	-	vf-c skel frag 30-40%	vf <1%
ON 38A	156'	Mixed skel frag g/p	vf-vc bry-ech-moll foram pkst	gray	-	vf-vc skel frag 40%	vf-f <1%
ON 42A	166'	Mixed skel frag g/p	vf-vc bry-ech-moll foram pkst	gray-tan	-	vf-vc skel frag 40%	vf <1%
ON 25B	176'	Marl	Foram-bry silty mdst	gray-tan	-	vf-vc skel frag 15%	vf 2-5%
ON 28C	191'	Marl	Bry-foram siltst/mdst/marl	brown-gray	-	vf-vc skel frag 20%	vf 1%
ON 21D	203'	Marl	Foram-bry silty lime marl	brown-gray	-	vf-c skel frag 5-7%	vf-f 1%
ON 26D	207'	Mixed skel frag g/p	Bry-ech skel frag pkst-wkst	gray	borings, geopetal	vf-vc skel frag 45%	f-vc 1-3%
ON 30D	211'	Bry-ech g/p	C-VC bry-ech skel frag grst/pkst	d. gray	-	f-vc skel frag 25-30%	f-c 2%
ON 18E	220'	Mixed skel frag g/p	C bry-ech-moll pkst	gray	-	c-vc skel frag 20-25%	vf-m 1%
ON 33E	227.5'	Bry-ech g/p	Bry-crab-ech skel frag muddy pkst	gray	-	vf-vc skel frag 15-20%	f-c 3%
ON 24F	237'	Mixed skel frag g/p	Marine cemented leached moll-bry-ech grst	gray	-	c-vc skel frag 20-25%	f-c 1%
ON 46F	250'	Bry-ech g/p	Bry-ech skel frag pkst-wkst	gray	-	vf-vc skel frag 25-30%	m-c 5%
ON 56F	263'	Bry-ech g/p	Bry-ech skel frag wkst	gray	boring	vc skel frag 7%	f-m 1%
ON 8G	268'	Mixed skel frag g/p	Bry-ech-moll skel frag muddy pkst	gray	-	vf-vc skel frag 15-30%	vf-vc 1-5%
ON 16G	274'	Bry-ech g/p	Intraclastic bry-ech skel frag muddy pkst	gray	-	vf-vc skel frag 40-45%	vf-vc 3%
ON 38H	318'	Bry-foram wkst	Bry-ech skel frag muddy pkst/wkst in patches	gray	-	vf-vc skel frag 25%	f-m 2%
ON 11I	324'	Bry-foram wkst	Vf-vc bry skel frag wkst/pkst	gray	-	f-vc 45%	f-c 1%
ON 27I	330'	Bry-foram W/P	F-vc bry skel frag wkst/pkst	gray	-	f-vc 30-40%	f-m 3-5%

APPENDIX E: Onslow County Core thin section analysis

Carbonate grain shape	Siliciclastic grain shape	Well/poorly washed	Mollusk	Gastropod	Oyster	Pectin	Byozoan	Echinoderms	Forams	Brachiopods	Coral
subangular	subround	poor	-	-	-	-	R-absent	R	R	R	-
subround	subround	poor	-	-	-	-	-	-	R	-	-
subround	subround	poor	-	-	-	-	C-A	C-A	R	C	-
subround	subround-subangular	poor	C	C	-	C	A	A	A-C	R	R
subangular-round	subround-round	poor	C-A	-	-	C-A	C-A	C	A	R	-
subangular-round	subround	poor	A	-	-	A	C	C-A	A	-	-
subangular-round	subround	poor	-	-	-	-	C	-	A-C	-	-
subangular-round	subround	poor	-	-	-	-	C	-	C	-	-
subangular-round	subround	poor	-	-	-	-	C-R	-	A	-	-
subangular-round	subround	poor	C	-	-	C	A	C	A-C	-	-
round	subround	well	R	-	-	R	A	A	C	-	-
subangular-round	subround	poor	C	-	-	-	A	R	C	-	-
subangular-round	subround	poor	R	-	-	R	A	C	C	-	-
subangular-round	subround	well	A	-	-	R	A	C	C	R	-
angular-round	subangular	poor	-	-	-	-	A	A-C	C	R	-
subangular-subround	subround	poor	R	-	-	R	C	C	R	-	-
subangular-subround	subround	poor	C	C	-	C	A	C	A	R	-
subangular-subround	subround	poor	-	-	-	-	A	A	A	R	-
subround-round	subangular	poor	-	-	-	-	A	R-absent	C-A	R	-
subangular-subround	subround	poor	-	-	-	-	A	C-R	C	R	-
subangular-subround	subround	poor	-	-	-	R	A	-	A	-	-

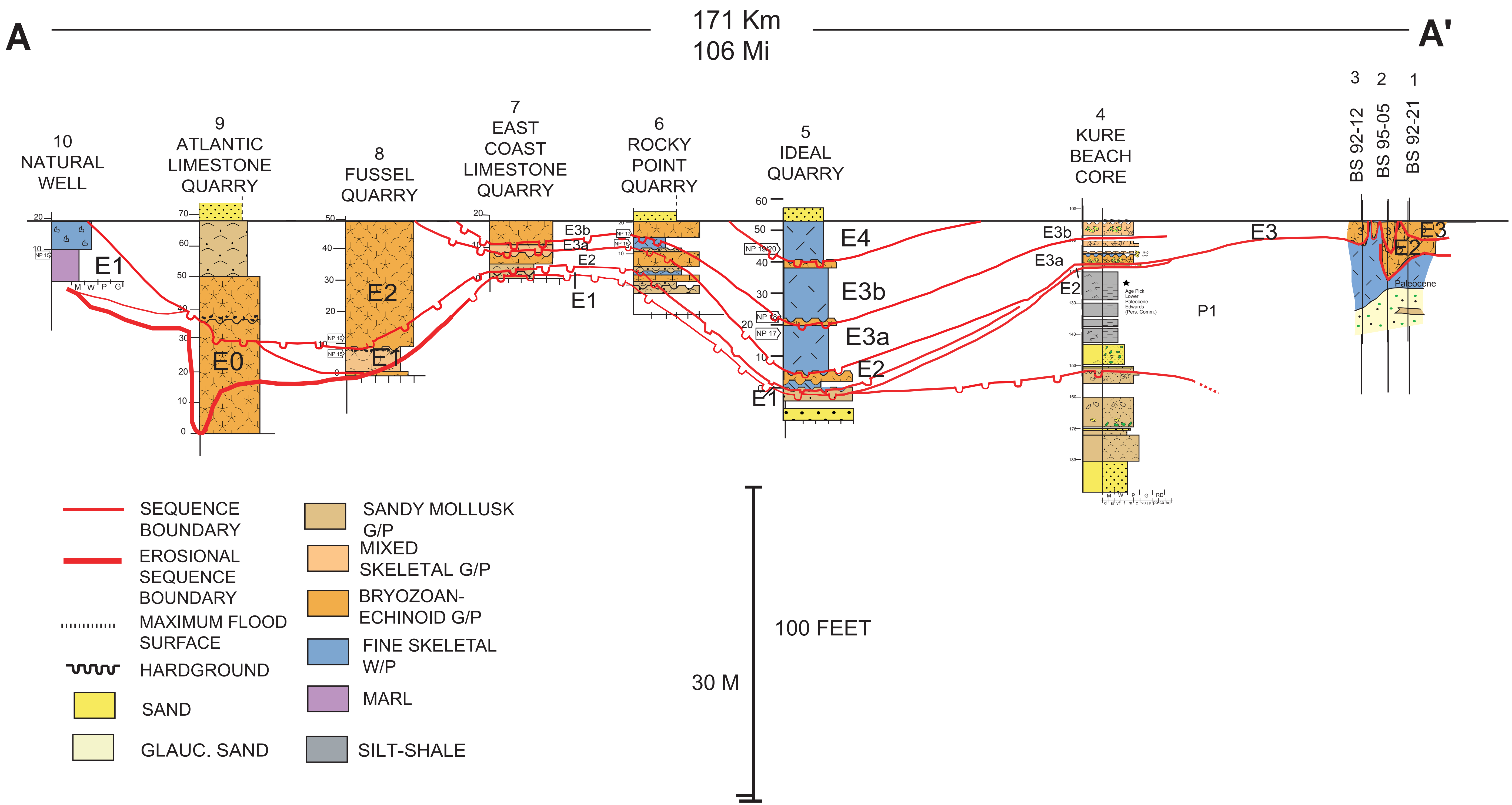
APPENDIX E: Onslow County Core thin section analysis

Sponge	Crustaceans	Ostracod	Barnacle	Indet. skel grains	Lime clasts	Matrix	Glauconite%	Phosphate %	Quartz	Other grains
-	R-absent	-	-	A	R	Terrigenous silt/clay dominant	R m 3-5%	R m-c 5%	vf-f 20-25%	-
-	R-absent	R	-	C	C	Terrigenous silt/clay dominant	R f-c 5-10%	R vf-f 5-7%	<1-25%	-
-	R-absent	-	-	C	-	Lime mud dominant	R f 1-2%	R f 1-2%	c <10%	-
-	-	-	-	C	-	Lime mud dominant	R f-m 1-2%	R vf-f <1%	vf <1%	-
-	R-C	C	-	C-A	-	Lime mud dominant	R f 2%	R vf-f 1-2%	vf-f <1%	-
-	A-C	A	-	A	-	Lime mud dominant	R f-m 2%	R vf-f 2%	vf <1%	-
-	-	-	-	R-C	-	Mixed	R vf 1-2%	R vf 1-2%	vf 2-5%	-
-	-	-	-	C-A	-	Mixed	R f 1%	R vf-f 1-2%	vf 1%	-
-	-	-	-	C-A	-	Mixed	R f-m 1-2%	R f <1%	vf-f 1%	-
-	R	R	-	C	-	Lime mud dominant	R m 1%	R f-m 1%	v-vc 1-3%	-
-	R-C	R-C	-	A	-	Lime mud dominant	R f-m 3-7%	R f-m 2%	f-c 2%	-
-	-	-	-	C	-	Lime mud dominant	R f-m <1%	R m 2-3%	vf-m 1%	-
-	C	R	-	C-A	-	Lime mud dominant	R f-m 1%, R vc <1%	R f-m 2%	f-c 3%	-
-	-	-	-	A	-	Lime mud dominant	R m 1-2%	R m 1-2%	f-c 1%	detrital skel frags
-	-	-	-	A	-	Lime mud dominant	R f 1-2%	R vf-f 1-2%	m-c 5%	qtz lithoclast
-	-	-	-	C	-	Lime mud dominant	R f <1%	R f <1%	f-m 1-2%	-
-	R	R	-	A	-	Lime mud dominant	R vf-f 1-2%	R vf-f 1%	vf-vc 1-5%	detrital skel frags
-	R	-	-	A	-	Lime mud dominant	R f 2%	R f 2-3%	vf-vc 3%	-
-	-	-	-	C	-	Mixed	R m 1%	R m 3%	R f-m 2%	-
-	C-R	R	-	A	-	Terrigenous silt/clay dominant	R f-m 1-2%	R f 1-2%	f-m 1%	-
-	C	C	-	A	-	Terrigenous silt/clay dominant	R f 1%	R f 1%	f-m 3-5%	-

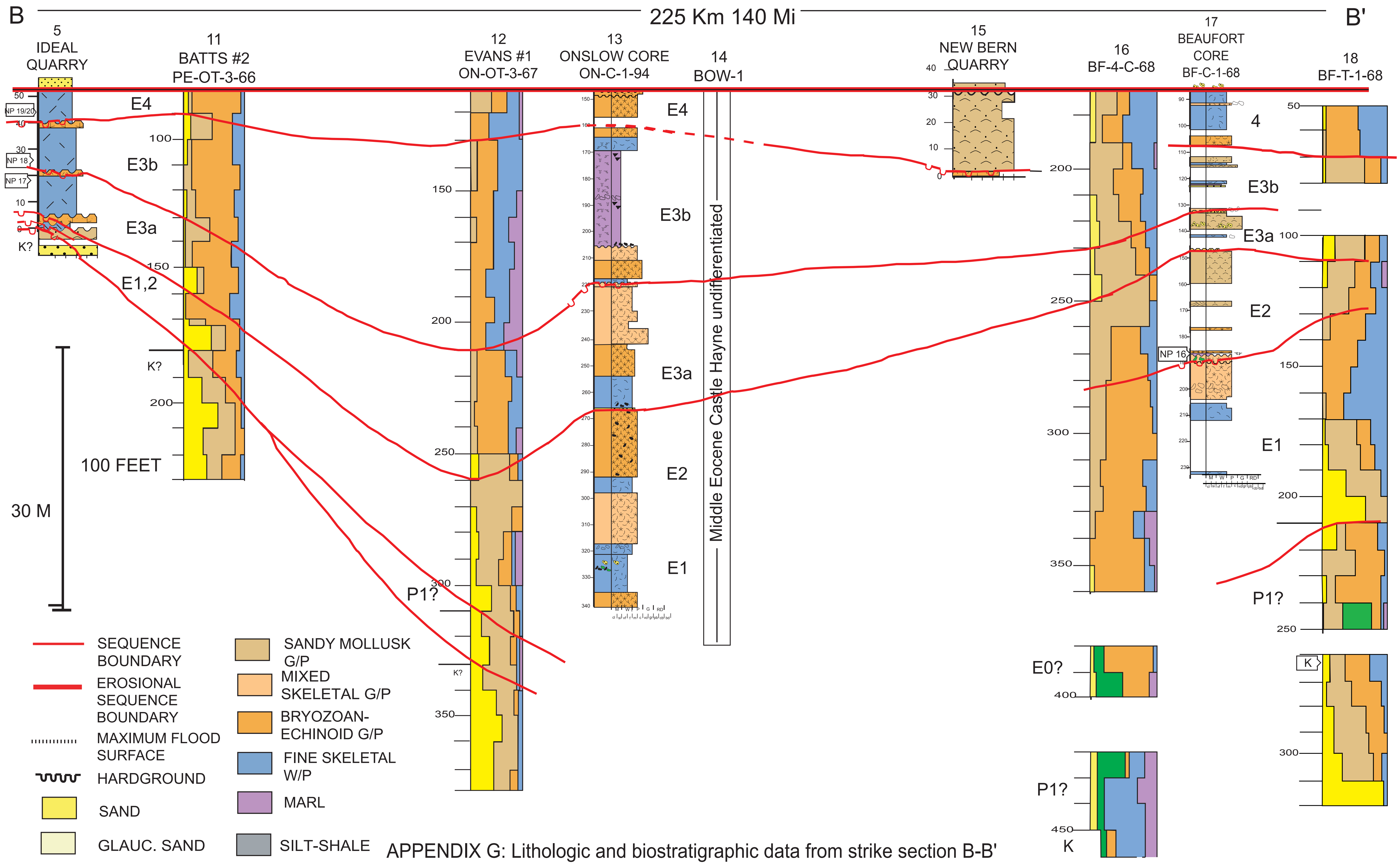
APPENDIX E: Onslow County Core thin section analysis

Micritization	Phosphate impreg.	Glauconite impreg	Calcite cements	Dolomitization	Porosity Type	NOTES
C	-	R	C-R pink rim	-	IP 2-5%	
A	R-C	C	R pink f equant	-	IP, fracture 5-7%	
C	C	C	A pink f equant, rim	-	IP 50-60%	
A	C	C-A	C pink rim, f equant, c equant	-	MO IP 10%	
A	C	C	R pink f equant	-	MO BP 10-15%	
A	C	C	C-A pink f and c equant	-	MO IP 30-35%	
C	R-C	-	R pink vf bladed	-	v low <5%	
C-A	-	-	R pink f equant	-	v low 4%	
C	-	-	R pink f equant	-	v low <3%	
A	C	C	C-A pink f equant, bladed	-	MO IP BP 25%	
A	C	A	C pink rim, f equant, R purple	-	MO BP IP 30-40%	
A	C	C	C pink turbid bladed, f equant	-	BP 25-30%	
A	C-A	C-A	C pink bladed, f/c equant	-	MO BP 20%	
A	C	R	A pink rim, bladed, f/c equant	-	MO BP IP 45%	
A	C	C	C pink bladed, rim, f/c equant	-	IP BP 5-7%	
C	-	-	R pink f equant	-	IP BP 5%	v. thin slide
C	C	C	C-A pink rim, bladed, f equant	-	MO BP 15-20%	
A	C	C	C pink rim, bladed, f/c equant	-	BP 15-20%	shell grit?
A	R	R	-	-	MO BP <5%	v. thin slide
A	R	R	R pink f equant	-	BP MO 10%	
A	R	R	C pink f/c equant	-	BP IP fracture 10%	

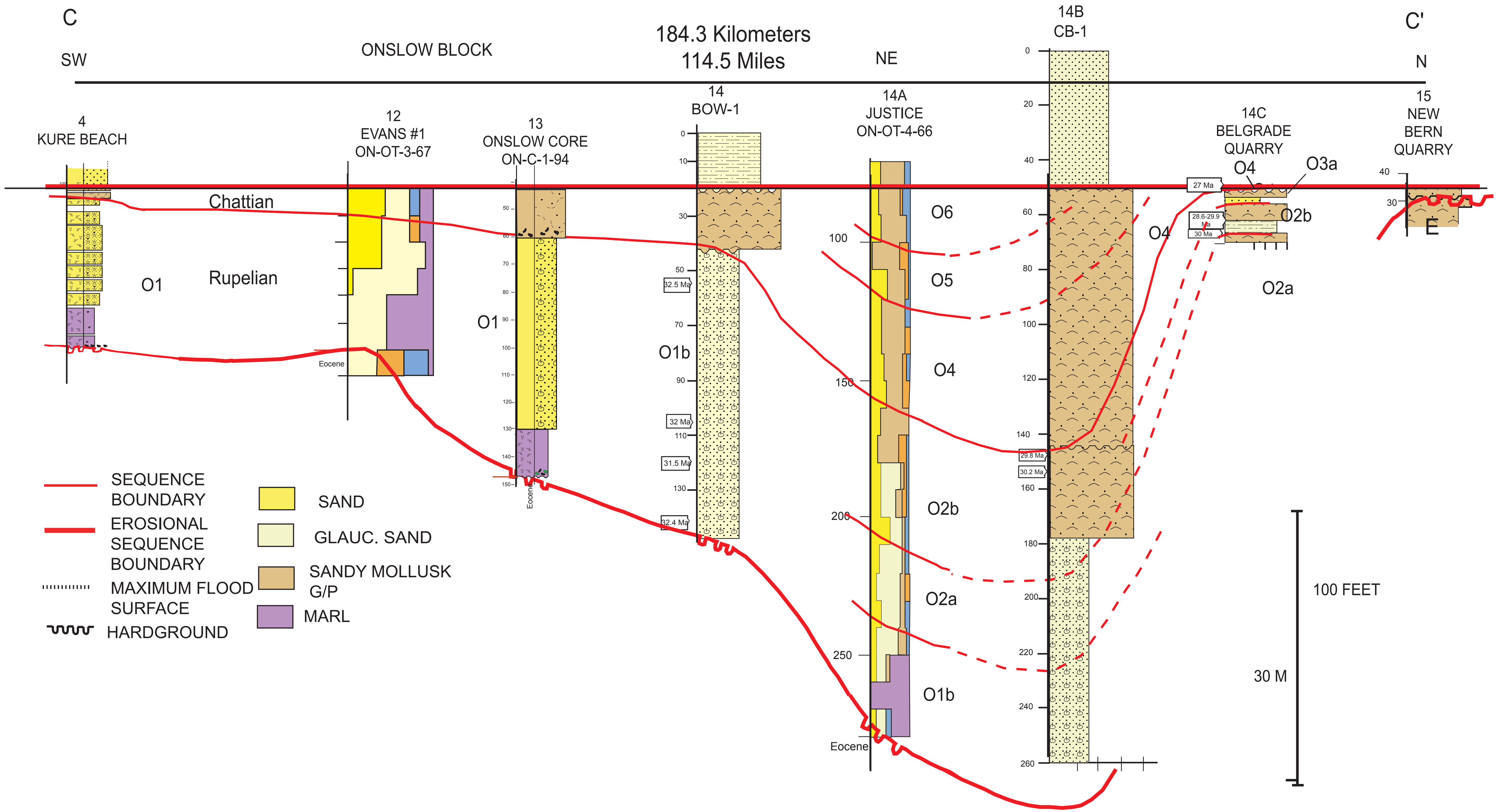
APPENDIX E: Onslow County Core thin section analysis



APPENDIX F: LITHOLOGIC AND BIOSTRATIGRAPHIC DATA OF DIP CROSS-SECTION A-A'.



APPENDIX G: Lithologic and biostratigraphic data from strike section B-B'



APPENDIX H: Lithologic and biostratigraphic data from cross-section C-C'.

TOTAL EOCENE
14 sections
52 seq

Percents

	SB	LST	TST	mfs	HST		SB	LST	TST	mfs	HST
Present	12	12	18	31	32		25	25	37	61 Y	62
With Hardground	20	1	0	0	0		42	0	0	0	0
Not determined	10	0	20	0	20		21	2	41	0	38.
Absent	6	35	11	20	0		12	73	22	39	0
	48	48	49	51	52						

UPDIP
7sections
22 seq

	SB	LST	TST	mfs	HST		SB	LST	TST	mfs	HST
Present	1	1 Y	4 Y	11	11		5	5	19	50	50
With Hardground	17	0	0	0	0		81	0	0	0	0 ?
Not determined	2	1	11	0	11		9	5	52	0	50
Absent	1	19	6	11	0		5	90	29	50	0
	21	21	21	22	22						

DOWNDIP
7sections
30 seq

	SB	LST	TST	mfs	HST		SB	LST	TST	mfs	HST
Present	11	11	14	20	21		41	41	50	69	70
With Hardground	3	0	0	0	0		11	0	0	0	0
Not determined	8	0	9	0	9		30	0	32	0	30
Absent	5	16	5	9	0		18	59	18	31	0
	27	27	28	29	30						

APPENDIX I: Total Eocene sequence stratigraphic statistics

TOTAL PALEOCENE
2 Sections
2 Sequences

	SB	LST	TST	mfs	HST
Present	1	2	1 Y	1	1
With hardground	1	0	0 ?	0	0
Not Determined	0	0	1 n.d.	0	1
Absent	0	0	0 N	1	0
	2	2	2	2	2

Percents

	SB	LST	TST	mfs	HST
Present	50	100	50	50	50
With hardground	50		0	0	0%
Not Determined			50	0	50
Absent				50	0

TOTAL OLIGOCENE
8 Sections
20 Sequences

	SB	LST	TST	mfs	HST
Present	6	8	0	6	7
With hardground	7	0	0	0	0
Not Determined	5	0	13	2	13
Absent	1	12	7	12	0
	19	20	20	20	20

	SB	LST	TST	mfs	HST
Present	32	40		30	35
With hardground	37	0		0	0
Not Determined	26	0	65	30	65
Absent	5	60	35	30	

APPENDIX J: Total Paleocene and Oligocene sequence stratigraphic statistics

TOTAL PALEOGENE
24 Sections
74 Sequences

	SB	LST	TST	mfs	HST
Present	19	22	19	38	40
With hardground	28	0	0	0	0
Not determined	15	1	34	2	0
Absent	7	47	18	33	33
	69	69	71	73	73

Percents

	SB	LST	TST	mfs	HST
Present	27	31	27	52	55
With hardground	40	0	0	0	0
Not determined	22	1	48	3	0
Absent	11	68	25	45	45

APPENDIX K: Total Paleogene sequence stratigraphic statistics