Late Cenozoic Evolution of Sedimentation and Slope Stability Along the U.S. Atlantic Margin

Bradley Kevin Craig
Coastal Carolina University

Follow this and additional works at: https://digitalcommons.coastal.edu/etd

Part of the Geophysics and Seismology Commons

Recommended Citation
https://digitalcommons.coastal.edu/etd/12

This Thesis is brought to you for free and open access by the College of Graduate Studies and Research at CCU Digital Commons. It has been accepted for inclusion in Electronic Theses and Dissertations by an authorized administrator of CCU Digital Commons. For more information, please contact commons@coastal.edu.
Late Cenozoic evolution of sedimentation and slope stability along the U.S. Atlantic margin

Bradley K. Craig

Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science in Coastal Marine and Wetland Studies in the College of Science Coastal Carolina University 2014

Dr. Jenna Hill
Dr. Daniel S. Brothers
Dr. Richard F. Viso
Dr. Richard N. Peterson

August 4, 2014
Conway, South Carolina
Acknowledgements

This project would not have been possible without the guidance and assistance of many individuals directly involved or otherwise. Most notably, my thesis advisor, Dr. Jenna Hill, for being patient, providing an environment to think critically, and pushing me to develop as a scientist and person. I would also like to thank Dr. Danny Brothers for his insight that he provided throughout the project. A special thank you to Dr. Rich Viso and Dr. Rick Peterson for your assistance in the thesis production. Each of you has offered invaluable insight through this process and facilitated the development of this project and manuscript.

To members of the Groundwater Discharge Measurement Facility and Geophysics lab at Coastal Carolina University: Thank you for being a supportive, engaging, and interesting group of people. You all have provided insight and thoughts into this project while ensuring that fun is had and work is completed at the proper time. Thank you and good luck to you all—members past, present, and future. A special and sincere thanks to Matt Carter, Leigha Peterson, Sarah Chappel, Beckett Hills, Brian Johnson, Shinobu Okano, Jamie Brusa for assisting in interpretations and positive attitudes! Thank you also to United States Geological Survey employees that I met and communicated through emails and phone calls that provided data and questions through the process.

Lastly, thank you to my wife Miranda, who put up with weeks gone, long hours away and has supported me through it all.
Abstract

The U.S. Mid-Atlantic margin, from the Norfolk Canyon south to Cape Hatteras, exhibits three major seafloor morphologies: elongated shelf-edge blowouts, the Currituck submarine landslide, and a large slope-sourced canyon failure. The late Cenozoic evolution of slope stability on the Middle Atlantic margin can be linked to the framework geology as well as spatial and temporal variations in sedimentation patterns across the margin. The framework geology impacts sediment pathways, while the shape of the margin influences the position of sediment depocenters across the margin. Changes in sedimentation rates and sediment source dictate the amount of sediment being delivered to each region and can vary through time. High sediment supply can lead to progradation of deposits across the shelf and slope that can increase the probability of larger sediment failure. Lower sediment supply tends to be associated with sediment deposition on the outer shelf and shelf-edge, which leads to oversteepening the upper slope and increases the probability of progressive slides. Here, I used a dense grid of industry multichannel seismic data across the outer shelf and slope of the U.S. Mid-Atlantic margin to investigate the evolution of geologic framework evolution and spatial variability in sediment depocenters over time. The Currituck region of the margin has a sigmoidal morphology, characterized by a rounded shelf-edge with a relatively gentle slope gradient (< 6°). This morphology, combined with rapid sedimentation across the middle slope appears to have preconditioned the margin for retrogressive slope failure. In contrast, sediment buildup on the shelf-edge at the blowout region to the north resulted in the development of an angular shelf-edge and a steep upper slope gradient, > 11°. This led to oversteepening and downslope sediment bypass, resulting in the heavily canyonized slope morphology observed on the slope today. The large slope-sourced canyon failure region exhibits an intermediate margin shape of the Currituck and blowout regions, where sediment progradation on the shelf-edge and upper slope led to a large canyon-confined failure that on the upper slope. Across the study area, it appears that much of the modern morphology has been inherited from the spatial distribution of depocenters emplaced as much as 11 mya. These results highlight the role of framework geology and sediment distribution in preconditioning the margin for slope failure.
Table of Contents

List of Figures .......................................................................................................................... vi

Introduction ................................................................................................................................1

Regional Settings .......................................................................................................................7
  Sediment Sources ....................................................................................................................9
  Gas Distribution .....................................................................................................................10
  Submarine Landslides ..........................................................................................................11

Methods ....................................................................................................................................14

Results ......................................................................................................................................18
  Middle Miocene .....................................................................................................................19
  Upper Miocene ......................................................................................................................20
  Pliocene ................................................................................................................................21
  Quaternary ............................................................................................................................22

Discussion ................................................................................................................................23

Conclusions ..............................................................................................................................34

References ................................................................................................................................37

Appendix A ..............................................................................................................................44

Tables .......................................................................................................................................68

Figures .....................................................................................................................................69
# List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1</td>
<td>U.S. Atlantic Margin bathymetry A) The mega-elongated pockmarks or “blowouts” B) The Currituck Submarine landslide scarp C) Large slope sourced landslide</td>
<td>69</td>
</tr>
<tr>
<td>Figure 2</td>
<td>Retrogradation, Aggradation, and Progradation in relation to sediment influx and sea level, modified from Emery and Myers 1996</td>
<td>70</td>
</tr>
<tr>
<td>Figure 3</td>
<td>End member shelf-edge morphologies (A) Sigmoidal (B) Oblique from Brothers et al. (2013a)</td>
<td>71</td>
</tr>
<tr>
<td>Figure 4</td>
<td>Sea level curve over the last 30 million years (Haq et al., 1989)</td>
<td>72</td>
</tr>
<tr>
<td>Figure 5</td>
<td>Borehole locations and trackline location across the U.S. Atlantic Margin, published reference lines are represented in green (Poag and Ward, 1993; Klitgord et al., 1994)</td>
<td>73</td>
</tr>
<tr>
<td>Figure 6</td>
<td>Klitgord et al. (1994) Line 28 across the blowout margin. (A) uninterrupted profile (B) interpreted profile</td>
<td>74</td>
</tr>
<tr>
<td>Figure 7</td>
<td>Klitgord et al. (1994) Line 29 across the blowout margin. (A) uninterrupted profile (B) interpreted profile</td>
<td>75</td>
</tr>
<tr>
<td>Figure 8</td>
<td>Middle Miocene sediment thickness. Contours are every 0.25s in two-way travel time. Arrows indicate inferred paths of paleo-fluvial systems from (Poag and Sevon, 1989; Hobbs, 2004)</td>
<td>76</td>
</tr>
<tr>
<td>Figure 9</td>
<td>Upper Miocene sediment thickness. Contours are every 0.25s in two-way travel time. Arrows indicate inferred paths of paleo-fluvial systems from (Poag and Sevon, 1989; Hobbs, 2004)</td>
<td>77</td>
</tr>
<tr>
<td>Figure 10</td>
<td>Pliocene sediment thickness. Contours are every 0.25s in two-way travel time. Arrows indicate inferred paths of paleo-fluvial systems from (Poag and Sevon, 1989; Hobbs, 2004)</td>
<td>78</td>
</tr>
<tr>
<td>Figure 11</td>
<td>Quaternary sediment thickness. Contours are every 0.25s in two-way travel time. Arrows indicate inferred paths of paleo-fluvial systems from (Poag and Sevon, 1989; Hobbs, 2004)</td>
<td>79</td>
</tr>
<tr>
<td>Figure 12</td>
<td>Representative profiles for seismic lines across the margin used for depth vs distance and gradient vs distance plots</td>
<td>80</td>
</tr>
<tr>
<td>Figure 13</td>
<td>WesternGeco Line 82136 across the blowout margin. (A) uninterrupted profile (B) interpreted profile</td>
<td>81</td>
</tr>
</tbody>
</table>
Figure 14.  Base of Middle Miocene horizon interpreted from representative profiles in (A) the northern blowout region and (B) the Currituck slide and southern canyon failure regions. Base of Middle Miocene horizon gradient along representative profiles from (C) the northern blowout region and (D) the Currituck slide and southern canyon failure regions. 0 km distance along the profile indicates the location of the shelf-edge.......................................................... 82

Figure 15.  (A) Interpreted horizons from WesternGeco line 82136. (B) Horizon gradient along the profile: The 20 reflector indicates the base of Quaternary, 30 is the base of Pliocene, 40 is the base of Upper Miocene, and 45 is the base of Mid-Miocene. 0 km distance along the profile indicates the shelf-edge.................................................. 83

Figure 16.  WesternGeco Line 82130 across the blowout margin. (A) uninterrupted profile (B) interpreted profile........................................ 84

Figure 17.  WesternGeco Line 82183 across the blowout margin. (A) uninterrupted profile (B) interpreted profile........................................ 85

Figure 18.  WesternGeco Line 82171 across the blowout margin. (A) uninterrupted profile (B) interpreted profile........................................ 86

Figure 19.  Base of Upper Miocene horizon interpreted from representative profiles in (A) the northern blowout region and (B) the Currituck slide and southern canyon failure regions. Base of Middle Miocene horizon gradient along representative profiles from (C) the northern blowout region and (D) the Currituck slide and southern canyon failure regions. 0 km distance along the profile indicates the location of the shelf-edge.......................................................... 87

Figure 20.  BOEM seismic profile MA-006 across the shelf. (A) uninterrupted profile (B) interpreted profile........................................ 88

Figure 21.  Base of Pliocene horizon interpreted from representative profiles in (A) the northern blowout region and (B) the Currituck slide and southern canyon failure regions. Base of Middle Miocene horizon gradient along representative profiles from (C) the northern blowout region and (D) the Currituck slide and southern canyon failure regions. 0 km distance along the profile indicates the location of the shelf-edge.......................................................... 89

Figure 22.  WesternGeco Line 82166 across the blowout margin. (A) uninterrupted profile (B) interpreted profile.......................... 90
Figure 23.  Base of Quaternary horizon interpreted from representative profiles in (A) the northern blowout region and (B) the Currituck slide and southern canyon failure regions. Base of Middle Miocene horizon gradient along representative profiles from (C) the northern blowout region and (D) the Currituck slide and southern canyon failure regions. 0 km distance along the profile indicates the location of the shelf-edge.

Figure 24.  O’Grady et al. (2000) Type classifications.

Figure 25.  WesternGeco Line 82126 across the blowout margin. (A) uninterrupted profile (B) interpreted profile.

Figure 26.  (A) Interpreted horizons from WesternGeco line 82126. (B) Horizon gradient along the profile: The 20 reflector indicates the base of Quaternary, 30 is the base of Pliocene, 40 is the base of Upper Miocene, and 45 is the base of Mid-Miocene. 0 km distance along the profile indicates the shelf-edge.

Figure 27.  (A) Interpreted horizons from WesternGeco line 82130. (B) Horizon gradient along the profile: The 20 reflector indicates the base of Quaternary, 30 is the base of Pliocene, 40 is the base of Upper Miocene, and 45 is the base of Mid-Miocene. 0 km distance along the profile indicates the shelf-edge.

Figure 28.  WesternGeco Line 82147 across the blowout margin. (A) uninterrupted profile (B) interpreted profile.

Figure 29.  (A) Interpreted horizons from WesternGeco line 82147. (B) Horizon gradient along the profile: The 20 reflector indicates the base of Quaternary, 30 is the base of Pliocene, 40 is the base of Upper Miocene, and 45 is the base of Mid-Miocene. 0 km distance along the profile indicates the shelf-edge.

Figure 30.  WesternGeco Line 821151 across the blowout margin. (A) uninterrupted profile (B) interpreted profile.

Figure 31.  (A) Interpreted horizons from WesternGeco line 82151. (B) Horizon gradient along the profile: The 20 reflector indicates the base of Quaternary, 30 is the base of Pliocene, 40 is the base of Upper Miocene, and 45 is the base of Mid-Miocene. 0 km distance along the profile indicates the shelf-edge.
Figure 32. (A) Interpreted horizons from WesternGeco line 82166. (B) Horizon gradient along the profile: The 20 reflector indicates the base of Quaternary, 30 is the base of Pliocene, 40 is the base of Upper Miocene, and 45 is the base of Mid-Miocene. 0 km distance along the profile indicates the shelf-edge.

Figure 33. (A) Interpreted horizons from WesternGeco line 82171. (B) Horizon gradient along the profile: The 20 reflector indicates the base of Quaternary, 30 is the base of Pliocene, 40 is the base of Upper Miocene, and 45 is the base of Mid-Miocene. 0 km distance along the profile indicates the shelf-edge.

Figure 34. WesternGeco Line 42 across the blowout margin. (A) uninterrupted profile (B) interpreted profile.

Figure 35. (A) Interpreted horizons from WesternGeco line 42. (B) Horizon gradient along the profile: The 20 reflector indicates the base of Quaternary, 30 is the base of Pliocene, 40 is the base of Upper Miocene, and 45 is the base of Mid-Miocene. 0 km distance along the profile indicates the shelf-edge.

Figure 36. WesternGeco Line 82172a across the blowout margin. (A) uninterrupted profile (B) interpreted profile.

Figure 37. (A) Interpreted horizons from WesternGeco line 82172a. (B) Horizon gradient along the profile: The 20 reflector indicates the base of Quaternary, 30 is the base of Pliocene, 40 is the base of Upper Miocene, and 45 is the base of Mid-Miocene. 0 km distance along the profile indicates the shelf-edge.

Figure 38. (A) Interpreted horizons from WesternGeco line 82183. (B) Horizon gradient along the profile: The 20 reflector indicates the base of Quaternary, 30 is the base of Pliocene, 40 is the base of Upper Miocene, and 45 is the base of Mid-Miocene. 0 km distance along the profile indicates the shelf-edge.
1. Introduction:

Geohazards such as earthquakes, tsunamis, and submarine landslides can pose a considerable threat to low-lying coastal populations. Although these events are far more common on tectonically active margins (e.g., the western North American margin), less frequent events have occurred on the passive Atlantic margin of the United States. Earthquakes are often the primary triggers of submarine landslides, which in turn can generate tsunamis (Locat and Lee, 2002). The Currituck submarine landslide, shown in Figure 1, Cape Fear slide complex, and Munson-Nygren submarine landslide are a few of the hundreds of slide scarps across the U.S. Atlantic margin. In one of the most well documented historical events, the 1929 Grand Banks magnitude 7.2 earthquake triggered a submarine landslide that generated a tsunami with an 8 m run-up. Other historical tsunamis on the U.S. Atlantic margin (USAM) include the 1926 Bernard, Maine 3 m tsunami with an unknown source and the 1964 Long Island, New York tsunami with a run-up of 0.28 m (Lockridge et al., 2002). The most recent large earthquakes across the USAM include of the 1886 magnitude 7.3 Charleston earthquake and the 2011 magnitude 5.8 Mineral, VA earthquake.

The potential for tsunamis produced by submarine landslides constitutes a high risk of flooding for the coastal populations and habitat of the U.S. Atlantic coast (ten Brink et al., 2014). A submarine landslide can displace large volumes of sediment and disturb the overlying water column. As the water column returns to equilibrium it is able to produce a
tsunami. The size of the tsunami is related to the amount of sediment displaced during the landslide. Large volumes of sediment accumulate on passive margins. Passive margins are the result of continental rifting, although tectonic activity along these margins tends to subside over time as the plates spread farther from the active rift and sedimentary processes take over. Passive margins generally are characterized by wide, gently dipping continental shelves that consist of several kilometers of terrestrial and marine sediment deposits. During sea level lowstands, rivers and glaciers extended across the shelf delivering a large amount of sediment to the continental shelf, slope and rise. Rapid sedimentation across a margin can lead to under compaction, oversteepening and overpressure, creating unstable conditions prone to slope failure. While earthquakes typically trigger sediment failure on passive margins, the sediment is usually preconditioned prior to failure. Preconditions can include slope morphology, sediment loading and elevated pore pressure.

Sediment loading along continental margins is one of the primary causes of overpressure in the sediment, which can increase the probability of submarine slope failure (Dugan and Flemings, 2000). As sediment accumulates, water is trapped within the pore space of the grains. With continued sediment deposition, the sediment grains below impermeable layers are compacted due to the build up of pressure from the overlying sediment. Water trapped within the pore space is relatively incompressible; as the lithostatic pressure continues to increase due to sediment influx, the pore fluids create space between grains, decreasing shear strength of the sediment. As the sediment continues to compact, overpressured pore fluids will either migrate elsewhere along bedding planes or faults, or become trapped by an impermeable sediment layer, creating a potential slip plane for a slide to occur.
It is important to understand how different margin morphologies develop over time in response to local differences in sedimentation and antecedent geology since this can have a major impact on preconditioning factors that lead to failure. Sediment distribution and seafloor morphology on passive margins is a product of sea level, sediment influx, energy within the system, and framework geology (O'Grady et al., 2000; Goff, 2001; Brothers et al., 2013a). The antecedent geology can direct sediment delivery and the spatial distribution. Relative sea level, along with tectonics and sediment supply controls accommodation space or the space available for sediment accumulation on a continental margin. Terrestrial sediment can be transported across the margin via currents, deltas, through canyons, and slope failures to be deposited on the shelf, slope and rise. Millennial sea level fluctuations due to climatic and glacial cycles also strongly influence sediment deposition across a margin. Retrogradation of sediment packages occurs when sediment supply is less than the rate of formation of accommodation space (Emery and Myers, 1996) (Figure 2). Aggradation of sediment packages occurs when sediment supply and the rate of accommodation space formation are roughly balanced (Emery and Myers, 1996) (Figure 2). Progradation of sediment packages occurs when sediment supply exceeds the rate of accommodation space formation (Emery and Myers, 1996) (Figure 2). Once the accommodation space is filled on the shelf, sediment will be deposited elsewhere across the margin, often bypassing the shelf and depositing on the slope or rise. On passive margins where the continental shelf is broad and gently dipping, a relatively small vertical change in sea level can cause large lateral changes in the position of the shoreline. Lower base level due to sea level fall causes rivers to adjust their equilibrium profile and incise the continental shelf. Large rivers cut valleys into
the shelf, providing a direct pathway for terrestrial sediment delivery to the slope and rise. During relative sea level highstands, river valleys across the shelf become inundated and the river mouths are shifted landward, moving the depocenters farther landward. Spatial changes in depocenters due to sea level fluctuations will influence the overall shape of a margin (Schlager and Adams, 2001).

The USAM morphology has been described and classified in multiple studies (e.g., O'Grady, 2000; Goff, 2001; Brothers et al., 2013a). The USAM has a relatively steep continental slope with gradients reaching up to 6.3° - 7.7° and average gradient of 3.7° ± 0.4° associated with a variety of stratal patterns and high amounts of canyon incision (O'Grady, 2000; Brothers et al., 2013a). In order to describe along strike variations across the USAM, Brothers et al. (2013a) developed a classification of slope morphology with two end-members: oblique and sigmoidal (Figure 3). The morphology of the margin is shaped by the complex interactions of sediment deposition, currents, and relative energy across the margin, and can be linked to the stability of the slope. An oblique shelf-edge is characterized as an angular transition from shelf to slope with the highest gradient on the upper slope (Figure 3A). Oblique margins are associated with sharp shelf-edge rollovers, sediment deposition near the shelf-edge, and lower wave and current energy in the system, similar to the central Mid-Atlantic portion of the USAM (Brothers et al., 2013a). Progressive landslides are often associated with oblique shaped margins due to the high degree of sediment accumulation on the shelf-edge. Progressive landslides can aid in the formation of slope-sourced canyons, where sediment is eroded from the shelf-edge and upper slope, then transported to the lower slope. Sigmoidal margins have a shelf-edge that gently transitions to the slope and maintain the highest
gradient (7°-10°) on the middle and lower slope (Figure 3B). Sigmoidal margins are associated with sediment accumulation on the lower slope and higher energy environments that can lead to retrogressive slides, similar to the Hudson Apron (Brothers et al., 2013a). This classification system allows for a consistent description of along slope morphologic variability linked to the slope stability within each region.

The first-order morphology of the USAM is dominated by large canyons, including both shelf-sourced and slope-sourced canyons, as well as numerous submarine landslide scarps; all are important mechanisms for sediment transport from the shelf to the rise (Twichell et al., 2009; Brothers et al., 2013b). Shelf-sourced canyons extend across the slope landward onto the shelf. Having evolved from direct connections to terrestrial drainage systems during relative sea level lowstands, these canyons funnel large volumes of sediment across the shelf and slope and are often linked to major deep sea fan systems (Shepard and Emery, 1973; Shepard 1981; Brothers et al., 2013b). Slope-sourced canyons are confined to the continental slope with canyon heads located on the slope and are derived from localized slope failures that are important for sediment transportation down slope (Twichell and Roberts, 1982; Pratson et al., 1994; Goff, 2001; Brothers et al., 2013b). Canyon morphology and distribution can be correlated with overall margin morphologies. Slope-sourced canyons are abundant where the continental slope exceeds 6°, and the flow pattern trends directly down slope. Where the slope gradient is less than 5° canyon spacing is 2 to 10 km (Twichell and Roberts, 1982). Slumps, currents and biogenic erosional forces are also common mechanisms of sediment transport along the shelf-edge and slope (Pratson et al., 1994).
The USAM has a long history of constructional and destructional evolution and is characterized by numerous open-slope and canyon-sourced landslides (Twichell et al., 2009). Steep slopes, active gas venting from the seafloor and recent earthquake activity suggest that the USAM remains dynamic and contains several sites for potential failure (Brothers et al., 2014; ten Brink et al., 2014). One of the largest geomorphic features on the mid-section of the USAM, the Currituck landslide north of Cape Hatteras, removed up to 150 km$^3$ of sediment from the continental slope to the rise and likely produced a tsunami equivalent to a category 3-4 hurricane storm surge (Prior et al., 1986; Giest et al., 2009; Locat et al., 2009) (Figure 1). South of the Norfolk Canyon, several extremely large, elongated shelf-edge depressions, or “blowouts”, are actively venting methane and have been suggested as indicators of incipient slope failure (Hill et al., 2004; Newman et al., 2008) (Figure 1). Slope-sourced canyons dominate the slope in this region with recently discovered pockmarks and active seeps based on multibeam and ROV dives (Brothers et al., 2013c; Skarke et al., 2014). It has been postulated that methane gas trapped within the sediment elevates the probability of slope failure in the blowout region that may generate a tsunami along the North Carolina and Virginia coastline (Driscoll et al., 2000).

The goal of this study is to examine the subsurface architecture and margin evolution from the Norfolk Canyon south to Cape Hatteras to better understand how the framework geology contributes to both variation in morphology along the margin and development of large-scale slope failures. We hypothesize that:
1. There are distinct differences in the subsurface stratal architecture and underlying geology of the continental margin between the shelf-edge blowout region south of Norfolk Canyon and the Currituck Slide region.

2. The spatial distribution of large depocenters, which is a function of long-term sediment supply, is a first order control on distribution of large submarine landslides.

2. Regional Setting:

The USAM formed through a complex series of tectonic processes including convergence, rifting, and subsidence. Paleozoic convergence and orogenic events formed the Appalachian Mountains along the east coast of the U.S., producing a series of thrust faults that laid the foundation for the rifting of Pangaea (Klitgord et al., 1988). The Atlantic Ocean formed as a result of the rifting of North American and African plates during the late Triassic and early Jurassic, roughly 238-187 Ma (Schlee et al., 1976; Klitgord et al., 1994). Initial stages of the Atlantic basin provided shallow warm waters for the formation of the Mesozoic Reefs (187-130 Ma) and carbonate platforms that eventually acted as dams for terrestrial sediment (Schlee et al., 1976). The Atlantic basin continued widening throughout the Cenozoic and the USAM continued to subside due to thermal cooling and sediment loading. Weathering of the Appalachians provided siliciclastic sediment to the passive margin, forming a seaward thickening sediment wedge infilling accommodation generated by subsidence (Poag, 1978; Poag and Sevon, 1989; Klitgord et al., 1988).
Sediment composition and depositional patterns have varied greatly since the initial formation of the USAM. Sea level was highest, ~250 meters above modern, during the Lower/Upper boundary of the Cretaceous (100 mya), which provided a large amount of marine accommodation space (Haq et al., 1987). At the start of the Oligocene, sea level fell to an average level of 150 m above modern and remained relatively constant until the Early Miocene. Prior to the Middle Miocene, sedimentation varied from carbonate to siliciclastic, typically dominated by chemical weathering of the Appalachians during climatic warm periods (Poag and Sevon, 1989). During the Oligocene and Early Miocene, temperatures in North America started to transition from wet tropical conditions to a drier subtropical climate (Poag and Sevon, 1989). Climate fluctuations from glacial to interglacial conditions eroded the highest amounts of terrestrial sediment from the Middle Miocene to present (Poag and Sevon, 1989). The shift to a subtropical climate initiated intense mechanical weathering and rapid erosion of the Appalachian Mountains, allowing Mid-Miocene rivers to deliver a large amount of sediment to the outer shelf and upper slope. Progradation of deltaic clinoforms extended the shelf-edge farther seaward, while submarine canyons were cut into Oligocene clastic sediment (Mountain, 1987; Poag and Sevon, 1989; Pratson et al., 1994). The Middle Miocene clinoform accumulation rates (~16,000 km³ Myr⁻¹) are more than twice that of any other time period, filling accommodation space on the shelf by the Pliocene (Poag and Sevon, 1989; Mountain et al., 2007).

Global temperatures started to cool in the Middle Miocene leading to the onset of North American glaciation in the Pliocene (Haq et al., 1987; Poag and Sevon, 1989) (Figure 4). Sea level rose during the Pliocene highstand and migrated across the Florida-Hatteras Slope,
eroding the Upper Miocene sediment there (Pinet and Popenoe, 1985). Ice sheets spread over northeastern North America during the Pleistocene, eroding large volumes of glaciofluvial and glaciomarine sediment that was subsequently delivered to the New England margin, Hudson Apron, and Mid-Atlantic margin (Poag and Sevon, 1989). Widespread canyon/channel incision of the slope and upper-rise, along with onlapping base-of-slope fan/apron complexes suggest slope failures and generation of mass flows were the dominant sediment transport processes during the Quaternary.

2.1 Sediment Source

Major sources of sediment to the Mid-Atlantic portion of the USAM include the Paleo-Roanoke drainage from North Carolina, Paleo-James, and Paleo-Potomac-Susquehanna Rivers (Poag and Sevon, 1989; Theiler et al., 2013) (Figure 1). The Paleo-Roanoke River is one of the few drainage systems where source sediment has been delivered directly from erosion of the southern Appalachians Mountains to the USAM offshore of North Carolina (Thieler et al., 2013). The Paleo-Roanoke has been documented as a varying source for sediment to the Mid-Atlantic USAM as far back as the Late Jurassic (Poag and Sevon, 1989). Large seaward thickening wedges of sediment across the inner shelf of North Carolina indicate a large volume of sediment were delivered by the Paleo-Roanoke River during the Late Pliocene and Quaternary (Mallinson et al., 2010). The Paleo-Susquehanna, Paleo-Potomac, and Paleo-James Rivers have dominated drainage to the north (Figure 1). Prior to the Pleistocene, these rivers flowed directly east across the margin; however, the formation of the Accomack Spit, redirected these fluvial systems south through Chesapeake Bay.
Following the formation of the Accomack Spit, the Paleo-Susquehanna, Paleo-Potomac, and other fluvial drainages from the Chesapeake Bay converged before exiting the mouth of the bay, supplying sediment to the margin (Hobbs, 2004). The Paleo-James River exited the mouth of the Chesapeake Bay without converging with the other fluvial systems of the Chesapeake Bay and redirected southward, either flowing parallel to shore and turning offshore farther south or flowing southeast towards the shelf-edge (Hobbs, 2004).

2.2 Gas distribution

The Paleo-Susquehanna, Paleo-Potomac, Paleo-James, and Paleo-Roanoke Rivers delivered a large amount of organic-rich terrestrial sediment to the Mid-Atlantic USAM. This organic material is often a primary source of biogenic gasses trapped within sediment, which can lead to seabed fluid flow and gas expulsion along the margin. Gas venting has been documented along the modern Mid-Atlantic continental shelf at the Blake Ridge near the Cape Fear Complex (Brothers et al., 2013c) and south of the Norfolk Canyon (Hill et al., 2004; Newman et al., 2008, Skarke et al., 2014). Potential sources of gas can range from thermogenic gasses from the Upper Jurassic and Lower Cretaceous basement rocks to diagenetic breakdown of trapped organic materials in the sediment (Hill et al., 2004; Thieler et al., 2014). Overpressure, fluid flow, and gas expulsion can result in post depositional modification of margin morphology through formation of pockmarks or by preconditioning sediment for failure. Pockmarks, found extensively along the USAM, are thought to have formed through gas or pore water eruption and are described as circular to elliptical with U-shaped and V-shaped cross sections; some are several kilometers across and 50 m in relief.
(Hill et al., 2004; Newman et al., 2008; Brothers et al., 2014) (Figure 1). Pockmarks can be used to infer areas of high pore pressure that have preconditioned the sediment for failure and may be used as an early indicator of submarine landslides (Hovland et al., 2002, Hill et al., 2004).

2.3 Submarine landslides

Submarine landslides are known to have occurred on gently sloping, passive continental margins around the world. Submarine landslides can be separated into two primary types of slides, progressive and retrogressive. Progressive slides occur when the failure is initiated on the shelf-edge or upper slope and sediment is removed from top to bottom. Earthquakes and downslope gravitational processes can initiate progressive slides, which are often associated with slope-sourced canyons, and are frequently smaller than retrogressive failures. Retrogressive slides, often associated with large submarine slides, are also triggered by earthquakes and initiate on the middle to lower slope (Locat and Lee, 2002). Sediment removal from the middle slope removes structural support for the upper slope sediment wedge, leading to instability and subsequent failure. Submarine landslides on passive margins normally occur in regions that have a low (<5°) average gradient across the slope, much lower than the angle of repose. Low gradient slides imply that other factors besides oversteepening, pore fluid overpressure, earthquakes, and antecedent geology have preconditioned the slope for failure.
Several large retrogressive landslides have been described on the Atlantic margin. One of the most recent and best-recorded large submarine landslides along the eastern Atlantic continental slope occurred along the Grand Banks off the coast of Newfoundland in 1929. A magnitude 7.2 earthquake initiated a large submarine landslide that removed up to ~200 km$^3$ of sediment (Piper et al., 1986; Piper et al., 1999; Fine et al., 2005). One of the largest passive margin landslides in the world is the Storegga Slide, located off the northern coast of Norway within the Norwegian Basin, an area similar in margin morphology to the USAM. This massive slide occurred ~8,200 years ago and excavated up to 3,500 km$^3$ of sediment from the landslide scar (Bryn et al., 2005; Haflidason et al., 2005). Although not as large as Storegga, the Cape Fear complex of submarine landslides is located southeast of Cape Fear, North Carolina on the eastern side of the Carolina Trough. The slide complex contains 5 major slide scarps (>100 km$^3$ in total) that have likely occurred in the past 30,000 years (Hornbach et al., 2007). The Cape Fear Slide within the complex is one of the largest submarine landslide events on the USAM encompassing ~25,000 km$^2$ of sediment on the slope (Embley, 1980). Prior et al. (1986) suggest that the Currituck landslide, located northeast of Cape Hatteras, is between 24 and 50 ka and resulted in displacement of over 165 km$^3$ of sediment from the USAM. Bathymetric data show at least three main scarp remnants at the slide site (Figure 1). The slide debris appears to have a maximum width of 55 km and extends as far as 180 km from the toe of the remnant slope (Figure 1). It has been suggested that the landslides must have occurred simultaneously to produce enough energy to transport the sediment to the abyssal sea (Locat et al., 2009). Given that all of these major slides occurred on slopes with <5° gradient, suggests that additional factors helped precondition the margins for mass failure.
Preconditions for failure are unique to each slide. Pre-failure strata in the Norwegian Basin dipped no more than 2°, indicating that preconditioning factors other than over-steepening may have been necessary. Earthquakes, associated with glacio-isostatic rebound along the margin, along with increased pore pressure from rapid depositional events and gas hydrate destabilization, may have contributed to the slide (Bryn et al., 2005). The Cape Fear Complex contains many slides, each with its own characteristics and mechanisms that may have triggered the slides, although there are regionally consistent mechanisms that may have played a role in many of the slides. Actively venting gas and methane hydrates have been identified within Cape Fear region, implying that over-pressurization has contributed to preconditioning the sediment failures (Hornbach et al., 2007). Numerous faults and doming structures associated with salt diapir tectonics are common in this region as well and also may have both preconditioned and triggered failure (Hornbach et al., 2007; Popenoe et al., 1993). Since salt deposits tend to be less dense than the surrounding material, the salt will flow upward along bedding planes and can exert stress on the overburden resulting in localized faulting. Locat et al. (2009) concluded that the mechanism for the initiation of the Currituck slide was most likely an earthquake that caused a sudden increase in pore pressure. Earthquakes have been documented within the region along the U.S. east coast of magnitudes great enough to initiate a submarine landslide. Most recently, in 1886 a magnitude 6.9 earthquake occurred about 200 km offshore of Charleston, SC and many other earthquake epicenters have been documented elsewhere onshore (ten Brink, 2009).
Tsunamis, often resulting from these large retrogressive submarine landslides, can be very
destructive to a coastline by temporarily elevating the local sea level for a period of several
hours. Tsunami inundation can destroy homes, infrastructure, and coastal habitats. The Grand
Banks slide off the coast of Newfoundland produced a tsunami that had an initial run up of
13 m and wave amplitude of 3-8 m (Fine et al., 2005). The tsunami killed 28 people and
water level measurements across the Atlantic as far away as Portugal detected the tsunami
(Fine et al., 2005). The Storegga Slide is estimated to have produced a tsunami up to 12
meters in Norway and 20-30 m in Shetland (Bryn et al., 2005). Hornbach et al. (2007)
modeled the Cape Fear Slide using modern bathymetry and suggested the slide produced a
tsunami greater than 2 m. Estimates from the Currituck Slide suggest this failure would have
resulted in a tsunami wave height run up within the range of 2.35-8.80 m (Geist et al., 2009).
Understanding the processes that influence the formation of large submarine landslides on
the USAM can aid in identifying possible future tsunami events.

3. Methods:
The data presented here consist of multichannel seismic data (MCS) acquired from the U.S.
Geological Survey (USGS) and the Bureau of Ocean Energy Management (BOEM). Five
horizons that represent allostratigraphic surfaces were identified in 159 MSC profiles across
the study region: Seafloor, Base of Quaternary, Base of Pliocene, Base of Upper Miocene,
and Base of Middle Miocene (Klitgord et al., 1994). The base of each unit is an erosional
unconformity that is regionally consistent across the margin. Unconformities are readily
identified within the seismic sections, providing a basis for identifying a given unit in
multiple profiles throughout the study area. Allostratigraphic units are not lithostratigraphic
units, but are unconformity-bounded units defined by erosional surfaces (Poag and Ward, 1993). These units were initially identified by Klitgord et al. (1994) in the USGS C-1-78-NA dataset using regional MCS profiles with 10 km line spacing across the USAM. Two previously interpreted seismic lines, 28 and 29, from this report were used as characteristic profiles to aid the interpretation of industry data (Figure 5). Strike and dip lines provided by the USGS and BOEM that intersect lines 28 and 29 (Figure 6,7) were used to correlate consistent allostratigraphic units across the region. Allostratigraphic units identified by Poag and Ward (1993) in the seismic stratigraphy are the Phoenix Canyon (Middle Miocene), the Mey (Upper Miocene), the Toms Canyon (Pliocene), and the Hudson Canyon (Quaternary) Alloformations. Echo amplitude attenuation limited further identification of older allostratigraphic units in the profiles presented here. These allostratigraphic units are ground truthed by Poag and Ward (1993) using various well logs, geophysical surveys, and terrestrially exposed outcrops (Figure 5). The ages of the regional allostratigraphic units have been constrained using radiometric dating of sediment and biostratigraphy of well log data and available cores (Poag and Ward 1993). Allostratigraphic units provide a good basis for first-order reconstruction of Cenozoic history of the continental shelf and slope offshore of North Carolina and Virginia.

Western Geco collected over 150 seismic lines in two datasets within the study region using 100 m group spacing, 3.6 km streamer with 14 air guns for a 36 hydrophone array. The multichannel seismic (MCS) data have a 10 to 50 m vertical resolution and penetrate up to 5 seconds of two-way-travel (twt) before attenuation limits interpretation. All data and results (profiles, surfaces, and isopach maps) are presented here in two-way travel time in seconds.
Variation of seismic velocity throughout the region within interpreted units eliminates the potential for reasonable conversion of time to depth, and two-way travel time is assumed as 1500 m/s velocity.

The Western Geco seismic data were processed using 7 steps, including demultiplexing, wavelet filtering, trace sorting for gain recovery, normal moveout corrections, notch mute stacking, T.V. filtering, and frequency migrations. The primary dataset presented here is the processed Western Geco 82 (WG82), USGS ID W-4-82-NA, Northern Mid-Atlantic data set (Figure 5). This dataset encompasses outer shelf and slope of the northern blowout region, the Currituck Slide, and the Southern canyon failure region (Figure 1). The subset of WG82 coverage presented here includes 83 dip lines from (2.5 km line spacing) from Norfolk Canyon south to the Currituck Slide. 11 strike lines are spaced 13-15 km across the shelf and the rise. The secondary data set, Western Geco 80 (WG80), USGS ID W-6-80-NA, extends south of WG82 filling in gaps over the Currituck Slide and extending the survey south (Figure 5). The WG80 survey covers the southern Currituck Slide scarp (Poag and Sevon, 1989) and extends past a large slope-sourced canyon failure to where the shelf-edge/slope turns southwest and continues south along the coastline (Figure 1). The MCS coverage used from this dataset consists of 38 dip lines at 2.5 km spacing extending from the shelf to the lower slope and 17 strike lines spaced 2.5-3 km across the shelf to the lower slope.

Exploration companies contracted by BOEM collected surveys B-04-82-AT, B-11-82-AT, and B-16-76-AT surveys, from which eleven additional MCS profiles across the shelf were used. The data were collected and processed similar to the Western Geco datasets and have a
vertical resolution of 0.013-0.067 s twt (10-50 m). Six strike lines along the shelf spanning the study region allowed for the identification of paleo-river valleys. Five dip lines linked the BOEM datasets with the Western Geco datasets in order to constrain the shelf data with the allostratigraphic horizons identified farther offshore (Figure 5). Paleo-river valleys were identified by erosional U and V shaped unconformities in the strike lines.

Due to the age of the Western Geco and BOEM seismic data, the line positions have significant navigational errors that initially prevented line-to-line correlation. In order to rectify the navigation, features identified in the best available bathymetry were compared with seafloor reflectors from the seismic profiles to identify shot point offsets. The profile positions were corrected by linearly shifting the shot points and interpolating the x and y positions. Once the navigation was corrected, the interpreted MCS data could be compared across the study area using representative profiles, horizon surface maps and isopach maps.

Five horizons (Seafloor, Base of Quaternary, Base of Pliocene, Base of Upper Miocene, and Base of Mid-Miocene) were interpreted across the survey data. These horizon data were gridded into sediment thickness isopach maps (Figure 8, 9, 10, 11). The sediment thickness maps were constructed using IHS Kingdom Suite and ESRI ArcGIS. In Kingdom Suite, the age-surface horizons were subtracted providing a unit thickness between horizons. In Kingdom Suite, data points were interpolated into 50 m x 50 m data points, the interpolation distances was limited to 2500 m. Data points were exported from Kingdom Suite as xyz files for import into ArcGIS. The xyz data were gridded in ArcGIS using an inverse-distance weighted (IDW) gridding method. Grids were subsequently clipped to the area of the study.
region. Isopach maps provide unit thickness information, which can be used to interpret depocenter locations during each constrained time period.

Ten representative profiles were selected to demonstrate first order morphologies across the margin; lines 82126, 82130, 82136, 82147, 82151, 82166, 82171, 42, 82172a, and 82183 (Fig. 12). The 5 Horizons from each line were exported and converted from three-dimensional latitude, longitude, and depth profiles (x,y,z) to distance vs. depth (d,z) profiles using Pythagorean Theorem to find the distance between two points. In Mathworks Matlab, a smoothing function was used over 21 data points at a distance of 2.1 km to remove high frequency oscillations. Matlab was also used to create a slope (m) vs. distance profile for each line. Slope was calculated by using the equation \[
m = \left( \frac{\tan^{-1}\left(\frac{(z_{i+1} - z_i)}{(d_{i+1} - d_i)}\right)}{\pi} \right) \cdot 180\]. Where \(z_i\) is the vertical position and \(d_i\) is the horizontal position. The 2-D profiles represent along track changes in depth and slope.

4. Results:

The Mid-Atlantic USAM exhibits considerable along-strike variation in morphology across the margin, with three main morphologic regions: the shelf-edge gas blowouts, the Currituck Slide, and the southern large slope-sourced canyon failure region (Figure 1). The blowout region contains a string of elongated, actively venting pockmarks, up to 4 km long, 1 km wide, and 50 m deep, on the outer shelf south of the Norfolk Canyon (Hill et al., 2004) (Figure 1A). The blowout region is limited to the north by the Norfolk Canyon and spans 50 km south along the shelf-edge. Smaller slope sourced canyons in the blowout region are the
dominant morphologic feature on the slope, and slide debris covers the lower slope. The Currituck submarine landslide is the major morphologic feature that dominates the slope south of the blowout region. The Currituck Slide is estimated to have removed 165 km$^3$ of sediment from the slope in series of retrogressive failures (Prior et al., 1986). The Currituck region is centered on the Currituck Slide, extending from the end of the blowout region, 50 km south across the slope (Figure 1B). The southern most region, herein referred to as the southern canyon failure (SCF), is defined by a large slope-sourced canyon across the upper slope and slide debris on the lower slope (Figure 1C) (Table 1). The SCF region spans 100 km south from the Currituck Slide to where the margin bends southwest, just north of Cape Hatteras (Figure 1C). Given the density of seismic data coverage across the region, several representative profiles were selected from each region for more detailed analysis. Profiles 82126, 82130, 82136, 82147, and 82151 cover the northern blowout region; the Currituck Slide is observed in profiles 82166, 82171 and 42; and profiles 82172a and 82183 represent the SCF region (Figure 12). A detailed description of each representative profile can be found in Appendix A. Here we present descriptions of the seismic stratigraphy, thicknesses of the allostratigraphic units, surface evolution, shore-parallel strike lines, and shore-perpendicular dip lines for the four identified unconformities: Middle Miocene Unconformity (MMU), Upper Miocene Unconformity (UMU), Pliocene Unconformity (PU), and Quaternary Unconformity (QU).

4.1 Middle Miocene (16.4 – 11.2 Ma)
A pair of parallel reflectors diverging on the lower slope characterizes the Middle Miocene Unconformity (MMU) across the shelf (Figure 13). The shape of the MMU surface appears to be relatively consistent across all three regions where the unconformity exhibits a sigmoidal margin profile with a convex slope (Figure 14). In general, the MMU has a shallow gradient (<3°) beneath the upper slope that steepens to 6-7° under the mid slope, then decreases to <2° on the lower slope to lower slope (Figure 15). Sediment deposition above the MMU comprises the Middle Miocene allostratigraphic unit, which is constrained on top by the Upper Miocene Unconformity (UMU). During the Middle Miocene, the Mid-Atlantic region was characterized by widespread progradational clinoform deposition (up to 0.7 s thick) across the outer shelf, but deposition and subsequent erosion led to significant variation on the slope (Poag 1978) (Figure 8). These clinoforms have a more oblique shape in the northern blowout and SCF regions (Figure 16, 17); while in the Currituck region clinoforms extend farther downslope, with a more sigmoidal wedge shape (Figure 18) (Table 1). Sediment deposition on the mid-slope was slightly thicker in the Currituck region, where the Middle Miocene package is up to 0.3 s thick, compared with <0.1 s in the northern blowout and SCF regions (Figure 8). To the south, some of the thickest deposits occurred on the lower slope and lower slope of the Currituck and SCF regions, with as much as 0.77 s of Middle Miocene deposition (Figure 8).

4.2 Upper Miocene (11.2 – 5.3 Ma)

The Upper Miocene Unconformity (UMU) is defined by top of the Miocene clinoforms across the shelf, converging downslope with the MMU. Both unconformities increase in
echo amplitude and diverge on the lower slope (Figure 13). The shape of the UMU changes from sigmoidal in the blowout region to an oblique shape in the Currituck region (Figure 19). In the blowout region the UMU gradient is gentle across the shelf, the upper slope steepens to <11°, then shallows on the middle slope to (6°-8°), and the lower slope flattens to <2° (Figure 19). In the Currituck and SCF regions UMU gradient at the shelf-edge is shallow (<2°), steepening across the upper slope to 5° and up to ~8° across the middle slope (Figure 19). Downslope, the gradient flattens to <2° across the lower slope (Figure 19). The Upper Miocene allostratigraphic unit is comprised of sediment deposition above the UMU, which is constrained above by the Pliocene Unconformity (PU). The outer slope is covered by a thin (<0.1 s) Upper Miocene layer of sediment across the blowout and Currituck region, in contrast to the thicker (<0.13 s) sediment covering the SCF region (Figure 9). The Paleo-Roanoke River incised the Miocene clinoforms on the outer shelf in the SCF region (Figure 20). The primary depocenter (>0.7 s) of Upper Miocene sediment is located across the lower slope of the SCF (Figure 9). Thinner Upper Miocene sediment (<0.5 s) is distributed across the lower slope in the blowout and Currituck region (Figure 9).

4.3 Pliocene (5.3 – 2.6 Ma)

The Pliocene allostratigraphic unit lower bound is the Pliocene Unconformity (PU) and upper bound is the Quaternary Unconformity (QU). Internal reflectors for the PU across the shelf are discontinuous. The upper and middle slope reflectors have increased echo amplitude resulting in visually brighter reflectors (Figure 18). Internal reflectors within the Pliocene unit onlap the unconformity on the lower slope (Figure 18). The shape of the PU mimics the
underlying UMU across all three regions (Figure 21). The PU across the blowout region is concave where the gradient is gentle at <2° across the shelf. Seaward of the shelf-edge the gradient increases to 7°-9° on the slope, and the lower slope the gradient flattens to <2° (Figure 21). The Currituck and SCF region PU is a shallow convex slope, while the margin is sigmoidal shaped. The upper slope steepens from <2° across the shelf to 5°. The gradient steepens to 7° on the middle slope, then decreases to <2° on the lower slope (Figure 21). Thin Pliocene sediment (<0.1 s) veils the shelf and upper slope of the blowout, Currituck, and SCF regions. Thin sediment covers the middle slope (<0.12 s) in the blowouts and SCF regions, whereas the Currituck region is covered with thicker (0.21 s) sediment (Figure 10). The primary Pliocene depocenter (<0.5 s) was located on the lower slope from the Currituck north to the blowout region, and to the south, 0.23 s sediment covers the SCF lower slope (Figure 10).

4.4 Quaternary (2.6 Ma – Modern)

The Quaternary allostratigraphic unit is confined by the Quaternary Unconformity (QU) below and the seafloor above. The QU is identified across the shelf, slope, and rise as the first continuous bright reflector (Figure 22). In the blowout region, the QU has a concave slope and an oblique profile. In the SCF region, the QU shape is sigmoidal with a concave slope, while the Currituck region QU has a sigmoidal profile and convex slope (Figure 23). The unconformity in the blowout region is steep (7°-9°) across the upper slope, and the gradient drops to <2° on the lower slope (Figure 23). The QU has a shallow convex sigmoidal shape across the Currituck region, where the shelf-edge the gradient is shallow
(<2°) then steepens across the upper slope to 5° (Figure 23). The middle slope has several peaks in gradient where canyons and submarine landslides have removed a large amount of sediment across the shelf and slope (Figure 11). The gradient decreases to 4°-5° across the upper slope and flattens to <2° on the lower slope (Figure 23). Quaternary sediment is relatively thin across the margin, with the thickest depocenters (<0.4 s) on the canyon interfluves across the blowout and SCF region, as well as on the intact slope strata block in the Currituck region (Figure 11). Quaternary sediment thinly blankets (0.12-0.27 s) the shelf and slope in the blowout and Currituck regions (Figure 11). A 0.1-0.22 s thick Quaternary layer covers the SCF region across the shelf. Quaternary sediment on the upper slope thickens to 0.4 s, and then the unit thins to 0.15-0.22 s across the lower slope (Figure 11).

5. Discussion:

After the initial rifting phase, passive margins evolve due to thermal subsidence, eustacy and sediment delivery (Poag, 1978, Mountain; Kiltgord et al., 1988; Poag and Sevon 1993). Sediment deposition along a margin is largely controlled by the balance of accommodation space and sediment supply. Therefore, depocenters change spatially across the margin with eustatic fluctuations and terrestrial erosion rates. Fluvial drainage systems that extend across the shelf during sea level lowstands deliver large volumes of sediment to the margin causing depocenters to migrate seaward. Enhanced sediment accumulation along one part of the margin can lead to sediment bypass in other areas. Large geologic features such as paleo-reefs or bedrock outcrops can alter depositional patterns by acting as sediment dams or redirecting depositional pathways (Adams and Schlager, 2000). Erosional processes related
to ocean currents, canyon development and submarine slope failures can also reshape a margin. Ocean currents are a powerful erosive force that can remove and redeposit sediment along the flow pathways or limit deposition by deflecting sediment within the water column (Pinet and Popenoe, 1985).

Regional seismic surveys and detailed bathymetric data can be used to investigate how local and regional variations in framework geology influence the post-rift evolution of margin morphology. Using global scale bathymetry, O’Grady et al. (2000) developed a first order classification scheme for passive margins around the world, describing a broad classification of general morphological types. Brothers et al. (2013a) narrowed the focus to the USAM to highlight the role of antecedent geology in controlling regional morphological variations within a single margin. The discussion here will concentrate on the development of major morphological differences among sub-regions of the mid-Atlantic portion of the USAM. The presence of major morphological features as distinct as the northern blowouts, the Currituck Slide and the SCF suggest that there may have been considerable local variability in the Cenozoic sedimentation history within the Mid-Atlantic that led to the development of these features.

O’Grady et al. (2000) developed a seafloor morphology classification system for passive margins with 5 morphologic types (Figure 24). The O’Grady et al. (2000) classification is based on global bathymetric data with a spatial resolution of ~13 km² per pixel. A Type 1 margin such as the Niger Delta is classified as having a very low continuous gradient across the slope of <2° and few noteworthy seafloor features (O’Grady et al., 2000) (Figure 24).
Due to the low gradient, distinguishing the lower slope from the lower slope is difficult. Type 1 margins are found in regions with high sedimentation, unstable-prograding substrata, and few canyons. Type 2 margins, exemplified by the Currituck region and the Hudson Apron of the USAM, are sigmoidal in shape and among the most common passive margin morphologies. The gradient at the shelf-edge is 2.2°-4.5° and the continental slope is relatively smooth with few canyons (O’Grady et al., 2000) (Figure 24). Similar to Type 1, Type 2 margins are dominated by prograding strata and high sediment input. Type 2 margins are often associated with large slope failures due to high sedimentation, relatively weak substrates, and steeper gradients than Type 1 margins (O’Grady et al., 2000) (Figure 24).

Type 3 continental margins are relatively steep, with slope gradients of 4.4° - 6.5°, and have a medium to high density of slope-sourced canyons across the continental slope (O’Grady et al., 2000) (Figure 24). Low sediment supply and relatively high rates of sediment removal due to mass wasting are characteristic of Type 3 margins. Examples of this type include New Jersey margin and the blowout region of the USAM. Type 4 margins have the steepest gradients across the slope, ranging from 5° - 9.5° (Figure 24). Canyon incision across the slope is widespread, as illustrated by the Bay of Biscay on the French Atlantic margin (O’Grady et al., 2000). Type 5 describes a stepped margin that has a low slope, 2.5° - 4°, with plateaus and escarpments across the margin, associated with salt domes and complex sediment history, as represented by the Gulf of Mexico (O’Grady et al., 2000) (Figure 24).

The large spatial scale and low resolution restricts whole margins to a singular morphological type in this classification system. These divisions are effective in describing the first order morphology the modern seafloor, yet do not account for local or regional variations that can result from antecedent geology.
To investigate how regional differences in framework geology can lead to along strike variability in margin morphology, Brothers et al. (2013a) developed a classification scheme for the USAM. In this study, portions of the USAM were divided into 4 different groups that span a continuum of morphological profiles with sigmoidal and oblique end members. The curvature of each end-member shape is a product of the environmental energy conditions (Brothers et al., 2013a). The Sigmoidal end member, similar to the O’Grady et al. (2000) Type 2, is described as having abundant sediment influx, a high energy environment at the shelf-edge, a relatively low slope gradient of 2°-4°, and a gentle transition from shelf to slope with a convex shelf-edge rollover. This margin type typically has sediment deposition focused on the middle to lower slope that is often linked with retrogressive slope failure, similar to the Southern New England/Hudson Apron and Currituck slide region (Figure 3).

The oblique margin end member is similar to the O’Grady et al. (2000) Types 3 and 4 (e.g., Mid Atlantic margin and blowout region) (Figure 3). Regions with weak shelf-edge currents and lower sedimentation rates tend to produce oblique margins, where the maximum sediment accumulation is focused on the shelf-edge and sediment typically bypasses the upper/middle slope through gravity driven flows (Adams and Schlager, 2000). The gradient of the slope is much higher at the shelf-edge between 6.3°-7.7°, but decreases to <3° down slope (Brother et al., 2013a) (Figure 3). Sedimentation rates are typically low on oblique margins and much of the lower slope deposition is often driven by small canyon failures and progressive slides. Antecedent geology aids in development of the margin in that previously deposited sediment can fill regional accommodation space causing sediment to be deposited farther offshore.
The Brothers et al. (2013a) classification scheme provides some important insight into the influence of framework geology on regional variations in margin morphology and considers the whole mid-Atlantic region of the USAM as a single unit despite distinct morphological differences at a localized scale. The blowout region is characterized by a heavily slope-sourced canyonized oblique margin with large gas venting pockmarks on the shelf-edge (Figure 1). The sigmoidal shape of the Currituck region is characterized by a large retrogressive slope failure that has removed large volumes of sediment from the upper and middle slope (Figure 3). Large slope canyon-sourced failures characterize the southern canyon failure region that has a sigmoidal margin shape. An investigation into the development of the antecedent geology can aid in the understanding of how margins are preconditioned for specific sediment failures, retrogressive submarine landslide or slope sourced canyon failure.

Reconstruction of the paleo-seafloor morphology suggests that these regions were once similar, and now exhibit vastly different seafloor morphologies due to differences in depositional history. The Middle Miocene unconformity (MMU) exhibits a largely similar sigmoidal profile and convex slope shape across all three major morphologic features on the Mid-Atlantic USAM (Figure 14 A&B). This unconformity suggests that, at the start of the Middle Miocene, the paleo-seafloor surface from the blowout region south to the SCF region had a gentle shelf-break with a consistent slope gradient (<7°) that continued 20-30 km downslope (Figure 14 A&B). Deposition above the MMU is characterized by large clinoforms built out across the outer shelf and upper slope across all three regions. The SCF
region though, appears to have undergone sediment deposition that is not found in the two other regions to the north. At the start of the Middle Miocene, sea level was rising and sediment deposition was in a short (< 1 ma) transgressive system tract (TST) (Haq et al., 1987) (Figure 4). The position of the SCF directly offshore of the Paleo-Roanoke River suggests that sediment was delivered from the Paleo Roanoke River during this early phase.

Sea level transitioned to a relative highstand, 14-15 mya at ~140 m above the modern, subsequently falling for the rest of the Middle Miocene to 50 m above modern sea level. This transition was punctuated with three small sea level oscillations (Haq et al., 1987) (Figure 4). Therefore, sediment deposition in all but the earliest Miocene was in a falling stage system track (FSST). During the Middle Miocene FSST, large volumes of sediment were delivered to the blowout region via the Paleo-James and Paleo-Susquehanna Rivers (Poag and Sevon, 1989), while the Paleo-Roanoke River was the primary source of sediment to the Currituck and SCF regions. This increase in sediment supply led to the formation of large prograding deltaic clinoforms across the outer shelf along the entire region. These clinoforms display a similar oblique morphology in both the blowout and SCF regions, with a large amount of sediment perched on the shelf edge, but little deposition farther downslope. In contrast, the wedge-shaped clinoforms in the Currituck region are more sigmoidal in profile and extended farther offshore across the upper slope, producing a smoother transition from the shelf to slope. A broad, rounded sigmoidal shelf-edge is associated with high-localized sediment supply, whereas a sharp angular shelf-edge is associated with low energy and sediment supply. The wedge-shaped Miocene clinoforms in the Currituck region are due to the high energy from the Paleo-Roanoke and a large amount of sediment supplied to the
slope. The smaller and more oblique Miocene clinoforms in the blowout region led to angular shelf-edge and oblique slope where sediment supply is less defined and energy from river system deposition is less constrained. The shape of these clinoforms set the stage for the primary differences in the development and shape of the margin.

At the start of the Upper Miocene, sea level was at a relative lowstand (Haq et al., 1987) (Figure 4). The UMU in the northern blowout region has an oblique shape with a concave slope inherited from the shelf-edge clinoform deposition during the Middle Miocene. Thin Upper Miocene sediment cover across the northern region implies a decrease in sediment supply during this time. In contrast, the UMU at the Currituck region is sigmoidal in shape with a more convex slope. This is likely a result of increased energy and sediment supply from the Paleo-Roanoke River that maintained similar shape as the MMU. Upper Miocene sediment blankets the middle/lower slope and lower slope of the Currituck region. With sea level low, the Paleo-Roanoke River incised the Mid-Miocene clinoforms in the Currituck Slide region (Figure 20). Slope progradation, due to sediment deposition on the middle slope, enhanced the prominent sigmoidal margin during the Upper Miocene (Figure 19). Sediment across the rise was deposited during a lowstand system tract where sediment onlapped the MMU then transitioned to parallel horizons across the lower slope (Figure 18). The parallel and continuous nature of the internal reflectors within this unit suggests that the Gulf Stream has not reworked these horizons. Seismic profiles parallel to shore across the inner shelf indicate that the Paleo-Roanoke River was the primary source of sediment to the Currituck and SCF regions at this time (Figure 20). High sediment supply from the Paleo-Roanoke River likely allowed for sediment accumulation on the slope during the lowstand,
contributing to the convex shape of the slope and enhancing the sigmoidal profile of the Currituck margin. The thickest sediment (>0.75 s) was deposited across the mid to lower slope of the SCF region during the Upper Miocene, leaving the shape of the shelf-edge relatively unchanged (Figure 9). The lack of identifiable paleo-river valleys in the blowout region from the Paleo-James and Paleo-Susquehanna suggest there is an additional source of sediment to the lower slope and rise. The Gulf Stream may have eroded and redistributed sediment from the Paleo-James north across the rise (Pinet and Popenoe, 1986) (Figure 17). During the relative lowstand, the northward flowing Gulf Stream current was deflected offshore from the slope onto the rise by the Charleston Bump, a 400 m bathymetric high on the Blake Plateau that obstructed the current flow during sea level lowstands (Pinet and Popenoe, 1986; Haq et al., 1988). The landward limb of the Gulf Stream extended onto the lower slope during relative lowstands, possibly forming a barrier for sediment deposition in the region and redistributing the sediment downstream of the flow path (Pinet and Popenoe, 1986). The lack of direct sediment deposition during the Upper Miocene at the blowout region on the shelf and slope maintained a seafloor with a shape defined by the preexisting Middle Miocene clinoforms (Figure 9).

At the end of the Pliocene, accommodation space across the shelf was filled and sediment began to bypass the shelf, predominantly during sea level low stands (Schlee et al., 1979; Poag, 1984). During the Pliocene, several cycles of glaciation provided source sediment from the Paleo-James and Paleo-Susquehanna rivers to the inner rise across the northern blowout region (Poag and Sevon, 1989). The steep oblique slope developed in the Miocene and lack of accommodation space caused Pliocene sediment to bypass the upper slope and deposit on
the lower slope, maintaining the sharp shelf-break and concave slope of the northern blowout region (Figure 21). A thin layer of Pliocene sediment blanketed the slope in the Currituck and SCF regions, with the depocenter focused on the lower slope (Figure 10). The BOEM MCS data across the shelf do not show evidence of paleo-river incision in the Currituck or SCF region, whereas Poag and Sevon (1989) suggest that the Paleo-James and Paleo-Susquehanna Rivers supplied sediment to the blowout region. This is also evidence from the seismic data of Pliocene river valleys in the northern regions. It is possible that valleys across the shelf were reworked or deposition was focused during highstands when rivers did not incise the seafloor but still spread sediment across the margin. During the Pliocene, relative sea level was at a highstand and the Gulf Stream axis had shifted back onto the middle slope, while the outer limb reached onto the lower slope (Pinet and Popenoe, 1986; Haq et al., 1988) (Figure 4). The reintroduction of the Gulf Stream may have limited sediment accumulation across the SCF region by redistributing sediment that was supplied to the region. Southern seismic profile Line 82183 (Figure 17) shows channelized sediment across the lower slope that coincides with Gulf Stream location (Pinet and Popenoe, 1986).

The Paleo-James and Paleo-Roanoke supplied a large amount of sediment to the Mid-Atlantic margin during Quaternary glaciations (Poag and Sevon, 1989; Hobbs, 2004; ten Brink et al., 2014). Seismic profiles along the margin suggest the slope-sourced canyons that dominate the modern seafloor in the blowout and SCF regions developed during this time. Quaternary deposition in the northern blowout and SCF regions was primarily located on the canyon interfluves or funneled down slope (Figure 11). Limited accommodation space on the shelf and upper slope meant that much of the sediment initially deposited on upper parts of
the margin was transported offshore via mass flows through preexisting canyons or the
formation of new upper slope sourced canyons (Brothers et al., 2013a). Paleo-river valleys in
the Pliocene and Quaternary sediment are not within the resolution of the MCS data,
although the Paleo-James and Paleo-Roanoke Rivers have been suggested for sediment
sources of Quaternary sediment prograded across the Mid Atlantic margin (Poag and Sevon,
1989; Riggs et al., 1995; Mallinson et al., 2010). In the Currituck region though,
reconstructions of the pre-failure landslide morphology imply there was a massive amount of
sediment accumulation (~750 m thick) across the slope at this time, much of which was
removed by the Currituck Slide (Locat et al., 2009). Sediment deposition on the outer shelf
of the oblique blowout margin resulted in the high density of slope-sourced canyons across
the margin (Figure 23). The sigmoidal shape of the Currituck region provided a platform for
sediment accumulation on the middle slope that eventually failed as a large retrogressive
submarine landslide (Figure 23).

The depositional history of these three regions appears to have diverged during Middle
Miocene, and the initial shape and location of the Miocene clinoforms on the shelf and upper
sloped played an important role in the evolution of the Mid-Atlantic USAM from the late
Neogene to the present. The Currituck region maintained the sigmoidal profile from the
larger, more wedge-shaped Miocene clinoforms in this area, whereas the blowout region kept
the oblique profile set by the smaller, more oblique Miocene clinoforms found here. The
regional clinoform shape preconditioned each region for different slope failures unique to the
shape of the margin. Sigmoidal margins like the Currituck region appear to be indicative of a
progradational history of abundant sediment supply and accumulation across the slope that
preconditioned the margin for large-scale retrogressive failure. On steeper oblique margins, such as the northern blowout and SCF regions, sediment bypassed the upper slope and slope-sourced canyons developed across the margin. The northern blowouts have been proposed as indication of incipient slope failure (Hill et al., 2004); however, the oblique profile of the margin here suggests that any large failure of the shelf-edge in this region would likely result in a slope-sourced canyon slide, similar to that observed in the SCF region, rather than a large retrogressive failure like the Currituck Slide.

The specific features of the Mid-Atlantic are unique to the region, although the shape of the slope is similar to other regions across the USAM, particularly southern New England (SNE). The region from the Hudson Apron in Southern New England south to Cape Hatteras has experienced over 31 submarine landslides (Twichell et al., 2009). Similar to the Currituck region, the Hudson Apron has a sigmoidal profile with few canyons that appear to be inherited from the underlying stratigraphy of late Cretaceous deposits built out on the shelf and upper slope (Brothers et al., 2013a). The lack of canyonization in both the Currituck region and the Hudson Apron can be attributed to the sigmoidal shape of the margin associated with few slope-sourced canyons and dominated by mass wasting events (O’Grady et al., 2000; Brothers et al., 2013a). Both regions are predisposed to retrogressive failures due do the underlying physiography. The Hudson Apron experienced Late Cretaceous sediment deposition on the slope and rise providing a platform for sediment accumulation across the slope (Brothers et al., 2013a). The sigmoidal profile of both regions allowed for sediment progradation across the slope. Thick sediment deposition across the slope predisposed the slope for failure by elevating the pore pressure and mobilizing pore
fluids. Sigmoidal shaped margins across the USAM have experienced similar sediment mass failures. Conversely, the blowout region is less similar to the rest of the U.S. Atlantic margin. Pockmarks are relatively pervasive across the USAM (Brothers et al., 2014), although the blowouts are only region that these large pockmarks are found. The northern blowout region and U.S. Mid Atlantic margin is considered to be representative of the oblique profile margin end member. Although the shelf-edge rollover is different in shape, the New England margin slope is concave shaped and canyon dominated. The mechanisms for the distinctions in shelf-edge rollover shape vary for the two regions. The New England margin shape is due to pro-glacial forebulge from continental glaciation, while the oblique concave shape of the blowout region is a result of the antecedent geology (Peltier, 1996; Brothers et al., 2013a). The uniqueness of the Mid-Atlantic USAM is due to the localized variation in sedimentation and antecedent geology.

6. Conclusion:

The regional morphology of the slope and location of sediment depocenters on the margin play an important role in preconditioning regions of the margin for instability. Understanding the first-order depositional patterns throughout the late Cenozoic to the present can provide a better understanding of the preconditioning effects of antecedent geology on slope stability in the blowout, Currituck and SCF regions:

1) The Blowout region margin morphology shape has evolved through time. The MMU shape is sigmoidal, but deposition of Middle Miocene clinoforms changed the shape
of the margin to an oblique shaped margin. The oblique shape of the margin was maintained due to relatively low sediment supply during the Middle and Upper Miocene. This shape allowed for sediment accumulation on the shelf, sediment bypass of the slope and further accumulation on the rise. Any future failure of shelf-edge will likely result in slope-sourced canyon failure.

2) The Currituck margin was similar in morphology to the blowout and SCF regions at the base of the Middle Miocene, but then diverged from the other two regions due to localized differences in shape of the Middle Miocene clinoforms. The Currituck region has maintained the shelf and upper slope structure of the larger, more sigmoidal Middle Miocene clinoforms due to high sediment deposition rates focused on the slope and rise through the Miocene and Pliocene. Large Quaternary sediment accumulation across the slope due to the high sediment supply from the Paleo-Roanoke River preconditioned the Currituck region for the large retrogressive submarine landslide that removed much of the Quaternary sediment on the lower slope.

3) The SCF region received a large Miocene amount of sediment from the Paleo-Roanoke River, where the MMU shelf-edge was rounded and the slope was concave compared with the northern blowout and Currituck regions. Large volumes of sediment and high energy from the Paleo-Roanoke River changed the shape during the Upper Miocene and Pliocene to the convex slope with an oblique margin profile exhibited in the Quaternary. High sediment deposition on the middle slope
preconditioned this region for larger slope sourced canyon failures than those observed on the northern blowout margin.

In summary, the shape of the antecedent geology and position of sediment deposition across the margin greatly influences the morphology and stability of the margin.
7. References:


Twichell, D.C., Roberts, D.G., 1982. Morphology, distribution, and development of submarine canyons on the United States Atlantic continental slope between Hudson arid
APPENDIX A

This section contains descriptions of Klitgord et al. (1994) seismic lines 28, 29, and 10 selected profiles including the depth and gradient profiles.

Line 28

USGS Line 28 from Klitgord et al. (1994) begins 67 km offshore of the Accomack Spit and extends 52 km perpendicular from shore to the shelf-edge, with a total line length of 214 km (Figure 6). Line 28 intersects the headwalls of the Norfolk Canyon near the shelf-edge, then diverges as the Norfolk Canyon is oriented roughly west to east, and Line 28 continues southeast, overlaying slope sourced canyon debris.

The deepest reflection surface identified on this profile, the Base of Middle Miocene unconformity (MMU), has a convex slope and a sigmoidal profile (Figure 6). This reflector defines the base of the Middle Miocene allostratigraphic unit, which is bounded on top by the Base of Upper Miocene unconformity (UMU). Sediment in the Middle Miocene allostratigraphic unit is thickest on the upper slope (up to ~0.7 s in two-way travel time from 0-6.7 km along the line) (Figure 6, 8). Here the internal reflectors are low amplitude, but relatively continuous and parallel to the MMU (Figures 6). The internal reflectors in the Middle Miocene allostratigraphic unit are transparent on the upper and middle slope (6.7 – 23 km along the line) where the unit thins to < 0.1 s (Figure 6, 8). The Middle Miocene allostratigraphic unit increases in thickness to 0.2-0.38 s on the lower slope, as the internal reflectors become more continuous and onlap the MMU (Figure 6, 8).
The UMU at the shelf-edge is oblique in shape, with a concave slope. This reflector defines the base of the Upper Miocene allostratigraphic unit, which is bounded on top by the Pliocene unconformity (PU). The Upper Miocene allostratigraphic unit is up to 0.13 s thick over the shelf (Figure 9). Internal reflectors within this unit are parallel to the base of UMU beneath the shelf, then onlap the base of the UMU (Figure 6). The Upper Miocene allostratigraphic unit is mostly transparent beneath the upper to middle slope, with 0.1-0.5 s thick sediment (Figure 6, 9). The lower slope thickness ranges from 0.1-0.5 s, where reflectors are continuous, low amplitude and onlap the base of UMU (Figure 6, 9).

The base of Pliocene Unconformity (PU) is concave beneath the shelf-edge and oblique in shape. This reflector defines the base of the Pliocene allostratigraphic unit, which is bounded on top by the base of Quaternary Unconformity (QU). The internal reflectors beneath the shelf are chaotic and transparent at the base of PU and onlap the base of PU, where sediment thickness ranges from 0.02-0.09 s (Figure 6, 10). Beneath the upper to middle slope there reflectors are transparent through the 0.02-0.1 s thick sediment. On the lower slope sediment is 0.18-0.44 s thick, where reflectors onlap the base of PU are continuous and low amplitude (Figure 6, 10).

The QU is concave down the slope and is oblique in profile. This reflector defines the base of the Quaternary allostratigraphic unit, which is bounded on top by the seafloor. Through the Norfolk Canyon mouth, sediment thickness ranges from 0.32-0.63 s (Figure 11). Here internal reflectors beneath the shelf are faint, where noise from seafloor refraction at the base of QU disrupts the reflectivity, but appear to onlap the base of QU (Figure 6, 11). Beneath
the upper to middle slope, low amplitude, relatively continuous dipping reflectors are present in the 0.22-0.43 s thick section (Figure 6, 11). The sediment in this unit is 0.20-0.42 s thick beneath the lower slope (Figure 11). Low amplitude and continuous reflectors onlap the base of QU (Figure 6).

**Line 29**

USGS Line 29 starts 65 km offshore of Corona, NC on the shelf and extends 170 km offshore perpendicular to shore (Figure 7). The shelf-edge is 31 km from the start of the line. Line 29 intersects slope-confined canyons across the upper and middle slope. Along the lower slope, the seafloor morphology is dominated by sediment debris from slope canyon failures.

The MMU on Line 29 has a convex slope and a sigmoidal profile. Sediment in the Middle Miocene allostratigraphic unit is thickest on the shelf (up to ~0.76 s) (Figure 8). Here the internal reflectors have low reflectivity, but are relatively continuous and parallel to the MMU (Figure 7, 8). The shelf-edge thins to between 0.3-0.46 s 30-34 km along the line (Figure 7, 8). The internal reflectors prograde across the shelf-edge and onto upper slope (Figure 7, 8). The internal reflectors range from chaotic to transparent on the upper and middle slope (34 – 42 km along the line) where the unit is 0.2-0.44s thick (Figure 7, 8). The Middle Miocene allostratigraphic unit increases in thickness to 0.64-1.1 s on the lower slope, as the internal reflectors become flat, continuous, and onlap the MMU (Figure 7, 8).
The UMU here exhibits an overall a sigmoidal profile with a concave slope. Sediment in the Upper Miocene allostratigraphic unit is thinnest on the shelf (< 0.14 s) (Figure 7, 9). The internal reflectors in this section are low amplitude, yet are relatively continuous and parallel to the UMU (Figure 7). The unit progressively thickens to 0.46 s at the shelf-edge where internal reflectors become more chaotic, but decreases downslope to a maximum thickness of 0.32 s (Figure 7, 9). The lower slope shows the greatest sediment thickness (up to 0.56 s) in the Middle Miocene allostratigraphic unit, where the internal reflectors dip down slope, then become flat and continuous (Figure 7, 9).

The PU on this profile is concave beneath the shelf-edge and is oblique in shape. This reflector defines the base of the Pliocene allostratigraphic unit, which is bounded on top by the Quaternary unconformity (QU). Outer shelf sediment above the base of PU is transparent and sediment thickness is not represented on the line (Figure 7). The inner shelf is 0.15-0.23 s thick where internal reflectors are continuous, flat until the shelf-edge where the reflectors become truncated on the slope (Figure 7, 10). Beneath the upper to middle slope the reflectors are dipping down slope and onlap the PU within the 0.23-0.35 s thick sediment (Figure 7, 10). On the lower slope sediment is 0.23-0.36 s thick, where reflectors toplap the base of QU are semi-continuous and have low reflectivity (Figure 7,10).

The QU here displays a sigmoidal profile with a convex slope is convex (Figure 7). The outer shelf is acoustically transparent and not well represented in the line (Figure 7). Beneath the inner shelf the Quaternary allostratigraphic unit is 0.15-0.32 s thick, and contains flat, bright, continuous reflectors that outcrop at the shelf-edge (Figure 7, 10). The thickest sediment in
this unit (up to 0.44 s) is found on the mid to upper slope, where the internal reflectors transition from chaotic on the upper portion to more continuous, dipping reflectors lower on the slope (Figure 7, 10). The sediment thins to < 0.36 s on the lower slope where high-amplitude, continuous reflectors onlap deeper reflectors or the QU (Figure 7, 10).

**Line 82126**

WG82 line 82126 (Figure 25) is 120 km offshore of the mouth of the Chesapeake Bay. Line 82126 begins on the canyon walls of the Norfolk Canyon on the shelf-edge and extends 47 km offshore. Slope-sourced canyons incise the upper and middle slope. Along the lower slope, the seafloor morphology is dominated by canyon debris.

The MMU here displays a sigmoidal profile with a gradient that ranges from 3°-4° beneath the shelf and slope, then decreases to 1°-2° on the lower slope (Figure 25). Sediment thickness beneath the shelf in the Middle Miocene allostratigraphic units ranges from 0.13-0.5 s (Figure 8, 25). Internal reflectors beneath the shelf are low amplitude and onlap the MMU (Figure 8, 25). The sediment in this unit thins to < 0.1 s on beneath the slope where the internal reflectors become more chaotic (Figure 8, 25). The sediment thickness increases to ~0.3 s on the lower slope (Figure 8). The low amplitude internal reflectors here are more continuous and onlap the base of MMU (Figure 25).

Beneath the shelf, the oblique UMU is overlain by low amplitude, parallel reflectors in the Upper Miocene allostratigraphic unit that onlap the UMU at the shelf-edge. The upper slope
UMU has the steepest gradient, up to 9° (Figure 9, 25, 26). Sediment thickness on the upper slope is relatively thin (< 0.1 s) and internal reflectors are not well resolved within this section. Unit thickness beneath the middle slope increases to 0.18 s as the gradient of the UMU drops to 5° (Figure 9, 25, 26). The thickest sediment in this unit (up to 0.5 s) is found on the lower slope where the gradient decreases to 1°-3° (Figure 9, 26). Here reflectors that onlap the UMU are continuous and low amplitude (Figure 25).

By the Pliocene and Quaternary unconformities on this profile exhibit an oblique shape with a concave slope. Pliocene shelf sediment thickness ranges from 0.02-0.09 s (Figure 10). Internal reflectors beneath the shelf are low amplitude and onlap the base of PU (Figure 10, 25). The slope sediment thickness decreases to < 1 s as the PU gradient reaches 9° and few internal reflectors are present (Figure 10, 25, 26). The PU gradient decreases to 1°-2° on the lower slope, where sediment thickness increases to 0.44 s (Figure 10, 25, 26). The relatively continuous, low amplitude reflectors here onlap the base of PU (Figure 10, 25, 26).

Quaternary sediment thinly (0.1-0.15 s) blankets the shelf and slope (Figure 11). Irregular seafloor bathymetry generates refractions that disrupt the internal reflections in this unit, but reflectors beneath the shelf appear to onlap the QU (Figure 25, 26). Beneath the upper slope and middle slope there are few low amplitude and continuous internal reflectors (Figure 25). The gradient of the QU is steepest on the upper slope, averaging ~4° with peak gradients reaching 9° on canyon walls (Figure 25, 26). On the lower slope, the gradient drops to 1°-2° and reflectors that onlap the base of QU are continuous, low amplitude (Figure 10, 25, 26).
WG82 Line 82130 is a northern profile 120 km east from the mouth of the Chesapeake Bay and 10 km south of the Norfolk Canyon (Figure 5). The line starts on the shelf-edge, extending 46.5 km down slope, where it intersects several slope-sourced canyons (Figure 5). The lower slope contains debris from slope confined sediment failures.

The base of the MMU on line 82130 has a shallow sigmoidal profile and convex slope (Figure 27). The Middle Miocene allostratigraphic unit is thickest on the upper slope (up to 0.67 s), where the MMU has a relatively shallow gradient (< 4°). Internal reflectors in this section gently dip on to deeper horizons (Figure 8, 16, 27). At the mid slope, the MMU gradient steepens to ~6° and sediment thins to < 0.1 s with few internal reflectors in the unit (Figure 8, 16, 27). On the lower slope, the MMU gradient decreases to 1°-2° and the Middle Miocene unit thickens to 0.38 s (Figure 8, 16, 27). There are few high amplitude continuous reflectors that onlap the MMU is in this area (Figure 16, 27).

The UMU here is also sigmoidal, but has a much steeper concave slope (Figure 27). The upper slope UMU gradient tends to be relatively steep (6°-8°) beneath the slope, but has a low gradient (~3°) inflection point ~10 km downslope (Figure 27). The UMU gradient decreases to (1°-3°) on lower slope (Figure 27). Upper Miocene sediment thickness beneath the shelf-edge and upper slope is < 0.13 s, where internal reflectors are gently dipping and onlap deeper reflectors (Figure 9, 16). The transparent middle slope unit thickens slightly to
0.18 s (Figure 9, 16). The lower slope thickness ranges from 0.1-0.5 s and contains several high amplitude, shallow dipping, continuous reflectors that onlap the UMU (Figure 9, 16).

The PU takes on a more oblique profile in line 82130 with a steep (6°-8°) upper slope gradient and ~3° inflection point at ~10 km, similar to the UMU, that flattens to < 2° on the lower slope (Figure 27). Pliocene sediment thickness beneath the outer shelf ranges from 0.064-0.11 s and internal reflectors in this unit are disrupted by surface noise (Figure 10, 16). Sediment on the upper and middle slope thins to < 0.012 s with no internal reflectors (Figure 10, 16). The lower slope has the thickest Pliocene sediment, up to 0.5 s, and contains few continuous, slightly dipping reflectors that onlap deeper reflectors or the PU (Figure 10, 16).

The QU has a concave slope with a generally steep gradient (7°-9°) beneath the upper slope that shows the same ~3° inflection at ~10 km, before decreasing to < 2° on the lower slope (Figure 27). Beneath the shelf, the Quaternary allostratigraphic unit is 0.09-0.16 s thick and internal reflectors are disrupted by seafloor noise (Figure 11, 16). The Quaternary sediment thickens to 0.34 s thick beneath the slope, containing many discontinuous reflectors (Figure 11, 27). The lower slope is covered by 0.21 s of Quaternary sediment comprised of low-amplitude, continuous, even reflectors that are exposed at the seafloor and onlap the QU reflector (Figure 11, 16).

**Line 82136**
WG82 line 82136 is 117 km offshore of the mouth of the Chesapeake Bay (Figure 5, 13). Line 82136 begins on the shelf 2.5 km landward of the shelf-edge blowouts and extends 36 km offshore. Slope-sourced canyons dominate the upper slope and funnel debris to the lower slope.

The MMU on this profile has a sigmoidal shape, with a shallow gradient (< 4°) beneath the upper slope that steepens to ~6° on the mid slope, then decreases to 1°-2° on the lower (Figure 15). The upper slope thickness of the Middle Miocene allostratigraphic unit ranges from ~ 0.57-0.7 s with low amplitude, gently dipping reflectors (Figure 8, 13). Beneath the middle slope, the unit thins to < 0.1 s and becomes acoustically transparent (Figure 8, 13). On the lower slope, the Middle Miocene sediment thickens to 0.3 s; several highly reflective, continuous reflectors onlap the MMU here (Figure 8, 13).

The UMU on line 82136 shows a more oblique profile (Figure 15). The unconformity surface is steep (6°-8°) and bimodal beneath the slope with a low of ~3° roughly 10 km downslope, before the gradient drops to 1°-3° on the lower slope (Figure 15). Upper Miocene sediment beneath the outer shelf and upper slope is characterized by low amplitude, discontinuous reflectors < 0.13 s thick (Figure 9, 13). The unit thickens downslope up to 0.18 s thick, where the internal reflectors become transparent (Figure 9, 13). The thickest Upper Miocene sediment (< 0.31 s) is found on the lower slope, here several high amplitude, shallowly dipping, discontinuous reflectors onlap the UMU (Figure 9, 13).
The oblique shaped PU steepens from a < 2° gradient beneath the shelf to a (7°-9°) gradient beneath the slope with a ~3° low ~10 km downslope, then flattens to < 2° on the lower slope (Figure 15). Pliocene sediment thickness beneath the shelf ranges from 0.064-0.11 s (Figure 9). Internal reflectors in this section are continuous and dip downslope where the sediment thins to < 0.012 s and the units becomes transparent beneath the upper and middle slope (Figure 10, 13). The thickest sediment (up to 0.5 s) is observed on the lower slope, where the unit contains few continuous, slightly dipping reflectors that onlap deeper reflectors or the PU (Figure 10, 13).

The QU is also oblique in shape, with a steep (7°-9°) slope that shows the same ~3° inflection point ~10 km downslope, and a < 2° on the lower slope (Figure 15). Quaternary sediment thinly blankets (< 0.27 s) the shelf and slope (Figure 11). The internal reflectors beneath the shelf are continuous, outcropping at the shelf-edge (Figure 13). On the slope, reflectors are disrupted by surface noise from the irregular seafloor bathymetry, while the lower slope contains flat, low amplitude, continuous reflectors (Figure 13).

**Line 82147**

WG82 line 82147 is located 108 km offshore of Virginia Beach, VA. Line 82147 starts on the shelf 5 km from the shelf-edge and extends a total of 35 km offshore, crossing the southern edge of the blowouts (Figure 5, 28). Slope sourced canyons are dominant across the upper and middle slope, while the lower slope morphology is made up of canyon debris.
On line 82147, the MMU has a shallow sigmoidal profile with a convex slope (Figure 29). The MMU gradient beneath the upper slope is relatively shallow (< 4°) but increases ~6° downslope, before decreasing to 1°-2° on the lower slope (Figure 29). Gently dipping oblique clinoforms 0.5-0.7 s thick make up the Middle Miocene allostratigraphic unit beneath the shelf and upper slope (Figure 8, 28). Sediment thickness decreases to < 0.1 s on the mid slope, thick with no observable internal reflectors (Figure 8, 28). The lower slope sediment thickness is 0.15-0.37 s; with few highly reflective, continuous flat reflectors that onlap the MMU (Figure 8, 28).

The UMU has an oblique profile with a steep concave slope gradient that peaks at ~11° on the upper slope, decreasing downslope with gradients ranging 4°-5° on the middle slope, and flattening out to a 1°-2° gradient on the lower slope (Figure 29). Upper Miocene sediment thickness beneath the shelf and upper slope is < 0.13 s with little or no reflectors observed (Figure 9, 28). The lower slope thickens to 0.5 s, containing high amplitude, parallel, and partially continuous reflectors that onlap the UMU (Figure 9, 28).

The PU slope is concave and has an oblique profile. The unconformity steepens from a < 2° gradient beneath the shelf-edge to a steeper gradient (7°-9°) beneath the slope, with a low of ~3° at ~12 km along the profile, then decreases to < 2° on the lower slope (Figure 29). The Pliocene sediment thickness beneath the shelf is 0.064-0.11 s and thickens seaward beneath the upper slope to 0.33 s (Figure 10, 28). High-amplitude, relatively continuous seaward dipping internal reflectors onlap the PU beneath the lower slope as the unit thickens to 0.5 s (Figure 10, 28).
The QU here has a convex slope and is sigmoidal in profile (Figure 29). The gradient of the unconformity ranges from 5°-7° beneath the upper slope, decreasing to < 2° beneath the lower slope (Figure 29). Beneath the shelf, the Quaternary sediment is 0.16-0.21 s thick, containing prograding reflectors (Figure 11, 28). Sediment thickens seaward to 0.36 s at the shelf-edge and up to 0.44 s thick beneath the middle and lower slope (Figure 11, 28). The mid slope Quaternary allostratigraphic unit shows relatively continuous, dipping internal reflectors (Figure 11, 28). The Quaternary sediment thickness is maintained on the lower slope where continuous, high-amplitude reflectors parallel the QU (Figure 11, 28).

**Line 82151**

WG82 line 82151 is located 108 km offshore of Virginia Beach, VA (Figure 5, 30). Line 82151 starts on the shelf 3 km from the shelf-edge and extends a total of 35 km offshore. The shelf morphology is smooth sediment with no indentions or canyons. Slope sourced canyons are dominant beneath the upper and middle slope. The lower slope morphology is comprised of canyon debris.

The MMU on line 82151 displays a shallow sigmoidal shape and convex slope (Figure 8, 30). The MMU gradient is < 4° beneath the upper slope, steepening to 6-7°, beneath the mid slope, then decreasing to 3°-4° beneath the lower slope (Figure 31). The Middle Miocene unit below the shelf is made up of low-amplitude, seaward-dipping reflectors 0.5-0.7 s thick (Figure 8, 30). The unit thins to < 0.1 s beneath the slope, where few reflectors are observed,
then increases to 0.55 s thickness with several high amplitude, relatively continuous flat reflectors that onlap the MMU (Figure 8, 30).

The UMU slope is concave and oblique in profile. The UMU gradient is rather steep (10°-11°) on the upper slope, decreasing to 4°-5° beneath the lower slope and to 1°-2° on the lower slope (Figure 31). The Upper Miocene sediment is relatively thin (< 0.13 s) and acoustically transparent beneath the shelf and upper slope (Figure 9, 30). On the slope, the unit is thin (< 0.13 s) and internal reflectors are transparent (Figure 9, 30). The upper Miocene package thickens seaward (up to 0.5 s) on the lower slope with several high amplitude, flat, and partially continuous reflectors that onlap the UMU (Figure 9, 30).

The PU on line 82151 has a concave slope with a shelf to slope transition that increases from < 2° beneath the shelf to a peak of ~8° beneath the upper slope, then gradually decreasing to < 2° beneath the lower slope (Figure 31). Pliocene sediment beneath the shelf and upper slope is relatively thin (< 0.11 s), with one visible high amplitude internal reflector that drapes the lower surface (Figure 10, 30). On the lower slope, the Pliocene unit thickens to 0.57 s, with higher amplitude, continuous, dipping reflectors onlap the PU (Figure 10, 30).

The QU is also oblique, a relatively steep (7°-9°) gradient beneath the upper slope that decreases in gradient to < 2° on the lower slope (Figure 31). The shelf is blanketed by 0.12-0.18 s thick Quaternary sediment, but noise from seafloor refraction makes internal reflectors difficult to identify (Figure 11, 30). Beneath the slope, Quaternary sediment thickness increases to 0.55 s, where the reflectors are transparent on the upper slope with mid slope
internal reflectors that are dipping and continuous (Figure 11, 30). On the lower slope, the Quaternary package remains up to 0.47 s thick, with flat, continuous that are parallel the QU (Figure 11, 30).

**Line 82166**

WG82 line 82166 is located 106 km offshore of Currituck, NC (Figure 5, 22). Line 82166 starts on the shelf 7.4 km landward of the shelf-edge and extends a total of 35 km offshore. The shelf morphology is smooth with no incisions. The upper and middle slope contains several major slide scarps associated with the Currituck Slide, and the lower slope is covered by slide debris.

The MMU on line 82166 is also sigmoidal in profile with a convex slope. The shelf and upper slope have a low shallow gradient (< 4°) that steepens beneath the mid slope to 6°-7°, then decreases to 3°-4° on the lower slope (Figure 32). The Middle Miocene sediment is thickest on the shelf (0.6-0.89 s), where internal reflectors in this unit show prograding clinoforms (Figure 8, 22). Sediment thickness beneath the shelf-edge/upper slope is 0.25-0.52 s and the bottom set of the clinoforms extends beneath the shelf-edge onto the upper slope before the unit decreases to < 0.3 s thick on the middle and lower slope, where the internal reflectors are low amplitude, discontinuous, and downlap onto deeper reflectors or the MMU then flatten out at the seaward edge of the profile (Figure 8, 22).
The sigmoidal UMU also displays a concave slope that increases in gradient from < 2° beneath the shelf to 5° beneath the upper slope and peaks at to ~8° on the middle slope, before decreasing to < 2° beneath the lower slope (Figure 32). Upper Miocene sediment thickness beneath the outer shelf and upper slope is < 0.1 s, with little reflectivity, and gradually increases seaward to up to 0.5 s on the lower slope, where the internal reflectors are continuous, high amplitude, and parallel the lower surface (Figure 9, 22).

On line 82166, the PU is retains the sigmoidal profile, but has a more convex slope. The PU gradient steepens from < 2° at the shelf-edge to fluctuate between 5°-8° on the upper and middle slope, then decreases to < 2° on the lower slope (Figure 32). Pliocene sediment beneath the shelf is < 0.11 s thick with low amplitude internal reflectors that onlap the PU (Figure 10, 22). Very little (< 0.012 s) Pliocene sediment is observed on the upper and middle slope, with thickest Pliocene deposit found on the lower slope where sediment thickness ranges from 0.12-0.5 s, and the internal reflectors are continuous, flat, and moderately reflective (Figure 10, 22).

The QU also exhibits a shallow, convex sigmoidal shape, but is truncated on the mid-slope by the Currituck slide scarp (Figure 32). The shallow (< 2°) QU gradient beneath the shelf-edge steepens to 5° beneath the upper slope with peaks of 7° on the mid slope, before decreasing to 3°-4° beneath the upper slope (Figure 32). Internal reflectors beneath the shelf are continuous and parallel the seafloor, with up to 0.17 s of sediment (Figure 11, 22). 0.1-0.2 s thick Quaternary sediment underlies the slope where the reflectors are truncated at the seafloor by the Currituck Slide scarp (Figure 11, 22).
Line 82171

WG82 line 82171 is located 106 km offshore of Currituck, NC (Figure 5, 18). Line 82171 starts on the shelf 7.4 km from the shelf-edge and extends a total of 46 km offshore. Similar to line 82166, the Currituck slide scarp dominates the shelf and slope morphology, while the lower slope is largely covered by slide debris.

Similar to the other profiles, the MMU on line 82171 shows a shallow sigmoidal shape with a convex slope (Figure 14, 33). An MMU gradient of 4°-5° is maintained from the shelf-edge to the lower slope, which then decreases to 2°-3° at the lower slope (Figure 14, 33). Thick Middle Miocene sediment (0.3-0.64 s) beneath the shelf contains internal reflectors that are low amplitude, discontinuous horizons that downlap onto deeper reflectors (Figure 8, 18). Beneath the slope, the sediment thickness decreases to < 0.3 s, and internal reflectors continue to be low amplitude, relatively discontinuous, and onlapping deeper reflectors or the MMU (Figure 8, 18). The thickest sediment (< 0.7 s) is found on the lower slope, where the low amplitude reflectors are gently undulating and onlap the MMU (Figure 8, 18).

The UMU here is also sigmoidal, but has a concave slope (Figure 19, 33). The UMU gradient is shallow (< 2°) beneath the shelf-edge, steepens to 5-8° beneath the upper and middle slope 5°, then gradually decreases to < 2° beneath the lower slope (Figure 33). Upper Miocene sediment thickness from the shelf to the upper slope is thin (0.05-0.1 s), with little reflectivity
Beneath the middle/lower slope, the sediment thickness increases to 0.4 s, showing several discontinuous, highly reflective horizons (Figure 9, 18).

Similar to the MMU on this line, the Pliocene and Quaternary Unconformities here show sigmoidal profiles with a convex slope (Figure 21, 33). The PU gradient steepens from < 2° at the shelf-edge to between 5°-7° on the slope, decreasing to < 2° on the lower slope (Figure 33). The Pliocene shelf sediment thickness is < 0.1 s, with low amplitude internal reflectors that onlap the PU (Figure 10, 18). Sediment thickness increases seaward, with the highest Pliocene sediment accumulation (up to 0.56 s) on the lower slope (Figure 8). The internal reflectors here are relatively continuous and flat (Figure 18).

At the shelf-edge the QU gradient is also shallow (< 2°), steepening beneath the upper slope to 5° (Figure 33). The middle slope displays several peaks in gradient at slide scarps, decreasing in gradient to 4°-5° beneath the upper slope; on the lower slope, the gradient flattens to < 2° (Figure 33). Quaternary sediment thickness ranges from 0.16-0.23 s across the entire profile (Figure 11). The internal reflectors show a slight degree of progradation and seaward thickening, but are truncated on both the upper and lower slope by the Currituck Slide scarps (Figure 11, 18).

**Line 42**

WG80 line 42 is located 113 km offshore of Currituck, NC (Figure 5, 34). Line 42 begins on the shelf-edge and extends a total of 50 km offshore across the Currituck Slide. Much of the
sediment on the upper and middle slope has been removed by multiple failures; however there is a large (~500 m thick) package of sediment on the lower slope that has been interpreted as a remnant delta deposit that remained intact during the failures (Locat et al., 2009). Seward of this feature, the lower slope is covered in slide debris.

All of the unconformities interpreted on line 42 show a similar concave shape beneath the slope. The MMU gradient increases from 4° to 6° beneath the upper slope, then decreases to 2°-3° by beneath the lower slope (Figure 35). A thick Upper Miocene sediment wedge (0.6-0.67 s) is observed beneath the shelf, which contains internal reflectors that downlap onto deeper horizons (Figure 8, 34). The sediment thins beneath the slope to < 0.1 s, where internal reflectors continue to be low amplitude, relatively discontinuous, and onlap the MMU (Figure 8, 34). The Upper Miocene sediment thickens on the lower slope to 0.2-0.38 s, where gently undulating, low amplitude, reflectors onlap the MMU (Figure 8, 34).

The UMU gradient on line 42 gradually decreases from 7-10° at the start of the profile on the upper slope to < 2° beneath the lower slope (Figure 35). The Upper Miocene sediment thickness gradually increases seaward from < 0.18 s thick beneath the shelf to 0.45 s on the lower slope (Figure 9, 34). The majority of internal reflectors of the lower slope are chaotic or transparent, but several continuous, highly reflective reflectors are present (Figure 9, 34).

The PU also shows a gradual decrease from 5-7° at the start of the profile on the upper slope to < 2° beneath the lower slope (Figure 35). Beneath the upper slope, the Pliocene sediment thickness is < 0.1 s, where internal reflectors are low amplitude and onlap the Base of QU.
(Figure 10, 34). Sediment thickens to 0.36 s beneath middle to lower slope as internal reflectors become more continuous and draping (Figure 10, 34).

The QU displays a very similar shape to the PU, where the steeper upper slope gradient (~5-8°) gradually decreases to < 2° beneath lower slope (Figure 35). The shelf is covered by 0.25-0.37 s thick sediment; here internal reflectors beneath are low amplitude, continuous, and parallel the seafloor (Figure 11, 34). Quaternary sediment on the upper slope is up to 0.21 s thick, with internal reflectors onlap the PU below, but is truncated by the seafloor above (Figure 11, 34). Lower slope reflectors are continuous, highly reflective, flat beneath the lower slope, and onlap the seafloor, where the thickest Quaternary sediment (up to 0.63 s) is preserved in the intact block, which displays high amplitude, continuous reflectors that are truncated on either side by slide scarps. The sediment package thins beneath the lower slope to < 0.2 s (Figure 11, 34).

**Line 82172a**

WG82 line 82172a is 80 km east from the mouth of the Albemarle Sound (Figure 5, 36). The line starts on the shelf 13 km landward of the shelf-edge and extends 42 km downslope, where the profile intersects several slope-sourced canyons. The lower slope contains debris from slope confined sediment failures.

The base of the MMU has a concave slope and sigmoidal profile; where the gradient beneath the shelf is < 3°, then steepens through the slope (6°-7°), and flattens out beneath the lower
slope at $< 2^\circ$ (Figure 14, 37). The shelf is ~0.5-0.8 s thick, where the internal reflectors downlap onto deeper horizons, are discontinuous, and low amplitude (Figure 8, 36). The shelf-edge and uppermost slope is 0.35-0.5 s thick; internal reflectors that are low amplitude, discontinuous, and onlap onto deeper reflectors or the Base of MMU (Figure 8, 36). The upper slope sediment thickness is 0.2-0.35 s; here internal reflectors are transparent (Figure 8, 36). The middle slope is 0.4-0.46 s thick, where internal reflectors onlap the MMU (Figure 8, 36). The lower slope contains gently undulating, low amplitude reflectors that onlap the base of MMU, and is covered with 0.5-0.65 s of sediment (Figure 8, 36).

The base of the UMU has a concave slope and oblique profile; gradient is shallow beneath the shelf ($< 2^\circ$), then steepens beneath the upper slope $9^\circ$, the mid slope gradient shallows to $< 5^\circ$, where the gradient lowers to $< 2^\circ$ beneath the lower slope (Figure 37). Shelf sediment is 0.1-0.25 s thick, containing bright, continuous internal reflectors that downlap onto the Base of the MMU (Figure 9, 36). The slope sediment thickness is 0.25-0.4 s, where internal reflectors onlap the base of the MMU and bright (Figure 8, 36). The middle and lower slope is thickly covered by 0.67 s of sediment; deeper internal reflectors within the Upper Miocene allostratigraphic unit parallels the Base of the UMU are continuous and bright (Figure 8, 36). Shallower reflectors are bright, continuous and parallel the base of PU. The lower slope is 0.33-0.55 s thick; here internal reflectors are continuous, onlap from the Base of the UMU and the majority of the internal reflectors are chaotic, low amplitude (Figure 8, 36).

The base of the PU is a concave slope and sigmoidal shape (Figure 21, 37). At the shelf the gradient is shallow ($< 2^\circ$), then steepens on the slope to $7^\circ$, and decreasing to $< 2^\circ$ on the
lower slope (Figure 37). On the shelf sediment thickness is 0.05-0.08 s and internal reflectors beneath the shelf are transparent (Figure 11, 36). The internal reflectors beneath the shelf-edge onlap the base of PU are gently dipping and continuous within the 0.07-0.13 s thick sediment (Figure 11, 36). A normal fault slumps sediment on the middle slope where the sediment is 0.05-0.09 s thick and internal reflectors are offset, continuous, and poor reflectors (Figure 11, 36). The upper and middle slope sediment thickness is 0.05-0.09 s (Figure 11). The lower slope sediment thickness is 0.15-0.23 s; here internal reflectors beneath the lower slope are flat, continuous, and dim (Figure 11, 36).

The Base of QU is a concave slope and the profile is oblique (Figure 23, 37). Shelf gradient is shallow ($< 2^\circ$), then steepens beneath the upper slope to $8^\circ$, gradient decreases to $6^\circ$ along the middle, and the gradient at the slope lower slope falls to $< 6^\circ$ (Figure 37). Spanning the shelf, sediment is 0.1-0.21 s thick; internal reflectors beneath the shelf are flat, continuous, and bright (Figure 11, 36). Beneath the shelf-edge, sediment is 0.21-0.31 s thick; here the internal reflectors are dipping, continuous, and low amplitude (Figure 11, 36). A normal fault slumps sediment cuts through the middle slope sediment that is 0.1-0.27 s thick; internal reflectors that are dim, low amplitude, and dipping down the slope (Figure 11, 36). Beneath the lower slope, the internal reflectors are low amplitude, chaotic and flat within the 0.17-0.26 s thick lower slope sediment unit (Figure 11, 36).

**Line 82183**

64
WG82 line 82183 is 82 km east from the mouth of the Albemarle Sound (Figure 5, 17). The line starts on the shelf 6.5 km from the shelf-edge. The overall length of the line is 39 km down the slope. Line 82183 on the slope intersects a large slope sourced canyons. The lower slope contains a large sediment failure channel and contains debris from slope confined sediment failures.

The base of the MMU has a convex slope and sigmoidal profile; where the gradient beneath the shelf is < 3°, then steepens through the slope (6°-7°), and flattens out beneath the lower slope < 2° (Figure 38). Thick sediment (0.5-0.7 s) beneath the shelf contains internal reflectors that downlap onto deeper horizons, continuous and bright (Figure 8, 17). The Middle Miocene allostratigraphic unit is ~0.5-0.6 s over the shelf down the upper slope, yet internal reflectors down the slope are low amplitude, discontinuous, and onlapping onto deeper reflectors or the Base of MMU (Figure 8, 17). Sediment thins (0.03-0.1 s) down the upper slope, where internal reflectors beneath the middle slope transparent (Figure 8, 17). The lower slope contains gently undulating, low amplitude internal reflectors in the 0.30-0.77 s thick unit (Figure 8, 17).

The base of the UMU has a concave slope and oblique profile; gradient is shallow beneath the shelf (< 2°), then steepens beneath the upper slope 9°, the mid slope gradient shallows to <5°, where the gradient lowers to <2° beneath the lower slope (Figure 38). Sediment thickness spanning the shelf is relatively thin (0.05-0.1 s) and internal reflectors are transparent (Figure 9, 17). The sediment thickens on the shelf-edge and upper slope to 0.13-0.25 s where internal reflectors are discontinuous and dim (Figure 9, 17). Slopes sediment is
0.06-0.1 s thick, containing internal reflectors that are chaotic, dipping, and low amplitude (Figure 9, 17). Lower slope region is covered by 0.02-0.73 s thick sediment; internal reflectors are undulating, semi-continuous, and low amplitude (Figure 9, 17).

The base of the PU is a shallow concave slope and oblique shape. At the shelf the gradient is shallow (< 2°) that steepens beneath the upper slope to 7°, gradient oscillates beneath the slope from 4°-6°, and decreases to < 2° on the lower slope (Figure 38). This reflector is the lower bound for the Pliocene allostratigraphic unit; the upper bound is the QU. Thin sediment drapes the shelf (0.05-0.08 s); the internal reflectors are flat and bright (Figure 10, 17). At the shelf-edge, seafloor multiples disrupts the internal reflectors in the 0.07-0.13 s thick sediment (Figure 10, 17). Beneath the slope, sediment thins to (0.05-0.09 s) where the internal reflectors are chaotic within the thin Pliocene allostratigraphic unit (Figure 10, 17). The lower slope internal reflectors undulate beneath the lower slope are semi-continuous, and low amplitude within the 0.15-0.23 s thick sediment (Figure 10, 17).

The Base of QU is a concave shaped slope and the profile is oblique (Figure 23, 38). Shelf gradient is shallow (< 2°), then steepens beneath the upper slope to 8°, gradient decreases to 6° along the middle, and the gradient at the slope lower slope falls to < 2° (Figure 38). This reflector is the lower bound for the Quaternary allostratigraphic unit; the upper bound is the seafloor. The internal reflectors within the 0.1-0.22 s thick Quaternary allostratigraphic unit beneath the shelf are discontinuous and bright (Figure 11, 17). The upper slope is covered in 0.2-0.4 s thick sediment that includes internal reflectors that are chaotic and disrupted by seafloor refraction (Figure 11, 17). Beneath the lower slope are downlap onto the other
internal reflectors or onlap and exposed at the seafloor within the 0.15-0.22 s thick Quaternary sediment (Figure 11, 17).
<table>
<thead>
<tr>
<th>Modern</th>
<th>Blowouts</th>
<th>Currituck</th>
<th>Southern Canyon Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seafloor</td>
<td>Oblique; concave slope</td>
<td>Sigmoidal; convex slope</td>
<td>Sigmoidal; convex slope</td>
</tr>
<tr>
<td>Modern</td>
<td>Mega-pockmarks on the shelf-edge; Slope-sourced canyons dominate the</td>
<td>Retrogressive failures in the Currituck Slide complex have removed large volumes of sediment from the upper and lower slopes</td>
<td>Large slope-sourced canyon failure surrounded by numerous smaller slope-sourced canyonson the upper slope</td>
</tr>
<tr>
<td>Quaternary</td>
<td>Depocenters are focused on canyon interfluves, Paleo-James and Susquahanna River supplied sediment</td>
<td>Thick sediment from the Paleo-Roanoke River deposited on the slope (Poag and Sevon, 1989)</td>
<td>Paleo-Roanoke River depocenters are focused on canyon interfluves</td>
</tr>
<tr>
<td>QU</td>
<td>Oblique; concave slope</td>
<td>Sigmoidal; convex slope</td>
<td>Sigmoidal; convex slope</td>
</tr>
<tr>
<td>Pliocene</td>
<td>Oblique; concave slope</td>
<td>Sigmoidal; convex slope</td>
<td>Sigmoidal; convex slope</td>
</tr>
<tr>
<td>Pliocene</td>
<td>The primary source of sediment is from the Paleo-James and Paleo-Susquahanna Rivers. Depocenters are focused on the lower slope</td>
<td>Thin unit Sediment deposition is focused on the middle and lower slope.</td>
<td>Gulf Stream has eroded the lower slope</td>
</tr>
<tr>
<td>PU</td>
<td>Oblique; concave slope</td>
<td>Sigmoidal; convex slope</td>
<td>Sigmoidal; convex slope</td>
</tr>
<tr>
<td>Upper Miocene</td>
<td>Oblique; concave slope</td>
<td>Sigmoidal; convex slope</td>
<td>Sigmoidal; convex slope</td>
</tr>
<tr>
<td>Upper Miocene</td>
<td>No identifiable paleovalleys across the shelf. Sediment deposition on the lower slope/inner rise suggest sediment deposition is from a secondary source</td>
<td>Thin unit of sediment covers the shelf and slope, with thicker deposition across the rise</td>
<td>Paleo-Roanoke River incised the shelf and deposited sediment on the lower slope and inner rise</td>
</tr>
<tr>
<td>UMU</td>
<td>Oblique; concave slope</td>
<td>Sigmoidal; convex slope</td>
<td>Sigmoidal; convex slope</td>
</tr>
<tr>
<td>Middle Miocene</td>
<td>Oblique clinoforms deposited on the outer shelf</td>
<td>Sigmoidal, wedge shaped clinoforms extend from the outer shelf onto the upper slope</td>
<td>Oblique clinoforms deposited on the outer shelf</td>
</tr>
<tr>
<td>MMU</td>
<td>Sigmoidal; convex slope</td>
<td>Sigmoidal; convex slope</td>
<td>Sigmoidal; convex slope</td>
</tr>
</tbody>
</table>

**Table 1:** Summary results for each region, Blowouts, Currituck, and Southern Canyon Failure, and each time period: Middle Miocene (MMU), Upper Miocene (UMU), Pliocene unconformity (PU), and Quaternary unconformity (QU). Slope is recorded on the upper (U), middle (M), and lower (L) slope.
Figure 1: U.S. Atlantic Margin bathymetry A) The mega-elongated pockmarks or “blowouts” B) The Currituck Submarine landslide scarp C) Large slope sourced landslide
Figure 2: Retrogradation, Aggradation, and Progradation in relation to sediment influx and sea level, edited from Emery and Myers 1996
Figure 3: End member shelf-edge morphologies (A) Sigmoidal (B) Oblique from Brothers et al. (2013a)
Figure 4: Sea level curve over the last 30 million years (Haq et al., 1989).
Figure 5: Borehole locations and trackline location across the U.S. Atlantic Margin, published reference lines are represented in green (Poag and Ward, 1993; Klitgord et al., 1994).
Figure 6: Klitgord et al. (1994) Line 28 across the blowout margin. (A) uninterrupted profile (B) interpreted profile
**Figure 7:** Klitgord et al. (1994) Line 29 across the blowout margin. (A) uninterrupted profile (B) interpreted profile
Figure 8: Middle Miocene sediment thickness. Contours are every 0.25s in two-way travel time. Arrows indicate inferred paths of paleo-fluvial systems from (Poag and Sevon, 1989; Hobbs, 2004)
Figure 9: Upper Miocene sediment thickness. Contours are every 0.25s in two-way travel time. Arrows indicate inferred paths of paleo-fluvial systems from (Poag and Sevon, 1989; Hobbs, 2004)
Figure 10: Pliocene sediment thickness. Contours are every 0.25s in two-way travel time. Arrows indicate inferred paths of paleo-fluvial systems from (Poag and Sevon, 1989; Hobbs, 2004)
Figure 11: Quaternary sediment thickness. Contours are every 0.25s in two-way travel time. Arrows indicate inferred paths of paleo-fluvial systems from (Poag and Sevon, 1989; Hobbs, 2004)
Figure 12: Representative profiles used for depth vs distance and gradient vs distant plots.
Figure 13: WesternGeco Line 82136 across the blowout margin. (A) uninterrupted profile (B) interpreted profile
Figure 14: Base of Middle Miocene horizon interpreted from representative profiles in (A) the northern blowout region and (B) the Currituck slide and southern canyon failure regions. Base of Middle Miocene horizon gradient along representative profiles from (C) the northern blowout region and (D) the Currituck slide and southern canyon failure regions. 0 km distance along the profile indicates the location of the shelf-edge.
Figure 15: (A) Interpreted horizons from WesternGeco line 82136. (B) Horizon gradient along the profile: The 20 reflector indicates the base of Quaternary, 30 is the base of Pliocene, 40 is the base of Upper Miocene, and 45 is the base of Mid-Miocene. 0 km distance along the profile indicates the shelf-edge.
Figure 16: WesternGeco Line 82130 across the blowout margin. (A) uninterrupted profile (B) interpreted profile
Figure 17: WesternGeco Line 82183 across the southern canyon failure margin. (A) uninterrupted profile (B) interpreted profile
Figure 18: WesternGeco Line 82171 across the Currituck margin. (A) uninterrupted profile (B) interpreted profile
Figure 19: Base of Upper Miocene horizon interpreted from representative profiles in (A) the northern blowout region and (B) the Currituck slide and southern canyon failure regions. Base of Middle Miocene horizon gradient along representative profiles from (C) the northern blowout region and (D) the Currituck slide and southern canyon failure regions. 0 km distance along the profile indicates the location of the shelf-edge.
Figure 20: BOEM seismic profile MA-006 across the shelf. (A) uninterrupted profile (B) interpreted profile
Figure 21: Base of Pliocene horizon interpreted from representative profiles in (A) the northern blowout region and (B) the Currituck slide and southern canyon failure regions. Base of Middle Miocene horizon gradient along representative profiles from (C) the northern blowout region and (D) the Currituck slide and southern canyon failure regions. 0 km distance along the profile indicates the location of the shelf-edge.
Figure 22: WesternGeco Line 82166 across the Currituck margin. (A) uninterrupted profile (B) interpreted profile
Figure 23: Base of Quaternary horizon interpreted from representative profiles in (A) the northern blowout region and (B) the Currituck slide and southern canyon failure regions. Seafloor horizon gradient along representative profiles from (C) the northern blowout region and (D) the Currituck slide and southern canyon
Figure 24: Sea level curve over the last 30 million years (Haq et al., 1989).
Figure 25: WesternGeco Line 82126 across the blowout margin. (A) uninterrupted profile (B) interpreted profile
Figure 26: (A) Interpreted horizons from Western Geco line 82126. (B) Horizon gradient along the profile: The 20 reflector indicates the base of Quaternary, 30 is the base of Pliocene, 40 is the base of Upper Miocene, and 45 is the base of Mid-Miocene. 0 km distance along the profile indicates the shelf-edge.
Figure 27: (A) Interpreted horizons from WesternGeco line 82130. (B) Horizon gradient along the profile: The 20 reflector indicates the base of Quaternary, 30 is the base of Pliocene, 40 is the base of Upper Miocene, and 45 is the base of Mid-Miocene. 0 km distance along the profile indicates the shelf-edge.
Figure 28: WesternGeco Line 82147 across the blowout margin. (A) uninterrupted profile (B) interpreted profile
Figure 29: (A) Interpreted horizons from WesternGeco line 82147. (B) Horizon gradient along the profile: The 20 reflector indicates the base of Quaternary, 30 is the base of Pliocene, 40 is the base of Upper Miocene, and 45 is the base of Mid-Miocene. 0 km distance along the profile indicates the shelf-edge.
Figure 30: WesternGeco Line 82151 across the blowout margin. (A) uninterrupted profile (B) interpreted profile
Figure 31: (A) Interpreted horizons from WesternGeco line 82151. (B) Horizon gradient along the profile: The 20 reflector indicates the base of Quaternary, 30 is the base of Pliocene, 40 is the base of Upper Miocene, and 45 is the base of Mid-Miocene. 0 km distance along the profile indicates the shelf-edge.
Figure 32: (A) Interpreted horizons from WesternGeco line 82166. (B) Horizon gradient along the profile: The 20 reflector indicates the base of Quaternary, 30 is the base of Pliocene, 40 is the base of Upper Miocene, and 45 is the base of Mid-Miocene. 0 km distance along the profile indicates the shelf-edge.
Figure 33: (A) Interpreted horizons from WesternGeco line 82171. (B) Horizon gradient along the profile: The 20 reflector indicates the base of Quaternary, 30 is the base of Pliocene, 40 is the base of Upper Miocene, and 45 is the base of Mid-Miocene. 0 km distance along the profile indicates the shelf-edge.
Figure 34: WesternGeco Line 42 across the Currituck margin. (A) uninterrupted profile (B) interpreted profile
Figure 35: (A) Interpreted horizons from WesternGeco line 42. (B) Horizon gradient along the profile: The 20 reflector indicates the base of Quaternary, 30 is the base of Pliocene, 40 is the base of Upper Miocene, and 45 is the base of Mid-Miocene. 0 km distance along the profile indicates the shelf-edge.
Figure 36: WesternGeco Line 82172a across the Currituck margin. (A) uninterrupted profile (B) interpreted profile
Figure 37: (A) Interpreted horizons from WesternGeco line 82172a. (B) Horizon gradient along the profile: The 20 reflector indicates the base of Quaternary, 30 is the base of Pliocene, 40 is the base of Upper Miocene, and 45 is the base of Mid-Miocene. 0 km distance along the profile indicates the shelf-edge.
**Figure 38:** (A) Interpreted horizons from WesternGeco line 82183. (B) Horizon gradient along the profile: The 20 reflector indicates the base of Quaternary, 30 is the base of Pliocene, 40 is the base of Upper Miocene, and 45 is the base of Mid-Miocene. 0 km distance along the profile indicates the shelf-edge.