Figure 4.6 Sequence stratigraphic framework for the Lower Cretaceous sediments of the Albemarle Embayment. Upper sequence is for the youngest studied portion (identified as Sequence 2). Lower model displays the oldest two studied sequences (identified as Sequence 0 and 1); the oldest of which (Sequence 0) was only observed in the most basinal wells studied; therefore drawn surfaces are tentative. Model is 'separated' at the SB 2.0 surface, and flattened on the SB 3.0 (upper model) and SB 2.0 (lower model) surface in order to make the model more visually appealing. Surface names are shown at the extreme left and right. Flooding surfaces are black, maximum flooding surfaces are blue, and sequence boundaries are red. Orange line represents possible depths at which paleogeographic maps (Figures 4.7, 4.8, and 4.9) are drawn (orange lines located above and below SB 2.0 surface). Map of cross-section location is shown at bottom left. Seismic data (Chapter 3) was used as a guide for large sequence correlations. Parasequences constructed by matching similar successions in adjacent wells. Facies Association legend at bottom right. Vertical scale is 1 inch:1000 feet (1:1200). Measured depth is displayed (in feet).
WELL-CUTTINGS BASED, SEQUENCE STRATIGRAPHIC FRAMEWORK OF THE MIXED SILICICLASTIC-CARBONATE LOWER CRETAEOUS SEDIMENTS OF THE NORTH CAROLINA COASTAL PLAIN

by

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Bachelors of Sciences, McGill University, 2004

THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

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ABSTRACT

A lithology-based, sequence stratigraphic framework and depositional model for mixed siliciclastic-carbonate Lower Cretaceous sediments of the North Carolina coastal plain (southeastern U.S.) is proposed. Twenty-five lithofacies are recognized. Ten recurring facies associations are defined, and are merged into siliciclastic- and carbonate-dominated depositional profiles, comprising coastal plain to deep shelf depositional environments.

Parasequences are recognized from the well data, and are grouped into parasequence sets indicating progressive progradational or retrogradational (highstand and transgressive systems tracts, respectively) stacking patterns. Lowstand deposits are not recognized, although they probably occur in more basinward positions lying to the east. Seismic reflectors guided correlations between wells, and typically coincided with key sequence stratigraphic surfaces.

Three third-order sequences are defined, which are dominated by siliciclastic depositional processes. The late highstand deposits of Sequence 1, however, are carbonate rich. The low relative sea-level conditions during late highstand likely favoured climatic aridity, facilitating carbonate-dominated sedimentation.

Keywords: Sequence stratigraphy; Mesozoic; mixed carbonate-siliciclastic; Atlantic coastal plain; depositional model; basin analysis

Subject Terms: Sequence stratigraphy; Sedimentology; Continental Margins; Geology, Stratigraphic – Cretaceous
This book is dedicated to my family and Breanne. Through my travels, I have learned that there is nothing better than coming home to the family that you love.

To my family,

Through our family travels over the years, I began to love learning about the world around us. Rather spontaneously, I had begun collecting rocks from the places where we traveled; who would have known that it would lead to a future career as a geologist. Not only have I begun to learn about the modern natural world, but I also have a passion for learning about its past. Without your loving support to show me the world, and allow me to travel to distant places, I would never have been able to accomplish what I have.

To Breanne,

I do not know how to start thanking you. You provided distractions when I needed to relax, and you helped me focus on the project when I really needed to. I know that the many long hours I put into this project strained our relationship. I thank you enormously for your never ending patience, strength, and passion. I look forward to a long, long life together.

Love Always,

Richard
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# TABLE OF CONTENTS

Approval .......................................................................................................................... ii  
Abstract .......................................................................................................................... iii  
Dedication ....................................................................................................................... iv  
Acknowledgements ......................................................................................................... v  
Table of Contents ............................................................................................................ vii  
List of Figures .................................................................................................................. ix  
List of Tables ................................................................................................................... xi  

## Chapter 1: Introduction ............................................................................................... 1  
- Purpose of Investigation ............................................................................................. 1  
- Study Area ................................................................................................................... 4  
  - Tectonic setting ......................................................................................................... 4  
  - Global paleogeography and climate ......................................................................... 5  
  - Chronostratigraphy .................................................................................................. 9  
- Previous Research ....................................................................................................... 9  
- Project Objectives ....................................................................................................... 12  
- Database: ..................................................................................................................... 12  

## Chapter 2: Lithofacies Description and Methods ....................................................... 14  
- Geophysical Wireline logs ......................................................................................... 14  
- Core Data .................................................................................................................... 16  
  - Albemarle Embayment .............................................................................................. 17  
  - Offshore, United States Atlantic Margin .................................................................. 17  
- Well-Cuttings Data ..................................................................................................... 22  
  - Well-cuttings data errors and corrections ................................................................. 22  
  - Well-cuttings sample preparation and data collection methods ......................... 24  
  - Lithologic column construction method .................................................................. 27  
  - Cuttings fragment types and lithologies ................................................................. 30  
- Lithofacies Descriptions ............................................................................................. 34  
  - Siliciclastic Lithofacies Types ................................................................................. 35  
  - Carbonate Lithofacies Types ................................................................................... 52  

## Chapter 3: Seismic Data – Description, Methods, and Interpretation ....................... 77  
- Seismic Data Line Drawings ....................................................................................... 79  
- Well-to-Seismic Data Tie ............................................................................................ 82  
- Seismic Stratigraphy Interpretation and Discussion ................................................ 87  
- Conclusions ................................................................................................................ 93
LIST OF FIGURES

Figure 1.1 Study area ................................................................................................................................... 2
Figure 1.2 Plate tectonic reconstruction of the Lower Cretaceous (118.7 ma) ........................................................................................................... 6
Figure 1.3 Chronostratigraphic chart of lithostratigraphic nomenclature of the North Carolina coastal plain and major depositional basins. ........... 10
Figure 2.1 Description of core 2 of the offshore COST B-3 well ................................................................. 20
Figure 2.2 Description of core 3 of the offshore COST GE-1 well ............................................................... 21
Figure 2.3 Example of cut and polished cured epoxy "pucks" containing well cuttings and completed thin-sectioned well cuttings ........................................................................................................... 26
Figure 2.4 Portion of the DR-OT-2-65 well showing example of method and data used for construction of preliminary lithofacies column........ 28
Figure 2.5 A: Drill mud; B: Coal; C: Coal and ostracode shale; D: Coarse-grained quartzose sand .................................................................................. 32
Figure 2.6 A: Sub-arkosic arenite; B: Bioturbated quartz sandstone; C and D: Skeletal quartz sandstone ................................................................................... 40
Figure 2.7 A: Siltstone; B: Shale grading to siltstone; C: Planktonic foraminifera-bearing siltstone; D: Non-fossiliferous shale ........................................ 45
Figure 2.8 A: Diatomaceous Shale; B: Hardground fragment; C: Chert; D: Algal laminitite .......................................................... 50
Figure 2.9 A: Chicken-wire anhydrite; B: Algal Laminitite; C: Mioliolid packstone; D: Quartzose silty dolomitized lime mudstone ........................................ 54
Figure 2.10 A: Quartzose silty dolomitized lime mudstone; B and C: Skeletal-oid packstone and grainstone; D: Quartzose sandy skeletal grainstone ................................................................................... 58
Figure 2.11 A: Quartzose sand-bearing packstone; B and C: Mollusc Packstone; D: Peloid packstone.................................................. 62
Figure 2.12 A: Skeletal oncoid and peloid packstone; B: Pelletal packstone; C and D: Skeletal packstone ................. 67
Figure 2.13 A: Skeletal packstone; B: Planktonic foraminifera packstone; C and D: Marl ..................................................... 69
Figure 2.14 A: Marl; B: Lime mudstone; C and D: Hardground .......................... 73
Figure 3.1 Base map showing orientation of studied 2D seismic lines and position of wells that were tied to the seismic data .......................... 78

Figure 3.2 Pseudo-cross-section with raw stacked 2D seismic data (top) and seismic line drawings (bottom). .............................................. 80

Figure 3.3 Well to seismic data ties for selected wells from the Albemarle Basin. .................................................................................. 84

Figure 3.4 Seismic stratigraphic interpretation. A: Pseudo-cross-section using part of lines G-3, G-2 and G-1. B: Pseudo-cross-section using part of lines G-8 and G-5 ......................................................... 90

Figure 4.1 Tertiary Gippsland Basin depositional model .................... 99

Figure 4.2 Central Mexico, Cretaceous offshore bank depositional model .... 103

Figure 4.3 Dominant stacking patterns, showing one complete shoaling-upward succession for both A: siliciclastic-dominated system, from well HY-OT-1-65; and B: carbonate-dominated system, from well DR-OT-1-46 ................................................................. 112

Figure 4.4 Generalised facies association profiles of the Early Cretaceous sediments in the Albemarle Embayment of North Carolina. A: Siliciclastic-dominated sedimentation, B: Carbonate-dominated system .................................................................................. 115

Figure 4.5 Sequence 1 showing parasequence sets found within the DR-OT-2-65 well .......................................................... 124

Figure 4.6 Sequence stratigraphic framework for the Lower Cretaceous sediments of the Albemarle Embayment ......................... Fold-out

Figure 4.7: Siliciclastic-dominated paleogeographic map of the Early Cretaceous Albemarle Embayment .................................................. 139

Figure 4.8 Carbonate-dominated paleogeographic map of the Early Cretaceous Albemarle Embayment .................................................. 141

Figure 4.9 Transgressive paleogeographic map for the Early Cretaceous Albemarle Embayment .................................................. 143
LIST OF TABLES

Table 2.1 Summary of available well data sets and brief description of preliminary study of well cuttings from oil test wells selected for study. .............................................................. 15

Table 2.2 Summary of discontinuous Hatteras Light (DR-OT-1-46) core. ....... 18

Table 2.3 Lithofacies summary ......................................................................... 36

Table 3.1 Processing parameters selected for comparison of synthetic seismic logs (center) and shot point locations of tied 2D seismic lines (right) used in Figure 3.3. ......................................................... 83

Table 3.2 Interval transit times (sonic) and bulk density wireline log responses of lithofacies observed in cuttings. .................................................. 87

Table 3.3 Two-way-travel time and depth at which the zero crossing (moving towards the peak with increasing depth) of seismic reflectors and interpreted well picks occurs (from Figure 3.3). .......... 88

Table 4.1 Summary of key characteristics and features of the facies associations ........................................................................................................... 97

Table 4.2 Depths of significant sequence stratigraphic surfaces .................... 127

Table 4.3 Comparison of observed sequence boundaries with previous researchers ........................................................................................................ 130
CHAPTER 1: INTRODUCTION

Purpose of Investigation

Little work has focused on Lower Cretaceous strata of the Albemarle Embayment, largely due to the paucity of easily workable datasets. Strata do not outcrop extensively, and only one, highly discontinuous core has been collected from downdip, Mesozoic-aged sediments (Esso Hatteras Light no.1). However, well-cuttings and wireline logs from approximately forty oil test wells and one cored well provide valuable lithologic information for the onshore, downdip Mesozoic section (Figure 1.1). The goal of this study is to better describe and characterise the Lower Cretaceous sedimentary succession of the North Carolina coastal plain, by creating a lithology based sequence stratigraphic framework.

This study provides a much needed link between the well-studied Gulf Coast and Baltimore Canyon Trough regions and the emerging studies of the Scotian Shelf. The resulting depositional models can also be compared with coeval units from the eastern margin of the Atlantic Ocean (Western Europe and Morocco).

Results from this study also have application for hydrogeology and waste disposal. Ground water is a valuable resource of the North Carolina Coastal Plain (Richards, 1950). As the North Carolina coastal plain is further urbanized, understanding distributions of porosity and permeability will be important for both freshwater sources and waste disposal. The US Department of Energy (DOE) is currently evaluating the potential for long-term storage of carbon dioxide in the subsurface of the United States
Atlantic coastal plain (J. T. Litynski, 2007, personal communication).

No wells have tested coeval offshore North Carolina units, but these strata are prospective hydrocarbon exploration targets. Hence, documentation of facies, stacking patterns, and regional depositional sequences will be highly advantageous to future downdip exploration ventures. Early Cretaceous carbonates have been identified as an exploration target that resembles gas bearing units on the Scotian Shelf (e.g., Manteo prospect; Vigil, 1998). Hydrocarbon shows have been reported from Lower Cretaceous sandstones of the Baltimore Canyon Trough basin lying to the north of this study area (Mattick and Libby-French, 1988; Sawyer, 1988).
The Early Cretaceous experienced a number of global ocean anoxia events, extinctions, and strontium isotope excursions (Bralower et al., 1994, 1999; Erbacher and Thurow, 1997; Jones and Jenkyns, 2001). This resulted in the deposition of carbon-rich black shales in basinal positions, and limestone-marl sequences (Barron et al., 1985; Fischer et al., 1990; Francis and Frakes, 1993). A comprehensive depositional and sequence stratigraphic framework for this basin may provide an opportunity to study the influence of these events on a wide, high-wave energy, continental shelf of the Western North Atlantic passive margin.
The data sets incorporated in this study are commonly used by the petroleum industry. Well-cuttings, however, generally receive little attention in academia. This study demonstrates the usefulness of well-cuttings from deep drilled wells (1.5 to 2.25km) to characterise rock types and vertical stacking patterns in data-lean subsurface basins.

Finally, this study has provided the opportunity to observe and describe a mixed carbonate-clastic section in an area that has not been deformed by salt migration (unlike the Gulf Coast region). This study improves our understanding of the complex vertical and lateral facies relationships of these settings during the Early Cretaceous.

**Study Area**

**Tectonic setting**

The study area is located in the Albemarle Basin of eastern North Carolina (Figure 1.1). The basin is one of a series lying along the north-western Atlantic passive margin that developed in response to the opening of the Atlantic Ocean during the Late Triassic to Middle Jurassic period (Manspeizer, 1985; Owens and Gohn, 1985). Sediments filling the basin are bordered to the North by the Norfolk Arch (i.e., Fort Monroe High of Owens and Gohn, 1985) and to the south by the Cape Fear Arch (Richards, 1950; Bonini and Woollard, 1960). The Cape Fear Arch is also identified as the Great Carolina Ridge by Spangler (1950).

Middle Mesozoic Atlantic margin sedimentary basin fill onlaps westward onto the Triassic rift basin-fill sediments and Precambrian crystalline basement rocks that accreted during the Late Paleozoic Alleghania Orogeny. Late Mesozoic- to Cenozoic-aged
sediments prograde and thicken basinward (Spangler, 1950; Bonini and Woollard, 1960; Brown et al., 1972; Owens and Gohn, 1985). During the Early Cretaceous, the updip siliciclastic coastal plain fill passed seaward into a network of carbonate platforms and banks that mimicked the more extensive Jurassic Bahama-Grand Banks gigaplatform of Poag (1991; Brown et al., 1972, Poag and Valentine, 1988, Jansa, 1993).

**Global paleogeography and climate**

Normal marine salinity conditions existed in the North Atlantic Ocean since the Middle Jurassic, though the size of the Atlantic was much smaller than it is today (Gradstein and Sheridan, 1983, Scotese and McKerrow, 1990, Francis and Frakes, 1993, Scotese, 1995). Early Cretaceous paleogeographic plate reconstructions show a large, ancient Pacific Ocean (Panthalassa) and a small north to central Atlantic Ocean that was connected to the Tethys Sea (Figure 1.2A; Gradstein and Sheridan, 1983, Scotese and McKerrow, 1990, Francis and Frakes, 1993, Scotese, 1995).

Rifting of the supercontinent Pangea began in the Late Triassic and culminated in the development of the North Atlantic Ocean during the early Middle Jurassic (Gradstein and Sheridan, 1983, Scotese and McKerrow, 1990, Francis and Frakes, 1993, Scotese, 1995). Rifting between the North American and South American plates during the Mesozoic resulted in the Atlantic Ocean being connected to the Tethys Sea to the east and the ancient Pacific Ocean to the west. As a consequence of this connectivity, a westward flowing circum-equatorial current is believed to have developed, driven by the equatorial wind patterns (Gradstein and Sheridan, 1983; Haq, 1984; Francis and Frakes,
Figure 1.2A Plate tectonic reconstruction of the Lower Cretaceous (118.7 ma), modified from Scotese (1995). Arrows indicate inferred global paleocirculation patterns, modified from Gradstein and Sheridan (1983), and Haq (1984). Land area is shown shaded, highlands are dark grey. 200m depth contour is also drawn around continents. Study area is indicated by the asterisk within the box (Figure 1.2B).
Continued spreading of the Atlantic during the Early Cretaceous enlarged the Northern Atlantic Ocean beyond 30° North paleolatitude. This opening subjected the ocean to the effect of westerly winds, developing a clockwise North Atlantic gyre (Figure 1.2B; Gradstein and Sheridan, 1983; Haq, 1984; Francis and Frakes, 1993). Further, during the Cretaceous, the movement of small continental blocks in the Central America region appear to have deflected warm equatorial currents northwards to form the proto-Gulf Stream (Gradstein and Sheridan, 1983; Francis and Frakes, 1993). Evidence for the existence of the Gulf Stream from North Carolina during the Campanian is cited by Harris and Self-Trail (2006), though it is unknown if it is present prior to the Campanian.

Cretaceous climates were dominated by greenhouse conditions. This is thought to be the result of unrestricted North-South ocean circulation patterns. Further, as sea temperatures were much higher than present and the atmosphere possessed elevated levels of CO₂ (Barron, 1983), warmer climate flora and fauna were able to flourish at significantly higher latitudes (Francis and Frakes, 1993). The distribution of reefs was widespread to ~30° paleolatitude (Ziegler et al., 1984). Many of these reefs were composed of rudist bivalves resembling corals in shape, and occupied similar depositional settings. However, rudist bivalves do not share many morphological features of typical reef builders (encrusting, branching, colonial), and only a minority of rudists preferred hard-substrates (Masse and Philip, 1981; Ross and Skelton, 1993). Therefore build-ups or biostromes of rudist bivalves may be better referred to as rudist banks as opposed to reefs (Masse and Philip, 1981; Ross and Skelton, 1993).

Eustatic sea level changes due to glaciation are thought to be less than ten metres during the Cretaceous (Francis and Frakes, 1993; Christie-Blick, 1990; Fischer et al.,
The lack of recognized Cretaceous aged tillites has led to the belief that glaciation cycles were either non-existent, or of minimal effect (Francis and Frakes, 1993). Therefore coastal and shallow marine facies belt migration due to glacial-eustatic sea level changes are likely minimal or non-existent.
According to Read (1995), during global greenhouse times such as the Cretaceous, high frequency (fourth and fifth order), climatically driven sea level cycles were likely less than twenty metres. These climate cycles are dominated by the precession of the Earth's axis of rotation, a 19 to 23 k.y. Milankovitch orbital cycle. Longer term, third order cycles (0.5 to 5 m.y.) are thought to result in slow (few cms/k.y.) sea level changes up to fifty metres (Read, 1995). Cloetingh (1988) relates third order sea-level cycles occurring at a rate of 1-10cm/k.y. to fluctuations of horizontal stresses in the lithosphere that occur on the time scales of a few million years and longer.

**Chronostratigraphy**

The North Carolina coastal plain contains a thick onshore accumulation of Mesozoic-aged, North Atlantic passive margin sediments (over two kilometres penetrated by the Hatteras Light no. 1 Well; Brown *et al.*, 1972). Offshore to the north, sediment thicknesses exceed five kilometres in the Baltimore Canyon Trough (Owens and Gohn, 1985; Poag and Valentine, 1988). Figure 1.3 shows how the existing chronostratigraphy of Brown *et al.* (1972) and Zarra (1989) compares to neighbouring basins.

**Previous Research**

Spangler (1950) summarized early subsurface exploration below the North Carolina Coastal Plain, discussing general lithology, faunal zones, and structure from several wells and outcrops. He also summarized data from cores collected during the drilling of the Hatteras Light well (DR-OT-1-46). Correlations between wells and outcrops were based on faunal zones, electric logs, and lithological features.
Figure 1.3 Chronostratigraphic chart of lithostratigraphic nomenclature of the North Carolina coastal plain and major depositional basins. Lithostratigraphic nomenclature of the Baltimore Canyon Trough resembles the Scotian Shelf (Poag, 1982; Poag and Valentine, 1988). Brown et al. (1972) Unit G and Zarra (1989) K-4 and K-5 are the subject of this study (Heavy black box).

<table>
<thead>
<tr>
<th>Standard Chronostratigraphy</th>
<th>Long term and short term eustatic curves (Haq and others, 1987)</th>
<th>Formations Member / Stratigraphic Nomenclature</th>
<th>North Carolina</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (Mya)</td>
<td>Series</td>
<td>Scotian Shelf Formation</td>
<td>Brown and others, 1972</td>
</tr>
<tr>
<td>Cenomanian</td>
<td>U.K.</td>
<td>Washita Group</td>
<td>Unit E Lower Middle Cenomanian</td>
</tr>
<tr>
<td>98.9 (+/-0.6)</td>
<td></td>
<td>Dantzler Fredericksburg Formation Group</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td></td>
<td>Andrew Formation</td>
<td>Unit F K-6</td>
</tr>
<tr>
<td>105</td>
<td></td>
<td>Paluxy Formation</td>
<td></td>
</tr>
<tr>
<td>110</td>
<td></td>
<td>Moorengsport Fm., Ferry Lake Anhydrite</td>
<td></td>
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<tr>
<td>115</td>
<td></td>
<td>Rodessa Formation</td>
<td></td>
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<tr>
<td>120</td>
<td></td>
<td>Bexar Formation</td>
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</tr>
<tr>
<td>125</td>
<td></td>
<td>Donovan* James Sandstone Limestone</td>
<td></td>
</tr>
<tr>
<td>125.0 (+/-1.3)</td>
<td></td>
<td>Pine Island Shale</td>
<td>Unit G K-4</td>
</tr>
<tr>
<td>125.5+/-1.3</td>
<td></td>
<td>Sligo Formation</td>
<td></td>
</tr>
<tr>
<td>125</td>
<td></td>
<td>Dawson Canyon Formation</td>
<td></td>
</tr>
<tr>
<td>130</td>
<td></td>
<td>Lower Logan Canyon Formation</td>
<td></td>
</tr>
<tr>
<td>130.6+/-1.3</td>
<td></td>
<td>Lago Shale Mbr.</td>
<td></td>
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<tr>
<td>132</td>
<td></td>
<td>Upper Logan Canyon Formation</td>
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<td>Dawson Canyon Formation</td>
<td></td>
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<tr>
<td>132.8+/-1.3</td>
<td></td>
<td></td>
<td>Unit H K-3</td>
</tr>
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<td>133</td>
<td></td>
<td>Hosston Formation</td>
<td></td>
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<tr>
<td>135</td>
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<td>Naskapi Formation</td>
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<td>135.5+/-1.3</td>
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<td>Upper Mississauga Formation</td>
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<td>138</td>
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<td>Modified from Mancini and Puckett, 2005</td>
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<td>Modified from Eliuk, 1978</td>
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<td>Modified from Brown and others, 1972</td>
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<td>Modified from Zarra, 1989</td>
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<td>140</td>
<td></td>
<td>This Study</td>
<td></td>
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</tbody>
</table>
Brown et al. (1972) constructed a regional lithostratigraphic subsurface model for the United States Atlantic Coastal Plain from North Carolina to New York, to characterise the regional hydrogeology. Seventeen chronostratigraphic units were defined in the Albemarle Basin (Figure 1.3). Data sets used in that study included well-cuttings and geophysical logs. Biostratigraphic dating was accomplished using Ostracode faunas and to a lesser degree, foraminifera. In North Carolina, Brown et al. (1972) described the current study interval, Unit G, as Albian to Aptian aged. It consists of chiefly marine sediments with abundant shale, sand, and locally abundant limestone. They did not attempt detailed lithologic correlations between wells.

Zarra (1989) used wireline logs, seismic, and limited foraminiferal biostratigraphy to construct a sequence stratigraphic framework for the Mesozoic and Cenozoic sediments of the Albemarle Embayment in five onshore exploration wells. He interpreted six Lower Cretaceous sequences, ranging in age from Berriasian to Albian (Figure 1.3), based on three biostratigraphic dates from a single benthic foraminifera genera (Choffatella decipens) and the published Ostracode biostratigraphy from Brown et al. (1972). Strata of the current study interval, labelled as the K-4 and K-5 sequences by Zarra (1989), were interpreted as terrestrial, marginal marine, and marine in origin.

Harris and Self-Trail (2006) identified Late Cretaceous depositional sequences from a continuous core drilled at Kure Beach, North Carolina. Coffey (1999), Coffey and Read (2002, 2004, 2007) also studied younger sediment sections (Palaeogene) using the same data sets and techniques applied in this study. Though, diachronous, similar facies are described (in the following chapters), suggesting that depositional controls have remained relatively constant through time within the Albemarle Embayment.
Project Objectives

This thesis describes and characterises the Lower Cretaceous sedimentary rocks and sequences of the North Carolina Coastal Plain. Lower Cretaceous strata corresponding to Unit G of Brown et al. (1972) and Zarra’s (1989) units K-4 and K-5 were selected for study because of the succession’s extensive thickness (up to 500m) and mixed carbonate-siliciclastic character (Figure 1.3). The North Carolina coastal plain region was chosen, as this area contains sufficient well density to allow documentation of regional depositional trends and facies variations across the thick onshore continental shelf of the middle United States Atlantic margin.

A lithology based sequence stratigraphic framework and depositional model for the Lower Cretaceous, mixed siliciclastic-carbonate succession of the North Carolina coastal plain (Albemarle Embayment) is presented. The depositional model is based on observed facies and stacking patterns in thin-sectioned well-cuttings, wireline logs, seismic surveys, and available core. In addition, coeval cores from neighbouring basins were studied to better understand regional stacking patterns and depositional environments. These cores also serve to “ground truth” cuttings and geophysical log responses from the Albemarle Basin.

Database:

More than eight hundred wells have been drilled in the North Carolina coastal plain. However, less than forty of these wells penetrate the thick marine Lower Cretaceous interval. Twelve wells initially were selected for study, based on: (a) existence of core; (b) geographic location; (c) well-cutting sample spacing; and (d)
quality of available geophysical logs. Approximately one thousand five hundred well-cutting intervals were studied optically from these wells. A subset of four wells was selected from the thick, continuous, downdip portions of the basin for detailed petrographic analysis of cuttings (six hundred thin-sectioned cuttings intervals). Well data, cuttings, and core are stored and maintained at the North Carolina Geological Survey (NCGS) located in Raleigh, North Carolina.

Well data are integrated with available 2D, multi-channel seismic-reflection data collected by the Geophysical Services Inc. for the Cities Service Oil and Gas Corporation in 1972. Five seismic lines (~150km line length) were chosen to aid correlations between studied wells. Paper copies are publically available at the NCGS.

For comparative purposes, eight cored offshore exploration wells and approximately one hundred fifty cuttings intervals from three of the cored wells were studied from the Baltimore Canyon Trough (5 exploration wells and 2 stratigraphic test wells) and Southeast Georgia Embayment (1 stratigraphic test well; Figure 1.1A). Well data, cuttings, and core for the offshore wells are stored at the Delaware Geological Survey in Newark, Delaware.
CHAPTER 2: LITHOFACIES DESCRIPTION AND METHODS

Lithologic facies are rock units possessing recurring lithologic, sedimentary structure, chemical, and biologic characteristics (Reading and Levell, 2005; J. MacEachern, 2008, personal communication). Lithofacies were determined primarily from thin-sectioned cuttings and cores from exploration wells drilled in the Albemarle Embayment focus area. Supplemental data were employed from analogous offshore wells drilled along the US Atlantic margin. Cores were studied during the summer of 2005 at the North Carolina Geological Survey (NCGS) and the Delaware Geological Survey. In addition, geophysical well logs were scanned, and well cuttings were sub-sampled for detailed study at Simon Fraser University. Cuttings analyses and interpretation were conducted in a similar manner to that outlined by Coffey (1999; see also Coffey and Read, 2004, 2007). The procedure employed is described below in the well cutting data section. The list of wells incorporated into this study can be found in Appendix A.

Geophysical Wireline logs

Geophysical wireline logs were scanned and copied at both the NCGS and Delaware Geological Survey, starting several hundred feet above and ending several hundred feet below the study interval. The logs were digitized using the Neuralog software package, and imported to the Petrel software package for queuing and viewing. A list of the digitized geophysical well logs can be found in Table 2.1.
Table 2.1 Summary of available well data sets and brief description of preliminary study of well cuttings from oil test wells selected for study. Wells marked with an asterisk (*) were studied petrographically. Geophysical log acronyms are as follows: 'GR' denotes Gamma-Ray, 'SP' denotes Spontaneous Potential, 'Cali.' denotes Caliper log, 'DT' denotes Sonic interval transit time log, 'Res.' denotes Resistivity log, 'Rhob' denotes Bulk Density log, and 'N.Par.' denotes Neutron Porosity. 'Carbonate rich' or 'Mixed carbonate-siliciclastic' indicates that studied depths possess well cuttings intervals that consist of >5% carbonate material; thin-sections of these intervals were prepared for detailed petrographic study.

<table>
<thead>
<tr>
<th>Well Code</th>
<th>Geophysical Logs:</th>
<th>Well cuttings Spacing - ft (m)</th>
<th>Brief description of study interval cuttings characteristics:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>North Carolina:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CK-OT-1-65</td>
<td>GR, SP, Cali., DT and Res.</td>
<td>10 (3.0)</td>
<td>Dominantly quartz sandstone and shale.</td>
</tr>
<tr>
<td>CR-OT-2-61</td>
<td>SP and Res.</td>
<td>10 (3.0)</td>
<td>Mixed carbonate-siliciclastic; abundant shale.</td>
</tr>
<tr>
<td>DR-OT-1-46 *</td>
<td>SP and Res.</td>
<td>10 (3.0)</td>
<td>Mixed carbonate-siliciclastic. Carbonate-lean intervals.</td>
</tr>
<tr>
<td>DR-OT-1-47</td>
<td>SP and Res.</td>
<td>10 (3.0)</td>
<td>Mixed carbonate-siliciclastic. Carbonate-lean intervals.</td>
</tr>
<tr>
<td>DR-OT-1-65</td>
<td>GR, SP, Cali., and DT</td>
<td>10 (3.0)</td>
<td>Mainly siliciclastic, local Carbonate-rich intervals.</td>
</tr>
<tr>
<td>DR-OT-3-65 *</td>
<td>GR, Cali. and DT</td>
<td>10 (3.0)</td>
<td>Mixed carbonate-siliciclastic. Carbonate-lean intervals.</td>
</tr>
<tr>
<td>HY-OT-1-51</td>
<td>None</td>
<td>30 (9.1)</td>
<td>Dominantly siliciclastic material; rarely carbonate-rich.</td>
</tr>
<tr>
<td>HY-OT-1-65 *</td>
<td>GR, SP, Cali., DT, Rhob and Res.</td>
<td>10 (3.0)</td>
<td>Abundant carbonate-rich intervals.</td>
</tr>
<tr>
<td>HY-OT-2-65</td>
<td>None</td>
<td>10 (3.0)</td>
<td>Mixed carbonate-siliciclastic. Local coal.</td>
</tr>
<tr>
<td>PA-OT-1-47</td>
<td>SP and Res.</td>
<td>~30 (~9.1)</td>
<td>Dominantly siliciclastic material; rarely carbonate-rich.</td>
</tr>
<tr>
<td>WH-OT-2-51</td>
<td>None</td>
<td>10 (3.0)</td>
<td>Abundant coarse-grained quartz sand; little carbonate.</td>
</tr>
<tr>
<td><strong>Offshore:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COST GE-1 *</td>
<td>GR, SP, Cali., DT, Rhob and Res.</td>
<td>30 (9.1)</td>
<td>Abundant carbonate; rare siliciclastic and anhydrite.</td>
</tr>
<tr>
<td>Shell 93-1</td>
<td>GR, SP, DT, and Res</td>
<td>20 or 10 (6.1/3.0)</td>
<td>Dominantly siliciclastic material; rarely carbonate-rich.</td>
</tr>
<tr>
<td>Tenneco 495-1</td>
<td>GR, SP, Cali., N.Por. and Res.</td>
<td>10 (3.0)</td>
<td>Abundant carbonate-rich intervals.</td>
</tr>
</tbody>
</table>
Geophysical well logs were used to tie cored intervals of wells to specific depths and tool responses. Further, these wireline logs were integrated with cuttings data to create lithologic columns.

Rarely, the values of the units of the well logs are inconsistent with observed cuttings lithologies. This is the case for the bulk density log of the DR-OT-2-65 well (it is likely that it should read higher densities), and the gamma ray log of the DR-OT-3-65 (which likely should read lower radioactivities). These errors are likely a result of only a portion of the well logs for the wells having been scanned and digitized for this project. In only digitizing a portion of the well, any scale changes between the header and study interval would not be captured. Well log scale changes are believed to be rare, and are only suspected to have affected the above two mentioned logs. For these logs, the absolute values from the erroneous log were not used, but the shape of the curve was used to judge relative petrophysical properties.

Core Data

Core from nine wells were studied for this project. The core served to ground-truth the lithologies, and to verify the stacking patterns indicated from the cuttings and geophysical logs. In addition, the core gives insights into the possible environments of deposition present in basins of the western Atlantic passive margin during the Early Cretaceous.
Albemarle Embayment

A single discontinuous core penetrates the study interval in the downdip, onshore Albemarle Embayment (Hatteras Light no.1; DR-OT-1-46). Recovery and preservation of this core is poor, limiting interpretations from the cored intervals solely on the basis of lithologic features (Table 2.2).

The majority of the cored intervals are moderately cemented, bioturbated (*Palaeophycus, Planolities*, and *Asterosoma* among identified traces), very fine- to fine-grained, sub-arkosic arenites, locally with bivalve (oyster) skeletal fragments. Shale-rich intervals show extremely limited recoveries. The few carbonate-rich intervals that were recovered comprise of sandy molluscan packstone and/or peloidal packstones.

Offshore, United States Atlantic Margin

Eight discontinuously cored offshore wells drilled in the Baltimore Canyon Trough and Southeast Georgia Embayment were studied. These wells are located along strike of the Albemarle Embayment depositional margin. The Baltimore Canyon Trough wells lie some 300-500 km northeast along the margin, whereas the Southeast Georgia Embayment well is situated 700 km to the southwest. Though all cores studied are of Middle to Upper Mesozoic age, few are directly time equivalent to the North Carolina study interval. This is because each well is sparsely sampled by core, and biostratigraphic dating is limited.

Despite the spatial and temporal differences between the studied cores, the lithologies and interpreted environments of deposition are believed to be comparable to those of the Early Cretaceous Albemarle Embayment region. The passive margin tectonic settings are similar, and the basins are separated by subtle basement highs.
<table>
<thead>
<tr>
<th>Box</th>
<th>Core</th>
<th>Depth (ft)</th>
<th>Lithology</th>
<th>Recovery (ft)</th>
<th>Colour</th>
<th>Porosity: Structures: Fossils</th>
<th>Other:</th>
</tr>
</thead>
<tbody>
<tr>
<td>11-14</td>
<td>77-86</td>
<td>6505 to 6581</td>
<td>Lower: F micaceous sandstone</td>
<td>27 of 94</td>
<td>good</td>
<td>none visible</td>
<td>none visible salt &amp; pepper texture (may be due to heavy minerals present, poorly cemented)</td>
</tr>
<tr>
<td>11-14</td>
<td>77-86</td>
<td>6487 to 6505</td>
<td>Upper: F to VF sandstone</td>
<td>total: good, but heterolithic</td>
<td>Oscillatory ripples?, mm-scale</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>87</td>
<td>6307 to 6317</td>
<td>LM sandstone</td>
<td>0.5 of 3</td>
<td>Off-white</td>
<td>good-excellent</td>
<td>none visible very poorly consolidated</td>
</tr>
<tr>
<td>11</td>
<td>75</td>
<td>6370 to 6373</td>
<td>LM sandstone</td>
<td>0.6 of 3</td>
<td>grey</td>
<td>good</td>
<td>none visible</td>
</tr>
<tr>
<td>15</td>
<td>92</td>
<td>7034 to 7039</td>
<td>M to C sandstone</td>
<td>0.3 of 5</td>
<td>medium-grey</td>
<td>high</td>
<td>none visible poorly consolidated, calcite cement</td>
</tr>
<tr>
<td>15</td>
<td>91</td>
<td>7021 to 7026</td>
<td>F to M sandstone</td>
<td>0.2 of 5</td>
<td>excellent</td>
<td>none visible</td>
<td>3&quot; core barrel piece recovered, poorly cemented</td>
</tr>
<tr>
<td>10</td>
<td>66</td>
<td>5642 to 5652</td>
<td>Sandstone?</td>
<td>&lt;0.1 of 10</td>
<td>unknown</td>
<td>it. grey</td>
<td>none visible core catcher with mud cake</td>
</tr>
<tr>
<td>10</td>
<td>67</td>
<td>5582 to 5587</td>
<td>F skeletal sandstone</td>
<td>4 of 5</td>
<td>low</td>
<td>claystone stringers</td>
<td>Oysters? Poorly consolidated</td>
</tr>
<tr>
<td>10</td>
<td>74</td>
<td>5230 to 5231</td>
<td>F skeletal sandstone</td>
<td>2 of 5</td>
<td>clay</td>
<td>none visible</td>
<td>large oysters &amp; other shell fragments; upper part locally medium-grained sandstone</td>
</tr>
<tr>
<td>14</td>
<td>81</td>
<td>6132 to 6137</td>
<td>F to VF sandstone</td>
<td>0.2 of 5</td>
<td>dark grey</td>
<td>fair</td>
<td>none visible</td>
</tr>
<tr>
<td>11</td>
<td>76</td>
<td>6370 to 6373</td>
<td>LM sandstone</td>
<td>0.5 of 3</td>
<td>dk. grey</td>
<td>good</td>
<td>none visible</td>
</tr>
<tr>
<td>17</td>
<td>97-98</td>
<td>7106 to 7123</td>
<td>F to M sandstone</td>
<td>10 of 17</td>
<td>good to excellent</td>
<td>none visible</td>
<td>some mica, poorly consolidated</td>
</tr>
<tr>
<td>20</td>
<td>101</td>
<td>7234 to 7238</td>
<td>M sandstone</td>
<td>0.2 of 4</td>
<td>poor</td>
<td>Styolites? none visible</td>
<td>found in sample bag, calcite cemented</td>
</tr>
<tr>
<td>20</td>
<td>102-103</td>
<td>7316 to 7336</td>
<td>M sandstone</td>
<td>9 of 20</td>
<td>good</td>
<td>none visible</td>
<td>poorly consolidated, sub-lithic arenite sand, abundant shell fragments</td>
</tr>
<tr>
<td>19</td>
<td>100</td>
<td>7191 to 7201</td>
<td>F sandstone</td>
<td>8 of 10</td>
<td>excellent</td>
<td>none visible</td>
<td>poorly cemented, slightly clayey</td>
</tr>
<tr>
<td>18</td>
<td>99</td>
<td>7123 to 7133</td>
<td>F to M sandstone</td>
<td>9 of 10</td>
<td>good</td>
<td>none visible</td>
<td>large drilling mud-cake present, flattened elongate clasts</td>
</tr>
<tr>
<td>18</td>
<td>107</td>
<td>7658 to 7664</td>
<td>VF to F sandstone</td>
<td>0.5 of 6</td>
<td>dark grey</td>
<td>poor</td>
<td>heterolithic (sand and finer material) small amount mica present</td>
</tr>
<tr>
<td>22</td>
<td>111</td>
<td>8727 to 8731</td>
<td>F to VF micaceous sandstone</td>
<td>0.2 of 5</td>
<td>dk. grey</td>
<td>poor</td>
<td>none visible</td>
</tr>
<tr>
<td>22</td>
<td>112</td>
<td>8736 to 8740</td>
<td>F to M, F micaceous sandstone</td>
<td>1 of 5</td>
<td>dk.grey</td>
<td>poor</td>
<td>none visible</td>
</tr>
<tr>
<td>22</td>
<td>108</td>
<td>7949 to 7953</td>
<td>F to M sandstone</td>
<td>1.5 of 10</td>
<td>poor</td>
<td>Oyster burrows, crypto-burrowing (Planolites), cryptically bedded</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>110</td>
<td>7949 to 7953</td>
<td>F to M sandstone</td>
<td>1 of 5</td>
<td>dk. grey</td>
<td>poor</td>
<td>none visible</td>
</tr>
<tr>
<td>23</td>
<td>111</td>
<td>8736 to 8740</td>
<td>F to M micaceous sandstone</td>
<td>1 of 5</td>
<td>dk. grey</td>
<td>poor</td>
<td>none visible</td>
</tr>
</tbody>
</table>

Table 2.2 Summary of discontinuous Hatteras Light (DR-OT -1-46) core. Data is arranged by core depth (ft), as written on core boxes, stored at the North Carolina Geological Survey. Abbreviations are as follows: Qtz quartz, VF very fine-grained, F fine-grained, M medium-grained, C-coarse-grained, VC very coarse-grained, It. light, m. medium, dk. dark. Cuttings interval studied is 6050 to 7770 ft (1844 to 2368 m).
Paleogeographic reconstructions (Figure 1.2B) show minor latitudinal differences between the basins (less than ± 5°), and all basins likely experienced similar wave energies and oceanographic conditions. The largest difference between the Baltimore Canyon Trough to the north and the Southeast Georgia Embayment to the south lies in their position relative to the ancestral Appalachian Mountains. The Baltimore Canyon Trough likely received a greater amount of siliciclastic material compared to in situ carbonate production, owing to its greater proximity to the ancient mountain range. The Southeast Georgia Embayment lies more distal and is situated at the southern end of these ancient mountains, and therefore probably received less siliciclastics. As such, deposition there was dominated by platformal carbonates. The Albemarle Embayment is located between these two basins, and records the transition between the northern siliciclastic-dominated and southern carbonate-dominated depositional regimes.

Two cored wells have proven to be particularly useful. The first, the COST B-3 well from the Baltimore Canyon Trough, is comprised of upward-coarsening, siliciclastic marine cycles, consisting of shale grading through interbedded shale and sandstone to quartz sandstone. The successions are unconformably overlain by deep shelf shales of the next cycle. A quartz sand-bearing molluscan (oyster) packstone conglomeratic unit locally is developed just below this marine unit (Figure 2.1). The second useful cored well is the COST GE-1, located in the Southeast Georgia Embayment. The cored sections of the well are dominated by skeletal-oooid grainstones underlying bedded anhydrite, interspersed with quartz sand-bearing miliolid foraminiferal wackestones to packstones. Erosional surfaces are commonly present in the skeletal-oooid grainstones, which generally overlie molluscan packstones and thin, shale-rich beds (Figure 2.2). More
Figure 2.1 Description of core 2 of the offshore COST B-3 well situated in the Baltimore Canyon Trough. This core is representative of the siliciclastic dominated intervals and captures several of the siliciclastic lithofacies types. Note the ~10 m (~30 ft) coarsening upward cycles delineated by flooding surfaces (FS – see chapter 4 for interpretation). Well location is shown on figure 1.1A (well #2).

<table>
<thead>
<tr>
<th>Location</th>
<th>Core Number</th>
<th>Date</th>
<th>Geologist</th>
<th>Horizon</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>COST B-3</td>
<td>F2</td>
<td>15/07/2005</td>
<td>B. Coffey/R. Sunde</td>
<td>Fig. 1 of 1</td>
<td></td>
</tr>
</tbody>
</table>

- **Lithology**: Conglomerate, M-VF Quartz Sandstone, Shale-Siltstone, VC-M Quartz Sandstone
- **Lithology Details**: Rip-ups, Horizontal Burrows, Trough Cross Beds, Root Traces?
- **Dep. Env.**: Coastal, Lower Shoreface, Upper Shoreface, Shelf, Inclined to Vertical

### Core 2, Description

- **11021 ft**: Burrow, Ripple laminated quartz sandstone, 11021 ft.
- **11016 ft**: Upper Shoreface Conglomerate M-VF Quartz Sandstone
- **11015 ft**: Lower Shoreface VC-M Quartz Sandstone
- **11010 ft**: Base Core

---

### Table: Core 2, Lithology

<table>
<thead>
<tr>
<th>Depth (ft)</th>
<th>Top Core 2</th>
<th>U15</th>
<th>Cbclnlle</th>
<th>Gralnlit</th>
<th>Typo(l)</th>
<th>Typo(l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11021</td>
<td>BP</td>
<td>BP</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11016</td>
<td>BP</td>
<td>BP</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11015</td>
<td>BP</td>
<td>BP</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11010</td>
<td>BP</td>
<td>BP</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 2.2 Description of core 3 of the offshore COST GE-1 well situated in the Southeast Georgia Embayment. This core is representative of the carbonate dominated intervals, and captures many of the carbonate lithofacies types. Well location is shown on figure 1.1A (well #8).

**Lithology**

- **Depth:** 7098.9 - 7040 ft
- **Core Number:** 3
- **Date:** 2007/7/18
- **Geologist:** B.C. & R.S.

**Description**

- **Carbonate Texture:**
  - Dolomitic mudstone
  - Shale-Siltstone
  - Anhydrite

- **Carbonate Phases:**
  - Ooid Grainstone
  - Skel Oolite
  - Ooid Grainstone

- **Pore Types:**
  - B.P.
  - B.P., M.
  - B.P., V., M.

- **Visible Porosity:**
  - Broken Shell fragment
  - Bivalve

- **Pore Texture:**
  - Dolomite-riddled and anhydrite cemented
  - Interbedded with possible paleosols.

- **Fossil Type(s):**
  - No recovery

- **Reservoir:**
  - No recovery, suspected to be shale as very top plains along grey nodular mudstone with some fish scales.

- **Topography:**
  - No recovery, suspected to be shale as very top plains along grey nodular mudstone with some fish scales.

- **Shale:**
  - No recovery, suspected to be shale as very top plains along grey nodular mudstone with some fish scales.
discussion concerning the lithologic descriptions follows below in the lithofacies section. Core descriptions of the other described core can be found in Appendix B.

Well-Cuttings Data

Fifteen oil-test wells were selected for well cuttings study, based on geographical location, thickness of study interval, and availability of complementary data sets (e.g., wireline well logs, core, biostratigraphy, and previous studies). Five wells from this list were evaluated in much greater detail, to reveal stacking patterns and geographic distributions of facies associations using petrographic analysis of well-cuttings.

For exploration wells in the Albemarle Embayment, continuous well-cuttings intervals were prepared and studied, starting approximately 45 m (150 ft) above and ending approximately 30 m (100 ft) below Brown’s et al. (1972) interpreted “Unit G”. This ensured that the complete study interval was logged, given the limited existing biostratigraphic control. For the offshore wells, only short intervals above and below the cored intervals, as well as intervals of interest that were identified from wireline logs were studied.

Well-cuttings data errors and corrections

Well-cuttings data are perhaps, the oldest data set available for studying subsurface lithologies, and are still widely used in the petroleum industry (Stolper, 1997). Cuttings yield direct lithologic information from the drilled strata, which can be used to calibrate geophysical data sets that provide more indirect assessments of rock properties.
Well-cuttings data sets, however, are subject to several collection errors that may bias the results. These include 1) contamination from previously penetrated beds (caving and recirculation), and 2) contamination from materials introduced to the well intentionally (e.g., materials to prevent loss of circulation) or unintentionally (e.g., pipe scale and bit shavings, cements used to set casing) during the drilling process (Swanson, 1981). Geophysical well logs were used to help identify intervals suspected of down-hole mixing processes. In particular, the caliper log was instrumental in identifying borehole collapse.

Well-cuttings are also subject to a sample lag time, related to the time differences that occur between the time they were drilled through and when the samples ultimately arrive at the surface where they are collected. Lag time corrections are best controlled at the well site, although if an error is suspected, it may be corrected with the aid of penetration rate (drilling-time logs) or mechanical logs (Swanson, 1981). As drilling logs were not available for the wells studied, all cuttings samples are plotted at the interval depth labelled on the cuttings sample bags.

Another data error, “spread” (also known as elutriation or differential settling) relates to the phenomenon of larger fragments tending to settle in the mud stream. This results in lithologies arriving at the surface out of order, or in a mixed state (Swanson, 1981). Use of geophysical logs may help to decipher such mixed cuttings, by tying lithologies to their expected geophysical responses.

Owing to the small size of cuttings fragments, lithologies that are characterised by larger sediment sizes may be difficult to identify in cuttings. Cuttings size is a function of the type and size of drilling tool used, and the consolidation of the drilled sediments.
Carbonate lithologies such as grainstones and boundstones, as well as clastic lithologies such as coarse-grained sandstone, breccias, and conglomerates, often are characterised by large grain sizes. The smaller well-cuttings may not incorporate enough of the texture of the rock, leading to the misidentification of rock lithology. Likewise, identification of porosity from cuttings alone is limited to pore-sizes smaller than the size of the cuttings fragments, unless inferences are made as to the nature of cuttings grain boundaries (e.g., euhedral crystals indicating the presence of a void). Wireline logs, used in conjunction with well cuttings data, were used to identify the presence of lithologies typified by large sediment calibres and their corresponding textures. Very coarse-grained cemented sandstones may be identified on the basis of preserved mineralization (cement) on grain boundaries. Although considerable variation exists in the cuttings fragment sizes within and between wells, the average cuttings fragment size in the studied wells was lower very coarse-grained sand calibres.

In rare instances, where extremely friable lithologies were penetrated, the resulting cuttings may be destroyed due to disaggregation in the drill hole, or due to the sample collection and preparation process. In these instances, only wireline logs can indicate the existence of these friable lithologies in the subsurface. To minimise the destruction of friable lithologies in this study, cuttings were washed in standing water, using a fine (30 mesh) sieve, dried, cemented in epoxy, and thin-sectioned for analysis.

**Well-cuttings sample preparation and data collection methods**

This thesis focused primarily on gathering lithologic data from well-cuttings. Results from these analyses have been incorporated with geophysical logs, the limited cores that are available, seismic data, and biostratigraphy, in order to better constrain
regional stratigraphic correlations. Cuttings analyses and interpretation was conducted in a manner similar to that proposed by Coffey (1999; see also Coffey and Read, 2002, 2004).

Well-cuttings samples from twelve wells drilled in the Albemarle Embayment, plus three from offshore wells in adjacent basins, were gently washed using a 30-mesh sieve in standing water, as the presence of friable lithologies prevented employment of higher pressure, more abrasive cleaning methods. Cuttings samples were subsequently dried using a vacuum to draw air through the sieve containing the sample.

Cuttings samples were examined with the aid of an optical microscope, to identify the proportions of carbonate versus clastic cuttings, noting fragments of lithologies that are typically more difficult to identify in thin-section. Magnetic material was removed at this stage, because these fragments are likely to be bit shavings or other metallic fragments originating from the drilling equipment. Table 2.1 summarizes the cuttings characteristics for each well.

The cuttings intervals containing more than 5% carbonate material (as determined through the stereo microscopic examination described above), friable, or unusual lithologies, were placed into paper cups, dried in an oven (~105°C for 24hrs), and set in epoxy (Petro-poxy 154). The epoxy was dyed blue for the majority of cuttings intervals, in order to more easily identify fragment boundaries and micro-porosity upon petrographic study. The cured epoxy pucks (Figure 2.3) were coarsely polished to expose the cuttings fragments, and then trimmed to thin-section dimensions. The cured epoxy pucks were subsequently professionally polished, mounted, and cut as thin-sections. Thin-sections were requested slightly thicker (45 microns) than typical geologic thin-
sections, such that carbonate textures are preserved following the staining process. All thin-sections were stained using Dickson’s solution (1965, 1966), in order to more easily identify carbonate lithologies and cements.

Five of the fifteen wells were studied in detail to accurately determine the lithology types and relative abundance in available sample intervals. These wells were chosen due to the abundance of carbonate material, large variety of lithologies, thickness of the study interval, and their downdip positions. Four of these wells are from the Lower Cretaceous of the Albemarle Embayment (DR-OT-3-65, DR-OT-2-65, HY-OT-1-65, and DR-OT-1-46), and one offshore well is from the Southeast Georgia Embayment (COST GE-1). The lithology types and proportions of lithologies of the cuttings intervals that were not thin-sectioned were determined using a binocular optical microscope, using appropriate aids such as carbonate stains (Alizarin Red) and charts to aid in the
estimation of particle abundances (Swanson, 1981). These proportions were normalized to one hundred percent. Thin-sectioned intervals were studied petrographically. Cuttings fragments were systematically point counted, to determine the abundances of each lithology. On average, greater than one hundred cuttings fragments were counted per thin-section.

The graphical method used to illustrate the cuttings data involved plotting depth along the vertical axis scaled at the same ratio as the geophysical well logs, in order to allow easy comparison of the data sets. The horizontal axis records the percent abundance of the cuttings lithologies, grouped by the lithofacies descriptions (below). Lithofacies are plotted from left to right in an order approximating the interpreted progressive basinward deposition of lithologies (see Chapter 4 for the basis of this interpretation). This method allows easy identification of vertical changes in the abundance of cuttings lithology types (Figure 2.4 shows an example), and was applied consistently to all wells.

The raw point-count data for thin-sectioned cuttings intervals and the percent abundance of lithofacies types for non-thin-sectioned intervals are reproduced in Appendix C. Cuttings percent plots can be found in Appendix D.

**Lithologic column construction method**

Upon completion of the detailed study of well cuttings from the four oil test wells in the Albemarle Embayment, lithologic columns were generated by comparing detailed well-cuttings lithology data with geophysical well logs and available core from the wells (only one well, DR-OT-1-46, has discontinuous core). Lithologic column construction was not attempted for the COST GE-1 well, as studied cuttings intervals were not continuous, and the well-cuttings interval is only 9.1 m (30 ft).
Figure 2.4 Portion of the DR-OT-2-65 well showing example of method and data used for construction of preliminary lithofacies column. First column at left is lithologic column produced by Brown and others (1972) for comparison. Legend for this column can be found in figure D.5 of appendix D. Middle left are the wireline logs available for this well. Note that the scale on the bulk density log is likely erroneous as the values do not match the lithologies observed in cuttings. Therefore only the shape of the curve was used to judge relative densities and not the absolute value. Middle is the cuttings percent abundance, grouped as per the lithofacies descriptions in this chapter. See appendix C for raw data. Arrows indicate repetitive successions described further in chapter 4. Middle-right is the resulting lithologic column. The lithofacies column was produced in a top down manner, to identify first appearances and/or increases of specific lithologies in the cuttings data, while tying the cuttings lithofacies to wireline responses. Legend for two lithofacies columns is at right, or alternatively figure D.7.
The lithologic column was constructed in a top down direction in order to identify first appearances and/or increases in specific lithologies in the cuttings data. The vertical resolution of the columns is typically equal to the vertical scale of the cuttings data (3 m, 10 ft). However, where geophysical logs indicate a change in lithology, and where cuttings data indicate more than one lithology present in abundance, the vertical resolution of the interpreted lithologic column was adjusted accordingly (Figure 2.4).

**Cuttings fragment types and lithologies**

Numerous cuttings fragment types and fragment lithologies are present in a single well-cuttings sample interval. Some cuttings fragments are artefacts of the drilling and sample collection process. Below is a description of these so-called ‘false’ fragment types, and how they are distinguished from the ‘true’ cuttings lithologies. These fragments were not tabulated in the rock fragment grain counts (Appendix C). It is important to understand the petrographic properties of these ‘false’ fragments in order to confidently distinguish them from the actual rock samples.

**Drill Mud:** These dried drill mud fragments are typically light brown to grey in colour, or, more rarely, red. In thin section, they are brown to light grey, and are present in moderate quantities in most of the studied sample intervals. Fragments consist dominantly of silt-sized quartz and other clay-sized siliciclastic material. As such, these fragments show a strong resemblance to siltstone and shale in thin-section.

Dried drill mud fragments are generally well rounded (due to slight abrasion during the cuttings washing process) and possess fractures and diffuse grain boundaries (due to their poorly consolidated nature, which allows the epoxy to infiltrate fragment margins). Fragments are poorly sorted, though some fragments contain convoluted
laminations (perhaps owing to the flow of fluids in the well cuttings collection apparatus at the drill site; and/or later plastic deformation when the drill mud was slightly wet). Larger drill mud fragments may incorporate fragments of actual rock (Figure 2.5A). Drill mud fragments can be distinguished by their spherical grain shapes, diffuse grain boundaries, fragment fracture patterns, poor sorting, and convoluted laminations.  

Modern plant material: In cuttings form, these fragments are a light brown to grey colour, whereas in thin section, they are a light red or orange colour (isotropic under crossed polars). Commonly, the plant cell walls are visible under high magnification in thin section.

These fragments are rarely present, though they are abundant where they occur. Most often interpreted to be splinters of wood, these are thought to be the result of contamination of the drilling mud. These may have been added to the drilling mud stream accidentally, or may represent plant material that was added intentionally to control drilling mud loss at permeable intervals. Optically and petrographically, they are easily distinguished as plant fragments, and most were removed during the sample-washing and preparation process.  

Metal Shards: These fragments are black, rusty, or metallic in colour. They are typically elongate in shape and are magnetic. In thin section, these fragments are opaque.

These fragments are present in trace quantities in nearly all well cuttings intervals. The metallic fragments most likely originated as bit shavings or other fragments liberated from the drilling equipment. These fragments were removed during the washing process with the aid of a magnet. Unfortunately, during the early sample preparation (uppermost portion of the Marshall Collins Well), these fragments were not
Figure 2.5: A: Drill mud; B: Coal; C: Coal and ostracode shale; D: Coarse-grained quartzose sand.

A: Drill mud containing glauconite (G), anhydrite (A), cryptic packstone (Pk), and fine-grained skeletal wackestone (Wk). Plane polarized light [PPL]. Well: DR-OT-2-65; 6260-6270 ft (1908-1911 m).

B: Coal containing disseminated, parallel laminations of pyrite (Py). Photograph of thin-section using optical microscope, reflected light. Well HY-OT-1-65; 5850-5860 ft (1783-1786 m).

C: Coal seam overlain by ostracode-bearing shale. The contact between lithologies was not preserved in core. Well COST B2; 13447 ft (4099 m).

D: Loose, coarse-grained quartzose sand. Cross polarized light [XP]. Well: DR-OT-3-65; 4310-4320 ft (1314-1317 m).
removed, and therefore comprise a large proportion of the opaque minerals in thin section.

Lithofacies Descriptions

Lithofacies descriptions are based primarily on thin-sectioned well-cuttings observations. Lithofacies abundances, associations, and geographic distributions in well-cuttings are also described. Cuttings descriptions are supplemented by core data, where applicable, as well as with geophysical well logs. Wireline log responses were evaluated using analogous cored intervals and the lithofacies columns of the HY-OT-1-65 and DR-OT-2-65 wells. These two wells were chosen because, the HY-OT-1-65 well does not appear to suffer large borehole washouts (as indicated by the caliper log), and the DR-OT-2-65 lies in a more central location within the downdip Albemarle Embayment. Further, these two wells have more complete geophysical well log suites. Due the limited aerial distribution of certain lithofacies types, other wells within the Albemarle embayment were used more sparingly to evaluate petrophysical properties.

Lithofacies are divided into two groups. The first, the Siliciclastic Lithofacies Types, comprise coal, quartzose sandstones, siltstones, shales, and glauconitic sandstones. The second, the Carbonate Lithofacies Types, comprise evaporites, limestones, and marls. Lithofacies are described in an order that approximates their interpreted depositional position along a marginal- or non-marine to deep-marine trend (see Chapter 4 for interpretation).
Classification of sandstones adopted in this study is that of Pettijohn et al. (1988). Dunham’s (1962) carbonate classification scheme is used to characterise the carbonate dominated sediments. Table 2.3 summarizes the key lithologic features of the lithofacies.

**Siliciclastic Lithofacies Types**

**Coal:** Coal fragments are identified as black, carbonaceous fragments that are opaque in thin section, with slight dark brown-red isotropic portions where the fragment is thinner. The original plant types could not be identified. Associated pyrite is commonly disseminated in parallel, discontinuous bands (Figure 2.5B).

This cuttings type is locally present in small quantities within the updip wells. It is typically associated with coarse-grained quartz sandstone, fine- to medium-grained quartz sandstone, siltstone, and shale. Identification of coal fragments may have been underestimated in some samples, due to difficulties in differentiating them from other opaque fragments in thin-section.

A small portion of a coal seam was penetrated by the COST B-2 cored interval (Figure 2.5C). In that locality, the coal is overlain by an ostracode-bearing shale. Coal also was observed in the first cored interval of the offshore Shell 93-1 well (offshore Baltimore Canyon Trough). In this core, the carbonaceous fragments are present in very fine-grained lithic sandstones. Broken bivalve fragments are also common in the sandstone. Traces of carbonaceous material (identified as roots) can also be found at the top of some of the clastic, coarsening-upward successions of the offshore COST B-3 well.
<table>
<thead>
<tr>
<th>Lithofacies:</th>
<th>Coal</th>
<th>Coarse-Grained Quartz Sandstone</th>
<th>Skeletal Quartz Sandstone</th>
<th>Chert</th>
<th>Graphitic Siltstone</th>
<th>Glauconitic Siltstone</th>
<th>Quartz Sand</th>
<th>Sandstone</th>
<th>Foraminifera Shale</th>
<th>Shale</th>
<th>Sandstone</th>
<th>Siltstone</th>
<th>Algal Laminites</th>
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</thead>
<tbody>
<tr>
<td>Colour:</td>
<td>Black</td>
<td>Tan to white</td>
<td>Light grey to white</td>
<td>Dark grey</td>
<td>Light brown</td>
<td>Light grey to white</td>
<td>Light brown to brown</td>
<td>Light brown</td>
<td>Tan to white</td>
<td>Light grey to white</td>
<td>Light grey to white</td>
<td>Light brown to white</td>
<td>Light brown to brown</td>
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<tr>
<td>Constituents:</td>
<td>Coal; pyrite</td>
<td>Individual grains of quartzose sandstone</td>
<td>Dominantly fine- to medium-grained, fine- to medium-grained, fine- to medium-grained, fine- to medium-grained, medium-grained, medium-grained, medium-grained, medium-grained, medium-grained, medium-grained</td>
<td>Chert</td>
<td>Anhydrite and/or preserved as carbonates</td>
<td>Associated with calcareous fossiliferous ooze</td>
<td>Dominantly fine- to medium-grained, fine- to medium-grained, fine- to medium-grained, fine- to medium-grained, fine- to medium-grained, fine- to medium-grained, fine- to medium-grained, fine- to medium-grained, fine- to medium-grained, fine- to medium-grained</td>
<td>Loose sand</td>
<td>Dominantly fine- to medium-grained, fine- to medium-grained, fine- to medium-grained, fine- to medium-grained, fine- to medium-grained, fine- to medium-grained, fine- to medium-grained, fine- to medium-grained, fine- to medium-grained, fine- to medium-grained</td>
<td>Rare sandstone</td>
<td>Rare sandstone</td>
<td>Rare sandstone</td>
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<td>Biota:</td>
<td>None identified</td>
<td>None identified</td>
<td>Disarticulated, abraded bivalves, planktonic foraminifera, rare echinoderms.</td>
<td>None identified</td>
<td>Rare planktonic foraminifera</td>
<td>Rare planktonic foraminifera</td>
<td>None identified</td>
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<td>Rare planktonic foraminifera</td>
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<td>Occurrence:</td>
<td>Dominantly in the updip wells, northern portions of the basin; but more common in the downdip and basin. Typically associated with non-fossiliferous sapropelic shales. May have a well preserved algal laminites.</td>
<td>Small quantities, associated with non-fossiliferous sapropelic shales. May have a well preserved algal laminites.</td>
<td>Small quantities, associated with non-fossiliferous sapropelic shales. May have a well preserved algal laminites.</td>
<td>Rarely present, found in small quantities, associated with non-fossiliferous sapropelic shales. May have a well preserved algal laminites.</td>
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<td>Core:</td>
<td>Coal bed underlyng 136-146 cm, coarse-grained sandstone to siltstone, particularly in the updip wells, northern portions of the basin. Associated with carbonates, skeletal-bearing quartzose sandy laminites.</td>
<td>Coarse-grained sandstone to siltstone, particularly in the updip wells, northern portions of the basin. Associated with carbonates, skeletal-bearing quartzose sandy laminites.</td>
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<td>Lithofacies:</td>
<td>Miliolid</td>
<td>Ooid Grainstone</td>
<td>Skeletal Grainstones</td>
<td>Miliolid and Pelletal Skeletal Grainstones</td>
<td>Pelletal Skeletal Grainstones</td>
<td>Miliolid and Ooid Grainstones</td>
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<td>Massive Miliolid Packstone and Sandy Lime Mudstone</td>
<td>Variable fine-grained skeletal material commonly dominated by foraminifera, corals and brachiopods, with uncommon benthic foraminifera and algae.</td>
<td>Miliolid skeletal packstone and sandy lime mudstone with associated skeletal fragments.</td>
<td>Miliolid skeletal packstone and sandy lime mudstone with associated skeletal fragments.</td>
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<td>Massive and Channel Miliolid Packstone</td>
<td>Variable fine-grained skeletal material commonly dominated by foraminifera, corals and brachiopods, with uncommon benthic foraminifera and algae.</td>
<td>Miliolid skeletal packstone and sandy lime mudstone with associated skeletal fragments.</td>
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**Occurrence:**
- Present in small quantities within carbonate mudstones or in small intervals within facies types that consist of carbonate mudstones.
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**Core Sample:**
- Present in small quantities within carbonate mudstones or in small intervals within facies types that consist of carbonate mudstones.
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- Present in small quantities within carbonate mudstones or in small intervals within facies types that consist of carbonate mudstones.

**Lithology:**
- Present in small quantities within carbonate mudstones or in small intervals within facies types that consist of carbonate mudstones.
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**Biota:**
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Wireline logs from coal beds have low gamma ray (20-40API) and density (2.2-2.3g/cm$^3$) values. Sonic (interval transit time) travel times are generally slow (120-100μs/ft), and caliper logs indicate minor borehole washout.

**Coarse-Grained Quartz Sandstone:** Coarse-grained quartz sandstones are colourless in thin-section. Grain sizes are typically greater than medium-grained sand, and therefore rarely is more than one grain captured in a cutting fragment of this lithofacies. In cuttings samples from the Albemarle Embayment, this lithofacies comprises individual well-rounded grains of monocrystalline quartz (dominant), polycrystalline quartz, feldspar, and chert (rare). The grains are well rounded, and do not display cemented rims in thin-section (Figure 2.5D) indicating potential for preserved porosity in the subsurface.

This lithofacies is more common in the northern portions of the basin, particularly in intervals lacking carbonate material. Isolated quartzose sand grains rarely constitute a significant portion of the cuttings fragments.

This lithofacies was observed in the poor quality core from the Albemarle embayment (Hatteras Light well – DR-OT-1-46) at several depths. The medium- to coarse-grained sandstone intervals are poorly cemented. Most appear intensively bioturbated (bioturbation index [BI]: 4-5), and compositions observed include sub-lithic quartz arenites, lithic arenites, and lithic-arkosic arenites.

Cemented coarse-grained quartz sandstones were also observed in core from the COST B-3 offshore well, drilled in the Baltimore Canyon Trough to the north. This lithofacies is found at the top of a coarsening-upward siliciclastic succession. It possesses root traces and/or large burrows that result in finer-grained sandstone being juxtaposed
alongside the coarse-grained sandstone. Sparse, broken, large oyster fragments are also present. This unit is approximately 1 m (3 ft) thick, and is sharply overlain by a conglomerate with quartz granules admixed with carbonate allochems (e.g., oncocoids/oyster fragments). The conglomerate is hematite cemented and contains disseminated pyrite. It also has large burrows, and is approximately 0.75 m (2.5 ft) thick.

Wireline logs from the coarse-grained sandstones in the DR-OT-3-65 well indicate a moderately clean gamma ray signature (80-110 API), and slow interval travel times (120-100μs/ft). A bulk density log was not collected for this well. The caliper log indicates some borehole collapse; thus, the sonic log response may be unreliable. Borehole rugosity and slow travel times support the observation that this lithology is poorly cemented and porous.

*Quartz Sandstone:* The quartz sandstone lithofacies is dominated by sub-arkosic arenites. It is typically light grey to white in colour, and more rarely may have a red colour imparted by the suspected presence of hematite. In thin section, these fragments are commonly colourless. Grain sizes vary, but are typically very fine-grained sand (rarely coarser than medium-grained). Grains are generally sub-rounded and are moderately-to-well-sorted. The sandstone fragments are dominantly ferroan calcite cemented, with more localized non-ferroan calcite. Gypsum, anhydrite, or silica cements are locally present. Biotite and muscovite grains are common in the more feldspar-rich samples. Glaucony and opaque minerals (dominantly pyrite) are common in more quartz-rich and finer-grained samples. Rare porosity is preserved between the particles. (Figure 2.6A)
Figure 2.6 A: Sub-arkosic arenite; B: Bioturbated quartz sandstone; C and D: Skeletal quartz sandstone.

A: Quartzose sandstone cuttings fragment in thin-section. Ferroan calcite-cemented sub-arkosic arenite. Carbonate stain indicates multiple cement generations – early calcite followed by ferroan calcite. Grains are upper very fine-grain sized. PPL. Well DR-OT-2-65; 5260-5270 ft (1603-1606 m).

B: Bioturbated, quartz sandstone. Pervasively bioturbated (Paleophycus and Planolities are among the identified traces), fine- to medium-grain sized quartz-feldspar arenite from the Hatteras Light well (core # 109). Unlike most cores of this lithology, this interval is well cemented by calcite. 7766-7776 ft (2367-2370 m).

C: Skeletal quartz sandstone. Sandstone classification indicates this is sub-arkosic arenite. Allochem is a neomorphically replaced mollusc fragment. Carbonate stain indicates multiple cement generations, with early non-ferroan calcite (stained pink) followed by ferroan calcite (stained blue). PPL. Well DR-OT-2-65; 5260-5270 ft (1603-1606 m).

D: Skeletal quartz sandstone from the Hatteras Light well, core interval #67. Skeletal fragments are disarticulated oysters (bivalves). 5582-5587 ft (1701-1703 m).
Fragments of this lithology are present in nearly all well-cuttings intervals, locally in abundance. This lithofacies is distributed throughout the basin, but is more common in the updip (western) and northern portions of the Albemarle Basin.

Quartz Sandstones are observed in core from the Albemarle Embayment (Hatteras Light well – DR-OT-1-I-46) at several depths throughout the study interval. The dominantly fine-grained (up to medium-grained) sandstone intervals are generally poorly cemented, with local, thin, tightly calcite-cemented intervals present. Sandstones commonly appear intensively bioturbated (BI 4-5; planolities, and asterosoma observed), with rare oscillatory ripples or flaser bedding preserved. Classifications observed include sub-lithic quartz arenites, lithic arenites, and lithic-arkosic arenites (Figure 2.6B).

This lithofacies is present near the tops of coarsening-upward packages in the COST B-3 offshore well (Figure 2.2). Symmetrical (rare asymmetrical) ripples, rare parallel laminations, and trough cross-stratification are associated with this lithofacies in core. Burrowing in these units is uncommon (BI 2), with local zones of intense bioturbation (BI 4-5; planolities, chondrites, schaubyclindrichmus and ophiomorpha observed). Sandstones grade up into coarse-grained quartz sandstones, or are unconformably overlain by shales of the next coarsening-upward package. Shales and siltstones underlying this lithofacies show a gradual upward increase in the abundance and thickness of quartz sandstone beds. The thickness of the quartz sandstone beds in the COST B-3 well ranges from 1.5 to 6 m (5 to 20 ft).

In the COST GE-1 well (core 3), micaceous, well-sorted, quartz sandstones possessing small carbonaceous fragments, are found at the base of the cored interval. Planar and oscillatory ripple laminations are preserved, though generally the interval is
intensely bioturbated (BI 4-5; Figure 2.2). The minimum thickness of this unit is 2.5 m (8 ft) as the lower contact was not captured in the core. The upper contact is suspected to be sharp, capped by shale, but core recovery was poor in the overlying interval.

On wireline logs, sandstone have low gamma-ray (30-60API) and density (2.2-2.4g/cm³) values. They also display moderate travel times (100-60μs/ft) on sonic logs.

Skeletal Quartz Sandstone: Skeletal quartz sandstones are dominated by sub-arkose arenites with skeletal fragments. Fragments of this lithofacies are light grey or white in colour in loose cuttings. Grain-size distributions and textures are similar to that of the quartz sandstones. Calcareous allochems are predominantly derived from mollusc bivalves (oysters), with rare echinoderm fragments, and ooids. Bivalves are disarticulated, abraded, and are rarely longer than 2 mm. They also are typically neomorphically replaced with sparry ferroan calcite (Figure 2.6C). Rare accessory minerals include opaques (mainly pyrite) and glaucony. In most instances, all interparticle porosity is filled with the ferroan calcite cement. Non-ferroan calcite is rare. Porosity is seldom preserved, but locally may occur between particles or as skeletal molds.

Fragments of this lithology were observed in nearly all well cuttings intervals throughout the basin, though generally they are less abundant than the quartz sandstone fragments. This lithology may be under-represented because of its general similarity with quartz sandstone cuttings fragments that lack bioclastic debris.

Skeletal quartz sandstones were observed in core from the Albemarle Embayment (Hatteras Light well – DR-OT-1-46) at several depths. The dominantly fine-grained (up
to medium-grained) sandstone intervals are densely cemented with calcite, and are typically intensively bioturbated (BI 4-5; *palaeophycus*, *planolities*, *asterosoma*, and *opiomorpha* among identified traces). Sandstone types observed include sub-lithic quartz arenites, lithic arenites, and lithic-arkosic arenites. Skeletal fragments most commonly comprise disarticulated bivalve shells that vary from mm to cm in length (Figure 2.6D).

This lithofacies was also observed in the COST B-2 and B-3 offshore wells. However, the abundances and sizes of the bivalve shell fragments are significantly decreased in these locations.

Gamma-ray logs derived from skeletal sandstones show low (40-60API) values. Density logs indicate a moderate density (2.5-2.6g/cm³) lithology. Sonic logs record fast travel times (90-50μs/ft), owing to the well-cemented character of this lithology. Caliper logs rarely indicate borehole washouts.

Siltstone: The siltstone lithofacies consists primarily of silt-sized quartz and feldspar floating in a phyllosilicate clay matrix. Rare glaucony can locally be observed. Fragments are grey to brown in the cuttings and light brown to near colourless in thin-section. Local dark brown and red siltstones have been identified as well. Generally, this lithology lacks fossil material. Rare accessory minerals include glaucony and opaque minerals (mainly pyrite). Some siltstone fragments are elongate or platy in shape, demonstrating fissility. Rare, laminated fabrics are present in the cuttings (Figure 2.7A).

Fragments of this lithology are abundant in most cuttings intervals throughout the basin. The siltstone lithofacies is typically associated with shale. Siltstones may be over-represented in grain counts, due to its general resemblance to dried drill mud fragments.
Figure 2.7 A: Siltstone; B: Shale grading to siltstone; C: Planktonic foraminifera-bearing siltstone; D: Non-fossiliferous shale.


B: Shale grading to siltstone that is thoroughly bioturbated. Well: DR-OT-1-46, core interval 104; 7400-7410 ft (2256-2259 m).

C: Planktonic foraminiferal-bearing (F) siltstone. Note the presence of rare sponge spicule (S). PPL. Well: DR-OT-1-46; 6960-6970 ft (2121-2124 m).

Dark grey, clayey siltstone in the Hatteras Light well core gradually coarsens upward into fine-grained quartz sandstone. It displays intense bioturbation (BI 4-5) and contains 1-2 mm-sized carbonate fragments that resemble echinoderms (Figure 2.7B).

A similar coarsening-upward profile is observed in core 2 of the COST B-3 well: fissile, quartzose siltstone and shale beds overlie a skeletal quartz granule lag. The shales and siltstones coarsen upward to fine-grained quartzose sandstone (Figure 2.1).

In core 3 of the COST GE-1 well, centimetre-scale, quartzose siltstone beds are interspersed within chicken-wire anhydrite. Thin, hematite-rich interbeds of siltstone also are found within the skeletal ooid grainstone beds near the top of the core (Figure 2.2).

Wireline gamma ray logs from the siltstones indicate a clay-rich lithology (>80API), consistent with the high amounts of clay mineral material observed in thin section. Caliper logs commonly indicate borehole washout, rendering the reliability of the density and sonic logs uncertain (recordings are 2.3-2.6g/cm³ and 100-80μs/ft, respectively).

**Planktonic Foraminifera-Bearing Siltstone:** Fragments of planktonic foraminifera-bearing siltstone are similar to the previously described siltstone. The facies is distinguished from siltstones due to the presence of planktonic foraminifera (Figure 2.7C). Glaucopy and opaque minerals (mainly pyrite) also are more common.

Planktonic foraminifera-bearing siltstones form a small percentage of cuttings fragments, where present. It is more common in the downdip and northern wells, typically associated with marls or diatomaceous shales.
This lithology was not observed in core. Due to the limited occurrence of this lithology, wireline log responses could not be confidently evaluated. A response similar to that of marl and/or diatomaceous shale, however, is expected.

**Non-Fossiliferous Shale:** Non-fossiliferous shale fragments consist primarily of clay sized material, with local interstitial silt-sized quartz. In cutting fragment form, its colour is dominantly dark grey to black. In thin-section, this lithofacies is light brown-grey, and also rarely dark-brown, red, or green. Green-coloured shale is common only in the lower parts of the studied section, and shows what resembles slickenslide surfaces on the cuttings boundaries. This lithofacies is friable. It commonly displays laminations that favour fissility, resulting in elongate and platy fragments (Figure 2.7D).

This lithology is abundant throughout the basin, comparable to the siltstone lithofacies. It may be over-represented in grain counts due to its resemblance to dried drill mud fragments. In addition, the friable character causes it to readily break into smaller fragments during sample washing (and presumably during drilling).

Non-fossiliferous shale is rarely penetrated by core. The best example is from core 2 of the COST B-3 well, which has fissile dark grey to black quartzose siltstone and shale (Figure 2.1). The shale-rich unit overlies a skeletal quartz granule lag deposit, and coarsens upward to fine-grained quartzose sandstone. Other examples were observed in the Hatteras Light well (Figure 2.7B) and in core 3 of the COST GE-1 well, but sample preservation and recovery from these intervals is poor.

Gamma-ray wireline logs from shale-rich intervals indicate a high values (>100API). The caliper log typically indicates borehole washout, rendering the reliability
of the density and sonic logs uncertain (responses are 2.3-2.6 g/cm³ and 100-80 μs/ft, respectively).

**Diatomaceous Shale:** Diatomaceous shale fragments consist dominantly of diatoms, claysized material, and rare sponge spicules (Figure 2.8A). Planktonic foraminifera, silt-sized quartz, and glaucony are also present, though are uncommon elements. Colour is light brown in thin-section, and fragments generally are elongate and angular in shape.

Diatomaceous shale fragments are rare, most commonly found in the down-dip and northern wells. They are found in association with marl and planktonic foraminifera-bearing siltstone lithofacies. Diatomaceous shale was not observed in core.

Well-log responses from diatomaceous shales in the DR-OT-3-65 well show high gamma ray (>120 API) values. Variable caliper responses indicate abundant borehole washout, rendering the reliability of the sonic log uncertain (interval transit time varied from 120-80 μs/ft). A bulk density log was not collected for this well.

**Glauconitic Sandstone:** The glauconitic sandstone lithofacies comprises fine- to medium-grained glauconitic sandstone, as well as individual grains of glaucony (well rounded to angular in shape). This lithofacies is dark green in cuttings format, and pleochroic green in thin-section. Variable amounts of phosphate may be associated (Figure 2.8B). Glauconitic sandstones typically include very fine-grained quartz and mollusc skeletal fragments. This cuttings type is rare.

Glauconitic sandstones were not observed in core, but glaucony was observed as a minor component in quartz granule, oyster-bearing lag deposits that cap upward-
Figure 2.8 A: Diatomaceous Shale; B: Hardground fragment; C: Chert; D: Algal laminite.

A: Diatomaceous Shale. Note the large diatom (D) in center. PPL. Well DR-OT-3-65; 4630-4640 ft (1411-1414 m).

B: Phosphatized (P) fine- to medium-grained glauconitic (G) sandstone interpreted as a hardground fragment. Lower very fine-grained quartzose (Q) sand is also present. PPL. Well DR-OT-2-65; 6500-6510 ft (1981-1984 m).

C: Chert (C); possesses planktonic foraminifera (PF), silt-sized glaucony (G), silt-sized quartz (Q), and minor amounts of phosphate (P). XP. Well: DR-OT-1-46; 6620-6630 ft (2018-2021 m).

D: Algal laminite, identified based on discontinuous, wavy laminations. Re-crystallization of calcite micrite (pink) has resulted in some ferroan calcite microspar (purple). Bright areas within the grain are chert (C). PPL. Well: DR-OT-3-65, 4730-4740 ft (1442-1445 m).
coarsening packages in the COST B-3 and COST GE-1 wells (Figures 2.1 and 2.2 respectively). Glaucony is disseminated throughout the units as very fine-grained sand. The lag deposits are sharply overlain by fissile quartzose silty shale deposits.

Due to the small abundance of glaucony-rich sands, geophysical log responses could not be confidently evaluated.

**Chert:** Chert fragments are generally colourless in thin-section. Fossils found within chert fragments include planktonic foraminifera and minor proportions of molluscs (Figure 2.8C). Silt-sized glaucony, rare quartz grains, and opaque minerals (mainly pyrite) are also present locally.

Chert is most commonly found in small quantities at the base of the studied section. Chert cuttings fragments are commonly found associated with glaucony, phosphate, and algal laminites (Figure 2.8D).

This lithology was not observed in core. Due to its uncommon occurrences, wireline well log responses could not be confidently evaluated.

**Carbonate Lithofacies Types**

**Evaporites (Anhydrite and/or Gypsum):** Evaporites preserved as cuttings are exclusively minerals of CaSO₄ (anhydrite and gypsum). Anhydrite is generally white in cuttings fragments, whereas gypsum is typically colourless. Both are colourless in thin-section when illuminated by plane-polarised light (PPL). Anhydrite, however, can be easily distinguished from gypsum when illuminated by cross-polarised light (XP) due to its 3rd order birefringence (gypsum displays low birefringence). Anhydrite fragments comprise
fine, randomly oriented needle-like crystals (Figure 2.5A). Gypsum generally forms elongate or platy crystals. Both cuttings types locally contain admixed fine quartz sand.

This lithofacies is rare. It is most common in southern and downdip portions of the basin. It is found in association with algal laminates, lime mudstones, quartzose sandy miliolid packstones, and ooid grainstones.

Evaporites are present in cores 2 and 3 of the COST GE-1 well in the following manners: a) as a cement in ooid-skeletal grainstones; b) as centimetre-sized nodules in lime mudstone or grainstones; c) as massive, chicken-wire anhydrite containing deformed, dolomitized or non-dolomitized lime mudstone, or siltstone interbeds (Figure 2.9A); and d) as layered evaporites (Figure 2.2). In core, thick anhydrite (~3.5m) overlies burrowed or oscillatory ripple-laminated lime mudstone-rich beds that are variably dolomitized. Ooid-skeletal grainstones generally underlie the anhydrite–lime mudstone package.

Evaporite expression on wireline logs indicate very low gamma ray values (~20API), and short sonic travel times (50-60μs/ft). Caliper logs indicate that no borehole failures occur through evaporite-rich intervals.

Algal Laminite: Algal laminites in thin section display alternating layers of blue and pink, due to the carbonate stain used (ferroan and non-ferroan calcite, respectively). This lithology is clear when it is not stained and illuminated by PPL. Laminations are undulatory and discontinuous. Laminites also commonly contain disseminated very fine-grained quartz sand (Figure 2.9B). Chert is rarely associated, and is present as discontinuous, undulatory laminae and nodules (Figure 2.8D).
Figure 2.9 A: Chicken-wire anhydrite; B: Algal Laminite; C: Miliolid packstone; D: Quartzose silty dolomitized lime mudstone.

A: Miliolid (M) wackestone, deformed within chicken-wire anhydrite (A). Thin-walled disarticulated bivalves (B) or ostracodes are present. PPL. Well COST GE-1, 6649.1 ft (2026.6 m).

B: Quartzose (Q) silty algal laminite. Re-crystallization of some of the micrite has resulted in discontinuous laminations of ferroan calcite microspar. Note that fragment is poorly washed, and possesses minor amounts of drilling mud (D) on the grain boundary. XP. Well: DR-OT-2-65; 6290-6300 ft (1917-1920 m).

C: Miliolid (M) packstone. Crystallization of some micrite (pink) to ferroan calcite microspar (blue) has imparted a grainy appearance to the matrix. Opaque minerals and local bivalve (B) fragments are present. Disseminated silt-sized quartz (Q) is present. PPL. Well: HY-OT-1-65; 6100-6110 ft (1859-1862 m).

D: Dolomitized, quartzose (Q) silty lime mudstone. Dark blue specks are scattered sponge spicules (S). Darker blue regions within the fragment are indications of between-crystal microporosity (P). This sample is from the base of the studied section of well HY-OT-1-65. PPL. 6070-6080 ft (1850-1853 m).
Algal laminites occur in small quantities in most sample intervals dominated by carbonate lithologies. It is more common in the southern and downdip portions of the basin.

The algal laminitite lithofacies were not observed in core. Owing to their small abundance, geophysical log responses could not be evaluated for the facies, though typical limestone responses are anticipated.

Miliolid Packstone and Wackestone: Miliolid packstone and wackestone fragments are white to light brown in colour. It tends to become blue stained by Dickson’s solution (1965, 1966), indicating the presence of ferroan calcite. Carbonate matrix material is commonly recrystallized to ferroan calcite microspar. Dominant fossil fragments are miliolid benthic foraminifera. Other associated fossils include bivalve, ostracode, and gastropod fragments, which typically are neomorphically replaced by ferroan calcite. Small amounts of very fine-grained quartz sand are locally associated with this lithology (Figure 2.9C).

Miliolid packstones and wackestones are locally present in small quantities within carbonate-dominated intervals. They are most commonly found in downdip and southern wells, and are associated with evaporites, quartzose sandy lime mudstones, and ooid grainstones.

In the COST GE-1 well, miliolid wackestones are present in thin-sectioned cuttings and core off-cuts. Miliolid packstones and wackestones (Figure 2.9A) are present in cored intervals of this well, and displays planar to symmetric ripple laminations. Variable, fabric-replacive dolomitization tends to destroy many of the original miliolid...
tests. Miliolid packstones to wackestones are closely associated with anhydrite, quartzose sandy lime-mudstones, and ooid skeletal grainstones in this core.

Due to their limited abundance, geophysical well log responses could not be confidently evaluated for this lithofacies, although typical limestone responses are expected.

**Quartzose Sandy Lime Mudstone:** The quartzose sandy lime mudstone lithofacies consists predominantly of micrite to ferroan calcite microspar in the shallower portions of the study interval. In deeper portions, it is more abundant, and consists of ferroan dolostone containing scattered sponge spicules. Very fine-grained sand to silt-sized quartz grains are disseminated throughout the lithofacies (Figure 2.9D).

Heavily dolomitized quartzose sandy lime mudstone can be found in cores 2 and 3 of the COST GE-1 well (Figures 2.2 and 2.10A). Thin-sections of core from quartz sandy miliolid packstones and wackestones that underwent fabric replacive dolomitization strongly resemble dolomitized quartzose sandy lime mudstone. This lithofacies is associated with evaporites and ooid skeletal grainstones.

Due to the limited abundance of quartzose sandy lime mudstone, geophysical well log responses of this lithofacies could not be confidently evaluated, although typical limestone and dolostone responses are anticipated.

**Ooid Grainstone and Packstone:** Fragments of ooid grainstone and packstone are white in cuttings form, and are typically purple in thin section due to the carbonate stain; they are
Figure 2.10 A: Quartzose silty dolomitized lime mudstone; B and C: Skeletal-ooid packstone and grainstone; D: Quartzose sandy skeletal grainstone.

A: Quartzose silty dolomitized lime mudstone. Note how the quartz (Q) and opaque minerals indicate preserved laminations. PPL. Well COST GE-1, 7053.1 ft (2149.8).

B: Mud-lean ooid (O) packstone with bivalve (neomorphically replaced) coated grains (CG). Ferroan calcite (blue) fills all void space, while small amount of preserved micrite displays a pink colour. XP. Well DR-OT-3-65; 4800-4810 ft (1463-1466 m).

C: Medium- to coarse-grained ooid grainstone from the offshore Baltimore Canyon Trough, the Shell 586-1 well. Depth 9054 ft (2759.7 m).

D: Quartzose sandy skeletal grainstone. Some of the mollusc (M) fragments have been recrystallized to ferroan calcite (M-F). Fine-grained quartz (Q) sand is clear. Ferroan microspar calcite (light blue) fills all pore space. PPL. Well DR-OT-3-65; 4570-4580 ft (1393 m).
clear where not stained. Grains are well rounded and well sorted, consisting dominantly of ooids (mainly concentrically laminated) and coated grains (Figure 2.10B). Fragments of grainstone show better sorting of grains and better rounding of allochems than packstone fragments. Grain cores include quartz and abraded skeletal fragments (likely mollusc). Fine-grained quartz sand, peloids, and round bivalve (neomorphically replaced) fragments are commonly associated. Echinoderm allochems are rarely associated.

This lithology is found in small quantities, confined to sample intervals containing abundant carbonate lithologies, most commonly in southern and downdip wells. It is typically associated with molluscan (bivalve) packstones.

Quartz-skeletal-ooid grainstone beds are common in core 3 of the COST GE-1 well (Figure 2.2). Associated skeletal fragments are dominantly abraded molluscan bivalves, with rare gastropod fragments and benthic foraminifera. Observed sedimentary structures include planar lamination, symmetric ripple laminae, and trough cross bedding. Ooid grainstones erosionally overlie fissile mudstone. Decimetre-scale grainstone beds show progressive upward increases in admixed beds of skeletal quartz sandstone and siltstone. Bed contacts are sharp, typically erosional. The ~6m ooid grainstone unit is overlain by chicken-wire anhydrite. A second skeletal-ooid grainstone unit erosionally overlies a burrowed, oscillation rippled to planar laminated dolomudstone at the top of this core. Unlike the lower ooid grainstone, this grainstone contains cm-scale interbeds of hematite-rich (red coloured) quartzose silty shale. The grainstone is tightly cemented by both calcite and anhydrite. In the Shell 586-1 well, drilled in the offshore Baltimore Canyon Trough, ooid packstones and grainstones are sharply overlain and underlain by skeletal packstones (Core #1, Figure 2.10C).
Gamma-ray wireline logs through ooid-rich intervals show generally reduced values (30-50API). Density log responses indicate relatively high densities (2.6-2.7g/cm³), and the sonic interval transit times are short (90-60μs/ft). Caliper logs indicate borehole washouts are uncommon.

**Quartzose Sandy Grainstone and Packstone:** The quartzose sandy grainstone and packstone lithofacies is identified on the basis of roughly equal proportions of quartz sand and fragmented skeletal material in the cuttings fragment. The carbonate classification scheme of Dunham (1962) has been used to identify these fragments as it was commonly observed that a micrite carbonate mud matrix is present (frequently recrystallized to ferroan calcite microspar). Fragments containing less carbonate allochems are grouped under the skeletal sandstones, following the terminology of Pettijohn *et al.* (1987).

Bivalves are the most common allochems in quartzose sandy grainstones and packstones, though echinoderms, peloids, and brachiopods are also associated. The long axis of allochems typically exceeds the dimension of the cuttings fragment itself (1-2 mm). The quartzose sand grains are typically very fine-grained. Matrix material is dominantly microspar to sparry ferroan calcite (stained blue by Dickson’s solutions, 1965, 1966, and clear when unstained; Figure 2.10D). A muddy siliciclastic matrix is rarely present, and displays a light brown colour in thin-section (Figure 2.11A). Mollusc
Figure 2.11 A: Quartzose sand-bearing packstone; B and C: Mollusc Packstone; D: Peloid packstone.

A: Quartzose sand-bearing packstone. Allochems are mollusc fragments (M). Matrix is made up of quartz silt (Q), argillaceous shale (S), and ferroan dolomite rhombs (D). PPL. Well: DR-OT-3-65; 4730-4740 ft (1442-1445 m).

B: Mollusc packstone. Majority of the shell fragments (bivalves) have been replaced with ferroan calcite microspar to spar (blue). Matrix is ferroan calcite microspar (dark blue). PPL. Well: DR-OT-2-65; 6290-6300 ft (1917-1920 m).

C: Quartzose sand-bearing mollusc packstone with uncommon miliolid benthic foraminifera (F) and glauconite (G). Bivalves (M) are replaced with ferroan calcite microspar to spar. Quartz (Q) sand is fine grained, and rare plagioclase feldspar (P) is present. Matrix is ferroan calcite microspar (purple). Black circle is an air bubble trapped under cover-slip. XP. Well: DR-OT-2-65; 5780-5790 ft (1762-1765 m).

D: Peloid packstone. Micrite matrix has been crystallized to ferroan calcite microspar. PPL. Well: DR-OT-1-46; 6950-6960 ft (2118-2121 m).
fragments are typically replaced by ferroan calcite. Non-thin-sectioned fragments of this lithofacies are white in colour.

The quartzose sandy grainstone and packstone lithofacies is present in limited quantities in most of well cuttings sample intervals throughout the basin. It is most commonly associated with bivalve packstones.

Quartzose sandy grainstone and packstone was not observed in core; however a range of skeletal sandstones to quartz sandy carbonate rocks have been observed in core. Intervals of the Hatteras Light well core (Figure 2.6D) and the Baltimore Canyon Trough offshore cores possess skeletal quartz sandstones (Figure 2.1), whereas cores from the SE Georgia Embayment contain quartzose sandy mollusc packstones and grainstones, as well as quartzose sandy ooid-skeletal grainstones (Figure 2.2).

Due to the limited abundance of this lithology, geophysical well log responses could not be evaluated, although they are expected to be very similar to those of mollusc packstones and grainstones.

**Mollusc Packstone and Grainstone:** Mollusc packstones and grainstones are light grey or white in cuttings format, and typically stain blue in thin section from Dickson’s solution (1965, 1966), indicating the presence of extensive, fabric-replacive ferroan calcite (fragments are clear when unstained). Matrix consists of ferroan calcite microspar or local sparry ferroan calcite, and most bivalve skeletal fragments are neomorphically replaced by sparry ferroan calcite (Figure 2.11B). A small proportion of coral fragments are present, and gastropods are rare. Due to diagenetic alteration and the small sizes of the cuttings fragments, bivalve types are rarely identifiable. However, unaltered oyster
fragments and, more rarely, rudists and inoceramids have been identified. Fine-grained quartz sand is commonly disseminated throughout these fragments (Figure 2.11C). Small, thoroughly recrystallized cuttings, referred to as “cryptic packstone” are included as mollusc packstones because of their close resemblance.

Fragments of mollusc packstone are abundant in most cuttings intervals throughout the Albemarle Embayment. In the COST GE-1 well, bivalve packstones typically underlie ooid-rich units, and are interbedded with thin, quartz sand-rich beds (Figure 2.2). Abrasion of the bivalve fragments is minimal. Highly abraded bivalve grainstones are closely associated with quartzose sandy ooid grainstones.

Wireline logs indicate a low radioactive signature (gamma-ray: 30-50API) for mollusc packstone and grainstone intervals. Density logs indicate a high density (2.6-2.7g/cm³), and sonic interval travel times are short (90-60μs/ft). Caliper logs indicate that borehole washout is not associated with this lithology.

Peloid Packstone: Peloid packstones consists of dark grey peloids encased in a light grey/white carbonate mud matrix. In thin section, this lithofacies is commonly a very dark blue due to carbonate staining with Dickson’s solution (1965, 1966), indicating abundant ferroan calcite. The peloids are generally fine-grained sand-sized, well-rounded, and sub-spherical (Figure 2.11D). Ooids, micrite-rimmed bivalves, and very fine-grained quartz sand are locally associated.

Cuttings of peloid packstones are sporadically distributed in small quantities within carbonate-dominated wells of the Albemarle Embayment. Thick beds of this lithology were not observed in core, but the skeletal-ooid packstone beds from the cored
intervals of the COST GE-1 well are rich in peloids (Figure 2.2). The oncoid beds of core 1 from the Shell 586-1 well contain abundant peloid grains (Figure 2.12A).

Gamma-ray wireline well logs indicate moderate radioactivity values for this lithofacies (40-70API). Density log readings and sonic interval transit times are low to intermediate (2.3-2.4 g/cm$^3$ and 90-70 µs/ft, respectively). Caliper logs indicate that borehole washouts are not pronounced.

Pelletal Packstone: In thin-section, pelletal packstones are dark purple in colour, due to staining by Dickson’s solution (1965, 1966), indicating extensive ferroan calcite. The micrite matrix shows variable amounts of recrystallization to ferroan calcite microspar. The pellets are lower very fine-grained sand sized, and are surrounded by micrite (figure 2.12B).

Pelletal packstones are locally present in very small quantities within carbonate-rich cuttings sample intervals of southern and downdip wells. This lithofacies was not observed in core. Due to its small abundance, geophysical well log responses could not be confidently evaluated, although typical limestone responses are expected.

Skeletal Packstone (Bryozoan, and/or Brachiopod): Stained thin sections of skeletal packstones are dominantly blue, due to fragment staining by Dickson’s solution (1965, 1966), indicating extensive cementation by ferroan calcite (colourless when not stained). The observed allochems include bryozoans, brachiopods, rare large benthic foraminifera, mollusc bivalves, and echinoderms (Figure 2.12C and D). Echinoderm-rich fragments locally show multiple generations of syntaxial calcite overgrowth cement (Figure 2.13A).
Figure 2.12 A: Skeletal oncoid and peloid packstone; B: Pelletal packstone; C and D: Skeletal packstone.

A: Skeletal oncoid and peloid packstone with significant argillaceous stringers visible near base. Offshore Baltimore Canyon Trough, well: Shell 586-1, 9036 ft (2754.2 m).

B: Pelletal Packstone (P). Variably quartz sand-bearing (Q), and largely altered to ferroan calcite with minor cross-cuttings calcite veins (V). XP. Well HY-OT-1-65; 5480-5490 ft (1670-1673 m).

C: Bryozoan (B) and benthic foraminifera (orbitolinid - F) packstone. Matrix in this example is quartzose silty argillaceous shale. PPL. Well DR-OT-3-65; 4570-4580 ft (1393-1396 m).

D: Pseudopunctate brachiopod-bearing packstone. Evidence of preserved porosity is based on presence of euhedral crystals lining some of the cuttings fragment boundaries (P). PPL. Well: DR-OT-3-65; 4660-4670 ft (1420-1423 m).
Figure 2.13 A: Skeletal packstone; B: Planktonic foraminifera packstone; C and D: Marl.

A: Mud lean, quartzose sandy echinoderm packstone. Carbonate stains indicate multiple cement generations: early calcite (pink) followed by a thin ferroan calcite (blue). PPL. Well: DR-OT-3-65; 4730-4740 ft (1442-1445 m).

B: Planktonic foraminifera (F) packstone. Trace glaucony (G) is present, as well as minor thin-walled bivalves (B). Matrix is predominantly micrite (dark pink), with minor ferroan calcite microspar (dark blue). PPL. Well DR-OT-2-65; 5260-5270 ft (1603-1606 m).

C: Marl with planktonic foraminifera (F), silt-sized quartz (Q), diatoms (D), and sponge spicules (S). PPL. Well: DR-OT-3-65; 4570-4580 ft (1393-1396 m).

Allochems show little evidence of abrasion. Disseminated very fine-grained quartz sand is locally admixed.

Skeletal packstones are present in small quantities throughout the basin. No particular association with other lithologies was observed.

Skeletal packstones were not observed in core. Due to its small abundance, geophysical well log responses could not be confidently evaluated, although typical limestone responses are anticipated.

**Fine-grained Skeletal Wackestone:** In thin section, skeletal wackestone cuttings fragments display a dark blue colour due to staining from Dickson’s solutions (1965, 1966), indicating the presence extensive ferroan calcite microspar in the matrix. Allochem types vary; planktonic and benthic foraminifera, and thin-walled bivalves are most common. Very fine-grained admixed quartz sand is rarely present.

Skeletal wackestones are locally present in small quantities within carbonate-dominated samples. No particular association with other lithologies was observed. This lithofacies was not observed in core.

Wireline well log responses from the HY-OT-1-65 well indicate intermediate to high gamma-ray values (40-70API) and intermediate densities (2.5-2.6g/cm³). Moderate sonic transit times (90-70µs/ft) and minor borehole washout also characterise well logs at depths corresponding to fine-grained skeletal wackestone cuttings.

**Planktonic Foraminifera Packstone and Wackestone:** In thin section, planktonic foraminifera packstones and wackestones display a predominantly blue colour due to the
carbonate stain (Dickson’s solution, 1965, 1966). The blue colour indicates the presence of abundant ferroan calcite. Fragments are clear when unstained. Well-sorted, thin-walled, very fine-grained to silt-sized planktonic foraminiferal tests dominate the unit. Locally, very fine-grained sand- to silt-sized quartz and glaucony are present (Figure 2.13B). Small, thin walled bivalves (<0.5mm) are rarely present.

Planktonic foraminifera packstones and wackestones are locally present in small quantities within carbonate-dominated intervals. This lithofacies is most commonly found in downdip wells, and is associated with marl and lime mudstone.

Planktonic foraminifera packstones and wackestones were not identified in core. Due to its paucity, geophysical well log responses could not be confidently evaluated, although typical limestone responses are suspected.

Marl (Argillaceous Lime Mudstone): Marls are highly variable in expression. Generally, they are light brown to colourless in thin section, and stain both pink and blue (by Dickson’s solution, 1965, 1966), indicating the presence of non-ferroan and ferroan calcite components, respectively. In the shallower parts of the study section, this lithofacies is fossiliferous, with planktonic foraminifera and sponge spicules common. Variable amounts of glaucony, and silt-sized quartz are present (Figure 2.13 C). In deeper portions of the study section; marls dominantly comprise clay-sized material containing variable amounts of calcite (ferroan and non-ferroan), dolomite, and admixed argillaceous shale, imparting a brown colour to the fragments in thin section (Figure 2.13D and 2.14A).
Figure 2.14 A: Marl; B: Lime mudstone; C and D: Hardground.

A: Argillaceous lime mudstone (Marl). This sample possesses silt-sized ferroan dolomite rhombs (D), disseminated lime mud (pink), disseminated silt-sized quartz (Q), and argillaceous shale (brown). This sample is from the base of the studied section of well HY-OT-1-65. PPL. 6100-6110 ft (1859-1862 m).

B: Lime mudstone, altered to ferroan calcite microspar. The cross-cuttings fractures (F) may be the result of breakage during sample drilling, collection, or processing. XP. Well HY-OT-1-65; 5460-5470 ft (1664-1667 m).

C: Phosphatic hardground fragment. Phosphate (P) is brown in colour, and possesses an unknown opaque mineral (O), possible green glaucony (G), as well as an encrusting barnacle (B). Remnant of foraminifera (F) and a silt-sized grain of quartz (Q) are present. PPL. Well DR-OT-3-65; 4830-4840 ft (1472-1475 m).

D: Hardground fragment. Phosphate (P) is brown in colour. Abundant foraminifera (F) and bivalve (B) fragments are variably replaced by and cemented with ferroan calcite. Glaucony (G) is also present. PPL. Well DR-OT-3-65; 4750-4760 ft (1448-1451 m).
Marls are present in small to moderate quantities in carbonate-dominated cuttings intervals of downdip and southern wells, where it is associated with lime mudstone. This lithofacies was not specifically observed in core.

The gamma-ray wireline log indicates an intermediate radioactivity values (50-80API) for marl-rich intervals. Low densities (2.3-2.4g/cm³) and moderate sonic transit times (90-70μs/ft) are common through intervals wherein abundant marl cuttings fragments are found. The caliper log typically indicates minor borehole washout.

**Lime Mudstone:** Lime mudstones consist of micrite zones lacking large allochems or quartzose sand. In thin section, this lithofacies typically displays a dark pink or blue stain colour (Dickson’s solution, 1965, 1966), indicating variable amounts of iron in the lime mud (Figure 2.14B). A light blue stain colour is common near the base of the studied interval due to preferential ferroan dolomitization. These fragments also contain scattered sponge spicules (resembling Figure 2.9D, but lacking quartz). Very fine-grained glaucony is rarely present.

Lime mudstones are present in small quantities within sample intervals containing abundant carbonate material, primarily in the southern and downdip areas of the Albemarle Basin. This lithofacies is most commonly associated with marl, and is most abundant at the base of the studied section.

Lime mudstones were not observed in core. Due to its scarcity, geophysical well log responses could not confidently be evaluated. Wireline log responses however, are suspected to be similar to those of marl, due to their close association, though possibly with slightly lower gamma-ray values and less borehole washout.
Phosphatic Sandstone and Hardground: Phosphatic cuttings fragments are black. In thin section, phosphatic fragments are light-brown to orange in colour (PPL), and are isotropic under crossed-polars (Figure 2.14C). Fossil components and accessory minerals are highly variable. Very fine-grained quartz sand and glaucony (Figure 2.8B), molluscs, as well as planktonic and benthic foraminifera are locally present. Allochems are commonly replaced by ferroan calcite and fragments typically contain ferroan calcite cement (Figure 2.14D).

Phosphatic sandstone and hardground cuttings fragments are locally present in very small quantities within carbonate-dominated sample intervals. It primarily lies in downdip portions of the basin, and is typically associated with glauconitic sandstone and marl.

Phosphate-rich sediments were not observed in core. Due to the paucity of this lithofacies, geophysical well log responses could not be confidently evaluated.
CHAPTER 3: SEISMIC DATA – DESCRIPTION, METHODS, AND INTERPRETATION

Seismic data from the onshore North Carolina coastal plain is limited to vintage two-dimensional [2D] multi-channel seismic lines (Zarra, 1989, 1990). Numerous 2D seismic lines have been collected offshore of the Albemarle Embayment. Limited data however, have been collected within the sounds landward of the barrier island complex. Two-dimensional surveys are more abundant in offshore areas to the north in the Baltimore Canyon Trough, and to the south in the Southeast Georgia Embayment, where offshore drilling took place in the 1980s (Zarra, 1990; Hutchinson et al., 1993).

This chapter describes the methods employed to interpret the processed seismic data and integrate it with the well data used in this study. The seismic reflectors guided correlations between the studied wells and provided insights into regional stratal geometries across the basin. Five seismic lines collected across the Albemarle Sound area (~150 km line length) were utilised. Three synthetic seismic logs were used to correlate seismic responses to lithologic descriptions generated from well cuttings and wireline logs. Figure 3.1 shows the well location and orientation of the studied seismic data.

The seismic data set studied was collected by the Geophysical Services Inc. for the Cities Service Oil and Gas Corporation in 1972. Synthetic seismic logs from a limited number of wells were generated by Chevron (U.S.A. – Central Region; undated). Paper copies of the stacked 2D seismic data and synthetic seismic logs are available to the public at the North Carolina Geological Survey [NCGS]. Paper copies of all available
data were prepared and transported to Simon Fraser University for study. Relevant data were scanned, to produce images for inclusion in this thesis.

The vintage seismic data that exists for this region has a low resolution. Stacked seismic data were digitally filtered to preserve the 12-33Hz data at 1.5sec TWT, and shot point intervals were every 91 m (300 ft). Though low resolution in comparison to many modern surveys, it remains useful for the correlation of major seismic reflectors between wells. Both Zarra (1989) and Coffey (1999), and Coffey and Read (2004) incorporated
this data when developing sequence stratigraphic frameworks of the North Carolina coastal plain.

### Seismic Data Line Drawings

The five 2D seismic lines selected form two pseudo-strike lines across the Albemarle Embayment, and produce a closed loop (Figure 3.1). Loop-tying is a method of correlation, in which interpretations are made across multiple strike- and dip-oriented lines in a ‘circle’, in order to confirm that reflector correlations are internally consistent.

Seismic reflectors through the study interval were traced at the zero crossing to produce simplified line drawings of the seismic data. The zero crossing constitutes the best approximation of where the lithologic changes occur, generating the velocity and density contrasts that produce the reflectors (see Well-to-Seismic Data Tie section below). These line drawings, along with scanned copies of the stacked 2D seismic data, are shown as two pseudo-strike lines in Figure 3.2. The line drawings allow easier observation of those reflector geometries and terminations that are most useful in identifying key seismic stratigraphic surfaces (c.f. Mitchum et al., 1977).

Seismic reflectors observed throughout most of the study interval are subparallel to one another. However, some areas have subtle, shingled, clinoform geometries. Few reflector terminations are observed in the study interval, but those observed include downlap and toplap within the shingled intervals. Interpretations of these patterns are discussed below.
Figure 3.2A Pseudo-cross-section using part of lines G-3, G-2 and G-1. Scanned, stacked 2D seismic data (top) with seismic line drawings showing zero crossing (towards the reflection peaks) at bottom. DR-OT-1-46 well is projected into seismic section from 20km downdip (SE), therefore giving the false impression that the well lies updip of DR-OT-2-65. Orientation of the profile is shown in Figure 3.1 (A to A').
Figure 3.2B Pseudo-cross-section using part of lines G-8 and G-5. Scanned, stacked 2D seismic data (top) with seismic line drawings showing zero crossing (towards the reflection peaks) at bottom. Orientation of the profile is shown in Figure 3.1 (B to B').
Well-to-Seismic Data Tie

Chevron produced a number of synthetic seismic profiles for each well, using different parameters (frequencies, wavelets, and filters). The first step in correlating the data sets was to confirm which synthetic seismic log best fit the stacked 2D seismic data. This was conducted by aligning the synthetic logs against the seismic data set, and visually determining which synthetic log showed the most reflector pattern similarity through the study interval. A small number of shot points from the stacked seismic data were used to make the correlation, based on their proximity to the well and quality of the data (areas where poor data are minimal). Table 3.1 summarizes the parameters chosen from the synthetic seismic profiles, as well as the seismic line and shot-point interval used to make the tie. The data used for the tie can be found in Figure 3.3.

The second step was to correlate the two-way travel times on the seismic data to the depth scale of the well data. This was accomplished by smoothing and inverting the scanned sonic well log (DT - interval transit time) to generate a velocity log (shown in green in Figure 3.3) comparable to the log produced by Chevron (shown in black in Figure 3.3). The digitized sonic well log (units: μs/ft) was smoothed using Microsoft Excel by applying a thirty-one-point moving average, in order to reduce the number of data spikes. The sonic well log data were re-imported to Petrel as a new, smoothed sonic log. The calculator tool in Petrel was then used to create a velocity well log (units: ft/s) by inverting the smoothed sonic log and multiplying it by one million, to correct the units in microseconds. The generated curve was then pattern-matched to the velocity log provided by Chevron. The velocity log generated (depth scale displayed in feet) was linearly stretched (using Adobe Illustrator) to best match the Chevron velocity log (depth
Table 3.1  Processing parameters selected for comparison of synthetic seismic logs (center) and shot point locations of tied 2D seismic lines (right) used in Figure 3.3.

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scale given as two-way travel time [TWT] measured in seconds). As the project study interval constitutes only a small portion of the total well thickness, linear stretching of the generated velocity log is considered appropriate for matching the seismic TWT vertical scale to the well log depth scale (given in feet). Further, only a portion of the digital wireline well logs were available for conversion to velocity logs for this study.

Finally, the cuttings percent lithology data collected during petrographic study was added for comparison, graphed at the same vertical scale as the generated velocity log. Lithofacies identified via the cuttings analysis were graphed in an approximate high-sonic velocity and high-density (left) to low-sonic velocity and low-density (right). Table 3.2 lists the sonic velocities and bulk densities for the lithofacies as described in Chapter 2. This method helps to identify the lithologic causes of changes in acoustic impedance (resulting from down-hole changes in density or velocity). Changes in impedance are expressed as reflectors on the seismic logs. As seen on the well to seismic data tie (Figure 3.3), the zero crossing (from trough to peak with increasing time) occurs where marked changes in lithofacies types and, therefore, acoustic impedance occur.
Figure 3.3A Well to seismic data ties for selected wells from the Albemarle Basin. A: DR-OT-3-65 (Marshall Collins #1) well, northern onshore basin. Left: Cuttings data (depth scale in feet) with cuttings legend at base. Left of Center: Velocity log; black is supplied by Chevron; green was produced by inverting the well's sonic log. Right of Center: synthetic seismic log provided by Chevron. Right: Stacked 2D seismic traces from line G-3 (collected and processed by Geophysical Services Inc.) with TWT (time scale in seconds).

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DR-OT-3-65 (Marshall Collins #1)

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Drilling History

- SB 3.0
- CMF 2.10
- SB 2.0
- Grey 1.4
- MFS 1.10
- SB 1.0

Legend:
- Algal Laminate / Miiloid Packstone and Wackestone
- Peloid Packstone
- Lime Mudstone / Marl
- Quartz Sandstone
- Diatomaceous Shale
- Coarse-grained Quartz Sandstone
- Coal
Figure 3.3B Well to seismic data ties for selected wells from the Albemarle Basin. B: DR-OT-2-65 (Mobil #2) well, downdip basin. Left: Cuttings data (depth scale in feet) with cuttings legend found in A. Left of Center: Velocity log; black is supplied by Chevron; green was produced by inverting the well’s sonic log. Right of Center: synthetic seismic log provided by Chevron. Right: Stacked 2D seismic traces from line G-2 (collected and processed by Geophysical Services Inc.) with TWT (time scale in seconds). MFS 1.10 reflector not present, although the position of this surface is dashed at the interpreted depth – see Chapter 4 for the interpretation.

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Grey 1.1B
(MFS 1.10)
SB 1.0
1.6
SB 0.0
Figure 3.3C Well to seismic data ties for selected wells from the Albemarle Basin. C: HY-OT-1-65 (Mobil #3) well, southern basin. Left: Cuttings data (depth scale in feet) with cuttings legend found in A. Left of Center: Velocity log; black is supplied by Chevron; green was produced by inverting the well’s sonic log. Right of Center: synthetic seismic log provided by Chevron. Right: Stacked 2D seismic traces from line G-1 (collected and processed by Geophysical Services Inc.) with TWT (time scale in seconds).

<table>
<thead>
<tr>
<th>Depth (ft)</th>
<th>Cutting Lithology</th>
<th>Velocity Log</th>
<th>Synthetic Seismic Log</th>
<th>2-D Seismic (Line G-3)</th>
<th>TWT (sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4900</td>
<td></td>
<td>Slow 7000</td>
<td>Fast 17000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5000</td>
<td></td>
<td>From Synthetic Seismic</td>
<td>Generated from Sonic log using Petrel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5200</td>
<td></td>
<td>1.2</td>
<td>SB 3.0</td>
<td>Grey 2.0</td>
<td></td>
</tr>
<tr>
<td>5400</td>
<td></td>
<td>1.3</td>
<td>Grey 2.1</td>
<td>MFS 2.10</td>
<td></td>
</tr>
<tr>
<td>5600</td>
<td></td>
<td>1.4</td>
<td>SB 2.0</td>
<td>Grey 1.1</td>
<td></td>
</tr>
<tr>
<td>5800</td>
<td></td>
<td>1.5</td>
<td>SB 1.0</td>
<td>MFS 1.10</td>
<td></td>
</tr>
<tr>
<td>6000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6200</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3.2: Interval transit times (sonic) and bulk density wireline log responses of lithofacies observed in cuttings. Only those with log responses described in Chapter 2 are listed (n/a = log not available). The responses were used to estimate acoustic impedance and to arrange the cuttings-based lithofacies percent data in Figures 3.3 (low acoustic impedance at left, high acoustic impedance at right).

<table>
<thead>
<tr>
<th>Lithofacies</th>
<th>Sonic (Interval Transit Time) (μs/ft)</th>
<th>Bulk Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>120-100</td>
<td>2.2-2.3</td>
</tr>
<tr>
<td>Coarse-Grained Quartz Sand</td>
<td>120-100</td>
<td>n/a</td>
</tr>
<tr>
<td>Quartz Sandstone</td>
<td>100-60</td>
<td>2.2-2.4</td>
</tr>
<tr>
<td>Skeletal Quartz Sandstone</td>
<td>90-50</td>
<td>2.5-2.6</td>
</tr>
<tr>
<td>Siltstone</td>
<td>100-80</td>
<td>2.3-2.6</td>
</tr>
<tr>
<td>Non-fossiliferous Shale</td>
<td>100-80</td>
<td>2.3-2.6</td>
</tr>
<tr>
<td>Diatomaceous Shale</td>
<td>120-80</td>
<td>n/a</td>
</tr>
<tr>
<td>Evaporites</td>
<td>50-60</td>
<td>n/a</td>
</tr>
<tr>
<td>Ooid Grainstone and Packstone</td>
<td>90-60</td>
<td>2.5-2.6</td>
</tr>
<tr>
<td>Mollusc Packstone and Grainstone</td>
<td>90-60</td>
<td>2.5-2.6</td>
</tr>
<tr>
<td>Peloid Packstone</td>
<td>90-70</td>
<td>2.3-2.4</td>
</tr>
<tr>
<td>Fine-grained Skeletal Wackestone</td>
<td>90-70</td>
<td>2.5-2.6</td>
</tr>
<tr>
<td>Marl</td>
<td>90-70</td>
<td>2.3-2.4</td>
</tr>
</tbody>
</table>

Table 3.3 summarizes the depth-time tie of the reflectors found throughout the study interval. The horizon-naming scheme was developed during the interpretation phase (see below and Chapter 4 for interpretation).

Seismic Stratigraphy Interpretation and Discussion

Seismic stratigraphic interpretations are based on reflector configurations and termination types, as described by Mitchum et al. (1977). Subparallel configurations are regarded to have resulted from uniform rates of deposition over a uniformly subsiding shelf or stable basin platform, whereas the observed shingled configurations are interpreted to reflect strong progradation with unit thicknesses that lies just within seismic resolution (Mitchum et al., 1977).
Table 3.3 Two-way-travel time and depth at which the zero crossing (moving towards the peak with increasing depth) of seismic reflectors and interpreted well picks occurs (from Figure 3.3).

<table>
<thead>
<tr>
<th>Reflector</th>
<th>DR-OT-3-65</th>
<th>DR-OT-2-65</th>
<th>HY-OT-1-65</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TWT (sec)</td>
<td>MD (ft)</td>
<td>TWT (sec)</td>
</tr>
<tr>
<td>SB 3.0</td>
<td>1.21</td>
<td>4380 - 4420</td>
<td>1.38</td>
</tr>
<tr>
<td>MFS 2.10</td>
<td>1.27</td>
<td>4640 - 4680</td>
<td>1.46</td>
</tr>
<tr>
<td>SB 2.0</td>
<td>1.31</td>
<td>4870 - 4910</td>
<td>1.49</td>
</tr>
<tr>
<td>MFS 1.10</td>
<td>1.39</td>
<td>5210 - 5250</td>
<td>not present</td>
</tr>
<tr>
<td>SB 1.0</td>
<td>1.44</td>
<td>5470 - 5520</td>
<td>1.57</td>
</tr>
<tr>
<td>MFS 0.00</td>
<td>not present</td>
<td></td>
<td>1.62</td>
</tr>
</tbody>
</table>

Observed seismic geometries are also related to the lithofacies associations observed in well cuttings (described in Chapter 4), in order to better understand the depositional settings associated with the seismic signals. This allowed the interpretation of reflectors at the top and base of the study interval (Sequences 0 and 2), which are largely subparallel to one another, to be identified as significant seismic stratigraphic surfaces. This iterative process of interpreting the seismic reflectors and well data together was applied to produce an integrated sequence stratigraphic framework. The result is an internally consistent sequence stratigraphic framework for the study interval.

Three sequences are defined and comprise transgressive and highstand systems tract deposits. Lowstand systems tract deposits were not recognized in the studied seismic data. Criteria used to identify lowstand deposits was the presence of wedged shaped, onlapping seismic geometries situated in basinal positions, coupled with facies associations indicating shallow water deposition in an otherwise basinal position (see Chapter 4 for facies association data interpretation). Lowstand system tract sediments are suspected to be located downdip of the study area.
Figure 3.4 shows colour-coded interpreted seismic-line drawings. Significant seismic stratigraphic reflectors (blue and red) were joined across the study area, resulting in regionally continuous interpreted reflection surfaces.

The red reflectors (SB 0.0, 1.0, 2.0, and 3.0) are mapped across the entire study area, and are interpreted to indicate sequence boundaries. Generally, they are subparallel to the overlying and underlying reflectors, indicating possible subtle relief on this surface. Further, within Sequence 1, shingled, grey colour-coded reflectors are truncated (top-lap) below the SB 2.0 reflector (see Figure 3.4A), indicating possible erosion of underlying strata.

Seismic reflectors marking the transgressive flooding surfaces are not recognized in the seismic data, due to lowstand systems tract sediments not being identified within the study area. Therefore, the identified sequence boundary reflectors appear coincident with the same seismic event as the transgressive flooding surface.

The blue reflectors (MFS 1.10 and 2.10) are generally continuous across the entire study area, and are interpreted as maximum flooding surfaces. These horizons tend to be subparallel to overlying and underlying reflectors. However, within Sequence 1, overlying, shingled grey reflectors downlap above the MFS 1.10 reflector (see Figure 3.4A). The MFS 1.10 reflector was not mappable in the downdip portions of the basin (in the vicinity of the DR-OT-2-65 well). This may be the result of unit thinning below seismic resolution (tuning), or from facies changes to lithologies with insufficient acoustic impedance contrast to generate reflectors. The approximate position of the MFS 1.10 surface is dashed on the cross-section for reference in the down-dip portion of the basin, based on well data (see Chapter 4 for interpretation). In Sequence 0, the maximum
Figure 3.4 Seismic stratigraphic interpretation. A: Pseudo-cross-section using part of lines G-3, G-2 and G-1. B: Pseudo-cross-section using part of lines G-8 and G-5.

A: Seismic stratigraphic interpretation of pseudo-cross-section A-A' using parts of lines G-3, G-2 and G-1. Three sequences are identified comprising the transgressive and highstand systems tracts (labelled left of center). Red = Sequence Boundaries (coincident seismic event as transgressive flooding surface) and Blue = Maximum Flooding Surfaces. Dashed blue line is interpreted position of MFS 1.10, based on well data. No seismic event is present for MFS 0.10. Note the progradational, shingled package in Sequence 1. DR-OT-1-46 well is projected into seismic section from 20km downdip (SE), therefore giving the false impression that the well lies updip of DR-OT-2-65. Vertical exaggeration is twice that of Figure 3.2 in order to aid in stratigraphic recognition. Orientation the profile is shown in Figure 3.1 (A to A').

B: Seismic stratigraphic interpretation of pseudo-cross-section B-B' using parts of lines G-8 and G-5. Three sequences are identified comprising the transgressive and highstand systems tracts (labelled left of center). Red = Sequence Boundaries (coincident seismic event as transgressive flooding surface) and Blue = Maximum Flooding Surfaces. No seismic event is present for MFS 0.10. Vertical exaggeration is twice that of Figure 3.2, in order to aid in stratigraphic recognition. Orientation the profile is shown in Figure 3.1 (B to B').
flooding surface (MFS 0.10) could not be identified by a discrete seismic reflector. The surface is thought to lie within the seismic trough, as the presence of abundant shales at these depths reduces acoustic impedance contrasts (see Chapter 4 for well-data interpretation). Further, the minor thickness of Sequence 0 may preclude seismic resolution of internal strata.

The grey colour-coded reflectors are subparallel to the overlying and underlying reflectors, are shingled (particularly within Sequence 1), or are discontinuous. Downlap and toplap terminations of these reflectors in the shingled interval of Sequence 1 are indicative of strongly progradational units. The shingled and discontinuous character of these reflections indicates that the units lie at the limit of seismic resolution for this survey.

Transgressive systems tract deposits are interpreted to be present between the transgressive flooding surface (identified by the seismic reflector designated as the amalgamated sequence boundary and transgressive flooding surface) and the overlying maximum flooding surfaces. Highstand systems tract sediments are generally thicker, and are recognized by the presence of shingled, prograding reflectors (e.g., Sequence 1; Figure 3.4A). Where shingled reflectors are not present, these units are found between the seismic events identified as maximum flooding surfaces and the overlying sequence boundaries. In both cases, well data was integrated to support the developed sequence stratigraphic framework (see Chapter 4 for well data interpretation).

Based on the broad, subparallel reflectors, the seismic data indicates that the sediments were laid on a low-angle, broad shelf that dips towards the east-southeast. No shelf break is apparent in the studied seismic data.
On the seismic cross-sections (Figures 3.2A and 3.4A), the deepest part of the basin is in the vicinity of the DR-OT-2-65 well. However, the DR-OT-1-46 well is projected 20 km from the SE, the seismic cross-sections erroneously indicate that it lies in an updip position relative to the DR-OT-2-65 well. The DR-OT-1-46 well occupies an equivalent or slightly more basinward position than DR-OT-2-65.

**Conclusions**

Though the 2D seismic data available for this study is considered vintage relative to modern surveys, it remains useful for developing sequence stratigraphic frameworks in an otherwise understudied basin. The data have helped to identify the lateral relationships between wells, and provide the geometric framework for sedimentation within the basin. Sediments were deposited on a broad, low-angle shelf that dipped gently towards the east-southeast.

Future, higher-resolution seismic surveys would likely record a much greater number of clinoform geometries, therefore increasing the confidence of interpretations based solely on seismic data in this region. Reprocessing of the pre-stacked data for this survey using modern methods may allow for increased data clarity and its resolution.

Three sequences are identified by integrating the vintage seismic data with well cuttings data. The observed seismic reflectors generally demarcate large systems tract changes (sequence boundaries and maximum flooding surfaces), due to significant changes in prevailing lithologies associated with these events. Rarely, reflectors also record clinoformal stacking patterns associated with interpreted highstand progradation.
Lowstand systems tract deposits are not recognized in the study area, and therefore transgressive flooding surfaces are superimposed directly upon the same seismic events as the sequence boundaries.

The developed framework comprises transgressive and highstand systems tract sediments, with suspected lowstand sediments located basinward of the study area. The described architecture is supported by well data discussed in Chapter 4. Future study of the downdip, offshore seismic data should reveal the presence of lowstand systems tract deposits.
CHAPTER 4: INTERPRETATION, DATA INTEGRATION AND DISCUSSION

Facies Associations

Chapter 2 focused primarily on descriptions of the lithofacies. As the dominant data set in this study comprises well cuttings, each lithofacies was defined largely on lithologic characteristic as observed in thin-section, supported by core observations. The described characteristics indicate only the character of the processes that operated on the sediment, and rarely do the processes have absolute environmental significance (Collinson, 1969). As this studies data sets comprise thin sectioned cuttings, larger scale sedimentary structures, bed contacts, and trace fossils are not identifiable (only recognizable in core or by indirect methods such as geophysical well logs). Therefore, many of the processes that acted on the sediments are poorly constrained. The preliminary lithologic columns constructed using the cuttings data revealed recurring stacking patterns and geographic distributions of the lithologies. Integrating this information with coeval cores studied from neighbouring basins, previous studies, and wireline logs permitted the lithologies observed in cuttings to be grouped into lithologic facies associations.

A facies association [FA] is defined as “groups of facies, genetically related to one another and which have some environmental significance” (Collinson, 1969). Each facies association may possess more than one facies, and likewise, each facies may occur in more than one facies association – the grouping defines the environmental context of the facies association (Collinson, 1969; Walker, 1992; Reading and Levell, 2005).
Grouping related facies aids in their interpretation, correlation, and mapping (Collinson, 1969; Walker, 1992; Reading and Levell, 2005).

Ten facies associations are identified for the studied Lower Cretaceous section of the Albemarle Embayment. The interpreted environments of deposition range from supratidal to deep-shelf settings. Table 4.1 summarizes the facies associations, as well as some of the key physical characteristics that were noted in Chapter 2.

Lithologic facies association columns were produced in a manner similar to that employed for the construction of preliminary lithologic columns (described in Chapter 2). The resulting FA columns, however, have an apparent lower vertical resolution because the facies are grouped. Facies Association columns are reproduced in Appendix D.

Coal (FA 1): The coal-bearing FA is dominantly composed of coal, but also may contain minor interbeds of quartz sandstone, siltstone, and shale. Though an uncommon FA, its thickness averages 1.8 m (6 ft) as determined from wireline logs. This FA is locally present in wells that lie in updip positions, typically overlying sand-rich units (FA 2), and underlying units that are interpreted as marine successions, commonly shales (FA 4) or mollusc-bearing packstones (FA 3).

This association is interpreted to have been deposited in a back-barrier, delta plain or coastal plain setting; environments of deposition include peat swamps, and tidal or coastal marshes. The associated pyrite in the coal indicates high sulphur contents, as is typically the case with coal deposits formed near marine basins (Ingram, 1987; Galloway and Hobday, 1996). Other possible depositional settings for coal-bearing FA include floodplain environments and cratonic basins, though the high sulphur content and passive
Table 4.1 Summary of key characteristics and features of the facies associations. More detailed explanation can be found in the text. Table continued on following page.

<table>
<thead>
<tr>
<th>Facies Association</th>
<th>FA 1: Coal</th>
<th>FA 2: Quartz and Skeletal Quartz Sandstone</th>
<th>FA 3: Sandy Molluscan Packstone and Grainstone</th>
<th>FA 4: Shale and Siltstone</th>
<th>FA 5: Deep Marine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dominant Constituent Facies</td>
<td>Dominated by carbonaceous cuttings fragments.</td>
<td>FA 2A: Medium-to coarse-grained quartz sand and finer-grained quartz sandstone. FA 2B: Skeletal- and glauconite-bearing quartz sandstone.</td>
<td>Quartz sandy molluscan packstone and grainstone.</td>
<td>Shale and siltstone.</td>
<td>FA 5A: Planktonic foraminifera siltstone and diatomaceous shale. FA 5B: Marl, fine-grained skeletal wackestone and planktonic foraminifera packstone and wackestone.</td>
</tr>
<tr>
<td>Stratigraphic Occurrence and Thickness</td>
<td>Rarely present in up-dip positions, typically overlies quartz sandy units. Mean thickness is 1.8 m.</td>
<td>Abundant throughout the basin. Typically overlies shaley or silty units, as well as units rich in molluscan fragments. Mean thickness is 5.5 m.</td>
<td>Abundant throughout the basin. Though variable, commonly found with shale-rich and quartzose sand-bearing units. Mean thickness is 5 m.</td>
<td>Abundant throughout the basin. Found with quartz sandstone and mollusc packstone. Mean thickness is 4.9 m.</td>
<td>Low abundance association largely confined to basinal regions. Typically associated with shale. Mean thickness is 4.6 m.</td>
</tr>
<tr>
<td>Interpreted Depositional Environment and Setting</td>
<td>Marginal marine back-barrier, delta plain, or tidal flat setting: Peat swamps or foreshore marshes.</td>
<td>High-energy, inner shelf setting. Mainly shoreface and barrier island settings.</td>
<td>Open marine, shallow shelf; middle ramp depositional setting. Subject to periodic storm wave reworking.</td>
<td>Low-energy setting below fair-weather wave base. Distal delta and offshore settings, rare protected lagoons or estuaries.</td>
<td>Open marine, deep shelf; basinal ramp depositional settings.</td>
</tr>
</tbody>
</table>

margin tectonic setting of the Albemarle Embayment strongly favours a marginal marine interpretation (Galloway and Hobday, 1996). The Snuggedy Swamp of South Carolina provides a modern example of back-barrier peat accumulation, occurring behind an abandoned barrier complex (Staub and Cohen, 1979; Galloway and Hobday, 1996). These peats likely would be preserved as thin, high-sulphur coals and carbonaceous black shales, with the thickest peats flanking the barrier sands (Renton and Cecil, 1979;
**Facies Association**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>FA 6A: Bedded evaporites (Anhydrite and Gypsum)</td>
<td>Dominated by quartzose sand-bearing ooid grainstones and packstones. Rare peloid and skeletal packstones present.</td>
<td>Dominated by mollusc peloid packstone.</td>
<td>Dominated by bryozoan and brachiopod skeletal packstones that show little reworking.</td>
<td>Phosphatic sandstone and hardground, glauconitic sandstone, and chert near the base of studied interval.</td>
<td></td>
</tr>
<tr>
<td>FA 6B: Most abundant, algal laminites and lime mudstones. FA 6C: Miliolid packstone and wackestone as well as lime mudstones.</td>
<td>Rarely present, observed in southern and down dip portions of the basin. Found with restricted facies and miliolid-rich facies. Mean thickness: 3 m.</td>
<td>Rarely present; found in the southern and down dip portions of the basin. Found with mollusc and other skeletal packstones. Mean thickness of 4 m.</td>
<td>Rarely present, observed in the southern and down dip portions of the basin. Found with peloid packstone and marly facies. Mean thickness of 5.2 m.</td>
<td>Low abundance, though present throughout the basin. Largely interpreted as surficial coatings, much less than 1 m thickness.</td>
<td></td>
</tr>
<tr>
<td>FA 6C: Miliolid packstone and wackestone as well as lime mudstones.</td>
<td>Deposited in the inner ramp setting, in an environment subject to restricted circulation. Shallow subtidal to supratidal water depths.</td>
<td>Deposited in a mid-to-outer-ramp setting, likely below storm wave base.</td>
<td>Deposited in outer-ramp settings, below storm wave base.</td>
<td>Deposited during transgression, in areas of low sedimentation rate, during periods of sea bed erosion, or due to winnowing by nutrient-rich semi-permanent bottom-water currents.</td>
<td></td>
</tr>
</tbody>
</table>

Galloway and Hobday, 1996). Holdgate (1984) provides a Middle Tertiary example from southeast Australia, which comprises thick, sulphur-rich, peat accumulations (Latrobe Valley formation) capping lagoonal deposits situated behind stacked barrier sands (Balook Formation). Basinward of the Balook sands, a thick accumulation of marine limestones and marls (Gippsland Limestone Formation) is present, suggesting relatively low siliciclastic depositional rates (Holdgate, 1984; Holdgate and Gallagher, 1997; Figure 4.1).
Figure 4.1 Tertiary Gippsland Basin depositional model (Southeast Australia). Carbonaceous and non-marine clays are deposited in the onshore region. Quartz sands are deposited in the shallow, high-energy inner shelf region, with carbonates deposited basinward. Modified from Holdgate and Gallagher (1997).

Quartz Sandstone (FA 2A): Coarse-grained quartz and well cemented quartz sandstone are present throughout the basin, but it is typically slightly thicker in the northern and updip portions of the basin. Its thickness typically ranges from 4.3 m to 7.6 m (14 ft to 25 ft). This facies is generally overlain by quartzose sand-bearing molluscan packstone (FA 3) or other units that are interpreted as shallow open marine deposits. Rarely, this association is capped by coal (FA 1). This facies is typically underlain by finer grained material, commonly containing marine fossils (e.g., FA 2B, FA 3, or FA 4).

The quartz sandstone facies association likely was deposited in a range of environments. Noting the passive margin tectonic setting of the Albemarle Embayment, possibilities include fluvial, proximal delta, and shoreface to shallow shelf regimes (Galloway and Hobday, 1996; Collinson, 2005; Johnson and Baldwin, 2005; Reading and
The absence of marine fossils, carbonate material, and glaucony in cuttings fragments favours a non-marine interpretation for this association. The lack of these grain types, however, does not discount it entirely from being deposited in the marine realm. Similar offshore core analogues from the Baltimore Canyon Trough and Southeast Georgia Embayment (described in Chapter 2) display stacked coarsening-upward cycles (approximately 10 m thick cycles) interpreted to be deposited in high-energy shoreface environments.

Skeletal Quartz Sandstone (FA 2B): The skeletal quartz sandstone facies association consists dominantly of fine-grained quartz sandstone with admixed carbonate skeletal material. This association may also contain fine-grained glaucony-bearing quartz sandstone, as well as minor thin beds of siltstone and shale. Allochons are dominantly well-rounded mollusc fragments, but rare echinoderm fragments and non-skeletal carbonate grains (such as ooids) are locally present. This association is present throughout the basin, with a thickness that typically ranges from 4 m to 6 m (13 ft to 20 ft). This association is generally overlain by quartz sandstone (FA 2A), and underlain by either finer-grained, carbonate-rich facies (FA 3) or finer-grained siltstones and shales (FA 4).

The presence of marine carbonate material and minor glaucony indicates that this sandstone was deposited in marine or marginal marine settings, such as deltas, shorefaces, and shallow shelf settings (Galloway and Hobday, 1996; Johnson and Baldwin, 2005). Similar Holocene examples associated with the present transgressive sea-level position are found on the western Florida shelf and southern United States Atlantic shelf. Well-sorted quartzose sands deposited in shorefaces and barrier island
systems occur landward of mollusc-bearing skeletal-quartz sand, and grade seaward into fully carbonate molluscan facies of the shallow, open marine inner shelf (Milliman et al., 1968; Ginsburg and James, 1974; Doyle and Sparks, 1980; Brooks et al., 2003a, b). Coffey and Read (2007) provide a Palaeogene example from the Albemarle Embayment, interpreting a similar skeletal-quartz sandstone facies association to have been deposited in a shoreface to shallow inner shelf setting. Glaucony is formed in marine settings of slow sedimentation or interrupted deposition (Cloud, 1955; Harder, 1980), further supporting an inner shelf setting for this facies association.

Quartzose Sandy Molluscan Packstone and Grainstone (FA 3): This facies association is dominated by mollusc packstones and grainstones. Also present in abundance are quartzose sandy packstones and grainstones. This association is present throughout the basin, with the greater thicknesses and abundances in the southern and downdip portions of the basin. The average thickness is 3.7 m (12ft), but it may locally exceed 9 m (30 ft). Two predominant vertical stacking patterns are apparent. The more common stacking pattern has sandy molluscan packstones capping quartz-sand-rich units (FA 2), and are overlain by finer-grained, shale-rich units (FA 4) or other deep, open-marine units (FA 5). The second expression comprises a thick (typically 6 m) molluscan-rich, carbonate bed encased in shale (FA 4) or other finer-grained sediments (FA 5). These beds are commonly capped by sand-rich units (FA 2) or ooid-bearing grainstones and packstones (FA 7).

The presence of quartz sand and abundant bivalves in this facies suggests an open-marine depositional environment, likely reflecting the shallow shelf (inner-middle
ramp). Variable mollusc fragment abrasion suggests deposition above storm-weather wave base. This association was deposited outboard of nearshore quartzose sand-dominated shorefaces and barrier islands, particularly in regions of low siliciclastic input. The quartzose sandy molluscan packstone and grainstone FA also developed across broad areas of the shelf as transgressive lags during the early stages of transgression. Lithologic differences between these two depositional scenarios are minor, and so they can only be distinguished on the basis of associated rock types and vertical stacking patterns. Surficial sediments on the modern southern United States Atlantic shelf and western Florida shelf are composed of abundant mollusc shell-bearing facies that grade landward to skeletal quartz sands (Milliman et al., 1968; Ginsburg and James, 1974; Brooks et al., 2003a, b). Radiocarbon dating and limited thicknesses indicate that much of this skeletal material was deposited and thoroughly reworked during Holocene sea-level rise (Milliman et al., 1968; Ginsburg and James, 1974). Both authors further state that mollusc-bearing facies accumulation is continuing to take place outboard of the present-day siliciclastic-rich shorelines. Milliman et al. (1968) show that carbonate abundance is inversely proportional to the rate of siliciclastic accumulation, such that the highest percentages of carbonate is found in areas with the smallest terrigenous sediment influx. Wilson (1975) describes a Cretaceous example from central Mexico, where rudist bivalve build-ups formed basinward of ooid-skeletal sand banks, supporting the observed ooid-rich grainstone stacking pattern in the Albemarle Embayment (Figure 4.2).

Shale and Siltstone (FA 4): Facies Association 4 comprises unfossiliferous shale and siltstone. Skeletal quartz sandstones and sandy mollusc packstones are typically
Figure 4.2 Central Mexico, Cretaceous offshore bank depositional model. Updip depositional facies belts show a strong resemblance to the carbonate-dominated intervals of the Early Cretaceous Albemarle Embayment. Modified from Wilson (1975) with kind permission of Springer Science+Business Media (p. 323, Figure XI-3).

<table>
<thead>
<tr>
<th>FACIES 5a 5b</th>
<th>FACIES 6</th>
<th>FACIES 8</th>
<th>FACIES 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>MICRITE RUDIST KNOOLS WITH CREAMY, SHELLY, THICK-BEDDED LIMESTONE.</td>
<td>DOLITIC-BIOCLASTIC GRAINSTONE</td>
<td>LIGHT COLORED MICRITE, THIN TO MEDIUM BEDS. MINOR CYCLES OF MILIOLID GRAINSTONE; BIOSTROMES; MACROSTONE TO LAMINATED FENESTRAL MICRITE MUDSTONE.</td>
<td>ANHYDRITE FACIES WITHIN GOLDEN LANE BANK.</td>
</tr>
<tr>
<td>CAPRINIDS, RADIOBLOTS, COLONIAL CORALS, STROMATOPORIDS, LAMINATING ALGEAE, PHOLAD (KORING CLAMS), DICYCLOPS (BENTHONIC FORAM).</td>
<td>CAPRINIDS DOMINATE, TOUCASIA ON SLOPE TOPS, CHONDROIODONTA AT TOP, NERINEA, LARGE FORAMS), MILIOLIDS.</td>
<td>CAPRINID DEBRIS, SAVAGEOSA (RAD.), NERINEA, PARKERIA (STROM.), SOLNORDORA (RED ALGA), BASYCLADACEAN MILIOLIDS, LARGE FORAMS),</td>
<td>ESSENTIALLY NO BIOTA EXCEPT MILIOLID.</td>
</tr>
<tr>
<td>OVERLAPPING FACIES</td>
<td></td>
<td>RESTRICTED BIOTA, ALGAL STROMATOLITES, BIOSTROMES OF REQUIEMIA, TOUCASIA, S比利EA WHEN MARLY, BASYCLADACEANS, DICYCLOPS, MILIOLID.</td>
<td></td>
</tr>
</tbody>
</table>

Outer knolls, Inner knolls, Interreef sands, Salinity increase.

Tamabra Lst, El Abra Limestone, Shelly Margin knolls and patch reefs, few km wide. Inner Bank, 100km across.

Associated. This association is present throughout the basin and in great abundance. The thickness of this FA typically varies from 3.4 m to 6.7 m (11 ft to 22 ft), but is typically 4.9 m (16 ft) thick. Shale and siltstones commonly underlie quartz sand-rich units (FA2) and overlie molluscan-rich units (FA 3). This association rarely overlies deeper marine, marly facies (FA 5).

This facies association is interpreted to have been deposited in a low-energy setting, lying below or protected from wave energy. The thin, coarser-grained beds may
represent distal tempestites or remnants of material winnowed during high-energy events. Deposition of shale and silt is widespread in the low-energy settings of clastic-dominated shorelines and continental shelves (c.f., Johnson and Baldwin, 2005; Reading and Collinson, 2005). Ludwick (1964) described silt- and clay-sized sediments settling in basins behind and offshore of the segmented, sandy barrier islands in the modern northeastern Gulf Coast region. He also noted the presence of shell-rich sand patches and sand layering up to several centimetres thick in silt-to-mud dominated cores. Shales and silts are also locally deposited in the prodelta setting and estuaries (Galloway and Hobday, 1996; Johnson and Baldwin, 2005; Reading and Collinson, 2005).

Deep Marine (FA 5): A depositional term was chosen to name this fine-grained facies association, as opposed to a textural term, because the two sub-associations (FA 5A and FA5B) are interpreted to represent similar environments of deposition (described in the following paragraph). Facies Association 5A comprise a silica-rich end-member, which includes planktonic foraminiferal siltstones and diatomaceous shales. Facies Association 5B constitutes the carbonate-rich end-member, which includes marls, fine-grained skeletal wackestones, and planktonic foraminiferal packstones and wackestones. Volumetrically, these associations comprise a very small portion of all cuttings observed. Elements of the FA are present throughout the basin; however, they are more common and thicker in the basinal portions of the basin. Proportions of lithologies and bed thickness are variable, with a mean thickness of 4.6 m (15 ft) for both sub-associations. These associations are typically overlain by shale (FA 4), and are commonly underlain by quartzose sandy molluscan packstones (FA 3).
The open-marine fossil assemblage and fine-grained character supports an open-marine, deep shelf depositional environment interpretation for both sub-associations of FA 5. Facies Association 5A, the silica-rich end-member, likely accumulated distal to siliciclastic sediment sources, whereas the carbonate-rich end-member (FA 5B) likely accumulated in regions removed from siliciclastic sediment sources. Diatomaceous shales are pelagic deposits, resulting from productive surface waters, typically associated with marine upwelling (Maliva et al., 1989). However, in some basins nutrient supply directly from continental run-off may have been important in diatom proliferation (Maliva et al., 1989). Along the modern western Florida shelf, as well as along the southern United States Atlantic margin, planktonic foraminifera, lime mud, and clay minerals are presently being deposited in deep shelf to upper slope settings (Ludwick, 1964; Milliman et al., 1968; Ginsburg and James, 1974; Doyle and Sparks, 1980). If preserved in the rock record, these sediments would be referred to as marl or chalk (e.g., Ludwick, 1964). In the deep shelf to slope settings of the modern Otway continental margin, pelagic mud dominated by planktonic foraminifera, is presently accumulating (Boreen et al., 1993), and may constitute an additional modern analogue to the planktonic foraminiferal and marly sediments of the Albemarle Embayment. Holdgate and Gallagher (1997) provide a Tertiary example from the Gippsland Basin, whereby planktonic foraminiferal marls were deposited during transgressive system tracts in water depths >100 m.

Restricted Tidal Flats (FA 6): Facies Association 6 is divided into three sub-associations, FA 6A, FA 6B, and FA 6C) which represent similar environments of deposition (described in the following paragraph). FA 6A consists of bedded evaporites (gypsum or
anhydrite). FA 6B is dominated by algal laminites and quartz sandy lime mudstone, and is the most abundant sub-association. FA 6C comprises quartzose sandy miliolid packstones and wackestones, admixed with quartz sand-bearing lime mudstones. Facies Association 6 is typically found in the southern and downdip portions of the basin. The FA 6A evaporites have a mean thickness of 2.1 m (7 ft), whereas the other sub-associations (FA 6B and FA 6C) are slightly thicker, with a combined mean thickness of 4.6 m (15 ft). This set of sub-associations typically overlie ooid- and peloid-rich units, and are overlain by units containing more open-marine fossil assemblages, such as FA 3 or FA 5.

The associated facies indicate a depositional environment characterised by restricted marine circulation in shallow subtidal to supratidal water depths (0 to 3 m). Depositional environments such as these include sabkhas (FA 6A), tidal flats (FA 6B), and restricted lagoons (FA 6C). The presence of bedded evaporites is diagnostic of hypersaline conditions, owing to restricted circulation coupled with high rates of evaporation, and frequent, prolonged, subaerial exposure (Wilson, 1975). Cryptagal mats are often found in the restricted upper intertidal regions, due to their ability to withstand the stressful hypersaline environmental conditions and frequent subaerial exposure (Wilson, 1975; Kendall and Harwood, 2005). Lime mud resulting from the break down of calcareous green algae often accumulates in low-energy settings of tidal flats and shallow lagoons (Wilson, 1975). Miliolid benthic foraminifera inhabit a variety of environments, but where they constitute the prevailing allochem type in mud-rich units interspersed with bedded evaporites, as observed in the COST GE-1 core, the abundant miliolids are interpreted to indicate stressed, hypersaline conditions (Poag 1981; Brooks et al., 2005b;
Wright and Burchette, 2005). Abundant miliolids can be observed in the modern hypersaline lagoons of Shark Bay of Western Australia (Logan and Cebulski, 1970; James et al., 1999). Wilson (1975) describes a Cretaceous example from central Mexico, where abundant miliolids were deposited in the saline, inner-bank environments of the El Abra Limestone (Figure 4.2).

Ooid Grainstone and Packstone (FA 7): Facies Association 7 is composed dominantly of fine-grained quartzose sandy ooid-rich grainstones and packstones with a mean thickness of 3 m (10 ft). Packstones comprising peloids, coated grains, and molluscs or echinoderm skeletal fragments are locally present. This association is uncommon. It occurs in the southern and downdip portions of the study area. FA 7 is commonly overlain by the more restricted units included in FA 6, and is typically underlain by thick quartzose, molluscan-dominated carbonate units of FA 3.

Facies Association 7 is interpreted to have formed as skeletal-ooid sand sheets and shoals in a high-energy, shallow subtidal, inner ramp setting. Modern observations of ooids from the Bahama Bank and Texas Gulf Coast indicate that these particles form in sub-tropical to tropical, wave-agitated, high-energy settings, subject to active carbonate deposition (Newell et al., 1960; Rusnak, 1960). Commonly, elevated salinity is a contributing effect on ooid formation, as precipitation of calcite directly from sea water may occur (Rusnak, 1960). Wilson (1975) describes a Cretaceous-aged example from central Mexico, where rudist bivalve build-ups formed basinward of ooid-skeletal sand banks with restricted, inner-bank facies deposited further landward (Figure 4.2). A similar scenario of facies belts to the Cretaceous central Mexico carbonate shelf is
believed to have occurred in the Albemarle Embayment during periods dominated by carbonate accumulation.

Peloidal Packstone (FA 8): Facies Association 8 is dominated by peloid packstones, but also encompasses minor, thin beds of mollusc and other skeletal packstones. This association is rarely present; it is found only in the southern and downdip portions of the basin. This association has a mean thickness of 4 m (13 ft). Facies Association 8 is commonly overlain by a quartzose sandy molluscan packstones and grainstones (FA 3), and is underlain by a varied, skeletal-rich packstone (FA 9).

The peloidal packstone FA was likely deposited in a mid- to deep-ramp setting, downdip of shallower molluscan-rich build-ups and ooid shoals. Boreen et al. (1993) note the presence of similar pelletal-skeletal muds accumulating in the deep shelf to upper slope setting of the modern Otway continental margin. Wilson’s (1975) synopsis of standard facies belts indicates that pellet, peloid, and coated grains in micrite associated with bioclastic wackestone are commonly found in open marine, deep shelf settings, as well as shallow, protected, sub-tidal settings. Facies Association 8 likely has a similar expression and to the deep shelf muddy peloidal packstones described by these researchers.

Skeletal Packstone (FA 9): Facies Association 9 is dominated by bryozoan and brachiopod skeletal packstones that show little evidence of reworking. Mud-rich packstones comprising pellets, molluscs and echinoderm fragments, also form minor components of this association. Cuttings from this association are rare, found mostly in
the southern and downdip portions of the basin. Facies Association 9 averages 5.2 m (17 ft) in thickness and has two stacking expressions. It is most commonly found encased in shale (FA 4), but also can be overlain by a peloid-rich unit (FA 8) and underlain by finer-grained, pelagic sediments (FA 5).

The skeletal packstone FA is interpreted to have been deposited in a low-energy deep-ramp to outer-shelf setting, near or immediately below storm wave base. On the deep shelf to upper slope (130 m to 350 m water depth) of the Otway continental margin, a diverse assemblage of aphotic bryozoans, sponges, and azooxanthellate corals are accumulating with pelleted muds in the nutrient-rich, upwelling waters (Boreen et al., 1993). This may be a modern analogue to the biologically diverse Albemarle Embayment assemblage. From within the basin, a similar bryozoan/brachiopod/echinoderm facies accumulated during the Tertiary under mesotrophic to possibly eutrophic conditions in the middle to deep (30 m to 100m interpreted water depth) inner shelf setting (Coffey, 1999; Coffey and Read, 2004 and 2007). Facies Association 9 may have accumulated as isolated buildups in the outer-ramp setting (c.f. Burchette and Wright, 1992).

Hardground (FA 10): Facies Association 10 is characterised by phosphatic sandstone and hardground, glauconitic sandstone, and chert fragments in cuttings. This association is present throughout the basin, chert, however, is more common in the basal portions of the studied interval. Facies Association 10 constitutes a very small portion of the observed cuttings and is rarely present. It is interpreted to form as thin surficial coatings much less than 1 m in thickness. This facies is most commonly associated with molluscan packstones (FA 3) that overlie thick sandstone successions.
Facies Association 10 records episodes of condensed sedimentation, likely related to transgressive drowning of the shelf. Deposition of phosphate, glaucony, and chert is favoured in marine waters with elevated nutrient levels coupled with low rates of sedimentation (Odin and Letolle, 1980; Glenn and Arthur, 1988; Maliva et al., 1989; Scholle and Ulmer-Scholle, 2003; Gates et al., 2004). Low rates of sedimentation, combined with large supplies of phosphorous derived through upwelling is believed to result in phosphate deposition (Riggs, 1984). This occurred during the Tertiary along the southeastern North American margin during sea-level transgressions (Riggs, 1984), in mid- to deep-shelf, sediment-starved, current-swept settings (Coffey and Read, 2004, 2007). Harris and Self-Trail (2006) noted the presence of abundant phosphate and glaucony in the vicinity of transgressive flooding surfaces from an Upper Cretaceous core drilled in the North Carolina coastal plain. Glaucony is formed in close proximity to the sediment-water interface in marine settings of slow sedimentation or subject to prolonged interruptions in deposition (Cloud, 1955; Harder, 1980), most commonly in water depths of 60 m to 350 m (Odin and Letolle, 1980). Most nodular cherts develop in deep, quiet-water basinal settings, and result from the recrystallization of siliceous tests and sponge spicules (Maliva, 1989; Gates et al., 2004). Regions with high primary productivity, resulting from the upwelling or run-off from land of nutrient-rich waters, favour the occurrence of siliceous tests and spicules (Maliva, 1989; Gates et al., 2004). Thus, a deep-shelf, open-marine setting with high nutrient levels (more likely to occur during transgressive events) coupled with low sedimentation rates is favoured as the interpreted environment of deposition for phosphate, glaucony, and chert accumulations in the Lower Cretaceous sediments of the Albemarle Embayment (cf., Savrda et al., 2001).
Facies Association Stacking Patterns and Depositional Model

Stacking patterns

Two dominant vertical stacking patterns with a thickness of 15 m to 20 m (50 ft to 70 ft) can be identified from the lithologic facies association columns (Figure 4.3). The first is a siliciclastic-dominated succession that is characteristic of high-energy clastic continental shelves. The second is a carbonate-dominated succession that is more characteristic of carbonate continental shelves. These stacking patterns comprise end-members, and a degree of facies mixing occurs throughout the study area.

The more common, clastic-dominated succession (Figure 4.3 A) is found throughout the study area, but is typically found in the northern and updip portions of the basin. At the base of the package, a molluscan carbonate (FA 3) is locally mixed with phosphate and glauconite (FA 10), and likely represents a hardground surface(s) near the top of the mollusc-rich unit. The molluscan carbonate interval is overlain by deeper water units representing pelagic sedimentation (FA 5A) in basinal portions of the basin, whereas shale and siltstone (FA 4) are more prominent in updip positions. Marls and diatomaceous shales of FA 5 grade upward into shales and siltstone of FA 4. The shale is overlain by a quartzose sand-bearing molluscan carbonate (FA 3) in regions distal to those of abundant siliciclastic sedimentation. More commonly, the shale and siltstone are overlain by skeletal quartz sandstone (FA 2B). Both the molluscan skeletal carbonate and
Figure 4.3 Dominant stacking patterns, showing one complete shoaling-upward succession for both: A (top) siliciclastic-dominated system, from well HY-OT-1-65; and B (middle-bottom) carbonate-dominated system, from well DR-OT-1-46. Facies association-grouped cuttings percent data column is at left; arrows within column show shoaling cycles apparent in the data. Well logs (GR= Gamma Ray, RHOB= Density, SP= Spontaneous Potential, and ILD= Deep Resistivity) are shown for comparison to the interpreted facies association lithology column (middle right). Positions of flooding surfaces are shown in blue. Note that molluscan carbonate percent abundance may be overestimated, due to cuttings mixing at these depths. Facies Association legend is at base.
skeletal quartz sandstones grade upward into quartz sandstone (FA 2A), which is locally overlain by a coal-rich unit (FA 1) in the updip portions of the basin. The quartz sandstone or coal is typically overlain by a molluscan carbonate unit of the succeeding parasequence; the boundary represents a flooding surface, provided that it can be correlated in neighbouring wells (further discussion below).

The carbonate-dominated stacking succession (Figure 4.3 B) is less common, and is largely confined to the southern and downdip portions of the study area. This succession likewise starts with a basal molluscan carbonate (FA 3) locally containing phosphate and glaucony (FA 10), and probably corresponds to a hardground surface(s) near the top of the mollusc-rich unit. The molluscan carbonate unit is overlain by deeper water associations representing pelagic sedimentation (FA 5B) in basinal portions of the basin. In rare cases, the marly units (FA 5B) are overlain by thin skeletal packstones (FA 9), which subsequently grade upwards to molluscan peloid packstone (FA 8). Shale beds (FA 4) can be common, likely signifying proximity to a siliciclastic sediment source. These units grade into quartzose sand-bearing molluscan packstones and grainstones (FA 3), which then pass upward into quartz sand-bearing ooid-skeletal grainstone (FA 7). The ooid grainstone is locally capped by FA 6, dominated by algal laminitie (FA 6B), and represents deposition in a shallow-water, restricted lagoon to tidal flat. Very locally, bedded evaporites (FA 6A) and miliolid packstones (FA 6C) are recognised in this interval. At the top of the succession, the ooid grainstone or restricted tidal flat associations are overlain by the molluscan carbonate unit of the succeeding parasequence. The boundary represents a flooding surface, if it is regionally mappable (further discussion below).
By applying concepts described by Walther’s 1894 *Law of the correlation of Facies*, the described vertical stacking patterns of facies associations can be placed into depositional context. Given the relatively coarse datasets (cuttings and wire-line logs with limited core), and the variability within each package, only broad depositional profiles can be constructed.

Walther’s Law applies only to successions without major time breaks (Reading and Levell, 2005). In this study, cuttings fragments are insufficient to evaluate contacts per se, so study of the geophysical well logs, core analogues, and literature reviews were used to infer this information. Facies association contacts are assumed to be conformable, except in the instances where an association representing a deeper water depositional environment abruptly overlies a shallower-water facies association, and the abrupt contact can be correlated in neighbouring wells. The regionally correlatable abrupt contact is termed a flooding surface, and each shoaling-upward succession is interpreted as a parasequence.

**Depositional model**

All available data sets were integrated to construct idealized depositional models for the clastic- and carbonate-dominated systems (Figure 4.4). The two depositional profiles shown in Figure 4.4 comprise end-members of a continuum. The black lines to the right of the facies association names indicate the regions of maximum accumulation of each facies association, relative to the above shelf profile.

The model represents deposition on a broad, gently sloping continental shelf. Adopted shelf terminology is modified from Wright (1995), Galloway and Hobday (1996), and Boggs (2001). The carbonate sediments are interpreted to have accumulated
Figure 4.4 Generalised facies association profiles of the Early Cretaceous sediments in the Albemarle Embayment of North Carolina. Siliciclastic-dominated sedimentation (profile A) is most common. Carbonates (profile B) accumulated primarily during periods of low siliciclastic input to the shelf, largely during the relative sea-level lowstand transitioning from Sequence 1 to Sequence 2. Shelf setting indicated at top. Heavy lines represent region of maximum accumulation of facies types; light lines represent zone of likely accumulation. Facies association legend can be found in Figure 4.3.
A

**Facies Association Profiles:**

**Clastic Dominated:**

- **FA 1:** Coal
- **FA 2:** Quartz sandstone and skeletal quartz sandstone
- **FA 3:** Quartzose sandy molluscan packstone and grainstone
- **FA 4:** Siltstone / Shale
- **FA 5A:** Planktonic foraminifera-bearing siltstone and diatomaceous shale
- **FA 5B:** Marl and lime mudstone

**Carbonate Dominated:**

- **FA 6A:** Evaporites and dolomitized lime mudstone
- **FA 6B & 6C:** Algal Laminite, and miliolid packstone and wackestone
- **FA 7:** Quartz sand- and mollusc-bearing ooid grainstone
- **FA 2B:** Molluscan quartz sandstone
- **FA 3:** Quartzose sandy molluscan packstone and grainstone
- **FA 4:** Shale
- **FA 8:** Skeletal peloid packstone
- **FA 9:** Skeletal packstone
- **FA 5B:** Fine-grained skeletal wackestone, planktonic foraminifera packstone and wackestone, marl, and lime mudstone

![Graph showing facies association profiles with clastic and carbonate dominated facies.](image-url)
on a ramp. The carbonate ramp model (Ahr, 1973; Burchette and Wright, 1992) resembles high-energy siliciclastic shelves in terms of their hydrodynamics and morphologies. This depositional architecture is supported by the sub-parallel, regionally extensive reflectors derived from the seismic data (Chapter 3), and the lack of framework-constructing carbonate organisms.

The clastic-dominated system (Figure 4.4A) consisted of marginal marine environments (lagoons, fluvial, and delta plain), that graded seaward through shoreface, shallow shelf, and deep shelf settings. A biostrome, consisting mainly of molluse bivalve fragments, existed in the shallow shelf setting basinward of the quartzose sandstone-dominated high energy shoreface zone. This molluscan biostrome was probably best developed distally from siliciclastic point sources (e.g., deltas). Proximal to fluvial sediment influx areas, the abundance of siliciclastic material likely limited or diluted carbonate biota, resulting in thicker accumulations of siliciclastic sands, silts, and clays. The deep shelf and slope was characterised by pelagic sedimentation. The clastic-dominated system is similar to the Tertiary depositional model of the Gippsland Basin (cf. Holdgate and Gallagher, 1997; Figure 4.1).

The carbonate-dominated system (Figure 4.4B) consisted of restricted tidal flats and lagoons that graded basinward into high-energy, quartzose sandy ooid shoals and barrier islands. Basinward, these graded into a mollusc-rich shallow shelf. As water depths increased, carbonate mud accumulation became elevated and re-working of sediment by organisms resulted in the preservation of molluscan peloidal packstones. In carbonate-productive areas, bryozoan and brachiopod skeletal packstones may have been deposited, possibly in mounds. The deep shelf was characterised by pelagic
sedimentation. This carbonate-dominated system is less common than the clastic system, and received some siliciclastic material during deposition, likely transported to the area via longshore drift in shallow shelf settings or other bottom-water currents in deeper shelf positions. Burchette and Wright (1992) noted that the outer ramp zones of many carbonate ramps have admixed, suspension-derived terrigenous mud. The carbonate-dominated system is consistent with the Cretaceous depositional model of Central Mexico (Wilson, 1975; Figure 4.2). The Early Cretaceous-aged Mural Limestone of Mexico also possesses similar lithofacies to the Albermarle Embayment (Lawton et al., 2004).

During relative sea-level rises, much of the siliciclastic material supplied to coastlines is trapped and deposited in estuaries (Galloway and Hobday, 1996). A relative sea-level rise therefore favours smaller quantities of siliciclastic material reaching the open shelf, and facilitates biogenic carbonate production in these settings (Milliman et al., 1968; Ginsburg and James, 1974). Sea-level transgressions during the Early Cretaceous of the Albemarle Embayment are likely to have resulted in the widespread deposition of thin molluscan carbonates on the open shelf, similar to the modern molluscan accumulations on the southeastern North American and western Florida shelves (Milliman et al., 1968, Ginsburg and James, 1974). River-sourced siliciclastics were largely trapped in updip estuaries. In shelf settings subject to limited sedimentation or to nutrient-rich bottom-water currents, hardground surfaces may have developed (e.g., Savrda et al., 2001), resembling those found in younger strata during similar major sea-level transgressions within the basin (Riggs, 1984; Coffey and Read, 2004, 2007).
Discussion of Depositional Model

Sediment supply and accumulation rates

A subaerial environment with low siliciclastic sediment supply and humid climate is prone to heightened accumulation of organic matter, provided that the rate of organic matter accumulation exceeds the rate of decay (Talbot and Allen, 2005). Similarly, continental shelves with low siliciclastic sediment supply and arid climates are commonly prone to carbonate accumulation (Milliman et al., 1968; Ginsburg and James, 1974, Burchette and Wright, 1992, James, 1997). The presence of both carbonaceous material and calcareous material in the Lower Cretaceous sediments of the Albemarle Embayment suggests moderate to low rates of siliciclastic sediment accumulation.

A low rate of siliciclastic sediment accumulation is supported by the many pervasively bioturbated intervals in the discontinuous Hatteras Light well core. Pervasive bioturbation is indicative of slower rates of sediment accumulation with abundant oxygenation and high biomass giving sufficient time for burrowing organisms to disrupt the primary sedimentary structures prior to burial.

The total sediment accumulation rate for the compacted sediments of the study interval was calculated by dividing the sediment thickness of the downdip Hatteras light well (490 m, or 1600 ft) over the biostratigraphic duration of the study interval (~12 million years; biostratigraphic age control is discussed below), yielding 0.04 m/kyr. The actual sedimentation rate is likely significantly greater, as the calculated rate uses compacted sediment thicknesses and includes unconformity surfaces.

In the Baltimore Canyon Trough to the north, Poag and Sevon (1989) determined that sediment accumulation rates during the Late Jurassic and Early Cretaceous were
relatively low, as compared to other periods during the history of the margin. Though no data within the Albemarle Embayment was discussed, the similar tectonic settings and proximity of the basins suggests that they would experience similar depositional histories.

**Mixed carbonate-clastic systems**

Ginsburg and James (1974) discussed the interplay of terrigenous muds and carbonates, based on observations of modern continental shelves. The input of terrigenous mud is typically associated with large volumes of freshwater input, which reduces salinity, elevates water column turbidity, reduces light penetration, leads to clay-mud substrates that are unfavourable for most benthos, and dilutes indigenous carbonate (Ginsburg and James, 1974). However, carbonate sediments commonly can be found at the distal parts of shelves possessing major deltas, areas where mud deposition is reduced or absent (Ginsburg and James, 1974). This observation suggests a relationship between carbonate and siliciclastic abundance; such that carbonate content increases with greater distance from siliciclastic sources.

The extent and significance of mixed carbonate-siliciclastic sediments has been the topic of increased research effort during the past decade (e.g., Goldthorpe, 1997; Brooks et al., 2003b; Coffey and Read, 2004, 2007; Emerson et al., 2004; Halfar et al., 2004; McLaughlin et al., 2004; McNeill et al., 2004; Campbell, 2005; Cozar et al., 2006; Lagesse and Read, 2006; Best et al., 2007; Francis et al., 2007). Mount (1984) recognized four mixing processes that generate both temporally and spatially variable carbonate-siliciclastic mixtures. The first, "punctuated mixing", is where periodic storms or other sporadic extreme events transfer sediments from one depositional environment to another (Mount, 1984; Ager, 1993). The second, "facies mixing", is where carbonate- and
siliciclastic-dominated sediments are blended along gradational boundaries (Mount, 1984). The third, *in situ mixing*, is where autochthonous carbonate assemblages accumulated on or within siliciclastic-dominated substrates (Mount, 1984). Finally, "source mixing" is where admixtures are formed by eroded, allochthonous carbonate material being deposited with siliciclastic material (Mount 1984). Any or all of these processes likely act in a wide range of environments during different parts of the geologic record (Goldthorpe, 1997), and more than one process is likely present in a given sedimentary basin (Mount, 1984).

In the case of the Albemarle Embayment, the tropical paleolatitudinal setting during the Early Cretaceous (Chapter 1) favoured prolific carbonate activity. However, continuous unroofing rates of ~30 m/m.y. of the nearby uplifted, crystalline Appalachian Mountains during the past 180 m.y. likely contributed significant quantities of siliciclastic material to the basin during the Early Cretaceous (Matmon *et al.*, 2003). Periodic storms or other sporadic extreme events likely transferred significant quantities of sediments from the siliciclastic-dominated facies belts to carbonate-dominated regions of the open shelf, and vice-versa. Thus, "punctuated mixing" processes likely operated during the Early Cretaceous of the Albemarle Embayment. As proposed in the depositional model (Figure 4.4A), both "facies- and in situ mixing" processes likely operated. In inner shelf settings, molluscan-dominated facies likely graded laterally and interfingered with prodeltaic shale-rich facies. In positions distal to siliciclastic sediment sources (*e.g.*, deltas), molluscan carbonate facies likely grew and accumulated with quartzose sands of the inner shelf. "Source mixing" is not believed to have operated, because the observed carbonate material is considered autochthonous to the basin.
Shelf nutrient levels

Nutrient levels are considered to have been high in the Albemarle Embayment during the Early Cretaceous. This is supported by the presence of hardground fragments (FA 10) and molluscan packstones (FA 3). Hardground surfaces were developed during sea-level transgressions in the Albemarle Embayment during the Tertiary (Riggs, 1984), forming in the mid- to deep-shelf, sediment-starved, current-swept settings (Coffey and Read, 2004, 2007). During the Early Cretaceous, sea-level transgressions likely also resulted in the formation of hardground surfaces in similar settings. Further, carbonate allochem types found in the study area can be classified as the Heterozoan Association, as described by James (1997). This association is believed to be favoured in regions characterised by elevated nutrient levels (James, 1997).

Controls on carbonate allochem types

Mount (1984) noted that foraminifera-mollusc assemblages are more commonly found mixed with siliciclastic material than are chlorozoan and choralgal assemblages. This is probably the result of the effects of increased turbidity, unstable substrates, and the clogging of filter-feeding mechanisms associated with siliciclastic influx (Mount, 1984). These factors may favour molluscan and foraminiferal assemblages relative to the more siliciclastic-sensitive chlorozoan and choralgal assemblages (Mount, 1984). Within the Lower Cretaceous sediments of the Albemarle Embayment, molluscan carbonate assemblages are most commonly observed.
**Sequence Stratigraphic Framework**

By integrating the well cuttings data, 2D seismic, core analogues, wireline logs, and published literature, a sequence stratigraphic framework was erected for the Lower Cretaceous sediments of the Albemarle Embayment. This model incorporates the facies association-based stratigraphic columns (described in the early part of this chapter), 2D seismic data, and existing biostratigraphic data (Brown *et al.*, 1972; Zarra, 1989).

Facies association stratigraphic columns were correlated between wells using seismic reflectors. Seismic data integration ensured that stratigraphic correlations honoured the large-scale stratigraphic geometries that defined sediment packages across the basin, particularly the large systems tracts (Reading and Levell, 2005). Many of the seismic reflectors were generated from acoustic impedance contrasts generated at the surfaces demarcating the large systems tracts changes, owing to the significant changes in prevailing lithologies associated with these events (see Chapter 3).

Sequence stratigraphic surfaces and systems tracts were assigned in a manner similar to that employed by Coffey (1999) and Coffey and Read (2002, 2004, 2007), using the terminology of Van Wagoner *et al.* (1988). Figure 4.5 shows an example from the DR-OT-2-65 well, which illustrates how the sequence stratigraphic surfaces are assigned. Flooding surfaces are placed at the top of each shoaling-upward succession that could be correlated in neighbouring wells; these packages are interpreted as parasequences. Groups of parasequences that demonstrate progressive changes in
**Figure 4.5** Sequence 1 showing parasequence sets found within the DR-OT-2-65 well. Example represents ~175 m (~575 ft) of the total ~550 m (1800 ft) Lower Cretaceous sediments studied from this well. Wireline logs (GR = Gamma Ray and DT = Interval transit time) are shown on either side of the interpreted facies association lithology column (middle-left). Cuttings percent data grouped by facies association (middle-right) also includes arrows indicating repetitive shoaling upward cycles (parasequences). Large arrows (right) indicates overall trend of parasequence sets (towards right indicates shoaling, while towards left indicates transgression). Horizontal lines crossing figure represents significant sequence stratigraphic surfaces: Red = Sequence Boundaries [SB]; Green = Transgressive flooding Surfaces [TS] (generally coincides with sequence boundaries); Blue = Maximum Flooding Surface [MFS]; and Black = Flooding surfaces (named by the systems tract within which they are found). Systems tract and surface names are found at the left and right of the figure respectively. HST = High Stand Systems Tract; TST = Transgressive Systems Tract; LST = Lowstand Systems Tract. Lithofacies legend can be found in Figure 4.3.
stacking patterns are grouped as parasequence sets. Sequence boundaries are picked at
the tops of major regional shoaling-upward trends, and typically coincided with seismic
reflectors (red reflectors – Figure 3.4). Lowstand systems tract sediments are not
recognized in the study area (criteria used were thick, basinal accumulations of shallow-
water facies associations in cuttings, coupled with wedge-like onlapping geometries in
the seismic profiles). Lowstand sediment wedges are suspected to be situated downdip of
the study area. Therefore, transgressive surfaces coincide closely with the position of the
sequence boundaries, and could not be differentiated as discrete surfaces on the seismic
profiles. The transgressive systems tract consists of an upward-increase in deep water
facies associations, which combine to form overall retrogradational parasequence sets.
Maximum flooding surfaces were picked to coincide with the bases of regionally
extensive, deep-water facies associations, where they typically coincided with seismic
reflectors (blue reflectors – Figure 3.4). Highstand systems tract sediments consist of
upward-shoaling facies associations, which combine to form overall progradational
parasequence sets. The highstand system tract sediments rarely show shingled geometries
in the seismic data (grey reflectors – Figure 3.4), indicating strongly progradational
sedimentation at the limit of seismic resolution (Mitchum et al., 1977).

The three large-scale cycles identified in the study interval (Figure 4.6 – fold-out)
are interpreted as third-order sequences (refer to the Biostratigraphic age control in the
discussion below). In all cases, the highstand systems tracts are of greater thickness than
the transgressive system tracts. Table 4.2 lists the depths at which the significant
sequence stratigraphic surfaces were interpreted in each studied well. The depths of all
correlated higher frequency surfaces are presented in Appendix E.
Table 4.2 Depths of significant sequence stratigraphic surfaces. All depths represent measured depths in metres (equivalent depth in feet is in brackets). As no transgressive systems tracts were identified, the sequence boundary is coincident with the surface of transgression. A complete list of identified surfaces and depths can be found in Appendix E.

<table>
<thead>
<tr>
<th>Well</th>
<th>SB 3.0</th>
<th>MFS 2.10</th>
<th>SB 2.0</th>
<th>MFS 1.10</th>
<th>SB 1.0</th>
<th>MFS 0.0</th>
<th>SB 0.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>DR-OT-1-46</td>
<td>1869</td>
<td>2029</td>
<td>2079</td>
<td>2213</td>
<td>2244</td>
<td>2298</td>
<td>2335</td>
</tr>
<tr>
<td></td>
<td>(6132)</td>
<td>(6657)</td>
<td>(6820)</td>
<td>(7259)</td>
<td>(7361)</td>
<td>(7540)</td>
<td>(7662)</td>
</tr>
<tr>
<td>DR-OT-2-65</td>
<td>1678</td>
<td>1842</td>
<td>1885</td>
<td>2016</td>
<td>2048</td>
<td>2096</td>
<td>2115</td>
</tr>
<tr>
<td></td>
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<td>(6044)</td>
<td>(6184)</td>
<td>(6613)</td>
<td>(6718)</td>
<td>(6877)</td>
<td>(6939)</td>
</tr>
<tr>
<td>DR-OT-3-65</td>
<td>1357</td>
<td>1420</td>
<td>1484</td>
<td>1597</td>
<td>1673</td>
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<tr>
<td></td>
<td>(4451)</td>
<td>(4660)</td>
<td>(4870)</td>
<td>(5240)</td>
<td>(5488)</td>
<td>observed</td>
<td>observed</td>
</tr>
<tr>
<td>HY-OT-1-65</td>
<td>1541</td>
<td>1646</td>
<td>1712</td>
<td>1846</td>
<td>1911</td>
<td>not</td>
<td>not</td>
</tr>
<tr>
<td></td>
<td>(5057)</td>
<td>(5401)</td>
<td>(5618)</td>
<td>(6055)</td>
<td>(6270)</td>
<td>observed</td>
<td>observed</td>
</tr>
</tbody>
</table>

The lowermost sequence (Sequence 0) is present in the Hatteras Light (DR-OT-1-46) and Mobil #2 (DR-OT-2-65) wells. It is present in the other studied wells, based on regionally extensive bounding seismic reflectors (Figure 3.4). However, cuttings from these deeper intervals were not logged, owing to the fact that original sampling used poorly constrained biostratigraphic data. As this sequence was only observed in two of the wells, which were studied in detail, individual parasequences were not correlated. The lower and upper sequence boundaries that delineate this sequence correspond to seismic reflectors SB 0.0 and SB 1.0, and are dominated by stacked quartz sandstones and skeletal carbonates. The lower boundary is tentatively identified, as it lies at the base of the studied interval. The maximum flooding surface is interpreted to occur at the depth of a thick shale, diatomaceous shale, and marl-rich package, and likely corresponding to a seismic trough at this time-interval in the seismic profiles.

The middle sequence (Sequence 1) is present in all the wells studied. The transgressive systems tract has five shoaling-upward successions (parasequences), with
the top of the fifth coincident with the maximum flooding surface (MFS 1.10). Seismically, the maximum flooding surface is only mappable in the updip regions of the basin. In the downdip regions, it is believed that the limited thicknesses and subtle facies changes result in the termination of this seismic reflector. The highstand systems tract consists of eight upward-shoaling parasequences, with the greatest number of packages preserved in the downdip regions. This parasequence set is unique, in that it grades from siliciclastic-dominated facies at the base to carbonate-dominated facies at the top. Discontinuous and shingled seismic reflectors record basinward progradation within the highstand systems tract. The upper sequence boundary (seismic reflector SB 2.0) likely corresponds to non-deposition or small amounts of erosion in the updip regions, whereas the downdip regions possess evaporites, indicative of restricted waters lying in basinal positions. This sequence boundary corresponds approximately to the K-5 boundary of Zarra (1989).

The upper sequence (Sequence 2) is also present in all studied wells. The transgressive systems tract comprises six upward-shoaling successions, with the top of the sixth being coincident with the maximum flooding surface (MFS 2.0). This maximum flooding surface is resolvable seismically across the entire study area. The highstand systems tract consists of seven shoaling-upward successions, with the greatest number of successions preserved in the downdip regions. Rare, discontinuous seismic reflectors are recorded within the highstand systems tract. The upper sequence boundary (seismic reflector SB 3.0) also likely corresponds to a non-depositional or erosional surface in the updip regions, as the youngest parasequences are only preserved in downdip areas. This
sequence boundary corresponds approximately to the bases of Brown et al.’s (1972) Unit F, and Zarra’s (1989) K-6 sequence boundary.

Discussion of Sequence Framework

The sequence stratigraphic framework generated in this study for the Lower Cretaceous sediments of the Albemarle Embayment is significantly more detailed than that produced by Brown et al. (1972) and Zarra (1989). Although some of the identified sequence boundaries coincide with previous models (Table 4.3), there are apparent differences. An additional sequence is present, and higher frequency sequence stratigraphic surfaces can be correlated across the study area. This higher degree of resolution was made possible because of the detailed petrographic study of thin-sectioned well cuttings, subsequently integrated with seismic and biostratigraphic data from the previous researchers.

Biostratigraphic age control

Repeatedly, biostratigraphic dating of calcareous nannofossils was attempted to accompany this study, in an effort to provide more precise biostratigraphic age resolution. Unfortunately, these efforts were unsuccessful, resulting in only a single, broad ‘Cretaceous’ date (T. Bralower, personal communication, 2006). Recent work by the U.S. Geological Survey (J.M. Self-Trail, personal communication, 2006) on the discontinuous Hatteras Light core yielded more useful results. Self-Trail indicated the depth interval from 6309 to 7133 ft (1923 to 2174 m) can be assigned to calcareous nannofossil Zone CC9b, equivalent to late Albian to early Cenomanian, based on the 2004 timescale.
Table 4.3 Comparison of observed sequence boundaries with previous researchers (measured depth in metres; feet inside brackets). Upper Table: SB 3.0 is approximately equivalent to the base of Unit F (Brown et al., 1972) and Zarra’s K-6 sequence boundary; overall difference is the placement of the SB 3.0 surface ~30m (~100ft) deeper than previous studies. Middle Table: SB 2.0 is approximately equivalent to Zarra’s K-5 sequence boundary; the placement is ± ~50m (~165ft). Lower Table: The SB 1.0 boundary agrees best with both authors in the DR-OT-3-65 and HY-OT-1-65 wells; the placement is ± ~35m (~115ft). The SB 0.0 boundary agrees best with both authors in the DR-OT-1-46 and DR-OT-3-65 wells; the placement is ~20m (~65ft) shallower than previous studies.

<table>
<thead>
<tr>
<th>Well</th>
<th>This study</th>
<th>Brown et al., 1972</th>
<th>Zarra, 1989</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SB 3.0</td>
<td>Base of Unit F</td>
<td>K-6</td>
</tr>
<tr>
<td>DR-OT-1-46</td>
<td>1869 (6132)</td>
<td>1867 (6142)</td>
<td>not studied</td>
</tr>
<tr>
<td>DR-OT-2-65</td>
<td>1678 (5505)</td>
<td>1606 (5270)</td>
<td>1606 (5270)</td>
</tr>
<tr>
<td>DR-OT-3-65</td>
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<td>1332 (4371)</td>
<td>1328 (4360)</td>
</tr>
<tr>
<td>HY-OT-1-65</td>
<td>1541 (5057)</td>
<td>1517 (4978)</td>
<td>1517 (4980)</td>
</tr>
<tr>
<td></td>
<td>This study</td>
<td>Zarra, 1989</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SB 2.0</td>
<td>K-5</td>
<td></td>
</tr>
<tr>
<td>DR-OT-1-46</td>
<td>2079 (6820)</td>
<td>not studied</td>
<td></td>
</tr>
<tr>
<td>DR-OT-2-65</td>
<td>1885 (6184)</td>
<td>1825 (5990)</td>
<td></td>
</tr>
<tr>
<td>DR-OT-3-65</td>
<td>1484 (4870)</td>
<td>1572 (5160)</td>
<td></td>
</tr>
<tr>
<td>HY-OT-1-65</td>
<td>1712 (5618)</td>
<td>1685 (5530)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>This study</td>
<td>Zarra, 1989</td>
<td>Brown et al., 1972</td>
</tr>
<tr>
<td></td>
<td>SB 1.0</td>
<td>K-4</td>
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</tr>
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<td>2364 (7759)</td>
</tr>
<tr>
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<td>2048 (6718)</td>
<td>2130 (6990)</td>
<td>2130 (6990)</td>
</tr>
<tr>
<td>DR-OT-3-65</td>
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<td>1688 (5540)</td>
<td>1690 (5546)</td>
</tr>
<tr>
<td>HY-OT-1-65</td>
<td>1911 (6270)</td>
<td>2023 (6640)</td>
<td>1871 (6140)</td>
</tr>
</tbody>
</table>

(personal communication, 2006). Samples from 7503 to 7770 ft (2287 to 2368 m) probably fall within Zones CC4-3 (early Valanginian to early Hauterivian), but the fossil samples are not very abundant and poorly preserved (J.M. Self-Trail, personal communication, 2006). Although useful in confirming a different age of the lowest identified sequence from the upper two sequences, Self-Trail’s (2006) work is only based on a single well and therefore, improved biostratigraphic dates from neighbouring wells may further support the framework developed in this study.
Previous work by Brown et al. (1972) and Zarra (1989) therefore remains the most important work for dating the Lower Cretaceous sediments in the Albemarle Embayment. As shown on the chronostratigraphic chart (Figure 1.3), the study interval duration is ~12 million years, starting in the Upper Aptian and ending at the boundary between the Lower to Middle Albian.

The three sequences observed are thought to represent third-order sea-level changes. Third order sea-level cycles occur at rates of 1-10 cm/k.y. every 0.5-5 m.y. (Vail et al., 1977; Cloetingh, 1988; Read, 1995). The maximum duration of each sequence in the Albemarle Embayment is four million years (~12 million years divided by the three cycles). At present, the biostratigraphic dataset does not permit assessment of the magnitude of missing time expressed by the sequence boundaries. Higher order cyclicity in the study area is indicated by the parasequences.

**Tectonics**

Regional tectonics likely had a minor influence on the sedimentation patterns in the Albemarle Embayment. During the Early Cretaceous, subsidence of the north-western Atlantic margin was largely the result of sediment loading and thermal contraction (Sleep and Snell, 1976; Heller et al., 1982; Cloetingh, 1988). Erosion of the nearby crystalline Appalachian Mountains is generally considered to have been relatively constant since the Jurassic (Matmon et al., 2003). No previous studies of the basin have indicated regional tectonic events during the Early Cretaceous which could have for changed siliciclastic supply- or subsidence rates within the Albemarle Embayment.

The shape of Sequence 1, however, is different than that of Sequence 2 (Figure 4.6). In Sequence 1, the lower and upper sequence boundaries (SB 1.0 and SB 2.0
respectively) are sub-parallel to the maximum flooding surface (MFS 1.10). This implies similar rates of sediment accumulation and creation of accommodation space across the entire basin during deposition of this sequence. Similar rates of regional accumulation and creation of accommodation space likely occurred during Sequence 0, based on the bounding, regionally extensive, sub-parallel seismic reflectors. In the younger Sequence 2, the basal sequence boundary (SB 2.0) and the maximum flooding surface (MFS 2.10) are subparallel, whereas highstand systems tract shows evidence of significant basinal sediment accumulation, such that the overlying sequence boundary (SB 3.0) and underlying maximum flooding surface (MFS 2.10) are not parallel. One reason for this difference in sediment thicknesses may be a progressive increase in rate of basinal accommodation space creation relative to updip regions. This resulted in greater basinal sediment thicknesses in the highstand systems tract of Sequence 2.

The mechanism for spatially and temporally different rates of accommodation space creation can be explained in the context of sedimentation patterns during the preceding sea-level lowstand. Sediment loading is considered one mechanism for increasing subsidence (Sleep and Snell, 1976; Heller et al., 1982; Cloetingh, 1988). It is proposed that a large amount of sediment accumulated downdip of the study area during the time period spanning the relative sea-level lowstand conditions of Sequence 1 to Sequence 2, and that this sediment acted to increase basinal subsidence relative to that updip during the following sea-level transgression of Sequence 2. It is suspected that this sediment is the result of deposition of a thick carbonate platform, based on: 1) the observed abundance of carbonates that accumulated during the late highstand of Sequence 1; and 2) the presence evaporites that mark the overlying sequence boundary.
It is proposed that the basinal increase in subsidence rates of the youngest sequence (Sequence 2) are the result of a prolific carbonate platform that had aggraded to sea-level (resulting in locally restricted conditions basinward of the study area) which loaded the lithosphere. Further study of the offshore seismic data and future drilling may reveal the presence of a shelf-margin wedge, dominated by carbonate material.

In the Baltimore Canyon Trough and the Southeast Georgia Embayment, increased rates of basin subsidence due to sediment loading during the Aptian-Albian interval have been recognized (Heller et al., 1982; Poag and Sevon, 1989). Though no data from within the Albemarle Embayment was discussed, the similar tectonic setting and proximity of the basin to the Baltimore Canyon Trough and Southeast Georgia Embayment suggests they would experience similar subsidence histories. From within the basin, Whitten (1976) discussed evidence for rapid subsidence due to sediment loading during the late Aptian and early Albian periods. In this study, it is suggested that the observed increased subsidence rates are due to lithospheric loading of the shelf by a carbonate-rich shelf margin wedge deposited during Sequence 1.

Alternatively, differential accommodation space creation could also have been the result of spatially variable sediment compaction rates and magnitudes. Also, initiation of growth faults that lie below seismic resolution may have also produced the observed geometries.

**Climate**

One of the key features of the model surrounds the carbonate-dominated packages deposited during the late highstand systems tract of Sequence 1. This progradation is tentatively correlated with the Ferry Lake Anhydrite in the Northeastern Gulf of Mexico.
region, based on similarities in the lithologies and an approximate biostratigraphic age match. If correct, this may imply global climate changes that favoured evaporite and carbonate sedimentation. Lawton et al. (2004) also noted synchronized ooid-rudistid-pellet carbonate ramp and platform development during the early-middle Albian in northern Mexico and the United States Gulf of Mexico region.

Frequently, relative sea-level falls on mixed carbonate-siliciclastic continental shelves result in the deposition of abundant siliciclastic material within the lowstand systems tract (e.g., Wilson, 1975; Martindale and Boreen, 1997; Francis et al., 2007). Recent study of the Great Barrier Reef trend, however, shows that abundant siliciclastic material also may be deposited during sea-level highstands (Francis et al., 2007). The mixed carbonate-siliciclastic sediments of the Albemarle Embayment indicate dominantly siliciclastic sedimentation patterns during the transgressive and highstand systems tracts (lowstand systems tract sediments are not penetrated by exploration wells). However, during the late highstand of Sequence 1, carbonate sedimentation dominated, and this likely evolved into a carbonate-dominated shelf-margin wedge basinward of the study area. It is proposed that climatic changes (primarily relative humidity), tied to sea-level variations resulted in this depositional pattern.

Numerous researchers have acknowledged the importance of climate in carbonate deposition (e.g., Wilson, 1975; Riggs, 1984; Read, 1995; Francis et al., 2007). Read (1995) noted that during late stages of highstands and lowstands, much of the continent is emergent, likely leading to relative aridity due to expansion of land-surface area (also Riggs, 1984). This potentially enhances evaporation and reduces the potential of siliciclastic sediment transport via fluvial processes to the shelf. During deposition of the
late highstand sediments of Sequence 1, relative sea-level fall, coupled with long-term climate changes, could have resulted in a more arid climate (as indicated by abundant carbonates, evaporites, and ooids). During long-term sea-level rises, the development of extensive shallow seas could promote increased rainfall and more humid climates (Riggs, 1984; Read, 1995). This potentially favours peat development and increased siliciclastic sediment transport to the continental margin. The observed abundant siliciclastic material coupled with limited coals during the transgressive and early highstand systems tracts within the Albemarle Embayment could have been a result of more humid climates.

Variations in the influx of terrigenous sediment have been attributed to the demise (increased influx) and reestablishment (decreased influx) of Mesozoic carbonate platforms in the Scotian shelf region of North Atlantic margin (Jansa 1993). Jansa (1993) attributed the influx of terrigeneous sediment to either local changes in climate or tectonics. In the Albemarle Embayment, the increase in carbonate deposition during the late highstand of Sequence 1 is interpreted to be the result of decreased siliciclastic input, owing to climate aridification.

Observations of the Pliocene surficial shelf sediments of the southeastern United States provide an analogue. The spatial distribution and production rates of carbonates are likely very different in the Pleistocene relative to the Cretaceous owing to the predominantly ice-house and greenhouse conditions respectively. During the peak of the Wisconsin glaciation, sea-level was approximately 120 m (~400 ft) lower than present (Ingram, 1987). Locally in the southeastern United States, the climate was drier, colder, and windier than present (Ingram, 1987), and carbonates formed along the southeastern United States and western Florida shelves (Milliman et al., 1968; Ginsburg and James,
1974; Brooks et al., 2003a, b). During the present sea-level highstand, carbonate sedimentation is locally reduced, owing to the effects of increased siliciclastic sedimentation (Milliman et al., 1968; Ginsburg and James, 1974; Brooks et al., 2003a, b). Though a glaciation during the Early Cretaceous period is not being proposed, this modern evidence suggestsof decreased local humidity corresponding with sea-level falls. Further, evidence of a dry-to-wet climate transition during the Holocene sea-level rise is also recorded along the northeastern (Francis et al., 2007) and southeastern (Ferland and Roy, 1997) margin of Australia.

**Biologic controls**

Diatoms underwent significant diversification in the middle part of the Cretaceous, and as a group, are capable of extensive removal of dissolved silica from seawater (Maliva et al., 1989). Prior to this major diversification, most marine-derived dissolved silica was removed through the growth of siliceous sponge spicules, which recrystallized during diagenesis to chert (Maliva et al., 1989). Chert cuttings fragments, though volumetrically very small, were found to be most abundant at the base of the study section, whereas diatomaceous shales are much more common in shallower cuttings intervals. Though both lithofacies were deposited on the deep shelf, the change from chert to diatomaceous shale may be attributed to the radiation of diatoms during the middle part of the Cretaceous (Maliva et al., 1989).
Paleogeographic Maps

By integrating the well data, published literature, and interpretations, three paleogeographic maps have been created. The approximate stratigraphic positions of these maps are shown in Figure 4.6 (fold-out). These schematic maps are an attempt to place the observed facies associations into two-dimensional relative positions at different time slices within the studied sequences.

The paleogeographic maps focus on the marine and marginal marine realm, because this setting was most extensively sampled in the studied wells. Terrestrial paleodrainage patterns are drawn to match modern river systems; studies suggest that these drainage systems have been relatively stationary since the Cretaceous (Coffey and Read, 2004). In the Baltimore Canyon Trough, sediment isopach maps indicate that the major rivers draining the central Appalachian Highlands have remained relatively stationary through most of the Mesozoic and Cenozoic; and that these rivers exit the Piedmont at the Fall Line, near where they exit today (Poag and Sevon, 1989).

Updip wells that were not petrographically studied possessed abundant coarse siliciclastic material throughout the study interval; these wells may have penetrated age-equivalent non-marine sediments, but existing biostratigraphic data cannot confirm this. The paleoshoreline position of each time slice is drawn to approximate the general strike of the present-day Atlantic margin (NNE – SSW). The present configuration of the North Carolina coastline is the result of recent Holocene transgression and barrier island formation, and has a very limited preservation potential (e.g., Milliman et al., 1968; Ginsburg and James, 1974).
The siliciclastic-dominated system (Figure 4.7) shows the most common situation during the Early Cretaceous. Coarse siliciclastic material (FA 2) was concentrated near local fluvial sources that may have built minor delta-related perturbations in the shoreline trend. Siliciclastic material decreased in grain size with increasing distance from sediment sources, owing to the limits of sediment transporting currents and wave action. Carbonate (FA 3) accumulation was favoured in the offshore portions of the shelf that were isolated from siliciclastic input; these areas may have been more prominent in southern portions of the basin (c.f. Brown et al., 1972). The onshore coastal plain would have been subject to limited sedimentation; extensive swamp development may have resulted in peat/coal beds (FA 1) distal to fluvial sources. The preservation potential of sediments on the coastal plain, however, is minimal due to the limited accommodation in the updip region of the basin.

The carbonate-dominated paleogeographic map (Figure 4.8) shows the distribution of facies associations during the late highstand systems tract of Sequence 1. Climate aridification, coupled with relative sea-level fall, reduced fluvial input to the basin. Therefore, smaller volumes of freshwater and siliciclastic material were transported to the shoreline, favouring the development and preservation of carbonate facies. Alternatively, autocyclic changes in drainage patterns may have resulted in riverine material being brought to the shoreline at much greater distances along strike from the basin center. Small amounts of quartzose sands (FA 2) were deposited along the shoreline in the vicinity of fluvial sources and likely mixed along strike with carbonate facies via longshore drift. Terrigenous-derived fine-grained sediment accumulated further offshore or in protected settings proximal to deltas. A restricted, evaporative lagoon (FA
Figure 4.7A: Siliciclastic-dominated paleogeographic map of the Early Cretaceous Albemarle Embayment. Rivers brought siliciclastic material to the shoreline, where shallow-marine processes distributed sediment along strike. Areas distal to fluvial sources on the coastal plain likely developed peat-bogs. Carbonate facies developed distal to siliciclastic sources on the open shelf. Cross-sections and legend can be found on Figure 4.7B. See descriptions in text for more detail.
Figure 4.7B: Top: Cross-sections from Figure 4.7A. Cross-sections are drawn at the same horizontal scale as the map. Bottom: Legend; also applies to Figures 4.8 and 4.9.

Legend:

- FA 1: Coal
- FA 2A: Coarse-grained quartz sandstone
- FA 2B: Fine-grained quartz sandstone
- FA 3: Quartzose sandy mollusc packstone and grainstone
- FA 4: Shale and siltstone
- FA 5A: Diatomaceous shale and planktonic foraminifera siltstone
- FA 5B: Marl, lime mudstone and fine-grained skeletal wackestone
- FA 6A: Evaporites (anhydrite and gypsum)
- FA 6B: Algal laminite
- FA 6C: Miliolid wackestone
- FA 7: Quartzose sandy ooid grainstone and packstone
- FA 8: Skeletal peloid packstone
- FA 9: Bryozoan and brachiopod packstone
- FA 10: Hardground surface

6, evaporites grading basinward to quartzose sand-bearing lime mudstones and algal laminites, to miliolid wackestones, and possibly to peloidal facies) formed distal to fluvial sources in extreme updip areas. The restricted sediments grade basinward to quartzose sand-bearing, ooid (FA 7) barriers and shoals, formed in high-energy wave shoaling zones. The ooid facies grade basinward to open marine bivalve-rich skeletal biostrome facies (FA 3). Below wave-energy influence, the lime mud component
Figure 4.8 Carbonate-dominated paleogeographic map of the Early Cretaceous Albemarle Embayment. Climate is believed to have been more arid during the late highstand of Sequence 1; therefore reduced siliciclastic sedimentation (likely focused near rivers/deltas) took place. Carbonate facies are well developed in positions distal to deltas. Heavy, purple line striking NNE – SSW represents approximate limit of sediment preservation. Dashed lines indicate relative wave energies. Low-energy, restricted lagoon deposits exist in center of basin; and grades basinward over the quartzose sandy ooid barriers and shoals to open-marine, skeletal facies downdip (SSE). Legend is as Figure 4.7B. See descriptions in text for more detail. Cross-section at top left is drawn at same horizontal scale as map.
increased, resulting in skeletal peloid packstone facies (FA 8). Local bryozoan and brachiopod accumulations (FA 9) likely formed distal to deltas, and were possibly concentrated in a belt, possible as local buildups (Burchette and Wright, 1992). On the deep outer shelf, pelagic sedimentation of planktonic foraminifera-rich marls and lime mudstones dominated (FA 5B).

The transgressive paleogeographic map (Figure 4.9) shows the distribution of facies associations during a rapid relative sea-level rise. Significant volumes of siliciclastic material transported to the basin by rivers were trapped in estuaries, with minor volumes of mud and silt (FA 4) being transported and deposited on the open shelf. Quartz sand-dominated (FA 2) shorelines were prevalent, resulting from continued sediment reworking by waves, as the shoreline back-stepped. The coastal system likely resembled the modern Carolina coastline (Milliman et al., 1968; Ginsburg and James, 1974), with ephemeral sandy barrier islands, especially in the vicinity of large estuaries. Carbonaceous material (FA 1) likely was deposited in shallow back-barrier lagoons and marshes. Carbonate sedimentation was dominant on the open marine shelf, with abundant molluscs (FA 3) accumulating in the inner to middle ramp zone. Hardground surfaces (FA 10) likely formed in regions with limited sediment accumulation, localised marine upwelling or bottom-current sweeping. In the deep, outer shelf setting, hemipelagic sedimentation with planktonic foraminifera-rich marls and lime mudstones dominated (FA 5B).
Figure 4.9 Transgressive paleogeographic map for the Early Cretaceous Albemarle Embayment. Lagoons and peat swamps formed behind quartz sand-dominated barrier islands. Large estuaries formed in areas incised by rivers during preceding sea-level lowstand. Majority of siliciclastic material was deposited updip, resulting in abundant carbonate facies on the open shelf. Hardground surfaces locally formed in areas of limited sedimentation or exposed to nutrient-rich bottom currents. Cross-section is drawn at same horizontal scale as map. Legend is as Figure 4.7B. See descriptions in text for more detail.
CHAPTER 5: CONCLUSIONS

Hydrocarbon exploration wells have been drilled in the Albemarle Embayment of eastern North Carolina since as early as 1925, but there have been relatively few published studies that focus on the subsurface Mesozoic strata. This project has resulted in a lithology-based sequence stratigraphic framework for the subsurface Early Cretaceous sediments of the Albemarle Embayment (Figure 4.6 – fold-out). This framework can be used as an analogue for coeval strata found along the North Atlantic margin. It also provides an updip, subsurface stratigraphic reference section for offshore exploration targets within the basin (Manteo prospect; Vigil, 1998).

The datasets used in this project include drill cuttings and geophysical wireline logs from wells drilled between 1946 and 1965. Only one partial core samples the interval in this downdip study area (depth of study interval is 1.5 to 2.25 km). These datasets were integrated with 2D seismic data, which were collected and processed in the mid-1970’s. Finally, cores from more recently drilled offshore wells (situated in basins along strike to the north and south) were also studied, and relevant literature references were incorporated.

The successful use of these vintage datasets in generating a regional stratigraphic framework is of great value, as many underexplored basins in the world lack modern, easily workable datasets. By applying the methods and techniques utilized in this study, expensive sampling, coring, or seismic surveys may be better planned, or avoided entirely.
Sequence Stratigraphic Summary

Sequence stratigraphic surfaces were identified in a manner similar to that employed by Coffey and Read (2004). Regionally correlatable shoaling-upward cycles 15 to 20 m (50 to 70 ft) thick were identified in all of the studied wells. These packages were interpreted as parasequences; and likely record high frequency relative sea-level changes. Parasequences were grouped into parasequence sets that are characterised by either progressive progradation or retrogradation of relative sea-level. Sequence boundaries were assigned to the tops of progradational parasequence sets corresponding to the highstand systems tract. Maximum flooding surfaces were placed below facies interpreted to record the deepest-water facies association capping retrogradational parasequence sets (transgressive systems tract). These surfaces typically coincide with seismic reflectors showing regional downlap. Lowstand sediments were not identified in the study area (criteria used were shallow-water facies associations occupying a basinal position and wedge-like, onlapping geometries expressed on seismic profiles); they may be present downdip of the study area. On this basis, transgressive flooding surfaces are considered to coincide with the underlying sequence boundaries.

Three sequences were identified. The sequences are interpreted as third order sea-level cycles, with each sequence having a maximum duration of approximately four million years. The oldest, Sequence 0, was only identified in the two downdip wells. However, regionally extensive seismic reflectors suggest that this sequence persists in other wells below the studied interval. Sequence 0 is dominated by siliciclastics, with regionally extensive marls and shales marking the maximum flooding surface. Sequence 1 is siliciclastic-dominated at the base, but grades into carbonate-dominated facies
associations during late highstand conditions. The maximum flooding surface in this interval is seismically traceable updip, but due to either thickness changes or facies transitions, it is not seismically resolvable in basinal areas (Figure 3.4). The youngest identified sequence, Sequence 2, contains a carbonate-dominated transgressive package, but it grades abruptly to siliciclastics during the following relative sea-level highstand. The maximum flooding surface is marked by a marl/shale unit in southern regions, and by a thick diatomaceous marl/shale in the northern regions.

In all sequences, the highstand systems tract is thicker than the transgressive systems tract, and it typically possesses shingled seismic reflectors indicative of strongly progradational sedimentation (Figure 3.4). A large, carbonate-dominated shelf-margin wedge is suspected to be present downdip, deposited during the time interval spanning the sequence boundary (SB 2.0) separating Sequence 1 and Sequence 2. This is based on the late highstand systems tract of Sequence 1 being carbonate-dominated and capped by evaporites (indicative of restricted conditions downdip of the study area). Further, this shelf-margin wedge may have loaded the crust, altering regional subsidence rates so that basinal regions experiences more rapid creation of accommodation space during the younger sequences (Figure 4.6). Alternatively, growth faults may have developed in the downdip study area during the deposition of Sequence 2, altering the overall shape of this sequence relative to the older sequences.

The sequence boundaries identified in this project generally correspond to the positions of the sequence boundaries identified by Zarra (1989; Table 4.3). However, important differences exist between this and previously published studies. This study provides a more comprehensive sequence stratigraphic framework that includes major
flooding surfaces in addition to the sequence boundaries. It also identifies a previously unrecognised sequence within the study interval. Most importantly, it provides valuable lithologic, diagenetic, and rock property data with which to calibrate the seismic profiles, stratigraphic framework, and depositional models to.

**Mixed Carbonate-Siliciclastic Models**

This study makes an important contribution to the understanding of mixed carbonate clastic systems. It develops depositional profiles (Figure 4.4) and paleogeographic maps (Figures 4.7, 4.8 and 4.9) of facies associations within a large mixed carbonate-siliciclastic succession. It also corroborates the contention that climate plays a major role in controlling carbonate- versus siliciclastic-dominated sedimentation patterns. Arid climate cycles favour carbonate sedimentation, whereas humid climate cycles favour siliciclastic sedimentation (Wilson, 1975; Riggs, 1984; Read, 1995). This contention is supported by Pleistocene observations (Ferland and Roy, 1997; Francis *et al.*, 2007), and this study shows that this concept is applicable to more ancient, greenhouse climatic periods of earth’s history. Sea-level also plays a role in controlling carbonate versus siliciclastic abundance (Wilson, 1975; Martindale and Boreen, 1997); however, as observed in the late highstand carbonate-rich sediments of Sequence 1, relative sea-level falls do not always favour siliciclastic sedimentation.

The siliciclastic-dominated system (Figure 4.4A) was dominated by marginal marine environments (lagoons, coastal and delta plains), which graded seaward to deep shelf settings. A biostrome consisting dominantly of molluscs (likely rudist bivalves) existed in the shallow shelf setting, basinward of the quartzose, sand-dominated high-
energy shoreface zone. The molluscan biostrome assemblage was likely best developed in areas removed from siliciclastic point sources. Proximal to deltas, abundant siliciclastic material probable operated to preclude formation of or dilute concentrations of carbonate material, resulting in thicker accumulations of siliciclastics (e.g., sandstone, siltstone, and shale). The deep shelf setting was dominated by pelagic and hemipelagic sedimentation, typified by shale, diatomaceous shale, planktonic foraminifera-bearing siltstone, and marl in more distal settings.

The carbonate-dominated system (Figure 4.4B) was prominent only during the late highstand systems tract of Sequence 1. It consisted of restricted tidal flats and lagoons, which graded seaward to high-energy quartzose sand-bearing, shallow subtidal, ooid shoals and barriers. Basinward, this system graded to open-marine, mollusc-rich biostrome accumulations of the middle ramp, which were periodically reworked by storms or other high-energy events. As water depth increased, more carbonate mud accumulated, which was re-worked with benthic biota to form sediment-dominated by molluscs and peloids. In nutrient-rich, deep waters of the outer ramp, bryozoans and brachiopods flourished, resulting in the local deposition of skeletal packstone showing little evidence of re-working. The deep shelf was characterised by pelagic sedimentation, rich in planktonic foraminifera. Minor amounts of siliciclastic material were deposited within the carbonate succession; storm-mixing processes or longshore drift probably transported this material from sand-rich coastal regions.

During short-term sea-level transgressions, much of the siliciclastic material was likely trapped and deposited in estuaries lying updip of the coast (Galloway and Hobday, 1996). Therefore, transgressive events limited supply of siliciclastic material to the open
shelf, favouring biolgenic carbonate production (Milliman et al., 1968; Ginsburg and James, 1974). Molluscan carbonate production was widespread during this period, with pelagic sedimentation occurring in deep shelf settings. Hardground surfaces developed locally in regions characterised by low sedimentation and bottom scouring by nutrient-rich currents.

The processes believed to be responsible for producing the mixed carbonate-siliciclastic sediments of the Lower Cretaceous sediments of the Albemarle Embayment include "punctuate mixing" (i.e., storms or other periodic extreme events transfer sediment), "facies mixing" (i.e., sediments mix along diffuse boundaries of contrasting facies), and "in situ mixing" (i.e., autochthonous calcareous organisms accumulate on or within siliciclastic substrates) (Mount, 1984). "Source mixing" (i.e. eroded clasts from carbonate source terranes admix with siliciclastics) is not believed to have been an important contributor as the observed carbonate material appears to be autochonous (Mount, 1984).

Future Research

Future research opportunities within the Albemarle Embayment include the study of younger and older Mesozoic sediments in this basin using similar methods, in order to expand upon this sequence stratigraphic framework. Further study in this region will also improve our understanding of mixed carbonate-clastic systems, as they are extensively developed in this basin (c.f., Brown et al., 1972; Zarra, 1989; Coffey, 1999; Coffey and Read, 2004, 2007), and likely have varied throughout geologic time (Goldthorpe, 1997).
Further study of the existing seismic data, and the correlation of the sequence stratigraphic framework to the offshore data, should aid in the regional mapping, development, and understanding of Lower Cretaceous successions of the northwestern Atlantic margin. Importantly, study of offshore seismic data from the Albemarle Embayment may confirm the presence of the hypothesized carbonate-rich shelf-margin wedge at the top of Sequence 1, as well as lowstand systems tract deposits coevally developed at the time of other interpreted relative sea-level regressions. Additionally, future higher resolution seismic surveys or drilling may also determine whether growth faults lie in basinal positions.

Time constraints did not permit study and identification of ocean anoxia events nor investigation of strontium isotope excursions that have been identified in basinal settings of other Lower Cretaceous sediments (e.g., Bralower et al., 1994, 1999; Thurow and Erbacher, 1997; Jones and Jenkyns, 2001). However, this study has provided a lithology-based sequence stratigraphic framework that can be used to guide sampling and to evaluate the isotopic expression of these events in a broad passive margin, continental shelf setting (work that is ongoing at University of North Carolina, B. P. Coffey, personal communication, 2008).

Finally, further biostratigraphic analysis would aid in providing a more precise age resolution. This would be useful for confirming correlations between wells, and for correlating the observed sea-level variations to global eustatic sea-level charts (e.g., Haq et al., 1987; Hardenbol, et al., 1998).
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APPENDICES (ENCLOSED CD)

The CD-ROM attached forms a part of this work. The data file (5.9 mb) was created with Adobe Acrobat, and may be opened with any PDF capable program. The following is a Table of Contents for the data file (Titled: Sunde, 2008 Appendices):

APPENDIX A: Well Location and Kelly Bushing Data .............................. 163
APPENDIX B: Offshore U.S. Core Descriptions ...................................... 165
APPENDIX C: Well-Cuttings Point Count Data ................................. 183
APPENDIX D: Vertical Columns .......................................................... 213
APPENDIX E: Depth of Interpreted Sequence Stratigraphic Surfaces ...... 222