INTERPRETATION AND ANALYSIS OF SEQUENCE STRATIGRAPHY AND PALYNOMORPH ASSEMBLAGES OF MIOCENE-AGE SEDIMENTS IN SOUTHERN DELAWARE

by

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ABSTRACT

The Marshy Hope borehole (Nb53-08) sediments encompass the Calvert, Choptank and St. Marys Formations. This interdisciplinary study combines palynomorphs, biostratigraphy and stratigraphic units to interpret depositional environments and constrain correlations between locations in northwest Sussex County.

Sequence stratigraphy is utilized to subdivide core sediments and to correlate to other boreholes in the region. Seven sequences are recognized, including a shaved sequence in the St. Marys, a type previously recognized and described by Kidwell (1988; 1989; 1997). The Calvert Formation is composed of shelfal clay and silt which becomes a coarsening-upward alternation of sand and silt. The overlying Choptank Formation is composed of mostly fine to coarse sands with interbedded silt and clay. The St. Marys Formation is composed of estuarine silts, clays and fine sands punctuated by offshore silts and clays. The Calvert-St. Marys interval is interpreted at this site as a stack of highstand-dominated stratigraphic sequences which shallow-upward overall.

Palynomorphs record the depositional history of Miocene marine sediments in the Marshy Hope area in Delaware. The changes in species and abundance result in distinct biozones which are used to interpret depositional environments and correlate sediments to other sites in southern Delaware.

The flora is dominated by *Quercus, Carya,* and *Pinus*. Taxodiaceae/Cupressaceae/Taxaceae (TCT) and “exotic” taxa such as *Engelhardia* and *Symplocos* are also present. The Calvert Formation is interpreted as a warm-temperate climate, whereas the Choptank and St. Marys formations are interpreted as a slightly cooler warm-temperate climate. Stratigraphically constrained cluster analysis reveals three different pollen zones based on sample pollen assemblages. Zone 1 is characterized by abundant *Quercus, Carya* and low amounts of exotics *Engelhardia* and TCT. Zone 2 contains relatively low amounts of *Quercus* and exotic taxa and high abundances of *Pinus*. Zone 3 is characterized by high abundances of *Quercus* and exotic taxa such as TCT and *Engelhardia*. Dinoflagellate cyst identification result in a preliminary dinocyst zonation which includes seven dinocyst subdivisions.

Correlation of this site to Bethany Beach, Delaware is possible through sequence stratigraphic units based on lithologic analysis results and geophysical logs, stratigraphically constrained cluster analysis of pollen assemblages, and dinoflagellate cyst zonation.

Chapter 1

INTRODUCTION AND BACKGROUND

This study utilizes micropaleontology, stratigraphy, sedimentology and chronostratigraphy in order to fully understand environmental depositional settings and palynomorphic assemblages in Miocene-age strata that can be used for correlation to other sites. The hypothesis for this study is that the sequence stratigraphy of the Calvert, Choptank and St. Marys Formations can be used to infer changing environments based upon changing sediment lithologies. Moreover, the study tests the hypothesis that changes in the assemblages of fossil pollen and dinoflagellates, combined with a core-sediment and geophysical log-based sequence stratigraphic framework, allow for the correlation of sediments in the marine Miocene formations in northern and western Sussex County, Delaware. Specifically, palynomorph deposits will correlate closely to previous studies at Bethany Beach and facies will be representative of a nearshore shallow-marine depositional environment. Finally, the dinoflagellate cyst zonation will closely resemble the zonation put forth by de Verteuil and Norris (1996).

The objective of this study is to help understand the depositional history of northwest Sussex County and to constrain correlations to nearby sites using palynology, biostratigraphy and sequence stratigraphy; this also has implications for aquifer geology. Groundwater is one of the most important resources on earth, and aquifers are subsurface water-bearing sediments in which groundwater is stored. Many municipalities and industries such as agriculture use freshwater withdrawn from aquifers, so understanding the location, quality and extent of various aquifers is imperative for the monitoring of potential contaminants and managing of extraction of these water resources. With the use of fossil assemblages, the biostratigraphy of the Calvert, Choptank and St. Marys Formations, and their associated aquifers, can be determined and correlated to other previously unstudied areas in order to determine the subsurface geology of those areas.

Stratigraphy

For this study, sequence stratigraphy is utilized to subdivide core sediments into genetically related strata used to correlate to other boreholes in the region. Identifying and understanding the basic elements of sequence stratigraphy is of the utmost importance in analyzing and correlating sequences. Sequence stratigraphy is the study of the effects of eustasy and tectonics on accommodation space coupled with sediment supply to control the formation of stratal surfaces (Browning et al., 2006; Coe et al., 2005). Although sequence stratigraphic concepts can be applied to a variety of depositional systems such as carbonate systems, or non-marine depositional systems, this study will only focus on shallow-marine clastic depositional systems.

Parasequences

Sedimentary facies are bodies of sediment characterized by distinct lithologies or fossil components which reflect a certain depositional system. Parasequences are small-scale, relatively conformable, shallowing-upward packages deposited in lateral continuity to one another. Moreover, parasequences are bound by marine flooding surfaces, or unconformities, and can be correlated regionally (McLaughlin, 2005). Parasequence sets are successions of parasequences which form distinctive stacking patterns and can be progradational, retrogradational and aggradational based upon accommodation space and sediment influx (Coe et al., 2005). A progradational parasequence set depicts the shoaling upward and basinwards advance of a depositional system due to the increase in accommodation space being less than the constant rate of sediment supply. Parasequences that exhibit an overall deepening and landwards retreat of facies, meaning that the rate of increase in accommodation space is greater than the sedimentation rate are called a retrogradational parasequence set. An aggradational parasequence set occurs when the increase in accommodation space is equal to the sediment influx rate, and the shoreline neither shifts basinward or landward, but rather stays in the same position (McLaughlin, 2005; Coe et al., 2005).

A sequence is a succession of relatively conformable, genetically-related strata bound by unconformities or their correlative conformities. Sequences can be a few metres to hundreds of metres thick and can be composed of a succession of parasequence sets subdivided into systems tracts, which are separated by significant stratigraphic surfaces (Catuneanu, 2006; McLaughlin, 2005; Coe et al., 2005).

Surfaces

The sequence boundary is the most important surface in sequence stratigraphy. As sea level falls to a low point when sea level is below the top of the previously deposited coastal sediments, sediment from fluvial sources will push further out to the basin where there is more accommodation space available for deposition. The exposed nearshore coastal sediments are subject to weathering and erosion, resulting in an unconformity that is the sequence boundary (Coe et al., 2005).

As sea level begins to rise (commonly after the lowstand systems tract), the rate of rise continues to increase to a point where the rate of increase in accommodation space is greater than the sediments supply. This increase in relative sea level rise results in the first prominent marine flooding surface in a sequence, called a transgressive surface. This surface is marked by the change in deposition from progradational or aggradational parasequence stacking to a retrogradational, or landward, parasequence or parasequence set (McLaughlin, 2005; Coe et al., 2005).

The maximum-flooding surface caps the transgressive systems tract and marks the most landward position of the shoreline. Stacking pattern changes from retrogradational to aggradational or progradational. The maximum-flooding surface typically exhibits high amounts of bioturbation and substantial amounts of glauconite, phosphate, organic matter and deep-marine fossils due to slow sedimentation rates (McLaughlin 2005; Coe et al., 2005).

Systems Tracts

The highstand systems tract is bound by the maximum flooding surface at the base and sequence boundary above and indicates a time of a slowing rate of relative sea level rise and decreasing accommodation for sediments. The volume of sediment being supplied surpasses the volume of accommodation space, resulting in a progradation of the shoreline basinwards and a change upward from aggradational to progradational stacking pattern (Catuneanu, 2006; McLaughlin, 2005; Coe et al., 2005).

The lowstand systems tract overlies the sequence boundary and depicts the end of the sea level fall and the period before sea level rise, resulting in the most basinwards shift in facies. These stacking patterns are aggradational or slightly retrogradational (McLaughlin, 2005; Coe et al., 2005). The base of the lowstand systems tract is the sequence boundary which is the greatest extent of exposure and erosion of underlying strata. Relative sea level fall can expose older fossiliferous sediments to erosion, resulting in the occurrence of reworked biofacies once relative sea level increases. High abundances of terrestrial pollen may also be found in marine lowstand sediments due to fluvial transport of organic material to the ocean basin (McLaughlin, 2005).

The transgressive systems tract is deposited during a rise in relative sea level, and a landward shift in facies occurs. The base of the transgressive systems tract is defined by the transgressive surface, and the top defined by the maximum flooding surface. During this time, the rate of increase in accommodation space exceeds that of the sediment input, resulting in a retrogradational stacking pattern of sediments (McLaughlin, 2005; Coe et al., 2005).

Pollen Analysis

Pollen Morphology

Pollen morphology must be studied extensively in order to be proficient at pollen identification. Taxonomically speaking, pollen external morphology and surface ornamentation can be specific down to the family or genus level, are an indication of pollination strategy, and can be used to identify specific genera and assemblages within the pollen record. Pollen morphology is diverse with many different variations of pores, furrows (colpi) and sculpturing, and pollen size can vary within the same taxon within a certain range (Figures 1.1 and 1.2). Pores and colpi are the openings in which genetic material gets passed from the pollen grain to the recipient plant, and is a fundamental building block of identification. Pores, colpi and surface ornamentation variations can help infer pollination strategies and differentiate between taxa (Faegri and Iversen, 1989).

Pollination strategies are utilized by plants to disperse pollen grains from anther to a recipient's stigma. Pollination can be performed by wind, water or animal, and the method of pollen dispersal determines the amount of pollen released and the range of dispersal. (Faegri and Iversen, 1989).

Plants underrepresented in the pollen record include hyp-hydrogamous species, autogamous species, and zoophilous species. Hyp-hydrogamous plants pollinated underwater are rare and the thin exine of the pollen grains makes fossilization extremely difficult. Species which self-fertilize, or autogamous species, produce very little pollen which usually stays in the mother plant. In cases where pollen may be liberated from the plant by external forces, the low number of pollen produced results in underrepresentation in the pollen record (Faegri and Iversen, 1989). Zoophilous plants use animal transport to transfer pollen to the other recipient plants (Faegri and Iversen, 1989). These species utilize blossoms or rely on the specialized behaviour of the animal to release pollen grains firmly onto the animal; only the stigma of the same species can remove it. Zoophilous species are somewhat rare in the pollen record, as very little pollen is deposited directly onto sediments unless a transport animal dies or the sample is taken from directly underneath the male plant (Faegri and Iversen, 1989).

Anemophilous pollen comes from plants that use wind as a dispersal agent. Wind-pollinated plants produce the highest amount of pollen in pollen rain; therefore, most of the pollen in the pollen record constitutes anemophilious species. The individual grains completely separate or form only small clumps, as heavy clumps of grains would be less efficient for wind dispersal. Wind-pollinated pollen are typically dry and exhibit more smooth exines with less ornamentation, such as pores or sculpturing, which would restrict the possibility for wind dispersal. Some taxa, such as *Pinus* and *Picea* have evolved air bladder structures to help make wind dispersal more efficient (Faegri and Iversen, 1989).

Pollen rain is the total sedimentation of spores and pollen from the air in a given area (Traverse, 2008). As spores and pollen are the size of silt or very fine-grained sand, they have low specific gravity and can travel high above weather systems, low to the ground, through forests, or over plains and bodies of water. Wind dispersal of pollen grains is so vast and varied that some pollen grains may travel an astonishing number of kilometers away from the parent plant, while other grains will only be deposited at or a few feet away from the parent plant. Local pollen rain encompasses pollen and spore species which settle at or very near to the parent plant. Almost all pollen falls out of the air a few tens of meters from the source plant, and at least 95% of all pollen usually settles within a kilometer (Traverse, 2008). On a larger scale, regional pollen rain would include taxa which travel farther distances from the parent plant. Wind-transported pollen can be transported, on average, around fifty to a few hundred kilometers from the source plant until deposition in sediments or water. Some exotic pollen can travel even further by prevailing winds and ocean currents before settling down in sediments or bodies of water, although these types are rare (Traverse, 2008). Grain ornamentation, size, orientation relative to the direction of wind, local environment, height of the parent plant, surrounding ground cover, season and time of day are just a few of the factors taken into consideration when a grain is transported by wind (Faegri and Iversen, 1989).

Precipitation and terrestrial water sources are also important modes of transport for pollen grains. Precipitation washes the pollen from the higher air strata, vegetation and other pollen traps to the ground. Grains can then be transported into lakes, rivers and streams further away from the parent plant. Raining-out of pollen is an important factor in long-distance transport (Traverse, 2008). The Marshy Hope area during the Miocene was a shallow-marine continental shelf environment, making wind and water the most important modes of pollen transportation to the area. Although it is possible to find hyp-hydrogamous, autogamous and zoophilous plant species within the pollen rain, these are quite rare.

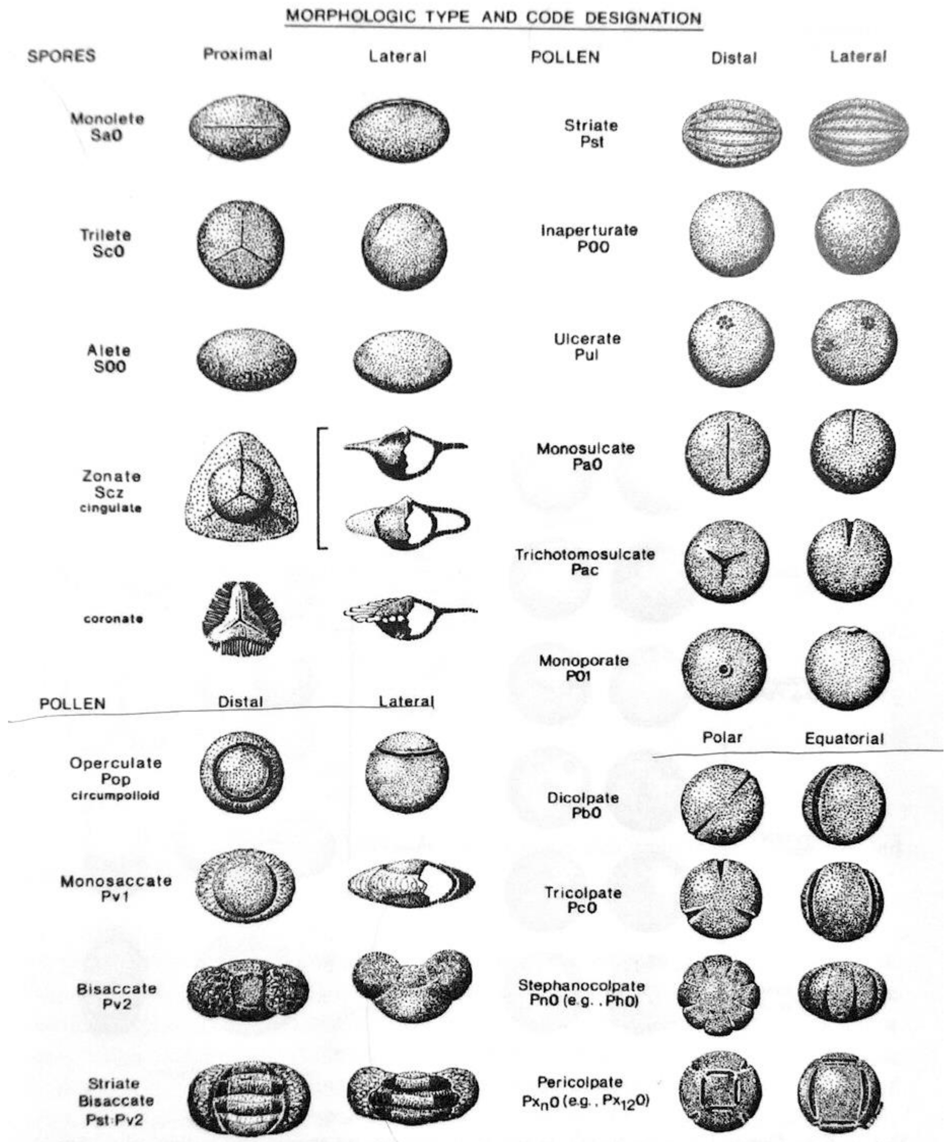

Figure 1.1: Pollen morphological types based on number and arrangement of colpi, pores and air bladders (Traverse, 2008).

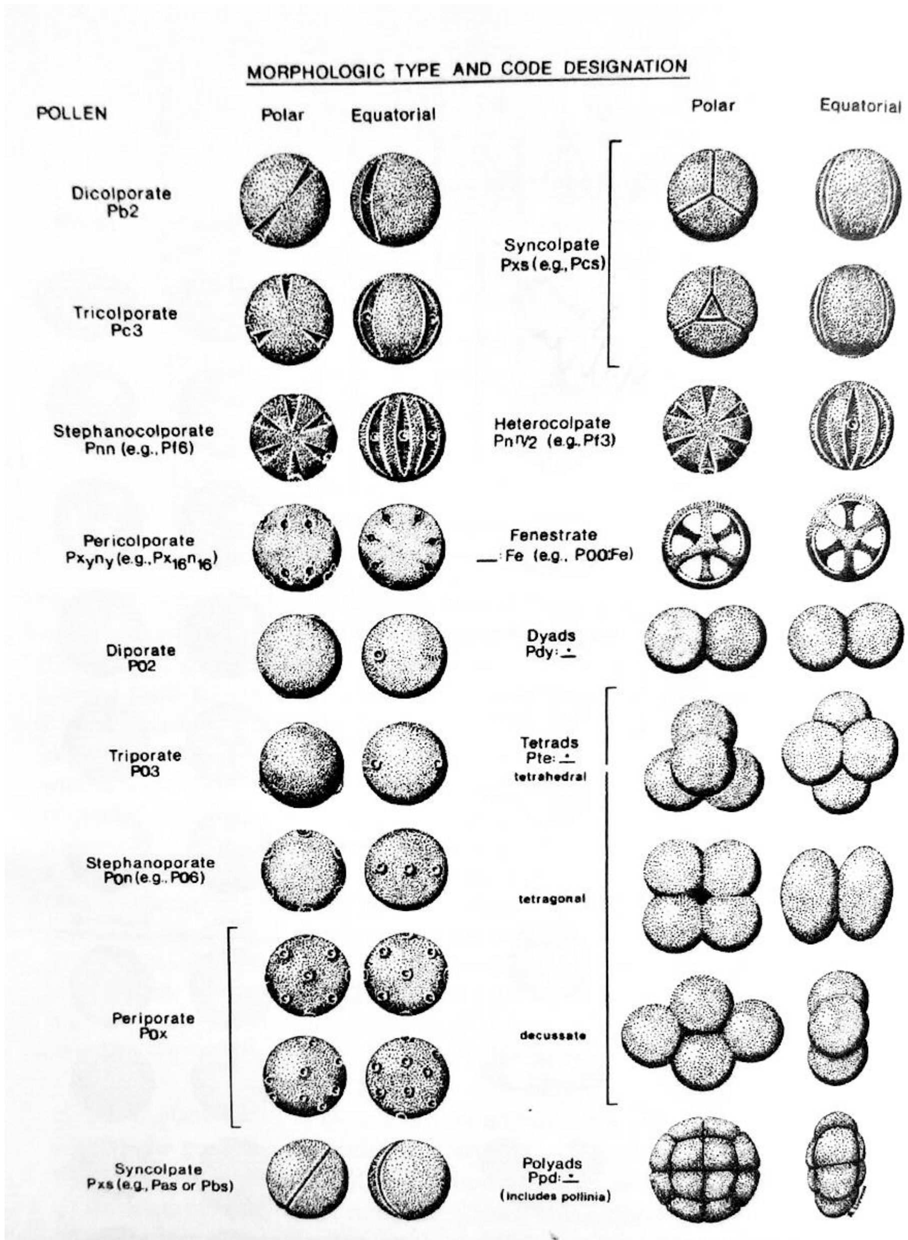

Figure 1.2: Pollen morphological types continued (Traverse, 2008).

Palynofacies

Palynofacies play an important role in constraining the age and environmental elements to sequence-stratigraphic analysis. Basic pollen analysis can provide direct information on changes in local or regional plant communities throughout time. Causes of these vegetation changes include climatic changes, major geologic events, and human disturbance (Traverse, 2008). Palynofacies reflect a particular environment of deposition, and changes in those environments will be reflected in the pollen record. In this sense, palynofacies can aid in recognizing correlatable transgressions and regressions in sequence stratigraphy, both of which are related to worldwide eustatic changes in sea level. Fossil assemblages can be used to trace facies changes which define sequence-stratigraphic depositional systems and surfaces (Traverse, 2008; McLaughlin, 2005).

Palynomorphs identified at the Bethany Beach site and used to correlate to other boreholes in the region include fossil pollen assemblages and dinoflagellate cyst taxa. A preliminary pollen zonation was achieved through stratigraphically-constrained cluster analysis of pollen taxa contained within the Bethany Beach sediments. Moreover, dinoflagellate cysts were identified and occurrences were interpreted in order to create a dinocyst zonation based on the zonation by de Verteuil and Norris (1996).

Previous Work

Studies involving lithology, biostratigraphy and sequence stratigraphy have been conducted on Miocene-age formations within Delaware (Figure 1.3). In one of the earlier studies of Delaware geology, Jordan (1962) investigated the geologic formations and described the stratigraphy of the Chesapeake Group. In eastern Sussex

County, Benson (1990) investigated and described the Chesapeake Group lithology, biostratigraphy and chronostratigraphy and interpreted paleoenvironments based on sand-size, macrofossils and microfossils. Ramsey (1997) studied the Chesapeake Group at various locations in Kent and Sussex counties and described lithologies and differentiated stratigraphic units. Recently, Miller et al. (2003), Browning et al. (2006) and McLaughlin et al. (2008) both applied sequence stratigraphy to Miocene-age sediments located in Delaware's eastern Sussex County.

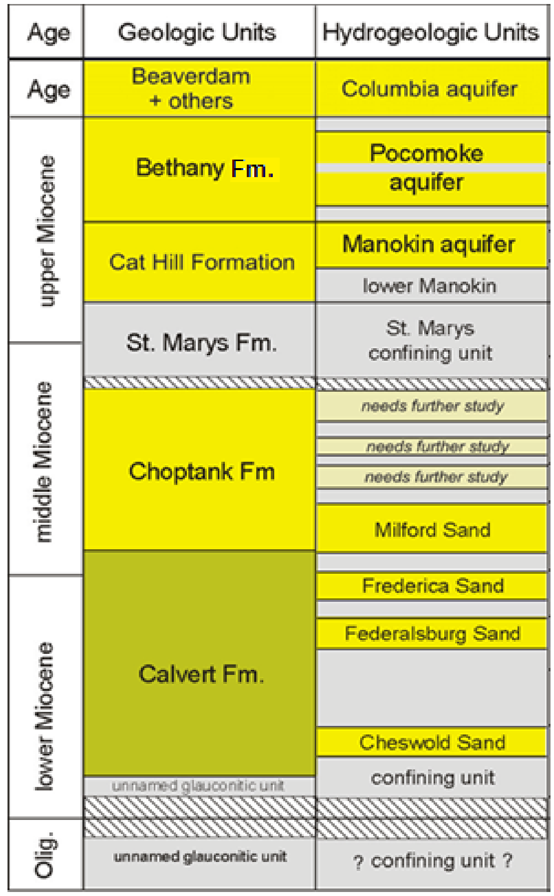

Figure 1.3: The Miocene-age geologic and hydrogeologic units in Delaware, including the Calvert, Choptank and St. Marys Formations. Yellow units indicate sandier lithologies whereas grey indicates muddy lithologies.

Calvert, Choptank and St. Marys Formation Stratigraphy

The Calvert, Choptank and St. Marys Formations are all a part of the larger Chesapeake Group, each having its own distinct lithology and sediment sequence (Benson, 1990). In 1904, George B. Shattuck was the first researcher to identify and describe the lithologies of the Calvert, Choptank and St. Marys Formations that comprise much of the Atlantic Coastal Plain Miocene strata in Delaware, Maryland and New Jersey (McLaughlin and Velez, 2006). At the Calvert Cliffs along the

Chesapeake Bay, Shattuck categorized vertical changes in lithology into 24 distinct zones, most of which can still be recognized in the Calvert Cliffs today (Kidwell, 1997; Buzas and Gibson, 1990). Shattuck placed zones 1-15 in the Calvert Formation, zones 16-20 in the Choptank and zones 21-24 are included in the St. Marys Formation (de Verteuil and Norris, 1996; Kidwell, 1997). Kidwell (1997) and de Verteuil and Norris (1996) slightly change this zonation by placing zones 1-16 in the Calvert Formation, zones 17-21 in the Choptank and zones 22-24 in the St. Marys Formation. Shattuck's (1904) different zones were subdivided based upon grain size, abundance of shell material and molluscan species (Kidwell, 1997).

The Calvert Cliffs, located on the western shore of the Chesapeake Bay, Maryland, gently dip to the southeast and expose close to 10 million years of Miocene strata (Kidwell, 1984). The cliffs reach 25-35 metres in height and can be followed along the shore in Calvert County for 40 km, allowing for detailed studies of lithologies, facies changes and unconformities (Kidwell, 1997). The Chesapeake Group is capped by younger, coarse sediments of uncertain age and displays a gentle dip and general eastward-thickening wedge (Kidwell, 1997). The Calvert, Choptank and St. Marys Formations of the Chesapeake Group are mostly medium- and coarse-grained shelly sands, silt and clays intermixed with fine sands, diatomite and shell material (Meng and Harsh, 1988). Previous paleoenvironmental studies of the Calvert Cliffs seem to agree that the Chesapeake strata depicts an overall shallowing with many small cycles of deepening and shallowing taking place (Kidwell, 1997).

Named for the famous Calvert Cliffs in Maryland, the Calvert Formation is the oldest and the thickest of the Chesapeake Miocene Formations, spanning from the early to middle Miocene in Maryland (Kidwell, 1984). The earliest sediments of the

Calvert Formation in Delaware contain glauconitic sand, commonly thought of as a reworking of the underlying Eocene formation as the lithologies of the two are very similar (Benson and Spoljaric, 1996). The upper packages consist of fine, silty sands that grade upward into very fine brown to olive-grey sandy silt and clay (Ramsey, 1997). Throughout the Calvert Formation are interbedded layers of brown to olive-grey silt, fine to course shallow-marine to estuarine sands as well as shells, clays and muds which signify a series of transgressions and regressions at the coast (McLaughlin and Velez, 2006; Benson, 1990).

The middle to upper Miocene Choptank Formation, named for the Choptank River in eastern Maryland, overlies the Calvert Formation. In Delaware, the Choptank is composed of medium- to coarse-grained, brown to olive-grey sands which fine upwards into a fine, silty sand and clay (Ramsey, 1997, Shattuck, 1904). The Choptank Formation is typically sandier than either the Calvert or St. Marys Formations and is also interbedded with layers of clayey silt, indicating past coastal transgressions and regressions (McLaughlin and Velez, 2006).

Previous studies of the stratigraphic relationships within the Calvert and Choptank formations in Maryland have been variable. Dryden (1930) found the contact between the Calvert and Choptank formations difficult to identify with the evidence for an unconformity disputable (Kidwell, 1984). Gernant (1970) later redefined, named and gave type sections to the five divisions of the Choptank Formation as recognized by Shattuck (1904). Moreover, Gernant studied the two formations and found variability in different locations. Kidwell (1984) investigated depositional sequences of the Calvert and Choptank formations in an outcrop of the Salisbury Embayment. Moreover, Kidwell (1984) utilized biostratigraphy and paleoenvironmental interpretation to recognize and describe seven depositional sequences: four in the Calvert Formation, two in the Choptank Formation and one in the St. Marys Formation.

The Bethany Beach sediments depict many variations of shoreface environments throughout the Calvert, Choptank and St. Marys Formations. Association of facies recognized by Miller et al. (2003) include estuarine, upper shoreface/foreshore, distal upper shoreface, lower shoreface, and offshore environments. These facies are interpreted as a wave-dominated shoreline. Sediments were deposited as in typical marine environments (Figure 1.4):

- Foreshore: dominated by fine to coarse sands;
- Proximal upper shoreface: sand dominated by shell hash;
- Distal upper shoreface: composed of fine to medium sand and some silt and clay;
- Lower shoreface: composed of fine sand and silt with some whole shells;
- Offshore: dominated by very fine sand, silt and clay.

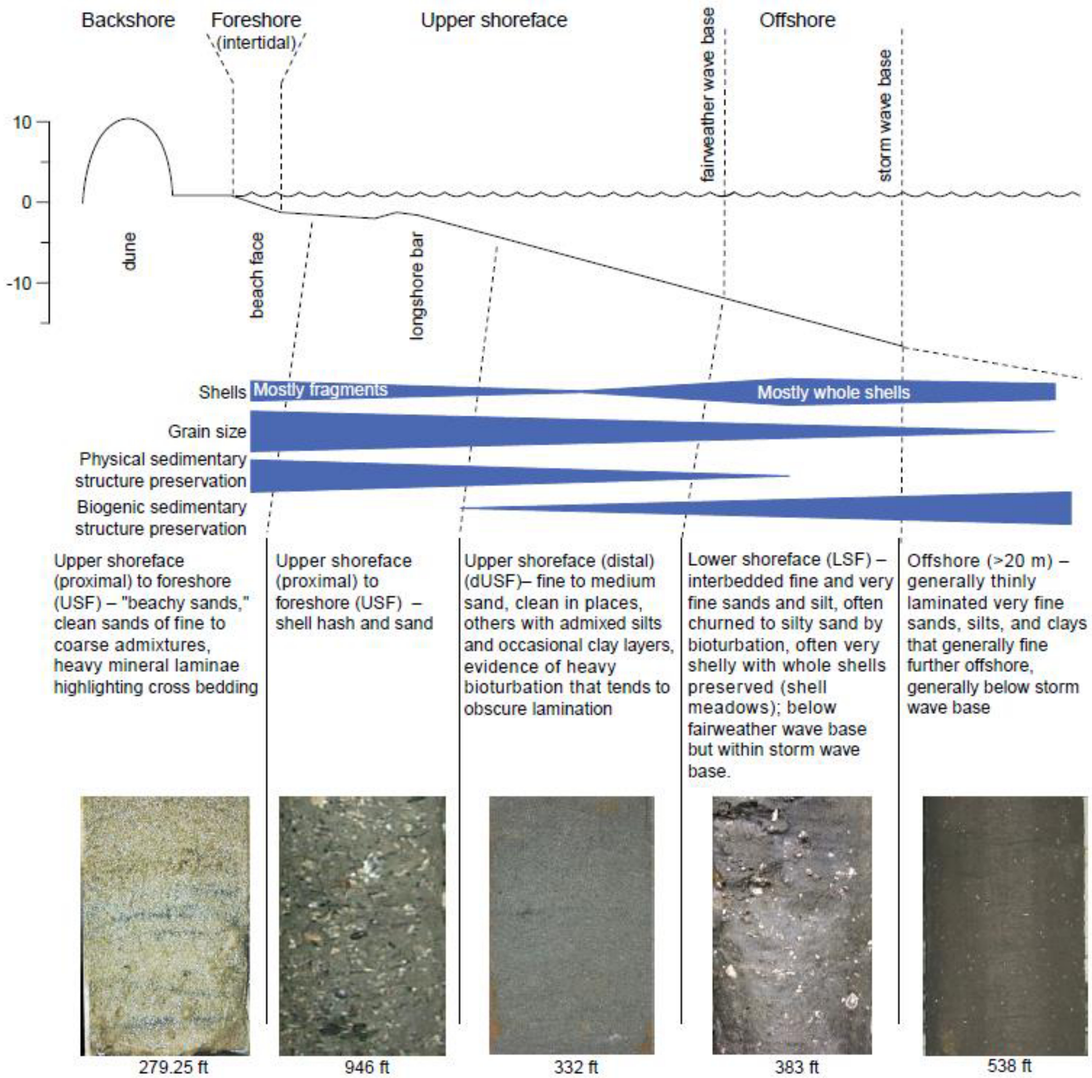

Figure 1.4: Wave-dominated shoreline facies model, summarizing general lithofacies and biofacies from Miller et al (2003) based on the Bethany Beach (Qj32-27) borehole and used to interpret the sediments from core Nb53-08. Illustration depicts the location of different environments along the shoreline and the corresponding sea level. Thickness of the blue lines indicates abundances of shells, grain size, physical sedimentary structures and biogenic trace fossils within the different environments. Photographs for each lithofacies are based on the Qj32-27 sediments at depths indicated underneath the photographs.

More recently, McLaughlin et al. (2008) interpreted sediments at Bethany Beach as a prograding wave-dominated shoreline based upon changes in sedimentology, microfossils and paleoenvironmental interpretations.

The Miocene stratigraphic record of the Middle Atlantic Coastal Plain in Maryland, Delaware and New Jersey shows a generally similar sequence stratigraphic record, with only minor differences in age, which is most likely the result of both changes in global sea-level and local subsidence in the region. Beginning at Island Beach and continuing updip to Bethany Beach, core sediments exhibit an increase in the number of sequences; three sequences are identified at Island Beach, six in Atlantic City, nine at Cape May and ten at Bethany Beach (McLaughlin et al., 2008; Browning et al., 2006). Previously, McLaughlin et al. (2008) built upon the study done by Miller et al. (2003) to characterize the formations and document the sequence stratigraphy of core Qj32-27. This information can now be used as a reference section for correlating other boreholes around the Sussex County region. Miller et al. (2003) and Browning at al. (2006) identified and named ten sequences (C1-C10) in the Calvert, Choptank and St. Marys Formations at Bethany Beach, each with its own set of systems tracts and surfaces which can include: Highstand Systems Tract (HST), Transgressive Systems Tract (TST), Maximum Flooding Surface (MFS), and Flooding Surface (FS). The Calvert Formation includes sequences C1 to C5 at Bethany Beach. Sequence C1 is the thickest with a thin TST and a very thick HST. Sequence C2 differs from the others in that it has a thicker TST relative to the HST, rather than a thin TST and thick HST. The next few sequences, C3, C4 and C5, follow the pattern of a thin TST and thick HST, although C4 also exhibits two additional FS. At Bethany Beach, the Choptank Formation begins in the middle of the HST in sequence C5 and continues through the beginning of sequence C9. The St. Marys Formation at Bethany Beach includes the last half of C9 and C10. Each sequence from C5 to C10 follows the trend of a thin TST and thick HST, and only C8 exhibits an additional FS (McLaughlin et al., 2008; Figure 1.5).

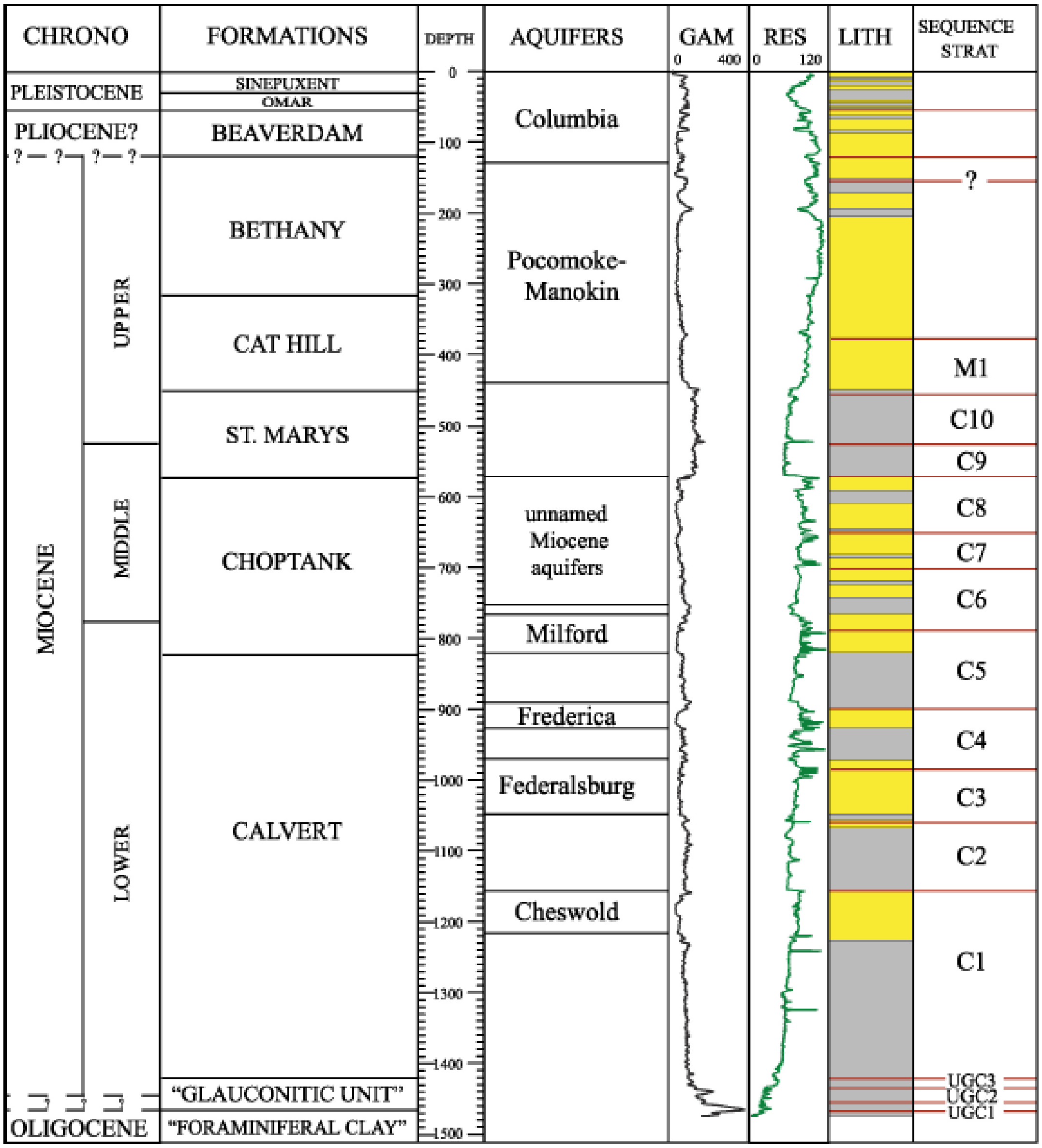

Figure 1.5: Summary stratigraphic column for core Qj32-27 at Bethany Beach, Delaware. Synthesis chronostratigraphy, formations, geophysical log signatures (gamma and single-point resistence), aquifers, lithologies and sequences recognized at the Qj32-27 study site. Yellow indicated sandier lithologies whereas grey indicated muddier lithologies (McLaughlin et al., 2008).

Palynology

Palynofacies are the assemblages of palynomorph taxa found in sediments which provide information on the sedimentary depositional environment (Traverse, 2008). In water, terrestrially derived palynomorphs will exhibit a relative decrease in numbers with increased distance from the source, which can be used to indicate relative distance to the shoreline as well as changes in relative sea level (Jaramillo and Oboh-Ikuenobe, 1999). Aquatic dinoflagellates can also be used as environmental indicators, as some species are sensitive to water temperature, salinity level and proportional changes related to distance from shore (Jaramillo and Oboh-Ikuenobe, 1999). Using multivariate statistical analysis, LeNoir and Hart (1988) studied late Miocene palynofacies from the Gulf of Mexico and found that changes in the lithofacies and their corresponding patterns and species of palynofacies are a result of changes in the depositional environment and relative sea level. Ultimately, changes in palynofacies of the Atlantic Coastal Plain are the direct result of primarily regional climatic changes, and interpreting each unique assemblage is crucial in determining climatic events (Pazzaglia et al. 1997).

Variations in the proportions of different pollen taxa throughout the stratigraphic column reflect changes in the vegetation, as well as the depositional environment, and few studies have been done on pollen assemblages of the Miocene formations in Delaware. Groot (1992; 1997) found that the most abundant taxa in the Calvert and Choptank Formations include *Quercus* (oak), *Pinus* (pine) and *Carya* (hickory), and a few exotic taxa, *Engelhardia* and Taxodiaceae-Cupressaceae-Taxaceae (TCT), which are presently found only in subtropical or tropical climates. The occurrence of these exotic species have been interpreted to indicate that during the deposition of the Calvert Formation, climate was warm and moist (Groot, 1992; 1997).

A more recent study done by McLaughlin et al. (2008) provides the most complete preliminary pollen zonation for the Miocene in southern Delaware (Figure 1.6). Four pollen zones were recognized in the Miocene of the Bethany Beach site. Each zone is dominated by *Quercus, Carya* and *Pinus* (McLaughlin et al., 2008). Zone 3 contains abundant *Quercus* and *Carya*, as well as *Fagus, Liquidambar* and a few exotics (*Pterocarya* and *Engelhardia*-type); Zone 4 is dominated by abundant *Quercus* and *Carya* with consistent *Pterocarya*; Zone 5 includes increased *Pinus, Quercus* and *Carya* and exotics including *Engelhardia*, *Podocarpus* and *Symplocos*; and Zone 6 is characterized by mostly *Quercus,* some *Pinus* and *Carya* and relatively high amounts of *Engelhardia*. The general trend from the lower Calvert Formation to the Choptank Formation includes a general decrease in *Quercus,* an increase in *Pinus* and *Carya* and a stable amount, if not an increase, of exotics (McLaughlin et al., 2008).

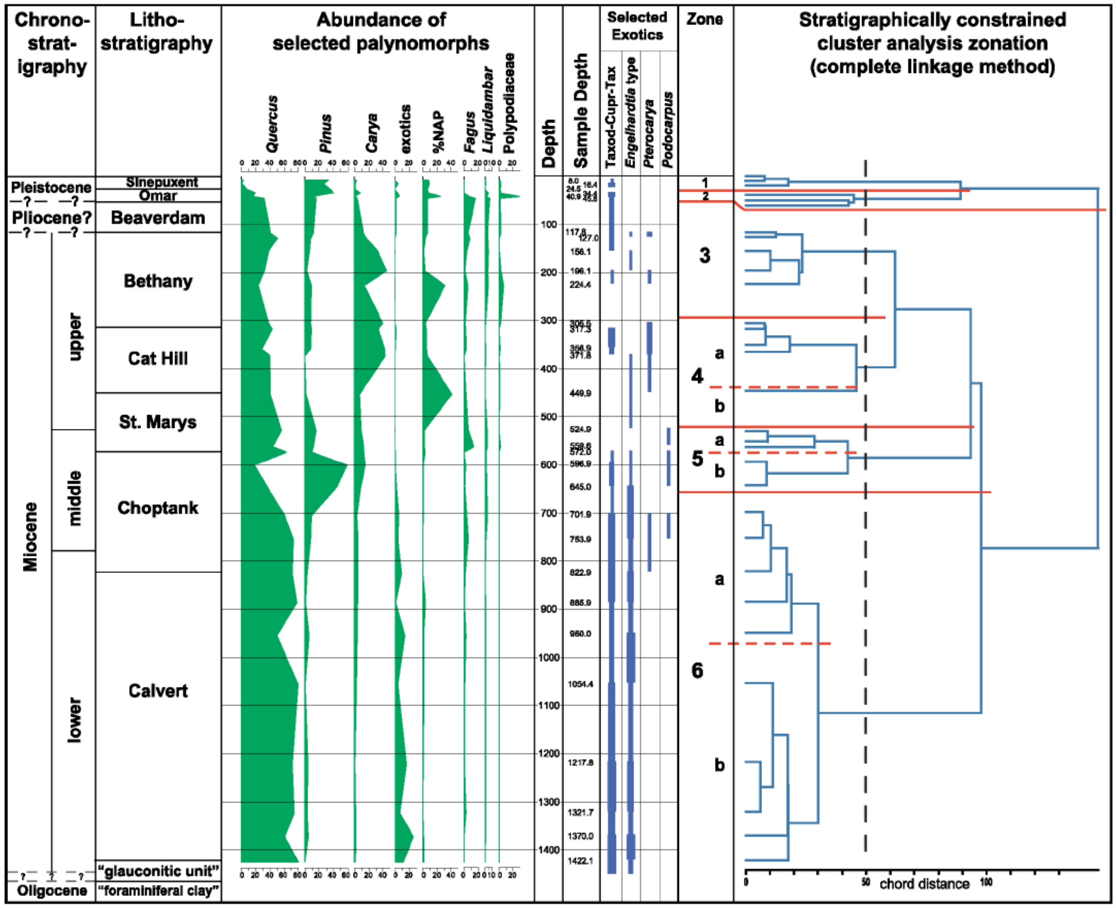

Figure 1.6: Pollen zonation for the Qj32-27 borehole at Bethany Beach. Pollen zones 1 through 6 are shown alongside the lithostratigraphy and chronostratigraphy of Qj32-27. Cluster analysis dendrogram used to define the zones shown on the right with zone and subzone boundaries depicted by red solid and dashed lines, respectively. Percentages of key palynomorphs are indicated by the green sawtooth graphs and exotic taxa relative abundances are represented by the various widths of the blue bars (McLaughlin et al., 2008).

Similar palynomorph zonation studies have been done in the North Sea Basin. Munsterman and Brinkhuis (2004) identified and described fourteen distinct dinocyst zones (M1 to M14) in the Miocene of the Netherlands sector of the North Sea. Dybkjaer and Piasecki (2010) revised the Neogene dinocyst zonation for the Danish region to fifteen dinocyst zones within the Miocene; with most being new zones and few being redefined. Larsson et al. (2011) conducted palynological analysis on the core previously studied by Dybkjaer and Piasecki (2010) to link the existing dinocyst stratigraphy to the terrestrial pollen signal. Four distinct climatic cooling and warming events in the Miocene were successfully detected within the studied succession, with a mean temperature range of 15-20°C. Warm-temperate palynological assemblages, such as Taxodiaceae-Cupressaceae indicate the dominance of a swamp-forest bordered by deciduous-evergreen mixed forests further inland (Larsson et al., 2011).

De Verteuil and Norris (1996) presented a dinoflagellate cyst zonation for Miocene strata from the Calvert Cliffs, Maryland which includes ten different dinocyst zones. All zones but one are interval zones, which are defined as the interval between the highest or lowest occurrence of one species and the highest or lowest occurrence of another; only one zone corresponds to the full range of a single taxa (de Verteuil and Norris, 1996). Each zone is named after the binomial name of one species that characterizes that zone in some way, and each has an estimate of its chronostratigraphic position based on biostratigraphic data (Figure 1.7). These differentiated zones prove useful in identifying and demarcating stratigraphic subdivisions within western North Atlantic sediments, and allow for stratigraphic correlations to sections located in New Jersey, Delaware, Maryland and Virginia (de Verteuil and Norris, 1996).

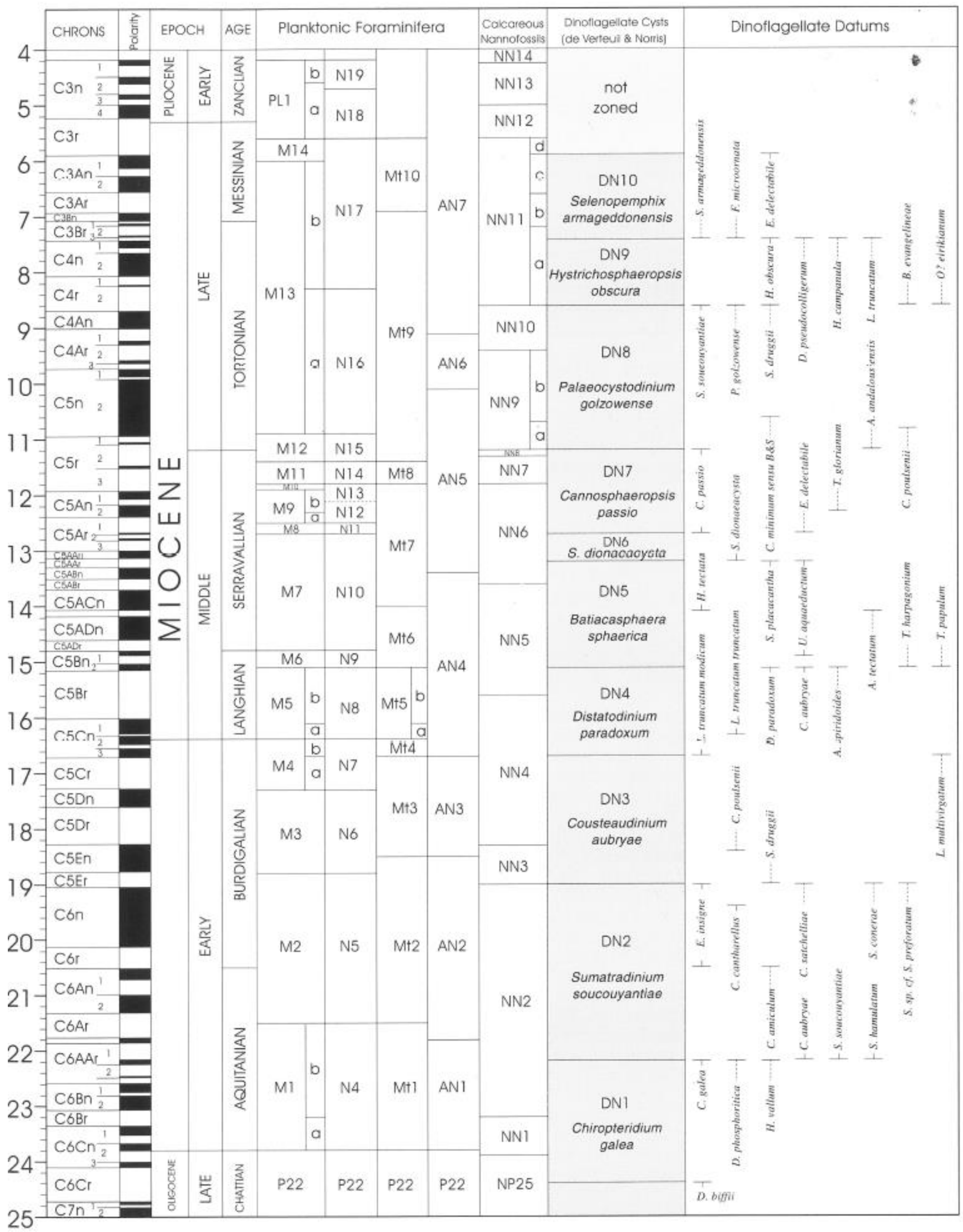

Figure 1.7: Chronostratigraphic positions of the ten dinocyst Zones DN1 through DN10 which uses the timescale from Berggren et al. (1995). Dinoflagellate Datums depict the highest and lowest occurrences of specific dinoflagellate species, which is the basis for the zonation (de Verteuil and Norris, 1996).

Chapter 2

METHODS

Sampling Methods

Continuous wireline coring was conducted in the Marshy Hope Wildlife area in western Delaware in spring 2009 (Figure 2.1). The drill rig used to extract the cores is set up with English system measurements; therefore, the primary unit of measurement is feet but metric equivalents are also listed. Cores were extracted in 5 or 10-foot lengths resulting in 74 separate discontinuous cores and their corresponding geophysical logs were taken (Figure 2.2). The borehole was drilled to a depth of 540 feet (163.07 m) as both the Calvert and Choptank Formations sediments span nearly 400 feet (121.92 m), encountered from approximately 100 feet (30.48 m)to the bottom of the hole. Wireline geophysical logs including natural gamma, single-point-resistance, 16- and 64-inch normal resistivity and spontaneous potential were obtained using Century Geophysical Corporation equipment owned by the DGS. Gamma logs record the natural radioactivity variations of different types of rocks which can be used to correlate between boreholes. Gamma value for quartz sands is low whereas shales, or sediments which contain more clay and silt show higher gamma values. Spontaneous potential logs respond to shale content and resistivity logs measure the resistance of a material to the flow of an electric current; clay and silt have low resistance, sand has high resistance, and pore water with high salinity will cause a decrease in resistance (Keys, 1990).

For this project, we took samples for lithologic and palynologic analysis. Samples extracted for lithologic analysis were taken approximately every 5 feet (1.52

m) of available core for a total of 67 samples. Lithologic samples taken from the core measured 1.2 inches (0.03 m) by 1 inch wide (0.025 m) to leave half of the core intact as a permanent record. Samples for palynological analysis were taken approximately every 10 feet (3.05 m) of available core within the finer silts and clays for a total of 32 samples. Palynology samples extracted measured 1.8 inches (0.045 m) by 1 inch wide (0.025 m). Tools used to obtain sediment samples included a knife and spoon, both of which were cleaned in between samples, as well as a geology hammer to aid in hammering through the core if needed. Samples were placed into plastic bags and secured, then labelled with the core number, box number of the core and depth of the sample. A place card with name, depth of sample taken and date was placed at each area sampled in the core.

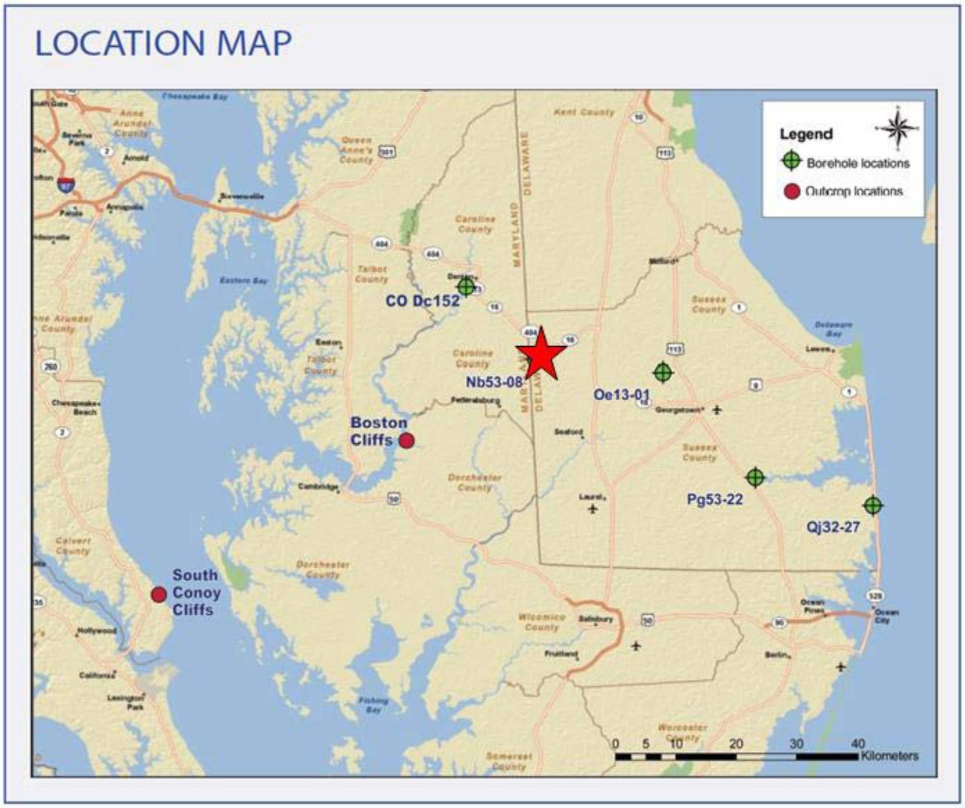

Figure 2.1: Map of southern Delaware with a red star indicating the location of borehole Nb53-08 at the Marshy Hope study site. Map shows other borehole locations in southern Delaware, including the location of borehole Qj32-27 at the Bethany Beach study site.

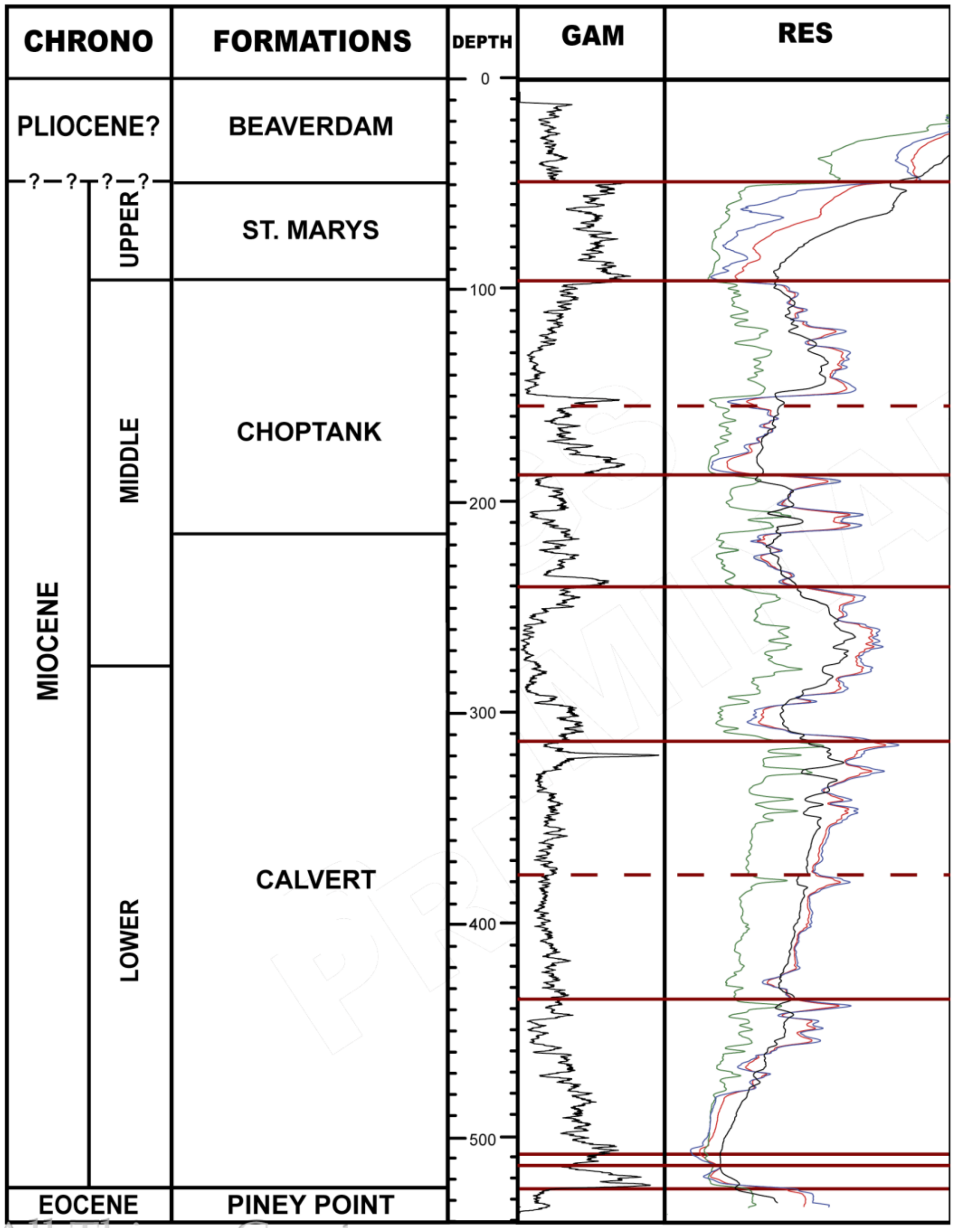

Figure 2.2: Chronostratigraphy, formations, geophysical logs and depth in feet of borehole Nb53-08 from Marshy Hope, Delaware. GAM-gamma ray log depicted in black, RES-various resistivity logs: blue line represents lateral resistivity, green line represents point resistance, red line represents short normal resistivity (16 inch), and the black line represents long normal resistivity (64 inch).

Laboratory Methods

Samples for lithologic analysis had dry weights recorded before being left to soak overnight in porcelain bowl with distilled water to soften each sample. The samples were then broken down manually using a mortar and pestle; sodium hexametaphosphate was added to assist disaggregation and prevent clay flocculation. Wet sieving was done at the sink with a 63 µm sieve to separate out the clay and silt, and then samples were dried under heat lamps. Once dry, each sample was again weighed to determine amount of clay and silt removed from each sample. Dry sieving was conducted on the remaining sample to differentiate very fine sand (0.063-0.125 mm), fine sand (0.125-0.250 mm), medium sand (0.250-0.500 mm), coarse sand (0.500-1.00 mm) and very coarse grains (1.00 mm and larger). Samples which had larger cemented pieces unable to be broken down were completely omitted from the sample, whereas smaller cemented grains were kept in the sample and counted as coarse grains. At depths where the core was completely cemented samples were not taken and those depths omitted from the lithologic analysis. The weight of each section of sample left on each sieve was weighed and recorded.

Laboratory methods for isolating pollen grains and dinoflagellate cysts for analysis is a very time-intensive process with many different steps, all of which are crucial to recovering as many palynomorphs as possible. Palynology processing was done in batches of sixteen samples at the Delaware Geological Survey lab.

A sample spike solution was made to allow estimation of absolute abundances of palynomorphs. The solution of 1.35 ml of a concentrated suspension of microspheres (formerly US Life Science Products, now PerkinElmer), 0.02 ml of Triton (to aid in the unclumping of spike grains), and 5.0 g of Dextran powder (to keep microspheres suspended in solution) in 50 ml of water was created to reach a solution of approximately 5,000,000 microspheres in 50 ml. A hemocytometer count was conducted repeatedly to ensure a uniform distribution of spheres.

Each sample was transferred to a plastic bottle after the bottle was weighed, and labelled with sample-specific numbers. The bottles were each half-filled with distilled water and placed in a 60°C overnight. To each sample, 0.5 ml of the spike solution was added in order to allocate approximately 60,000 microspheres per sample.

Removal of minerals began with the use of 37% hydrochloric acid (HCl) to demineralize carbonates. Excess liquid from each bottled sample was poured off and small amounts of HCl were added until each sample was unreactive to the addition of more HCl. Each sample was centrifuged, decanted and washed with distilled water until neutral. Physical separation of sand from finer materials was done by rinsing, swirling and decanting of fines for further palynologic processing. The remaining sand was placed in a 60°C oven and weighed when dry. The liquid fraction with fines and organics was treated with 48% hydrofluoric acid (HF) for several days to demineralize the silicate content of each sample, followed by a 20% HCl bath and neutralization with distilled water. After neutralization each sample was split in half with each fraction placed into 50 ml polypropylene vials in order to process for pollen and dinoflagellates separately.

For each pollen split, additional processing began with a 35% nitric acid (HNO_3) oxidation treatment for 5 minutes, then addition of water, centrifuging, and decanting the supernatant for multiple cycles until neutralized. A 5% ammonium hydroxide (NH_4OH) treatment was employed for 5 minutes to take out humic acid and neutralized with distilled water. Samples were then dehydrated using an acetic acid

($C_2H_4O_2$) rinse and centrifuged to prepare for acetolysis. Acetolysis was performed by creating a solution of acetic acid and sulfuric acid (H_2SO_4) which was added to each sample, and then samples were placed in a boiling water bath for 5 minutes. Samples were then rewashed with acetic acid and neutralized with distilled water.

Finally, a heavy liquid flotation method was employed to separate the organic residue and pollen from other non-organic matter. After washing each sample with 2% HCl and decanting, a zinc chloride (ZnCl) solution with a specific gravity of 2.0 was added to each sample tube, agitated, centrifuged and left for a few days so the pollen grains could rise to the top of the solution and mineral matter sink to the bottom. Once settled, pipetting was employed to collect all organics at the top of each sample which were transferred to a 15 ml tube. All samples were then washed with 2% HCl to remove the ZnCl, then rewashed and neutralized with distilled water. Samples which showed abundant fine organic matter obscuring the pollen were sieved through 7 µm filter sheets aided by the use of Sparkleen, distilled water and a suction system attached to the sink designed to rid the sample of excess organics.

Finally, each sample was stained with safranin, centrifuged, and supernatant decanted before being rinsed with ethanol to set the stain. After one last centrifuging the ethanol was decanted, and a fraction of each sample was pipetted onto the slide. Each pollen sample was double mounted on 1 inch by 3 inch slides by placing two drops of PVA on the slide, adding a drop of sample to the PVA, and gently placing the coverslip on top. A mixture of polyester resin and a hardener was used to secure the outer edges of the coverslips. In cases where pollen grains were sparse, a second slide was prepared.

For processing of the dinoflagellate splits, the demineralized residues were sieved through 25 µm sheets rinsed with soapy distilled water and a suction system attached to the sink designed to rid the sample of excess organics. No additional acid treatments were used unlike the pollen processing method.

The sieved residues were stained with safranin twice to ensure good stain colouration in the cysts, decanted and set with alcohol and centrifuged one last time. After pouring off the excess ethanol, each dinocyst sample was pipetted and mounted on 1 inch by 3 inch slides using PVA, polyester resin and a hardener.

Analytical Methods

Lithologic analysis methods included data capture and creation of a lithology relative abundance curve and a grain size abundance plot. Pollen analysis included microscope identification and analysis, pollen stratigraphic diagrams and statistical analysis, and dinocyst analysis methods included microscope identification and dinoflagellate cyst zonation.

A grain size abundance plot was constructed using the results of the grain size analysis of each sample. The weight of each size fraction was calculated as percentage of sample weight. A relative abundance curve was constructed from those percentages using the program Strater 3 to visualize grain size trends.

The composition of the sands were also analyzed and shown on a composite relative abundance curve. For each sample all sand fractions were recombined, thoroughly mixed and a small scoop of each was placed into a clean glass dish. Using a stereo (dissecting) microscope, visual fields totalling approximately 100 grains were examined and composition counted for the following categories: quartz, glauconite, opaque heavy minerals, mica, carbonate shells, feldspar, foraminifera and phosphate.

The program Strater 3 was used to construct the constituent relative abundance curve from percentage data derived from these counts.

Palynomorphs were identified and counted in each sample using an Omano compound microscope under 400X magnification. The oil immersion lens with a 1000X magnification was used to view pollen grains which were difficult to identify. Slides were counted to a minimum of 300 grains on one of the two coverslips, and slides which fell short of that number were not included in the study. Traverses began at the left edge of the middle the coverslip and moved across to the opposite edge. Traversing continued at the top of the coverslip, then the bottom; these alternations of traverses continued until the predetermined amount of grains were counted. Resources to aid in pollen identification included: Kapp et al. (2000), Pazzaglia et al. (1997), Traverse (2008), Groot et al. (1990), Groot (1992), Larsson et al. (2011), and also Nichols (1973), Larsson et al. (2006), Frederiksen (1984), Brush and DeFries (1981), Worobiec (2009), Kohlman-Adamska (1993), and Groot et al. (1995). The Delaware Geological Survey Quaternary Catalogue Database and the DGS Extant Palynomorph Database were also used in pollen identification. Pollen identification was usually made down to the family or genus level, although some taxa are identified only by their morphological type and texture.

Count data were entered into a computer spreadsheet in Excel for easier manipulation of data and as base files for the construction of pollen diagrams and statistical analysis in other programs. Raw pollen counts were converted to percentages for each sample and stratigraphic pollen diagrams were created with Strater 3 and Inkscape to depict the relative percentages of select taxa though the borehole.

Pollen concentration per gram of sediment in each sample was determined using counts of polystyrene microsphere spikes made while counting pollen grains. Pollen grain concentration was calculated by:

$$C_t = \frac{\left(\frac{Tc}{Lc}\right) \times M_s}{Wt_s} \tag{2.1}$$

Where:

Ct = the pollen concentration

$\frac{Tc}{Lc}$ = the ratio of pollen counts to microsphere counts in each slide

Ms = the number of microsphere grains added to the full sample

Wt_s = the weight of the sample in grams.

Stratigraphically constrained cluster analysis was employed to find samples with similar pollen taxa based on pollen percentage data to establish a pollen zonation for the Marshy Hope core. In order to be included in cluster analysis, each variable (taxa) in this study had to constitute at least 1% of the total pollen sum of at least one individual sample (usually 3 grains), and those which did not meet this criteria were omitted from the analysis. Overall, 32 pollen taxa were used for cluster analysis. For each sample, the raw pollen counts of qualifying taxa were turned into percentage data with each constituent taxa being part of a total 100%, and square root transformation was conducted on the percentage data. A square root transformation creates a normal distribution of all variables (taxa) and was done for this study to make each variable (taxa) as equally important as the rest and to take out the uncertainty of overly-abundant pollen from certain taxa (Faegri and Iversen, 1989). The program PAST 3.06

was used to conduct a stratigraphically constrained hierarchical clustering using the unweighted paired group method (UPGMA) with arithmetic mean, also known as average linkage clustering. In the UPGMA method, the between groups statistical distances, or dissimilarity measures, are defined as the average distance between each point in one cluster to every point in the other cluster. Clusters are joined based on the average distance between all members in the two groups (van Tongeren, 1995; Aldenderfer and Blashfield, 1984). Because the core sediments and pollen samples are ordered along the additional dimension of depth-time, stratigraphically constraining the cluster analysis ensures that only adjacent samples may be merged into larger clusters (Agterberg, 1990; Davis, 2002).

Dinocyst identification was conducted to identify zones put forth by de Verteuil and Norris (1996), and dinocysts were not counted. Dinoflagellate cyst identification differs from pollen identification due to many factors such as size, abundance, morphology and number of zones. Dinocysts are larger than most pollen grains and, while this makes them easier to see, they are much thinner-walled and "flimsy" which can obscure details. Dinoflagellates are found in predominantly marine environments (except for a few rare species found in certain freshwater lakes) and can be highly abundant in marine sediments, but they are not present in terrestrial settings. De Verteuil and Norris (1996) define 10 zones, each based upon the highest and lowest occurrences of specific taxa and resulting in approximately 62 dinocyst horizons. Many resources were used to help identify dinocysts using descriptions and visual aids including: de Verteuil and Norris (1996), Louwye (2000), Louwye and Schepper (2010), Fensome et al. (2009), Dybkjaer and Piasecki (2010), and Munsterman and Brinkuis (2004). Also used were McCarthy et al. (2000), Williams et al. (2004), El Beialy and Ali (2002), McCarthy et al. (2013), and Bankole et al. (2014). The species important to distinguishing zonation were identified and a dinoflagellate cyst zonation for the Marshy Hope core was created.

Depositional environment identification and sequence stratigraphic analysis were conducted based on the lithologic descriptions, grain size and component relative abundance curves, and gamma ray and resistance logs. Sequence stratigraphy classification and interpretation followed that by McLaughlin et al. (2008) and Miller et al. (2003) based on the borehole Qj32-27 in Bethany Beach, Delaware. Depositional environments inferred from lithologic descriptions of sediments found in core Nb53-08 follow the wave-dominated-shoreline facies model put forth by Miller et al. (2003) (Figure 1.4) and the facies model recognizes the following environments:

1. Fluvial to upper estuarine: dominantly poorly sorted sands, gravelly layers representing cut and fill channels and plant debris common.

2. Lower estuarine: poorly sorted sands mixed with interlaminated thin sands and clays; plant debris common; may be associated with shoreline-type sands.

3. Proximal upper shoreface: clean, high-energy fine to coarse sands; opaque heavy mineral laminae crossbedding; may have abundant shell material; deposited within fair-weather wave base closer to shoreline.

4. Distal upper shoreface: clean to slightly silt fine to very fine sand, common bioturbation which obscures lamination, deposited within fair-weather wave base.

5. Lower shoreface: interbedded fine and very fine sands, commonly silty and very shelly with whole shells preserved; deposited below fair-weather wave base.

6. Offshore: thinly laminated very fine sands, silts and clays; deposited below storm wave base.

Correlations of sequence stratigraphic units to other locations in southern Delaware were aided by the use of palynofacies of the pollen and dinoflagellate zonations.

Approximate ages were inferred from specific sand packages correlated from the Qj32-27 Bethany Beach borehole. Previously, an age-depth plot from core Qj32-27 by McLaughlin et al. (2008) was constructed and dated using strontium isotope age estimates (Figure 2.3). The depths of specific sand units in the Bethany Beach core, the unnamed glauconitic unit at the base of the Calvert Formation, the Milford sand unit at the base of the Choptank Formation and the unnamed Choptank sands ending at the base of the St. Marys Formation, were correlated to the same sand units in the Marshy Hope core. Using the age-depth plot for Qj32-27, the relative ages of the bases and top of the specific sand units were able to be inferred.

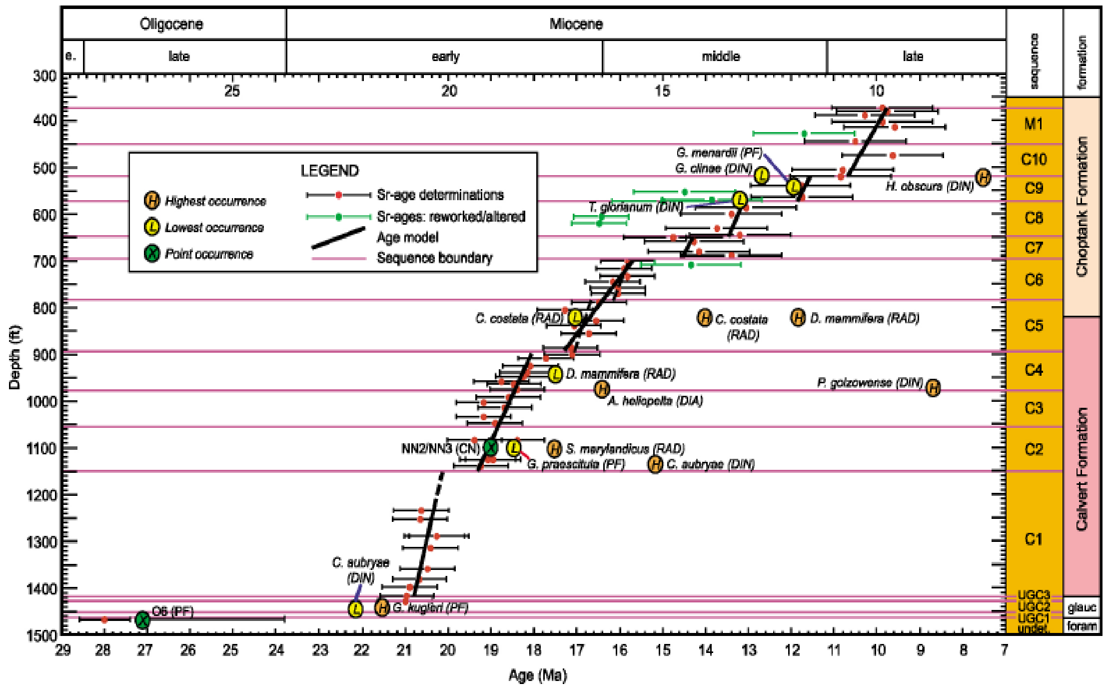

Figure 2.3: Age-depth plot for the Oligocene to Miocene section for Qj32-27 using strontium isotope age estimates. Sequences and formations are shown on the right and depth in feet shown on the left. Age-depth lines are based on strontium isotope age estimates with the primary age model represented by solid lines and an alternate model represented by a dashed line. Biostratigraphic occurrences include: RAD –radiolarian; PF- planktonic foraminifera; DIN –dinoflagellate; DIA- diatom; CN- calcareous nanofossil (McLaughlin et al., 2008).

Chapter 3

RESULTS

Two sections of results are presented: physical results and analytical results. Physical, lithological and palynological stratigraphic data are given for each formation. Analytical results include lithologic relative abundance and grain size abundance plots, as well as pollen cluster analysis. Cluster analysis allowed the zonation of samples with similar pollen taxa, and identification allowed the application of a dinoflagellate cyst zonation to the sediments in the cores.

Lithology

Study site Nb53-08 is an approximately 540 ft (163.07 m) borehole which was continuously cored in 5 and 10-foot intervals collected and described by the Delaware Geological Survey in 2009. Lithologic descriptions are based on core logs recorded and photographs of cores at the time of extraction along with lithologic and component analysis completed for this study. Lithology categories as defined by the Wentworth scale include: clay and silt; very fine sand; fine sand; medium sand; and coarse sand (Wentworth, 1922). Component categories include: quartz, glauconite, mica, opaque heavy minerals, feldspar, carbonate, foraminifera and phosphate. Sedimentary facies at Marshy Hope are composed predominantly of quartz sands and silts with common carbonate shell material which are all suggestive of a shallow-marine, wave-dominated environment. Sediment analysis results for lithology and composition weights (in grams) and percentages are shown in Table A.1 and Table A.2, and the relative abundance curves is shown in Figure 3.1.

At the Marshy Hope site, the deepest core reaches 534.45 ft (162.90 m) below the surface to the Eocene Piney Point Formation and the first two samples taken from the Piney Point Formation at 534.45 ft (162.90 m) and 529 ft (161.24 m) contain approximately 60% medium- and coarse-grained sands with 10% glauconite.

Calvert Formation

The Calvert Formation spans from approximately 527.3 ft (160.72 m) to approximately 215 ft (65.53 m). It is dominated by clayey silt coarsening upwards and terminating in fine- to medium-grain sand. Intermittent thin layers of shell material and fine- to-medium grain sand, as well as bioturbation are common (Figure 3.1).

The lower Calvert Formation sediments from 527.3 ft (160.72 m) to 481.45 ft (146.75 m) are composed of mainly silt and clay, except for a thin bed of glauconite sand, which increases in sand higher in the formation. Above 481.45 ft (146.75 m) sediments become interlaminated fine sand and silt. The first Calvert Formation sample at 524.35 ft (159.82 m) is composed of mostly silt, clay and very fine grains; glauconite contributes 40% of sediment materials, mica is found to contribute 16%, opaque heavy minerals 10% and foraminifera are present. The silt and clay continue up the cores until 474.8 ft (144.72 m), although constituents vary. In the samples at 524.35 ft (159.82 m) and 514.25 ft (156.74 m) foraminifera percentages range from 20% to 50%, and opaque heavy minerals increases to approximately 20%. At 509.35 ft (155.25 m) glauconite increases to approximately 60%, and a glauconite sand-rich zone occurs at 508.2 ft (154.90 m) to 506.5 ft (154.38 m). At 495 ft (150.88 m) mica increases in abundance from 5% at 495 ft (150.88 m) to 20% at 484.6 ft (147.71 m).

Samples from 474.8 ft (144.72 m), 469.8 ft (143.20 m), 458.5 ft (139.75 m), 446.55 ft (136.11 m), 440 ft (134.11 m), 436.3 ft (132.98 m) and 432.2 ft (131.73 m) exhibit a sequence of alternations of clay and silt zones with packages of more coarse-grained sands. The coarser packages are coarser, shelly sands which contain approximately 40% to 60% medium and coarse grains and approximately 2% to 10% shell material, except the sample at 440 ft (134.11 m) which attributes most of its coarse-grain component to quartz grains. The fine-grained alternations contain 90% or more fine and very fine grains and 1% to 20% glauconite.

An overall coarsening-upwards trend from sandy silt to silty sand begins at 427.2 ft (130.21 m) until 396.7 ft (120.91 m). Opaque heavy minerals, mica and some shell material constitute small percentages (1%-10%) of this coarsening-upward package. From 395 ft (120.40 m) to approximately 335 ft (102.11 m) there was no core recovery. Lithology of this missing interval can be inferred by calibrating the geophysical logs to lithology of existing cores. The gamma log from 395 ft (120.40 m) to approximately 380 ft (115.82 m) shows low values, and resistivity logs shows high values, indicating that the muddy fine to very fine sands persist from the lower samples. From 375 ft (114.30 m) to approximately 332 ft (101.19 m) gamma log values stay similar to values of sediments from below, although a few small value variations are observed. Geophysical logs indicate that sediments slightly coarsen-upwards, possibly with small interspersed zones of increased silt and clay.

The package from 332.9 ft (101.47 m) through 302.45 ft (92.19 m) continues to coarsen upwards from more fine and very fine sand to 40% coarse and medium sands and shell material. Shell material increases up this package from 1% at 332.9 ft (101.47m), 0% at 327.9 ft (99.94 m), 6% at 320.25 ft (97.61 m) and 11% at 302.45 ft

(92.19 m), and opaque heavy minerals contributes approximately 2% of the total throughout this package. Glauconite constitutes 5% of the sediments found in the sample at 302.45 ft (92.19 m).

The samples at 297.9 ft (90.80 m) and 292.7 ft (89.21 m) contain silty sand and clayey silt, respectively. Following these finer-grained samples, from 290.55 ft (88.56 m) to 242 ft (73.76 m) the upper part of the Calvert Formation is mostly sand with some thin beds of silt. A zone of fine sand characterizes the section beginning at 290.55 ft (88.56 m) through to 287.6 ft (87.66 m). A coarsening-upwards package begins at approximately 286.4 ft (87.29 m) through 256.25 ft (78.11 m) where medium- and coarse-grained sediments contribute 90% of the core; shell material also increases in this package from 0% to 10%. A gradual fining-upwards package defines the sediments from 247.7 ft (75.50 m) to 242 ft (73.76 m).

From 238.1 ft (72.57 m) to the top of the Calvert Formation at approximately 215 ft (65.53 m) begins as very fine sandy silt and fining upwards to chocolate brown clayey silt with very fine sand laminations. The sample located at 219 ft (66.75 m) includes mostly silt, clay and fine-grained sand with small amounts of coarse- and medium-grained material. The Calvert Formation terminates with a zone of chocolate brown clayey silt

Choptank Formation

The overlying Choptank Formation is composed of predominantly fine and medium sands with interbedded silt and clay, and thick layers of shell material are common (Figure 3.1). The formation begins at the top of the chocolate brown clayey silt at approximately 215 ft (65.53 m) until 205 ft (62.48 m) with a small zone of very shelly sand. Above this small zone from approximately 205 ft (62.48 m), sediments consist of clayey silt which then coarsens upward to silty fine-grained sand at 200 ft (60.96 m) where medium and coarse sands comprise approximately 40% of the sediments, and much of it shell fragments. Shell material drastically increases in percentage from 9% at 219.45 ft (66.89 m) to 60% at 200.95 ft (61.25 m), and glauconite increases from 1% to 10%. A change in lithology occurs from 185.5 ft (56.54 m) to 184 ft (56.08 m) from muddy sand to clayey silt with abundant bioturbation. In this transitional zone, carbonate percentages ranging from 5% to 10% and trace amounts of phosphate is observed. Capping this package is a zone of fine and very fine sand, silt and clay beginning at 184 ft (56.08 m) through approximately 180 ft (54.86 m).

At 175.8 ft (53.58 m) to approximately 150.5 ft (45.87 m) depicts a general coarsening-upward of sediments from below. The sample at 171.75 ft (52.35 m) is clayey silt containing 17% carbonate material which peaks in abundance at 66% in the sample at 165.95 ft (50.58 m). Various-sized sands with common shells continue upward until 150.5 ft (45.87 m).when sands exhibit an increase in silt and clay content. An important reddish-grey clay surface is observed at 150.5 ft (45.87 m) to 150 ft (45.72 m).

An overall fining upwards interval is observed from 150 ft (45.72 m) to the top of the Choptank at 93.1 ft (28.38 m) with two zones of shell hash at 138.5 ft (42.21 m) and 115.6 ft (35.23 m). Overlying this small finer-grained interval is a small package of medium and fine sand containing approximately 30% shell hash and small phosphate nodules at 138.5 ft (42.21 m). Silt and clay constituents again increase above the shelly sand and at 115.6 ft (35.23 m) are overlain by a zone of shell material comprising almost 50% of the sediments.

Between 112.8 ft (34.38 m) and 93.1 ft (28.38 m), the uppermost part of the Choptank Formation is muddy, very fine-grained sand with less shell material and a greater proportion of silt, clay and fine-grained sands than below. Sediments in this package have a mottled grey-tan colour and include organic layers, phosphate, pyrite cement, and plant fragments. At 95.7 feet (29.17 m), fine-grained sands with abundant silt and clay and sediments change to a lighter grey and brown colour which continues for approximately 12 more feet (3.66 m), crossing the boundary into the St. Marys Formation.

St. Marys Formation

The St. Marys Formation is composed of primarily silt, clay and very fine sand which continue throughout the formation (Figure 3.1). The formation begins at approximately 93.1 ft (28.38 m) with the first sample taken at 90 ft (27.43 m). At 93.1 ft (28.38 m) sediments are clayey silts with a small very fine sand fraction. Fine sand laminations, some with pyrite cement are observed, as are truncated burrows. A reddish-brown zone is observed at approximately 91 ft (27.74 m) until 91.2 ft (27.80 m). The medium grey-brown colouration of the sediments switch to light mottled greys and tans at approximately 90 ft (27.43 m), and this colour continues until approximately 82.9 ft (25.27 m) when sediments become a dark grey. At approximately 87.5 ft (26.67 m) a small layer of very coarse material is noted and at 86.5 ft (26.37 m) a thin, dark layer of organics is observed. Bioturbation is persistent throughout the entire St. Marys Formation. A large increase in glauconite content is observed from 5% at 90 ft (27.43 m) to 40% at 80.1 ft (24.41 m), and core logs indicate a contact from glauconitic sands at approximately 83 ft (25.30 m). At approximately 82.9 ft (25.27 m), silt, clay and very fine sand abruptly change back to a dark grey colour, and plant fragments persist. From 75.2 ft (22.92 m) to the top of the St. Marys at 50.5 ft (15.39 m) very clayey silt with very fine sand continue to dominate sediments. Glauconite abundance decreases, bioturbation and thin laminations continue.

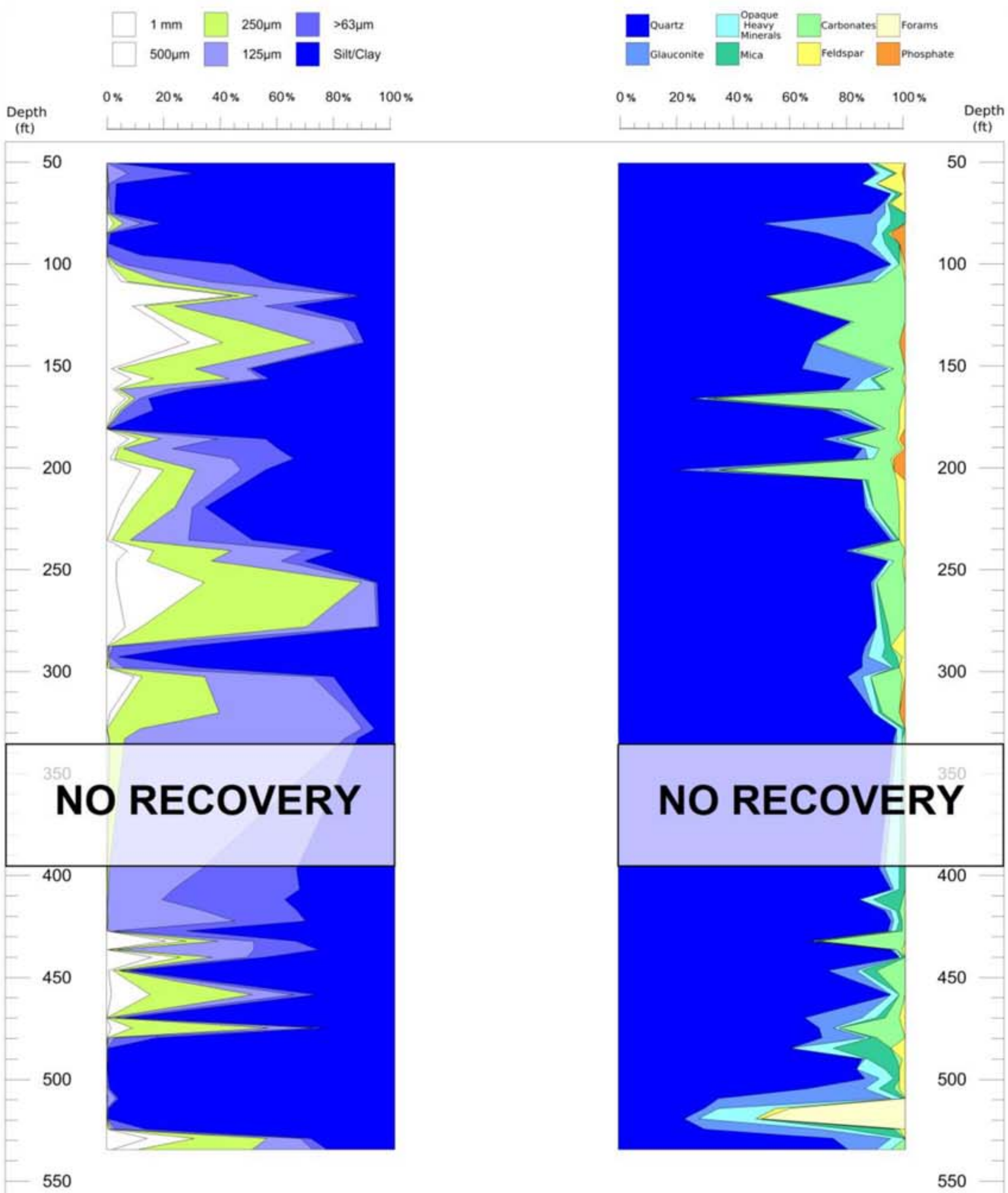

Figure 3.1: Lithology grain size and component relative abundance curves for samples from borehole Nb53-08. Depth in feet is shown on the sides and percentage is shown at the top of each curve. Grain sizes include the following: 1 mm, 500 µm, 250 µm, 125 µm, 63 µm, and silt and clay. Specific components of lithologic analysis includes: quartz, glauconite, opaque heavy minerals, mica, carbonate material, feldspar, foraminifer and phosphate.

Palynology

Raw pollen data for cores from Nb53-08 is shown in Table A.1 and the pollen diagram is shown in Figure 3.2. Pictures of thirteen representative pollen taxa are also shown in Figure A.4.

Calvert Formation

The Calvert Formation is dominated by arboreal terrestrial pollen with *Quercus* being most prevalent and exotic taxa being very common throughout the formation (Figure 3.2). The lower Calvert from 526.8 ft (160.57 m) to 447.15 ft (136.29 m) contains the highest amount of *Quercus* of the entire core with percentages nearing or exceeding 60% of the total pollen sum. The exotics Taxodiaceae-Cupressaceae-Taxaceae (TCT) and *Engelhardia* also show their highest percentages in the lower Calvert, reaching 17% and 11% respectively. Exotics *Symplocos* and *Podocarpus* contribute less than 1% each of the total pollen sum. Other taxa such as *Carya, Ilex,* Cyperaceae Type 1 (psilate) and Type 2 (scabrate)*, Nyssa, Pinus, Picea,* and *Tricolpollenites* Type 1 each constitute at least 1% to 15% percent of the total sum. Taxa with approximately 1% or less of the total pollen sum include *Alnus, Betula, Carpinus, Cornus, Corylus, Fagus, Fraxinus, Liquidambar, Podocarpus, Salix, Tilia*, *Tricolpollenites* Type 2, Type 3and Type 4, *Tsuga* and *Ulmus*.

The single middle Calvert Formation sample at 430.6 ft (131.25 m) is also dominated by *Quercus* (55%) and the exotic *Engelhardia,* which constitutes approximately 16% of the total pollen sum. The exotics TCT and *Symplocos* decrease to 0% in this sample. *Carya*, Cyperaceae Type 2, *Pinus, Picea*, and *Tricolpollenites* Type 1 all have percentages of total pollen sum ranging from 1% to 6%. *Alnus,* *Carpinus, Cornus, Corylus, Ilex, Nyssa, Podocarpus, Salix, Tilia, Tricolpollenites* Type 3, Umbelliferae and *Ulmus* all contribute less than 1% of the total pollen sum.

The upper Calvert Formation samples from 301.75 ft (91.97 m) to 225.65 ft (68.78 m), exhibits a decrease in *Quercus* abundances from the lower cores, from over 55% to percentages ranging from 25% to 45%. *Pinus* notably increases from below to 15% to 25% of total pollen sum, and *Picea* also increases to 5% to approximately 10%. The final Calvert Formation sample at 217.45 ft (66.28 m) exhibits an increase in *Quercus* to approximately 50% and a decrease in both *Pinus* and *Picea* to less than 7%. The first appearance of *Abies* is in this last sample of the formation, and contributes approximately 2% of the total pollen sum. Throughout the entire upper Calvert, TCT slightly increases to 5% to 10%, while *Engelhardia* decreases to approximately 3%, and *Symplocos* continues at 1% or less of the total pollen sum. *Carya, Cornus, Corylus, Ilex*, Cyperaceae Type 1 and 2, *Nyssa*, *Podocarpus, Tricolpollenites* Type 1, 2 and 5 and *Ulmus* all constitute percentages between 1% and 10%. Approximately 1% and less of the pollen sum is contributed by each of *Alnus*, *Betula, Fraxinus, Liquidambar, Periporopollenites, Salix, Tilia, Tricolpollenites* Type 3 and 4.

Choptank Formation

The Choptank Formation is dominated by arboreal terrestrial pollen with *Quercus* being most abundant (Figure 3.2). The Choptank Formation is represented by only one sample from the lower part of the formation at 175.20 ft (53.40 m). The upper Choptank Formation pollen assemblages are undetermined due to lack of palynomorphs in those samples. The only sample at 175.2 ft (53.40 m) exhibits a slight increase in *Quercus* from the Calvert Formation

Tricolpollenites Type 1 and *Ulmus* constitute 1% to 5% of the total percentage. *Nyssa* and *Ilex* both show slightly decreased percentages from those found in the upper Calvert Formation. *Alnus, Betula, Carpinus, Cornus, Corylus, Fagus, Fraxinus,* Cyperaceae Type 1 and 2, *Liquidambar, Podocarpus, Salix, Symplocos, Tilia*, and Umbelliferae each constitute 2% or less of the total pollen sum. Although still rare, non-arboreal pollen is more common in the Choptank Formation than in the Calvert below.

St. Marys Formation

The single sample analyzed in the St. Marys Formation at 59.85 ft (18.24 m) is dominated by arboreal pollen, with *Quercus* contributing nearly 50% of the total pollen sum (Figure 3.2). Exotic percentages drop drastically, as neither *Engelhardia* nor *Symplocos* were found in the samples and TCT constitutes less than 1% of the total sum. *Carya* shows a slight decrease to approximately 10% from the upper Choptank Formation and Cyperaceae Type 2 increases from less than 2% to almost 10%. *Tricolpollenites* Type 1 slightly increases to approximately 7% from below, and *Liquidambar* and *Ulmus* also show a slight increase to approximately 4% each. *Alnus, Carpinus, Ilex*, Cyperaceae Type 1 and *Salix* each contribute approximately 2% to the total sum, and *Betula, Fagus, Nyssa, Podocarpus, Tilia* and *Tricolpollenites* Type 2 contribute less than 1%.

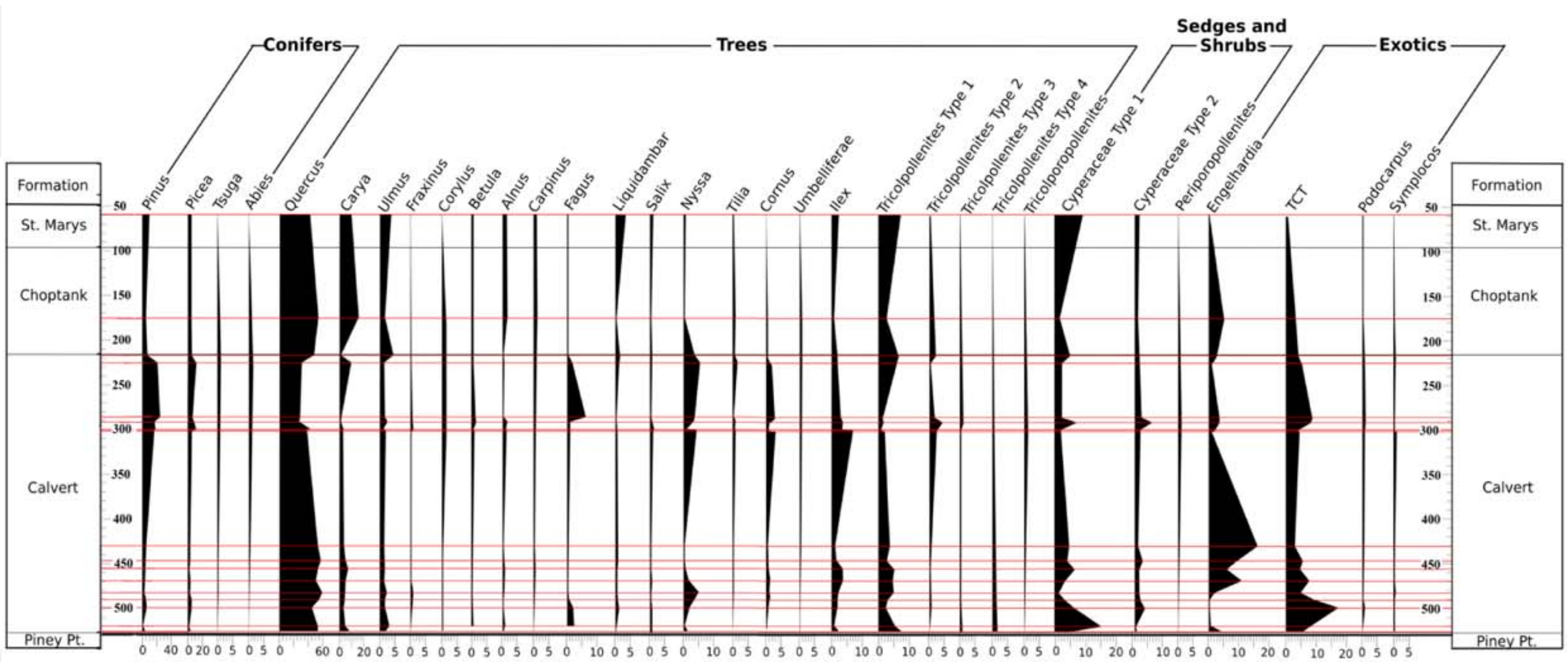

Figure 3.2: Pollen diagram for borehole Nb53-08 sediments. Diagram shows abundances of 32 taxa from the Calvert Formation through the St. Marys Formation. Diagram is based on samples which had at least 300 pollen grains which are indicated by red lines. Scale at the bottom is percentage for each taxa.

Dinoflagellates

A dinoflagellate cyst zonation for study site Nb53-08 was achieved by identification of dinoflagellate cysts in 32 samples and biostratigraphic ranges for taxa followed that of de Verteuil and Norris (1996). Occurrence data for dinoflagellate cysts is shown in Table 3.1, dinocyst zones are shown in Figure 3.3 and pictures of twelve representative dinocyst species are shown in Figure A.5

The sample at 526 ft (160.33 m) contained *Hystrichosphaeropsis obscura, Dinopterygium cladoides* and *Cordosphaeridium cantharellus*. The highest occurrences of both *D. cladoides* and *C. cantharellus* are in the top of the *Sumatradinium soucouyantiae* Zone (DN2), indicating that this sample is no higher than DN2 (de Verteuil and Norris, 1996).

Samples at 520.5 ft (158.65 m), 499.9 ft (152.37 m) and 490.9 ft (149.63 m) are designated as *S. soucouyantiae* Zone (DN2). This is based on the occurrences of *S. soucouyantiae,* which has its lowest occurrence in DN2. The sample at 490.9 ft (149.63 m) also contains *D. cladoides,* and possibly *C. cantharellus*, which both have their highest occurrences in DN2 and *Sumatradinium hamulatum* which has its lowest occurrence in the *S. soucouyantiae* Zone (de Verteuil and Norris, 1996). No informative dinocysts were found in the sample at 513.05 ft (156.38 m), but based on its position between two samples both zoned to DN2, this sample is also zoned to DN2. *Tuberculodinium* sp. was found in all four samples, and *Lejeunecysta* sp. was observed in the two lower samples and in the 490.9 ft (149.63 m) sample, although these taxa are not pertinent to the zonation. *Palaeocystodinium golzowense* was observed only in the 513.05 ft (156.38 m) sample, and *Operculodinium* *longispinigerum*, and *S. hamulatum* were both observed in the 490.9 ft (149.63 m) sample.

The sample at 483.05 ft (147.23 m) contains *C. cantharellus, Cribroperidininium tenuitabulatum* and*, D. cladoides*, which all have their highest occurrences within the *S. soucouyantiae* interval (DN2). *S. soucouyantiae*, is also found in this sample, which has its lowest occurrence in DN2 (de Verteuil and Norris, 1996).

Samples spanning from 469.65 ft (143.15 m) to 301.75 ft (91.97 m) are designated as DN2 to DN3. The sample at 469.65 ft (143.15 m) contains *S. hamulatum* placing this sample no lower than the *S. soucouyantiae* Zone and no higher than the *Cousteaudinium aubryae* Zone (DN3). Other dinocysts found but which do not provide zonation information include *Cyclopsiella elliptica/granosa, Lejeunecysta* sp., and possibly both *Pyxidiniopsis fairhavenensis* and *Lingulodinium multivirgatum.* Samples at 456.7 ft (139.20 m) and 447.15 ft (136.29 m) contained no dinoflagellates. At 444 ft (135.33 m), *S. soucouyantiae* was positively identified and a possible *S. hamulatum* was found, indicating a zonation no lower than the *S. soucouyantiae* Zone (DN2) and possibly no higher than the *Cousteaudinium aubryae* Zone designation, due to the highest occurrence of *S. hamulatum* (de Verteuil and Norris, 1996). *Lejeunecysta* sp. was also found in this sample. The following sample at 436.8 ft (133.14 m) contained no cysts. *S. soucouyantiae* is present at 430.6 ft (131.25 m), indicating a DN2 or higher zonation. *Lejeunecysta* sp. is also present in this sample. Subsequent samples at 412.75 ft (125.81 m) and 397.2 ft (120.07 m) contained no identifiable cysts. *S. hamulatum* was found in the sample at 301.75 ft (91.97 m), indicating a designation of a zonation no lower than DN2 and no higher than a DN3 designation. The following sample at 300.15 ft (91.49 m) contained no dinocysts.

Samples spanning from 292 ft (89.0 m) to 235 ft (71.63 m) are designated as the *S. soucouyantiae* Zone to the *Batiacasphaera sphaerica* Zone (DN5). The sample at 292 ft (89.0 m) contains *Distatodinium paradoxum* which suggests the sample occurs no higher than the *Distatodinium paradoxum* interval (DN4). *Systematophora placantha* is also present in this sample, which has its highest occurrence in the *Batiacasphaera sphaerica* interval zone or older (de Verteuil and Norris, 1996). A possible *Operculodinium longispinigerum* was present. The sample at 286 ft (87.17 m) contains very few identifiable cysts, none that allow it to be used for zonation. The sample at 235 ft (71.63 m) is designated as the *B. sphaerica* Zone or lower. *Apteodinium tectatum* is present in this sample which places this sample no higher than the middle of DN5 (de Verteuil and Norris, 1996). *S. soucouyantiae, P. golzowense, C. elliptica-granosa, Spiniferites solidago* and possibly *Labyrinthodinium truncatum modicum* and *Impagidinium* sp. are also found at this depth.

Taxa found at 225.65 ft (68.78 m) and 217.45 ft (66.28 m) includes *Trinovantidium papulum*, which constrains both samples to the *B. sphaerica* interval (DN5) or higher. *Palaeocystodinium golzowense, S. soucouyantiae, Lejeunecysta* sp.*, and Tuberculodinium* sp. are also all found within both samples. *C. elliptica-granosa* , *Multispinula* sp., and *Saturnidinium* sp. are also found in the sample at 217.45 ft (66.28 m).

The presence of *Habibacysta tectata* at 181.25 ft (55.25 m) designates this sample as no lower than the middle of *B. sphaerica* Zone (DN5). Other uninformative taxa found in this sample include: *Cerebrocysta poulsenii, Hystrichosphaeropsis* *obscura, Lejeunecysta* sp., *Sumatradinium druggi, S. soucouyantiae*, and *Tuberculodinium* sp.

A zonation of the *B. sphaerica* Zone to the *Cannosphaeropsis passio* (DN7) Zone is designated to the sample at 175.2 ft (53.40 m) and the sample at 109.8 ft (33.47 m). The upper limit of DN7 for these samples is based on the presence of *C. elliptica-granosa* which occurs up to and including DN7 (de Verteuil and Norris, 1996). *S. soucouyantiae* and *Lejeunecysta* sp. are also found in the sample at 175.2 ft (53.40 m). Between these two depths are samples at 167 .55ft (51.07 m), 150.4 ft (45.84 m) and 140.8 ft (42.92 m) which contained no cysts. The lower limit in the 109.8 ft (33.47 m) sample is based on the presence of *H. tectata*, which has its lowest occurrence in DN5 (de Verteuil and Norris, 1996).

The sample at 105.1 ft (32.03 m) also contained no cysts. The 95.6 ft (29.14 m) sample is zoned to the *C. passio* Zone (DN7) based on the presence of *Cannospaeropsis passio* which occurs only in DN7 (de Verteuil and Norris, 1996). The sample from 85 ft (25.91 m) contains no cysts. The sample found at 59.85 ft (18.24 m) contains *Trinovantedinium harpagonium*, *Lejeunecysta* sp.,*Tuberculodinium* sp. as well as *S. druggii* and *S. soucouyantia,* the latter two have their highest occurrence in the *Palaeocystodinium golzowense* Zone (DN8), demarcating this sample as DN8 or lower (de Verteuil and Norris, 1996). Moreover, in this sample possibly both *T. papulum,* and *Trinovantedinium ferugnomatum* were found but the identification was not positive. The final sample at 51 ft (15.54 m) contained no dinocysts.

Table 3.1: Occurrence data for dinoflagellate cysts at the Marshy Hope study site. Sample number and depth in feet are shown on the right side. The “P” represents a possible occurrence, but not a positive identification and a “X” represents a positive identification.

Sample	Depth	*Apteodinium tectatum*	*Cannosphaeropsis passio*	*Cerebrocysta poulsenii*	*Cordosphaeridium cantharellus*	*Cribroperidininium tenuitabulatum*	*Cyclopsiella elliptica/granosa*	*Dinopterygium cladoides*	*Distatodinium paradoxum*	*Habibacysta tectata*	*Hystrichosphaeropsis obscura*	*Impagidinium sp.*	*Labyrinthodinium t. modicum*	*Labyrinthodinium truncatum*	*Lejeunecysta sp.*	*Lingulodinium multivirgatum*	*Multispinula sp.*	*Operculodinium longispinigerum*	*Palaeocystodinium golzowense*	*Pyxidiniopsis fairhavenensis*	*Round Brown*	*Saturnidinium sp.*	*Spiniferites solidago*	*Sumatradinium druggi*	*Sumatradinium hamulatum*	*Sumatradinium soucouyantiae*	*Systematophora placantha*	*Trinovantedinium ferugnomatum*	*Trinovantedinium harpagonium*	*Trinovantedinium papulum*	*Tuberculodinium sp.*
105573-4.85	59.85														X									X		X		P	X	P	X
105577-1.6	95.6		X												X								X						X		
105579-4.8	109.8						X			X																					
105585-5.2	175.2						X								X											X					X
105586-1.25	181.25			X						X	X			P	X									X		X					X
105590-2.45	217.45						X								X		X		X		X	X				X				X	X
105591-0.65	225.65														X				X		X					X				X	X
105592-0	235	X					X					P	P						X				X			X					
105600-2.0	292								X									P									X				
105602-1.75	301.75														X										X						
105622-5.60	430.6														X											X					
105624-4.15	444.15														X						X				P	X					
105627-4.65	469.65						X								X	P				P	X				X						
105628-8.05	483.05				X	X		X											X		X					X					X
105629-5.90	490.9				P			X							X			X			X				X	X					X
105630-4.90	499.9																									X					X
105631-8.05	513.05														X				X		X										X
105632-5.5	520.5														X						X					X					X
105633-1.8	526.8				X			X			X																				

X: Present

P: Possible

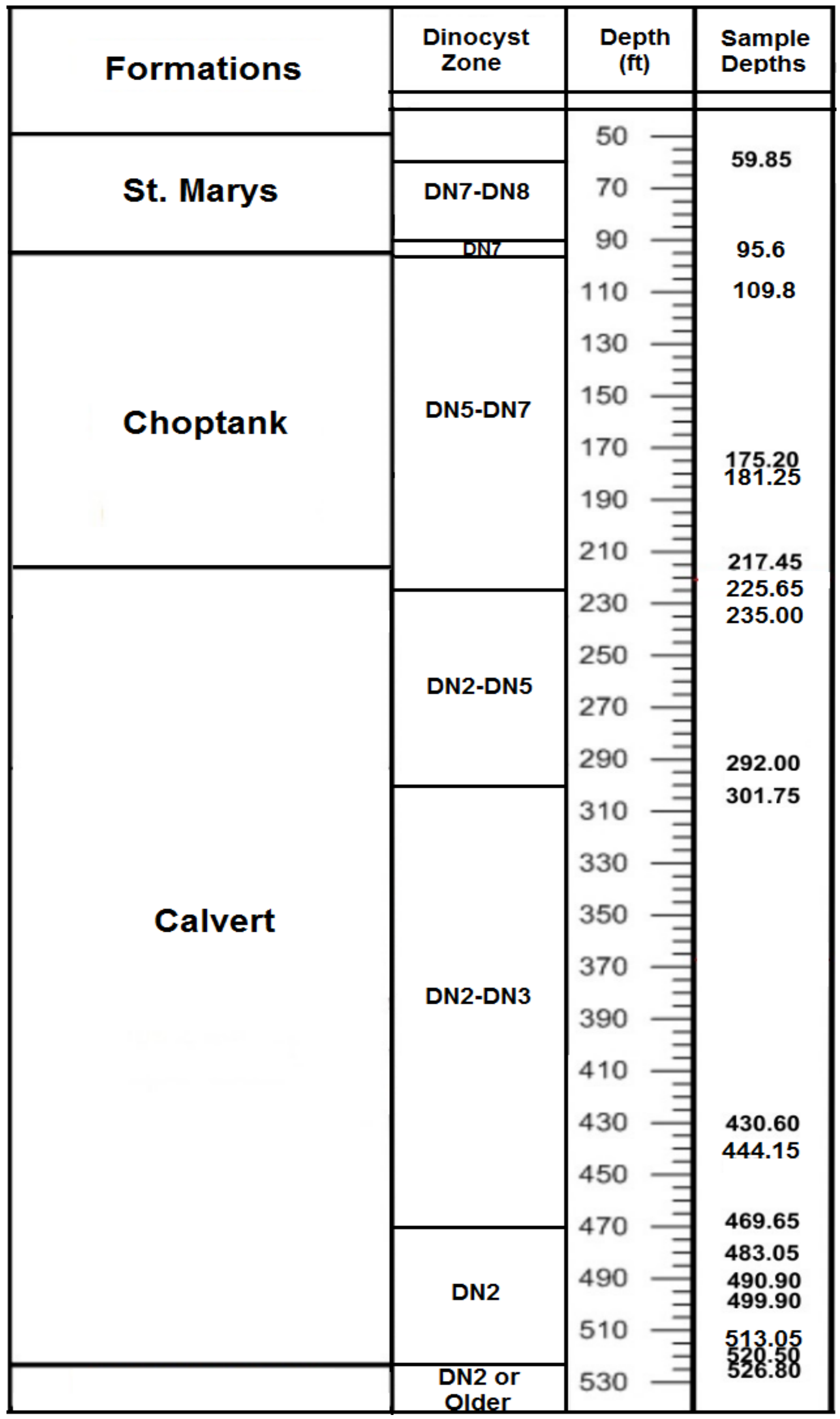

Figure 3.3: Dinoflagellate cyst zonation for core Nb53-08. Depth in feet and depth of samples are on the right, dinocyst zonation and formations are on the left.

Cluster Analysis

Stratigraphically constrained average linkage cluster analysis was performed to create a palynomorph zonation by clustering samples based on taxa. Three major clusters define the zonation (Figure 3.4) and can be superimposed on the pollen diagram (Figure 3.5) to show relative pollen abundances that characterize these zones.

Zone 3 encompasses the lower nine samples all from the Calvert Formation beginning at 526.8 ft (160.57 m) and ending at 430.60 ft (131.25 m). Zone 3 includes the highest amounts of exotics such as *Engelhardia*, and TCT. Cyperaceae Type 2, *Carya, Tricolpollenites* Type 1, *Tricolpollenite*s Type 4 and *Nyssa* also exhibit relatively high numbers in this zone. The upper part of Zone 3 contains more *Engelhardia* than the lowest part of Zone 3, whereas the lower part of Zone 3 contains more TCT than the upper part. A possible upper *Engelhardia* subzone and lower TCT subzone could be informally applied to Zone 3.

Upper Calvert Formation samples beginning at 301.75 ft (91.97 m) to 225.65 ft (68.78 m) comprise Zone 2. This zone exhibits more abundant *Pinus* and *Picea* than in Zone 3. *Carya* shows similar numbers to Zone 3, and the exotics *Engelhardia* and TCT show a slight decrease. *Ilex*, CyperaceaeType 1, *Nyssa, Tricolpollenites* Type 2, and *Fagus* numbers increase from Zone 3.

Zone 1 encompasses the uppermost Calvert sample at 217.45 ft (66.28 m), the single Choptank Formation sample at 175.2 ft (53.40 m), and the single St. Marys Formation sample at 59.85 ft (18.24 m). Zone 1 is dominated by *Quercus* and relatively high amounts of *Carya* and *Tricolpollenites* Type 1, *Liquidambar, Ulmus* and *Alnus*. Moderate amounts of *Picea, Pinus*, and *Engelhardia* are present and exotics TCT and *Podocarpus* are present in very low numbers, if present at all.

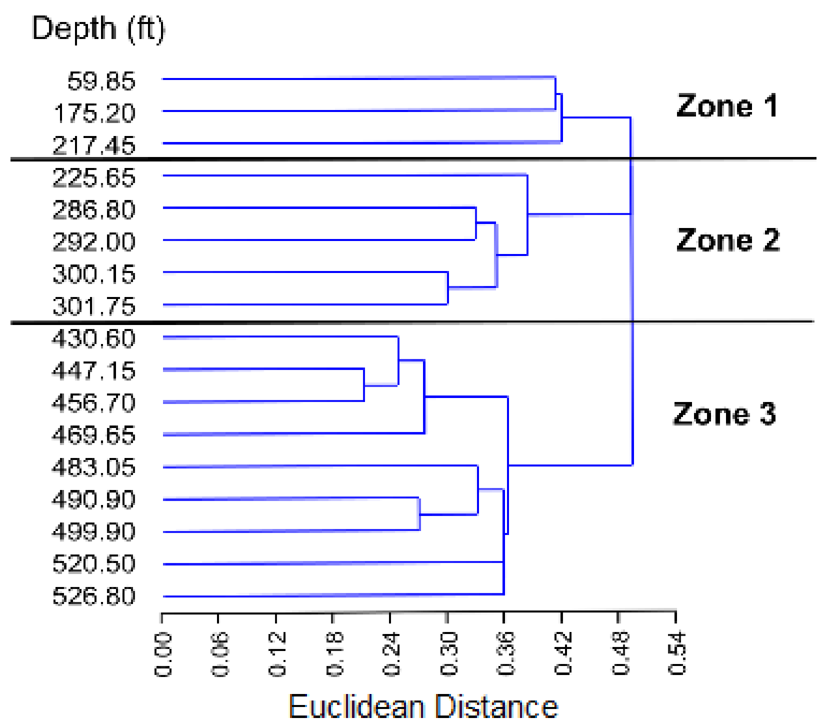

Figure 3.4: Results of stratigraphically constrained cluster analysis of pollen taxa within samples. Distance refers to Euclidean similarity distance.

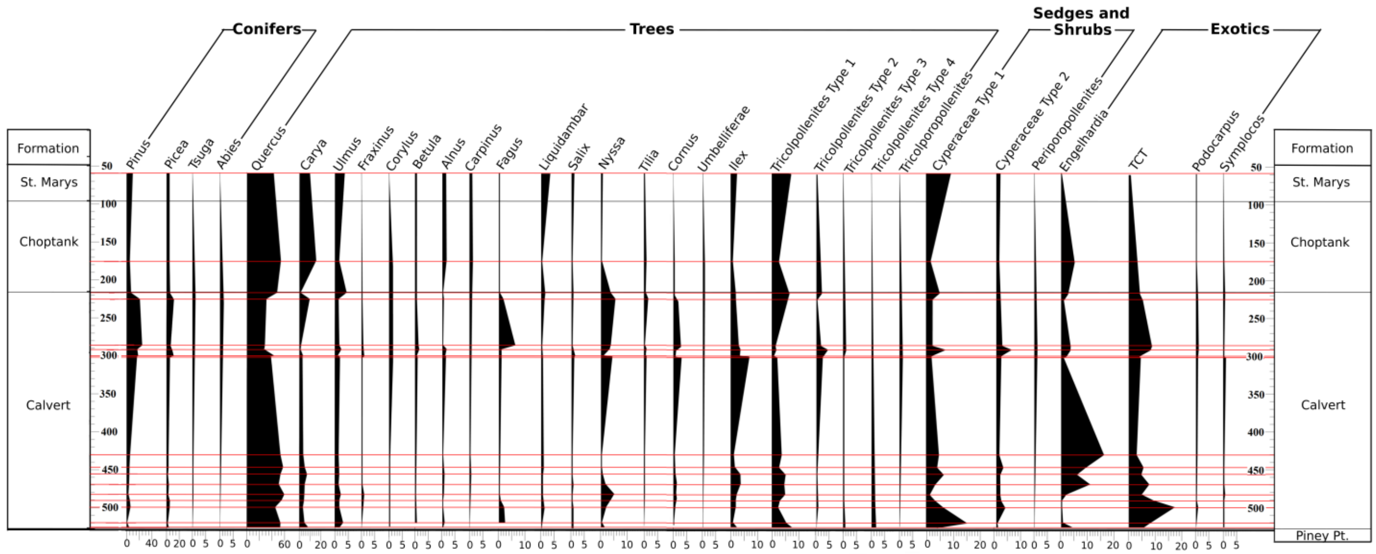

Figure 3.5: Stratigraphic pollen diagram for Nb53-08 with cluster analysis zonation. Cluster analysis is based on 32 taxa which met the predetermined criteria of contributing at least 1% of total pollen percentage for at least one sample. Blue dashed line indicates zone boundary.

Chapter 4

DISCUSSION AND INTERPRETATION

Discussion and interpretation of results encompass three sections. Depositional environments and sequence stratigraphy are discussed based on lithologic analysis results combined with gamma ray and resistivity logs (Figure 4.1). Paleoenvironmental interpretations are discussed based on pollen counts. Finally, correlation to the Bethany Beach site is based on correlation of pollen zones defined by cluster analysis (Figure 4.2), dinoflagellate cyst zonation, and sequence stratigraphy of the Nb53-08 core (Figure 4.3).

Depositional Environments

Sedimentary facies at Marshy Hope are composed predominantly of quartz sands and silts with common carbonate shell material that suggests a shallow-marine, wave-dominated shoreline environment. As with the studies done by Miller et al. (2003) and McLaughlin et al. (2008), depositional environments are interpreted from lithofacies and geophysical logs, and environments follow the wave-dominated shoreline facies model used by Miller et al. (2003) and McLaughlin et al. (2008) (Figure 1.4). Interpretation of depositional environments from lithofacies Figure 4.1 depicts the relative location of depositional environments throughout the Marshy Hope cores. The first two samples taken from core NB53-08 belong to the Piney Point Formation from the Eocene. These sediments consist mostly of medium/coarse sand and some shell fragments, which indicate a proximal upper shoreface environment.

The Calvert Formation sediments begin at approximately 527.3 ft (160.72 m), which is a major contact between the Piney Point sands below and the Calvert silts and clays above. Depositional environments throughout this formation are interpreted the same way as the Bethany Beach interpretations. Unit 1 encompasses sediments from 527.3 ft (160.72 m) through to 431.6 ft (131.55 m) and is a package of generally coarsening-upward, slightly sandy silt and clay with interspersed zones of medium- and coarse-grained sands. The lower samples of this package, from 527.3 ft (160.72 m) to 479.6 ft (146.18 m) are predominantly silt and clay (more than 85%) with low percentages of shell material, but high amounts of glauconite, opaque heavy minerals, mica and foraminifera dispersed throughout. Glauconite shows peak abundances of 40% at 524.35 ft (159.82 m), 60% at 509.35 ft (155.25 m) and 20% 504.45 ft (153.76 m), and foraminifera contributes 40% and 50% of the fine- and very fine-grained sands at 519.25 ft (158.27 m) and 514.25 ft (156.74 m) respectively. On geophysical logs, high gamma values and low resistance values throughout this lower package are suggestive of an offshore environment.

Above 479.6 ft (146.18 m) and until 431.6 ft (131.55 m) the upper part of unit 1 becomes much sandier than below with alternating horizons of muddy fine- and medium-grained quartz sands with zones of slightly sandy silt and clay. The muddy sand zones at 474.8 ft (144.72 m), 458.5 ft (139.75 m), 440 ft (134.11 m), 436.3 ft (132.98 m) and 432.2 ft (131.73 m) include shell percentages ranging from 10 to 30%. The slightly sandy silt zones, depicted by samples at 469.8 ft (143.20 m) and 446.55 ft (136.11 m), include glauconite content ranges from 10 to 20% and exhibit frequent bioturbation. Miller et al. (2003) also recognized these alternating zones of coarse- and fine-grained sediments in the Bethany Beach cores, and is suggestive of a shoaling upwards from offshore and lower shoreface environments to upper shoreface environments at both study sites.

Unit 2 is an overall coarsening-upwards trend which begins at 431.6 ft (131.55 m) through 302.1 ft (92.08 m). This unit is predominantly fine and very fine sands with thin laminations of silt. Resistivity log values are low in the lower part of the unit, but exhibit a slight increase moving upward, whereas gamma values show a slight decrease moving up the lower part of the unit. This is suggestive of an offshore or lower shoreface depositional environment (McLaughlin et al., 2008). Although very little core was recovered from approximately 396 ft (120.70 m) to approximately 336 ft (102.41 m), lithologies can be inferred from the geophysical logs. The gamma value shows a steady low value up through the missing section, whereas resistivity logs show a steady increase in value, indicating that lithology is getting slightly sandier up the borehole. This could possibly indicate a shoaling upwards from the lower shoreface environment of below to a distal upper shoreface environment.

Sediments at 332.9 ft (101.19 m) and 327.9 ft (99.94 m) are mostly fine-grained sands with siltier laminations, as below, but with a higher percentage of fine and medium clean sands. Moreover, gamma values increase and resistivity values decrease from the lower part of unit 2. At 320 ft (97.54 m), sediments continue to coarsen with fine and medium sands constituting over 75% of sediments. Shell material increases from 0% to almost 6% and a small amount of phosphate is observed. Resistivity values continue to slightly increase until approximately 312 ft (95.10 m), where is exhibits a sharp drop in value. Likewise, gamma log value begins to increase at the same depth. Curiously, the sample at 302.1 ft (92.08 m) is characterized by an increase in coarse-grained sands, shell material, as well as silt and clay from below; medium- and fine-grained sands decrease in abundance. This section is interpreted as a transition from distal upper shoreface to a proximal upper shoreface environment.

Unit 3 is a 10 ft (3.05 m) zone of interbedded fine and very fine sand and clayey silt beginning at 302.1 ft (92.08 m) which coarsens upwards to approximately 242 ft (73.76 m). The base of the unit begins with a small package of interbedded silty, very fine sand with sandy silt from 302.1 ft (92.08 m) until approximately 286.4 ft (87.29 m). Low resistivity value and relatively high gamma values from below coupled with changes in lithology suggests an offshore or lower shoreface depositional environment, consistent with similar lithofacies and log patterns at Bethany Beach by McLaughlin et al. (2008).

At approximately 286.4 ft (87.29 m), a sharp contact exists between the interbedded zone of clayey silt with silty sand below and the poorly sorted, fine to coarse sands above. The sediment sample at 278 ft (84.73 m) consists of fine and medium sands with an increase in shell material from absent to almost 6%. Lithologies and low gamma log values coupled with high resistivity values of this section of unit 3 suggests a proximal upper shoreface or foreshore depositional environment.

At approximately 247.7 ft (75.50 m) the coarse sands fine slightly to fine and medium sands. This fining-upwards is reflected in the sample at 245.6 ft (74.86 m) which contains approximately 30% silt and clay, compared to the 6% silt and clay of the sample at 256.25 ft (78.10 m). In this zone of finer, siltier sand, shell material decreases to 3% from 10%. Resistivity values show a marked decrease from below and gamma values show a slight increase, both until approximately 242 ft (73.76 m). Depositional environment of this last section of unit 3 suggest a continuation of the upper shoreface or foreshore of below. A sharp contact exists at 242 ft (73.76 m) between the very shelly, silty sand of unit 3and the overlying silty, clayey sand of unit 4.

Unit 4 is a generally coarsening-upward package of very fine sandy silt coarsening to silty sand beginning at approximately 242 ft (73.76 m) near the top of the Calvert Formation up to approximately 184 ft (56.08 m) into the Choptank Formation. The base of this package at 242 ft (73.76 m) until approximately 238.1 ft (72.57 m) is a zone of silty, clayey sand which overlies the shelly sand of unit 3. Continuing up-core, sediments turn from silty sand at 240.5 ft (73.30 m) to sandy silt at 235.4 ft (71.75 m) to clayey silt by approximately 226 ft (68.88 m). Sediment samples at 240.5 ft (73.30 m) and 235.4 ft (71.75 m) exhibit a shell content of 17% and 3%, respectively and glauconite percentage of both is a low 1% to 2%. Geophysical logs in the lower part of unit 4 indicate siltier lithologies with high gamma values and low resistivity values, which is suggestive of an offshore or lower shoreface depositional environment. The top of the clayey brown silt at approximately 215 ft (65.53 m) is the approximate Calvert-Choptank boundary, which is consistent with the Calvert/Choptank boundary at Bethany Beach site as determined by McLaughlin et al. (2016) and as defined by Ramsey (1997).

The upper part of unit 4 from approximately 213 ft (64.92 m) to 184 ft (56.08 m) coarsens upward from sediments below, exhibiting an increase in fine and medium sands and carbonate percentage. A marked change in geophysical logs at approximately 215 ft (65.53 m) to 205 ft (62.48 m) indicates a general coarsening from fine- and very fine-grained silt and clay to silty medium to fine sands. From approximately 205 ft (62.48 m) to 200 ft (60.96 m) sediments consist of clayey silt which then coarsens upward to silty fine-grained sand at 200 ft (60.96 m) until approximately 185.5 ft (56.54 m). Sediment samples at 205.9 ft 62.76 m) and 200.95 ft (61. 25 m) exhibit carbonate percentages of 10% and 60% respectively. Sediment lithologies, shell material percentage and geophysical log values indicate a transition from upper to offshore, followed by another shallowing upwards package from 200 ft (60.96 m) to approximately 185.5 ft (56.54 m).

Unit 5 spans from 184 ft (56.08 m) until 150 ft (45.72 m) as a coarsening-upward package of finer sands, silts and clay. The base of the unit begins with a burrowed surface at 184 ft (56.08 m). Above this small bioturbated surface and until approximately 171 ft (52.12 m) lies a zone of clayey silt, substantiated by geophysical log values and interpreted as a lower shoreface or offshore depositional environment.

At approximately 171 ft (52.12 m) fine- and medium-grained sand increases, as does carbonate content, and silt and clay decreases moving up the unit. Geophysical logs reflect this change in lithology to sandier sediments, as gamma values decrease and resistivity values increase until the top of the unit. This is indicative of an environmental change from offshore to lower shoreface. The sediment sample from 165.95 ft (50.58 m) exhibits a strong increase in shell material to 66% from 17% at 171.75 ft (52.35 m), suggesting a proximal upper shoreface depositional environment. Moving up the unit from 165.95 (50.58 m) to approximately 150.55 ft (45.89 m), the sand gets more heavily bioturbated and shell content decreases to 10% or less. The top of unit 5 at 150.55 ft (45.89 m) to approximately 150 ft (45.72 m) is a thin layer of reddish silty clay. This reddish colouration of the clay is suggestive of a subaerially weathered estuary or marsh clay (McLaughlin personal communication, January 12, 2016), suggesting a backshore to marsh or estuarine depositional environment.

Unit 6 begins at approximately 150 ft (45.72 m) and ends at the upper limit of the Choptank Formation at 93.1 ft (28.38 m). Interestingly, geophysical logs depict a steady fining-upwards of unit 6 beginning at approximately 150 ft (45.72 m), which is reflected in the sediment analysis. Beginning above this small zone of clay at approximately 150 ft (45.72 m) is a zone of slightly muddy medium- and coarse-grained sands with abundant shell hash (10-50%) and sparse bone fragments until approximately 120.1 ft (36.61 m). At this depth, a sharp contact of weathered shell material meets an approximately 1-ft (0.30 m) zone of very fine silty sand with sparse shell material. No laminations or bioturbation are noted in this finer zone. This succession of shelly sand overlain by silty, very fine sands with weathered shell at the contact can be interpreted as an upper shoreface to foreshore depositional environment followed by a short interval of marine regression, resulting in exposure and non-deposition of the shell material. Subsequently, a short marine transgression would bring in the silty, very fine sand observed about the weathered carbonate material.

Above this zone, at approximately 119.1 ft (36.30 m), unit 6 exhibits another large shell hash zone of a proximal upper shoreface/foreshore environment which continues until approximately 113 ft (34.44 m). Following this shell hash, sediments turn to silty fine sand and although shell fragments are still present, they contribute only approximately 10%. A small amount of pyrite is found in the sample at 108.6 ft (33.10 m) and glauconite constitutes 10% of sediments. The lithology continues to fine-upwards to very fine, siltier sand and exhibits fine laminations, bioturbation, pyrite cement and very sparse plant matter until the end of the unit at 93.1 ft (28.38 m). Sediment colour at approximately 95 ft (28.96 m) changes abruptly from a medium to dark grey to a very light grey mottled with tan and dark grey, which carries into unit 7 of the St. Marys Formation. All elements of this upper part of the unit imply a backshore to estuary or marsh depositional environment.

Unit 7 comprises approximately 40 ft (12.19 m) of the St. Marys Formation from 93.1 ft (28.38 m) to 50.5 ft (15.39 m). Geophysical logs of this unit indicate abundant clay at the bottom of the unit which slightly coarsens upward in the middle, followed by a very slight fining upwards to the top of the unit. The lower part of the unit begins at the Choptank/St.Marys Formation boundary at 93.1 ft (28.38 m). Sediments below this boundary are silty dark grey sands overlain by light grey and tan mottled clayey silt above. At 91 ft (27.74 m) to approximately 91.2 ft (27.80 m) a small layer of reddish-brown clay is observed, suggesting subaerially exposed shallow-marine clay. Abundant bioturbation, which seems to increase up the lower part of the unit, scattered plant debris and infrequent laminations, phosphate fragments and woody debris are all found throughout this unit. This lower unit suggests an estuarine or marsh depositional environment.

The upper part of unit 7 begins at approximately 82.9 ft (25.27 m) where the light mottled grey and tan clayey silt of the lower part of the unit meets the darker grey, glauconite-rich sediments of the upper part of the unit. This darker clayey silt colour persists until approximately 60 ft (18.29 m) where it turns to a mottled light and dark grey colour before changing back to the mottled light grey and tan colour at approximately 55 ft (16.76 m). An increase in glauconite percentage is observed at two samples from 85 ft (25.91 m) and 80.1 ft (24.41 m) to 20% and 40% respectively and the highest abundance is noted on the core logs as being at approximately 83 ft (25.30 m). Glauconite increase coupled with a change in sediment colour to darker marine muds indicates a marine transgression and an offshore to lower shoreface depositional environment.

From 75.2 ft (22.92 m) to 50.5 ft (15.39 m) very clayey silt with very fine sand to dominate sediments. Gamma log values depict a slight fining upwards in this last St. Marys section. At 70.7 ft (21.55 m) until approximately 75 ft (22.92 m) is a zone of scattered horizontal burrows and plant fragments. Another zone of heavy bioturbation is found from approximately 55 ft (16.76 m) to 58.5 ft (17.83 m), which also includes small bones, plant debris and woody fragments. Scattered bioturbation, thin laminations and sparse plant fragments characterize the rest of the section from 55 ft (16.76 m) to 50.5 ft (15.39 m). This last section is interpreted as a change in environments from offshore or lower shoreface to estuarine or marsh.

Shallowing-upward facies sequences are the most common type of shallow-marine deposits and exceptions are rare (Goodwin and Anderson, 1985). At this site, the Calvert-Choptank Formation sequences exhibit mostly disconformity-bound, upward-shallowing records of transgressive-regressive cycles; however, the lower St. Marys sequences exhibit no shallowing-upward regressive beds in this lower part. Kidwell (1988) found deepening-upward paralic sequences within the St. Marys Formation at the Calvert Cliffs location in Maryland. These shaved sequences consist of mostly shell-poor laminated to massive sandy silt and clay facies that normally deepen upward. Sequence boundaries, called stranding surfaces, are abrupt shallowing of facies characterized by burrowed firmgrounds with abundant carbonized wood (Kidwell, 1988; 1997). These rare, hemicyclic sequences can be referred to as estuarine due to the presumed coastal plain submergence (Kidwell, 1988).

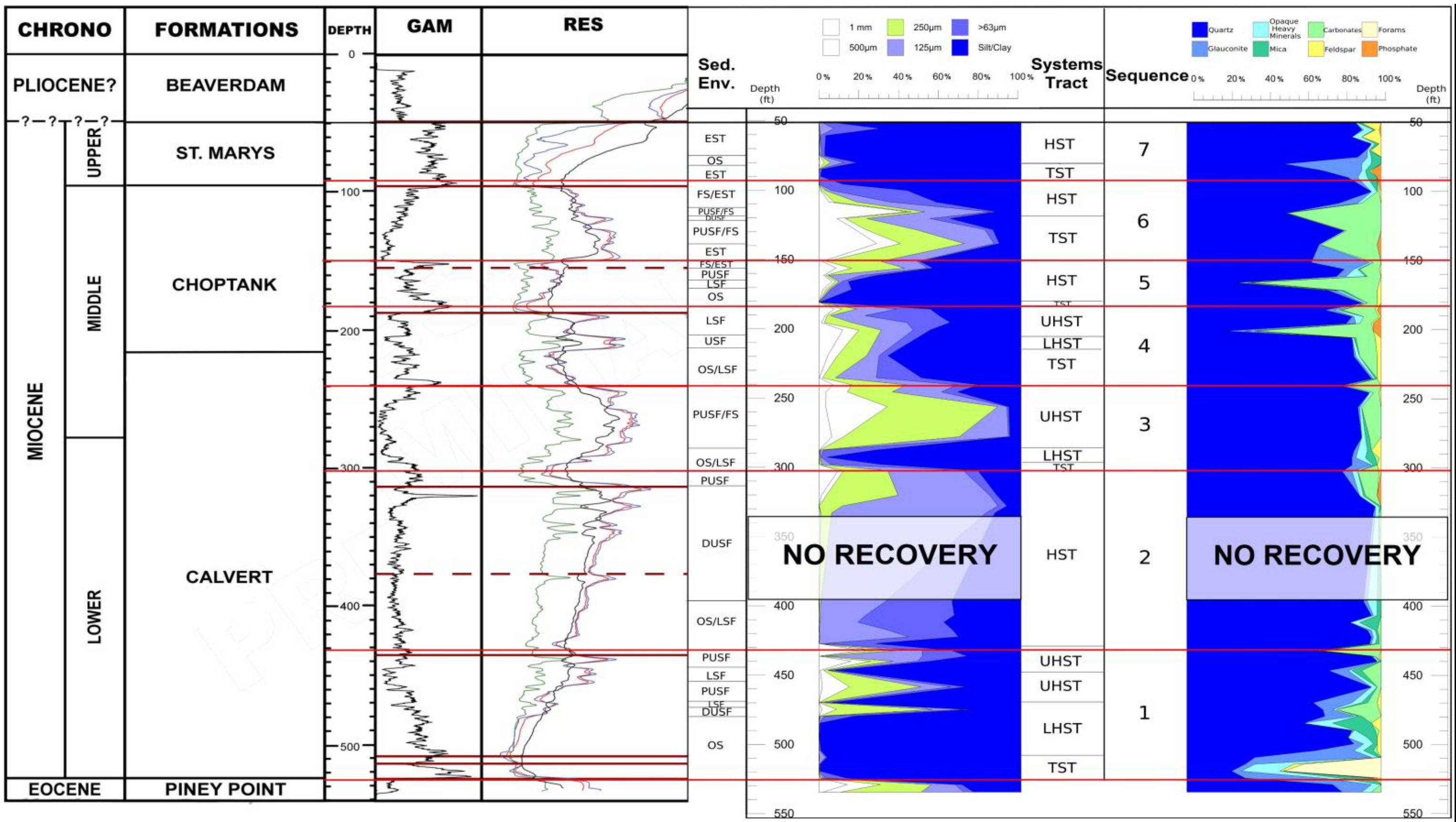

Figure 4.1: Depositional environments, systems tracts and sequences for the Nb53-08 borehole. Sedimentary environments include: OS- offshore; LSF- lower shoreface; DUSF- distal upper shoreface; PUSF- proximal upper shoreface; FS- foreshore; EST- estuary. Systems tracts include: TST- transgressive systems tract; HST- highstand systems tract; LHST- lower highstand systems tract; UHST- upper highstand systems tract.

Sequence Stratigraphy Interpretation

Sequence stratigraphy is the study of the effects of eustasy and tectonics on accommodation space coupled with sediment supply to control the formation of stratal surfaces (Browning et al., 2006; Coe et al., 2005). Previous studies by McLaughlin et al. (2008) and Miller et al. (2003) classified and interpreted the sequence stratigraphy of the Qj32-27 borehole at Bethany Beach, Delaware, which provide a good framework for the classification and interpretation of sediments at the Marshy Hope study area. Depositional environments inferred from lithologic descriptions of sediments found in core Nb53-08 follow the wave-dominated shoreline facies model put forth by Bernard et al. (1962), Harms et al. (1975; 1982) and McCubbin (1981). Sequence stratigraphic analysis was conducted based on the lithologic descriptions, core logs, grain size relative abundance curve, component relative abundance curve, and gamma ray and resistivity logs and results are shown in Figure 4.1.

Sequence 1 [527.3 ft (160.72 m) - 431.6 ft (131.55 m); Figure 4.1]. The TS/SB (transgressive surface/sequence boundary) of the first sequence is a major unconformity where silty offshore sediments overlie the coarser-grained sediments of the Piney Point Formation. The TST (transgressive systems tract) [527.3 ft (160.72 m)-508.2 ft (154.90 m)] coarsens upward from clayey silt to very sandy silt with vague laminations and scattered bioturbation until approximately 512.1 ft (156.09 m). A transitional contact is observed at 512.1 ft (156.09 m) and sediments return to clayey silt with heavy bioturbation until 508.5 ft (154.99 m). The MFS (maximum flooding surface) is located at a major burrowed surface with clayey silt at 508.5 ft (154.99 m) until 508.2 ft (154.90 m). The HST (highstand systems tract) [508.2 ft (154.90 m)- 431.6 ft (131.55 m)] begins with 1.7 ft (0.52 m) of fine-grained sand with a large amount of glauconite, corresponding to higher gamma values. The following sediments in the HST are divided into three parasequences, each separated by two marine flooding surfaces located at 473.7 ft (144.38 m) and approximately 448 ft (136.55 m). These parasequences form a general coarsening-upwards package from clayey silt to sandy silt to muddy, shelly sand. The SB is located at 431.6 ft (131.55 m) where upper shoreface sands are overlain by a sharp planar contact of offshore silts.

Sequence 2 [431.6 ft (131.55 m)-302.1 ft (92.08 m); Figure 4.1]. The extremely thin TST [431.6 ft (131.55 m)-430.2 ft (131.12 m)] is a zone of silt with rare very fine sand with bioturbation and thin laminations. A slight decrease in resistivity values marks the MFS, which occurs at 430.2 ft (131.12 m). The HST [430.2 ft (131.12 m)-302.1 ft (92.08 m)] is a coarsening-upward package beginning with lower shoreface very fine, silty sand transitioning to the medium shelly sand of a proximal upper shoreface. This package is capped by the clayey silt of the TS/SB of Sequence 3.

Sequence 3 [302.1 ft (92.08 m)-242 ft (73.76 m); Figure 4.1]. The TS/SB of Sequence 3 is clayey silt marked by a gamma increase where lower shoreface sediments overlie proximal upper shoreface sands. The thin TST [302.1 ft (92.08 m)-297 ft (90.53 m)] fines from silty, very fine sand to sandy silt. The MFS occurs at 297 ft (90.53 m) at a peak in glauconite within the silt, clay and very fine sand. The HST is separated into two packages: the siltier, lower HST from 297 ft (90.53 m) to 286.4 ft (87.29 m) and the upper HST at 286 ft (87.29 m) to 242 ft (73.76 m) composed of medium-grained sands.

Sequence 4 [242 ft (73.76 m)-184 ft (56.08 m); Figure 4.1]. The TS/SB is sandy silt offshore sediments with sparse bioturbation marked by a gamma log increase. The TST from 242 ft (73.76 m) to approximately 215 ft (65.53 m) is mostly inferred, as a large gap in core records exists through this depth. This section exhibits a slight deepening of sediments from sandy silt to clayey silt in an offshore environment, and a slight increase in carbonates is also observed. This slight deepening culminates at the MFS with the highest abundance of silt and clay and a peak in gamma values. The HST is divided into two parasequences separated by a marine flooding surface at 205ft (62.48 m). The lower HST [215 ft (65.53 m)-205 ft (62.48 m)] is characterized by very shelly sands of an upper shoreface environment which is capped by a marine flooding surface. The upper HST [205 ft (62.48 m)-184 ft (56.08 m)] begins as clayey silt with very fine sands containing large diameter shells, which then coarsens upward to silty sand with shell fragments and slight bioturbation.

Sequence 5 [184 ft (56.08 m)-150 ft (45.72 m); Figure 4.1]. The TS/SB caps Sequence 4 with the shelly, clayey silt sediments of a lower shoreface environment. The TST [184 ft (56.08 m)-180 ft (54.86 m)] is a package of offshore sediments composed of very clayey silt with faint laminations and sparse shell fragments. This tract is capped by the MFS at 180 ft (54.86 m) which occurs at a gamma log peak among the clayey silt. The HST [180 ft (54.86 m)-150 ft (45.72 m)] coarsens upward from lower shoreface to distal upper shoreface and proximal upper shoreface. At 150.55 ft (45.89 m) to 150 ft (45.72 m) is a small zone of reddish silty clay which is indicative of the oxidation and weathering of a paleosol at the top of sequence 5. Sediments in HST transition from clayey silt to sandy silt to shelly sand.

Sequence 6 [150ft (45.72 m)-93.1 ft (28.38 m); Figure 4.1]. The TST [150 ft (47.72 m)-119.1 ft (36.30 m)] begins with muddy fine and medium sand and carbonate material which increasing up the sequence. The TST culminates at a sharp contact between a very shelly bed with weathered shell below and very fine silty sands with smaller shell fragments above. This cap of very fine silty sand represents the MFS at 119.1 ft (36.30 m). The following HST [119.1 ft (36.30 m)-93.1 ft (28.38 m)] is a package of shelly variably sized upper shoreface sands which crosses the Choptank-St. Marys boundary at 93.1 ft (28.38 m). The HST begins as a bed of shell hash with a fine sand matrix until approximately 115 ft (35.05 m) when sediments fine upwards to fine silty sand and very fine silty sand until 93.1 ft (28.38 m). Fine laminations, plant matter, smaller shell fragments, variable bioturbation as well as a colour change from medium/dark grey to light grey and tan is found in this systems tract. Depositional environments transition from upper shoreface to estuarine.

Sequence 7 [93.1 ft (28.38 m)-50.5 ft (15.39 m); Figure 4.1] is a shaved sequence which shows a progression from light coloured estuarine or marsh sediments in the lower part, to glauconitic marine clays in the middle, and back to estuarine or marsh clays at the top. The SB [93.1 ft (28.38 m)] is marked by a large increase in gamma–log value and change in colouration from the dark grey silty sands of sequence 6 below to the mottled light grey clayey silt of above. The TST [93.1 ft (28.38 m) to 82.9 ft (25.27 m)] exhibits a fining-upwards from silty, very fine sand to clayey silt. At approximately 91 ft (27.74 m) to approximately 91.2 ft (27.80 m) a layer of reddish-brown clay is observed, suggesting shallow-marine clays which have been weathered in an estuarine or marsh environment. The MFS [82.9 ft (25.27 m)] exhibits a large increase in glauconite content and a sudden transition back to dark grey offshore muds. Sediments are mostly dark grey offshore marine muds containing irregular laminations, bioturbation and feldspar content which increases up core, and infrequent scattered plant fragments. The HST [82.9 ft (25.27 m)-50.5 ft (15.39 m)] is marked by a slight decrease in gamma log values, and the darker clayey silt colour beginning at the MFS persists until approximately 75 ft (22.86 m) where it turns to a mottled light and dark grey colour, indicating a change back to an estuarine or marsh environment. At approximately 55 ft (16.76 m) and until the end of the sequence at 50.5 ft (15.39 m) sediments change back to the mottled light grey and tan colour.

Paleoenvironmental Interpretation

The global climate history of the Miocene involved an initial warming followed by a global cooling event which resulted in the expansion and contraction of vegetation ranges (Davis, 1983). In North America, tectonic changes and the creation and evolution of orogenic belts resulted in climatic changes which led to changes in the abundance and distribution of vegetation taxa (Davis, 1983). Although there is a delayed response, vegetation taxa abundance reacts strongly to changes in regional temperature and general climate assumptions can be made based on the pollen assemblages (Faegri and Iversen, 1989; Traverse, 2008). The use of modern analogs involves relating a fossil pollen assemblage to the most morphologically similar modern species, which can help determine ecology and distribution of the fossil taxa (Graham, 1999). A paleoenvironmental reconstruction of the Marshy Hope site is inferred from the results of the pollen analysis and cluster analysis. The pollen taxa found at Marshy Hope reflect the vegetation of an area of unknown size, although the majority of pollen represents the immediate coastal area region (Groot, 1992).

Calvert Formation

The Miocene thermal optimum occurred in the early Miocene, at approximately 21 Ma until 15 Ma, and saw relatively high temperatures compared to the Middle or Late Miocene (Graham, 1999). On the basis of modern analogs, pollen analysis of the Calvert Formation assemblages suggests that the Calvert sediments were deposited in a moist, warm-temperate to subtropical climate.

The Calvert Formation is represented by 15 samples, spanning the entire formation, giving a good representation of pollen assemblages. Exotics which are rarely, if at all, found in Delaware - *Symplocos, Engelhardia* and Taxodiaceae-Cupressaceae-Taxaceae (TCT) – show the most relative abundance in the lower Calvert at 526.8 ft (160.57 m), 520.5 ft (158.65 m), 513.05 ft (156.38 m), 499.9 ft (152.37 m), 490.9 ft (149.63 m), 483.05 ft (147.23 m), 469.65 ft (143.15 m), 456.7 ft (139.20 m) and 447.15 ft (136.29 m). The modern range of *Engelhardia* and *Symplocos* include regions which are humid and warm-temperate to tropical such as Southeast Asia and Indonesia, and eastern Asia and the Americas, respectively (Xie et al., 2010; Wang et al., 2004). Coniferous TCT pollen thrives in moist environments as well, and is currently found in swamp forests (Larsson et al., 2011).

Temperate to subtropical adapted taxa such as *Tilia* and *Fagus,* while not found in high numbers compared to other taxa, have their highest abundances in the upper Calvert at 430.6 ft (131.25 m), 301.75 ft (91.97 m), 300.15 ft (91.49 m), 292 ft (89 m), 286.8 ft (87.42 m), 225.65 ft (68.78 m) and 217.45 ft (66.28 m) (Graham, 1999; Groot, 1991). Both drop in abundance through the Choptank and St. Marys Formations. Today, *Tilia* ranges from Manitoba through New England and down to Texas, and *Fagus* is found from New England to the great lakes and down to Mississippi (Sibley, 2009). *Alnus* and *Betula* are temperate to subtropical taxa which grow on the border of swamps or streams and have its highest abundance within the upper Calvert Formation (Larsson et al., 2001; Graham, 1999). Modern ranges of *Betula* vary from the colder regions of Alaska to the warmer and wetter stream banks and coastal areas of the southeastern United States (Sibley, 2009). In the Southeast, *Alnus* is currently found in wet soils on stream and pond margins and in swamps (Sibley, 2009).

Quercus, Pinus, Nyssa and *Ilex* are taxa found in temperate to warm-temperate climates today and are found in relatively high abundances in the Calvert Formation (Groot, 1991; 1992; Larsson et al., 2001). *Quercus* contributes approximately 50% to the total pollen sum, *Pinus* ranges from approximately 5% to 20% and *Nyssa* contributes up to 5% of the total pollen sum. Currently, one of the most widespread and dominant taxa in forests of the southeast United States is *Quercus*, which is found in a range of environments from Quebec to Kansas and down to Florida (Sibley, 2009). The modern widespread range and rapid expansion of *Quercus* during the current interglacial is attributed to the ability to adapt to the changes in climate (Davis, 1983). Currently, *Pinus* is found mainly in northern temperate regions in North America, although some species are restricted to the southeast and southwest United States. Of these southern taxa, many are found in moist soils of damp lowlands or bordering swamps (Sibley, 2009). Today, *Nyssa* is usually associated with wet soils and swamp environments found in the southeastern United States (Graham, 1999; Delcourt and Delcourt, 1987). The modern range of *Ilex* is predominantly the southeastern United States in deciduous-evergreen mixed forests in sandy soils of the coastal plain (Graham, 1999; Sibley, 2009).

The cool-climate taxa *Abies* and *Tsuga* make their first and only appearance in the upper Calvert (Groot, 1991; Groot et al., 1995). Today, *Abies* is found more commonly on the American West Coast, although a few species exist through Central and Eastern Canada in moist woodlands (Sibley, 2009). *Tsuga* is predominantly found on Canada's West Coast and in New England in the US, where it is found in cool, wet swales (Sibley, 2009).

The results of the pollen analysis are consistent with results reported from Groot (1992) and McLaughlin et al. (2008) whom concluded that the environment would be warm-temperate or subtropical, which is similar to the modern southern Atlantic Coastal Plain.

Choptank and St. Marys Formations

A decline in temperature occurred in the Middle Miocene at approximately 15 Ma to 14 Ma which initiated glacial climates in the Arctic and permanent ice cover on Antarctica (Graham, 1999). This global cooling would have affected all vegetation species, with some possibly dying out in their previous ranges if they did not adapt well to the changing climate, and some taxa shifting their geographical distributions in response (Davis, 1983). The Choptank and St. Marys Formation fossil pollen assemblages are similar and suggest a cooling in temperatures from the underlying Calvert Formation from subtropical to a warm-temperate climate. Pollen in the St. Marys sample indicates a moister environment than the Choptank, indicated by an increase in moist environment taxa.

Although there is only one sample representing the Choptank Formation at 175.2 ft (53.40 m), and only one sample from the St. Marys Formation at 59.85 ft (18.24 m), a trend can be seen in abundances from the underlying Calvert Formation.

Warm-temperate to tropical-adapted exotics *Engelhardia,* TCT and *Symplocos* all exhibit a decrease in abundance from the Calvert.

Temperate to warm-temperate *Quercus* exhibits a slight increase in percentage in both samples to approximately 50% from the Calvert Formation below. *Pinus* exhibits a decrease in percentage from approximately 20% in the underlying Calvert Formation to 4% to 10%, suggesting a cooler climate.

Temperate to sub-tropical *Carya* shows an increase from 9% in the Calvert Formation to 15% in the Choptank and a decrease to 9% in the St. Marys Formation. Modern *Carya* species range from Quebec and down to Florida in varied environments in the eastern United States (Sibley, 2009). Other temperate to warm-temperate taxa *Liquidambar,* and *Ulmus* slightly increase, with the former showing an increase to approximately 4% in the St. Marys sample from less than 1% in the Calvert Formation. *Liquidambar* grows on the border of swamps or streams, and is currently found in the southeastern United States from the lower Great Lakes to Florida (Groot, 1992; Sibley, 2009).

Cyperaceae (sedges), while relatively abundant in the lower Calvert Formation, see lower numbers in the Choptank sample, and then increase again in the St. Marys sample. Sedges are herbaceous vegetation and usually indicative of wetter environments, indicating that the St. Marys was possibly moister than the underlying Choptank (Graham, 1999; Yansa et al., 2007).

The results of the pollen analysis are consistent with results reported from Groot (1997) and McLaughlin et al. (2008) whom concluded that the environment of the Choptank and St. Marys Formations would be moist, warm-temperate and slightly cooler than that of the Calvert Formation.

Correlation to Other Sites

The previously studied borehole sediments from Bethany Beach, Delaware provide the best comparison for lithologic and palynologic analyses of the Marshy Hope study area. The Bethany Beach borehole was drilled in the spring of 2000 to a depth of 1470ft (448.06 m), providing a nearly continuous record of the Oligocene to Pleistocene. Natural gamma, spontaneous potential, 16-inch and 64-inch normal resistivity, lateral resistivity, single-point resistance and magnetic induction logs were obtained from the entire length of the hole. Samples were taken at specific intervals for lithologic and palynomorph analysis and cumulative percentage plots for grain size were created. Cluster analysis was performed on palynomorph samples to establish a pollen zonation. Dinoflagellates were also identified and interpreted in the context of de Verteuil and Norris' (1996) zonation (Miller et al., 2003; McLaughlin et al., 2008).

Correlation of Sequence Stratigraphy

Sequence stratigraphy was utilized for core Nb53-08 to subdivide the sedimentary sections and correlate them to other boreholes in Delaware, particularly core Qj32-27. The sequence stratigraphy of the Bethany Beach core was described in Miller et al. (2003) and Browning et al. (2006); further investigations of sequence stratigraphy and biostratigraphy was accomplished by McLaughlin et al. (2008). Bethany Beach stratigraphy has recently been updated based on new data by McLaughlin et al. (2016), which provides the basis figure for correlation (Figure 4.2; 4.3). Sequences 1 through 7 can be correlated to the C-sequences recognized at Bethany Beach in Miller et al. (2003) and McLaughlin et al. (2008). Correlation of borehole sequences is based on gamma ray and resistivity logs, and sequence stratigraphy of the Marshy Hope location and is shown in Figure 4.2.

Sequence 1 of Marshy Hope [527.3 ft (160.72 m)-431.6 ft (131.55 m)] corresponds almost perfectly to Sequence C1 [1421.1 ft (433.15 m)-1153 ft (351.43 m)] of Bethany Beach. Both are contained within the lower Calvert Formation and include the lower Cheswold sand unit. Above the lower Cheswold sand unit is strontium dated to 19.2 Ma at the Bethany Beach location.

Sequence 2 of Nb53-08 spans from 431.6 ft (131.55 m)-302.1 ft (92.08 m) and correlates to Sequences C2, C3 and C4 which spans from 1153 ft (351.43 m)-897.7 ft (273.62 m) at Bethany Beach. At both locations, the Cheswold sand and Federalsburg sand units are included in this correlation, although the Cheswold sand unit is much thicker at the Marshy Hope site. At Bethany Beach, Sequence 2 occurs in the interval between the lower Cheswold sand and Cheswold sand. A large spike in gamma value found within the Federalsburg sand unit of sequence 2 at approximately 320 ft (97.54 m) is much less pronounced at its Bethany Beach counterpart. The top of the Federalsburg sand unit is dated to 17.1 Ma at the Bethany location.

Sequence 3 [(302.1 ft (92.08 m)-238.1 ft (72.57 m correlates to Sequence C5 and a small part of C6 [897.7 ft (273.62 m)-787.1 ft (239.91 m)] at the Bethany location. Located in the upper Calvert Formation, sequence 3 at Marshy Hope contains the Frederica sand unit, and encompasses the interval between the Federalsburg and Frederica sand units as well as half of the Frederica sand unit at Bethany Beach. The base of the Frederica sand unit is strontium dated to approximately 16.5 Ma at Bethany Beach.

Sequence 4 [238.1 ft (72.57 m)-185.5 ft (56.54m)] correlates to the upper half of sequence C6 and sequence C7 [787.1 ft (239.91 m)-649 ft (197.82 m)] at the Bethany location. At Marshy Hope, sequence 4 crosses the boundary between the

Calvert and Choptank formations and includes the Milford sand unit. Sequence C6 at Bethany Beach includes the upper half of the Frederica sand unit, a small interval between the Frederica and Milford sand, and the Milford sand unit. The base of the Milford sand is dated to approximately 16 Ma.

Marshy Hope Sequence 5[185.5 ft (56.54 m)-150 ft (45.72 m)] correlates to most of sequence C8 [649 ft (197.82 m)- approximately 600 ft (182.88 m)] at Bethany Beach. Sequence 5 includes the relatively thin interval between the Milford sand unit and the unnamed sand unit in the lower-to-mid Choptank. Sequence C8 at Bethany Beach includes only the unnamed Choptank sands. This boundary has an estimated age of 13-14 Ma.

Sequence 6 [150 ft (47.72 m)-96 ft (29.26 m)] includes the mid-upper Choptank unnamed sand unit which correlates to the upper part of sequence C8 [approximately 600 ft (182.88 m)-575.2 ft (175.32 m)] at Bethany Beach. Sequence 6 includes the unnamed Boston Cliffs equivalent and C8 at Bethany Beach includes the upper portion of the unnamed Choptank sands. The base of Sequence 6 is strontium dated to approximately 11.8 Ma and 12.1 Ma near the top of the sequence.

The final Sequence at Marshy Hope, Sequence 7 [96 ft (29.26 m)-50 ft (15.24 m)] correlates to the same named section at Bethany Beach within sequences C9 and C10 [575.2 ft (175.32 m)- 452.05 ft (137.74 m)]. Sequence 7 includes the St. Marys confining unit located within the St. Marys Formation, as does C9 and C10 as defined at Bethany Beach. The top of this unit is dated to approximately 9.0 Ma at the Bethany location.

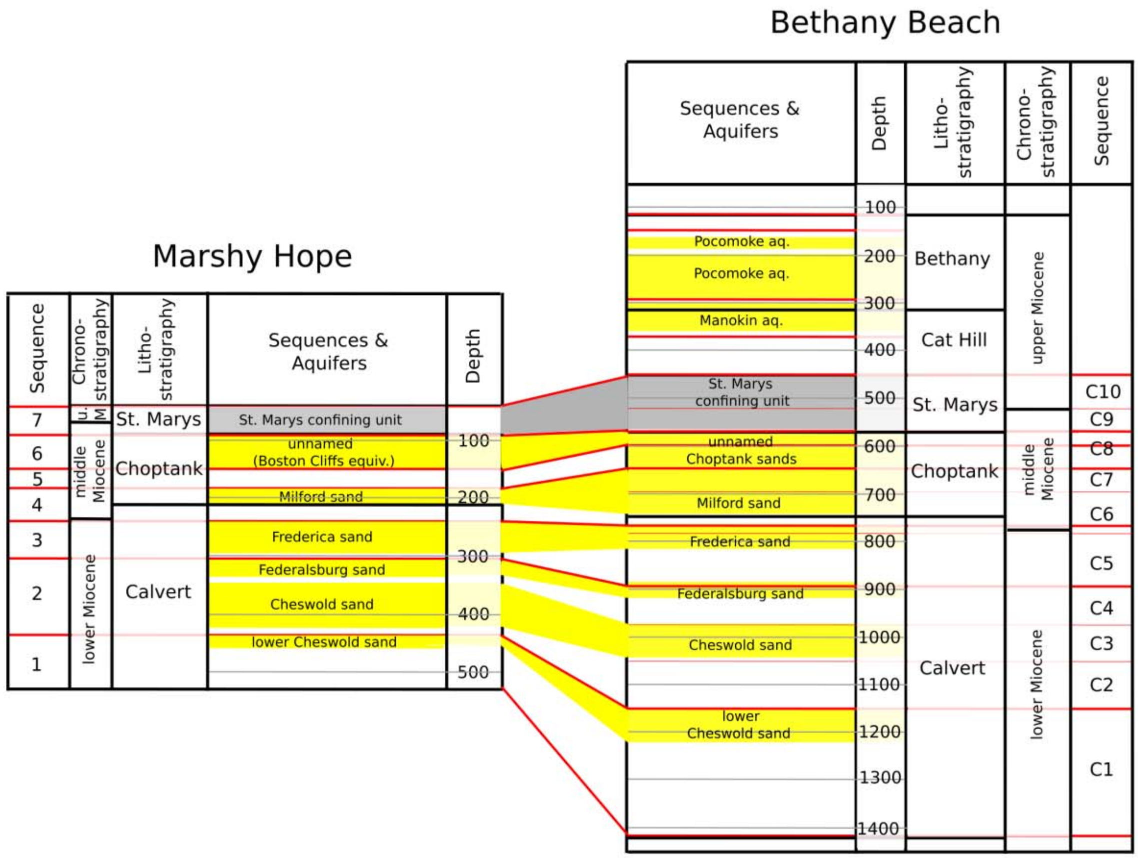

Figure 4.2: Correlation of sequences from the Marshy Hope borehole to the Bethany Beach borehole. The solid red lines trace the seven sequences within the Miocene formations of Marshy Hope to their relative positions within the Bethany Beach sequences C1-C10.

Correlation of Cluster Analysis

Cluster analysis was performed on core Nb53-08 which correlates closely to the cluster analysis results from the Qj32-27 core extracted from Bethany Beach, Delaware (Figure 4.3). The Bethany Beach cores have an established zonation of pollen which includes 6 distinct zones (McLaughlin et al., 2008). Zones 1 and 2 are located in Pleistocene sediments and Zone 3 encompasses possible Pliocene and upper Miocene sediments. Zone 4 is located within the Cat Hill Formation and partially in the St. Marys Formation. Zone 5 encompasses lower St. Marys and upper Choptank Formation sediments. Zone 6 includes samples in the lower Choptank and all of the Calvert Formation and can be split into two subzones. Only three zones from Bethany Beach are pertinent to the pollen zonation of Marshy Hope: Zones 5 and 6 and possibly Zone 4; therefore, they will be the only zones discussed.

The Zone 6 pollen assemblage is dominated by *Quercus* (50%-over 80%) and contains exotics such as *Engelhardia* (10% or more), common *Pterocarya* and rare *Podocarpus*. This zone can be differentiated into subzone ‘a’ and subzone ‘b’ based on more common taxa. Subzone ‘b’ is located in lower Calvert sediments and includes common TCT. Subzone ‘a’ is located in the upper Calvert and lower Choptank and includes more common *Pinus* and *Carya.*

The Zone 5 assemblage is dominated by *Quercus*, increased *Pinus* (over 70%), and *Carya* is more common than below. This zone can also be split into subzone ‘a’ and subzone b based on abundances of different taxa. Subzone ‘b’ spans from the upper Choptank to the boundary of the St. Marys Formation and includes more abundant *Pinus*. Subzone ‘a’ spans from the base of the St. Marys to the middle of the formation and is characterized by more *Quercus* than below.

The Marshy Hope core zonation results in three distinct zones encompassing the Calvert, Choptank and St. Marys formations which correlate well to zones 4 through 6 of the Bethany Beach core. Zone 3 of the Marshy Hope core correlates to Zone 6 subzone ‘b’ of the Bethany Beach core; *Quercus* abundance reaches close to 80%, *Engelhardia* constitutes 5% to 16% and TCT is much more abundant in the lower part of the Calvert than the top. *Podocarpus* is found in only 2 samples, and in very small numbers. Zone 3 at Marshy Hope correlates well to Zone 6 subzone ‘b’ at Bethany Beach based on relative taxa percentages.

All of samples of core Nb53-08 in Zone 2 exhibit very similar variations in taxa to Zone 6 subzone ‘a’ at Bethany Beach. Zone 2 is also dominated by *Quercus*, but at a lesser percentage (25%-55%) and *Pinus* show increased abundances from under 5% to almost 20% from Zone 3. *Carya* also shows a constant, if not increased, in percentage through Zone 2. *Engelhardia* exhibits a marked decrease in abundance from below to less than 5%. *Podocarpus* is still present in a few samples, although it is found in very small numbers. Two samples in Zone 6 subzone ‘a’ are located within lower Choptank sediments, and although Zone 2 contains samples located only in the Calvert Formation, ultimately, these two zones correlate nicely based upon relative taxa percentages.

Zone 1 of the Marshy Hope core includes one sample from the upper Calvert, one from the lower Choptank Formation and one sample from the St. Marys Formation, which share similarities to Zone 5 at Bethany Beach. Although there are two subzones within Zone 5, the low number of Marshy Hope samples do not allow for differentiation of these two subzones within Zone 1; hence, Zone 5 will be treated as one complete zone. *Quercus* is still abundant, slightly more so than in Zone 2, and shows percentages around 50%. *Carya* is also slightly more common than below with percentages increasing to 10% and 15% in the top two samples. *Engelhardia* is less common and abundance decreases upward into the St. Marys sample. Unlike Zone 5, *Pinus* abundance in Zone 1 decreases; however, this zone is consistent with Zone 5 of core Qj32-27.

The two pollen zonations created by using cluster analysis from both the Marshy Hope site and the Bethany Beach study area correlate well. The use of cluster analysis to create pollen zonations has proved useful for this study, and although each study used different clustering programs, the quantitative analysis and resulting zonations ended up being very similar.

Figure 4.3: Correlation of pollen cluster analysis from the Marshy Hope borehole to Bethany Beach. Dashed red lines indicate preliminary pollen zonation for Marshy Hope and differentiation of zones into subzones at Bethany Beach.

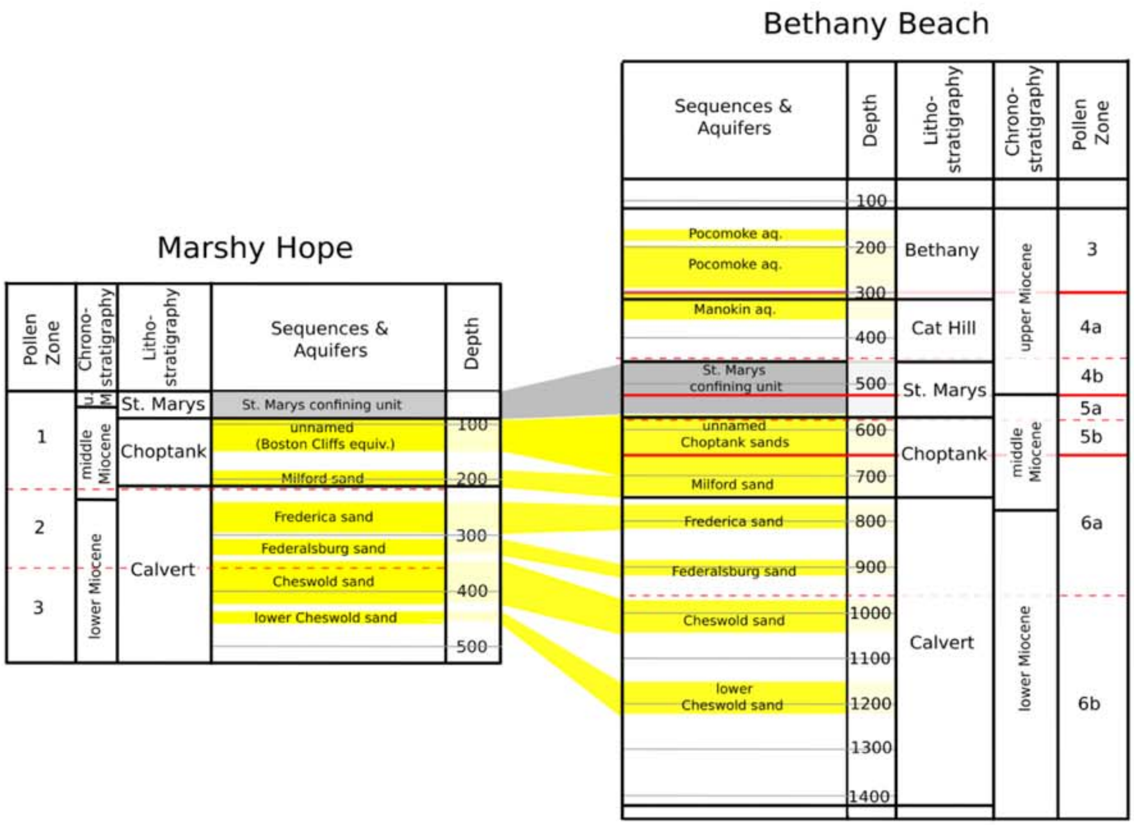

Figure 4.3: Correlation of pollen cluster analysis from the Marshy Hope borehole to Bethany Beach. Dashed red lines indicate preliminary pc
for Marshy Hope and differentiation of zones into subzo
Beach.

Correlation of Dinocyst Zonation

Dinoflagellate cysts are quite abundant in the Marshy Hope sediments and a relatively detailed zonation was applied. Although the Bethany Beach sediments contained dinoflagellates, not enough stratigraphically informative taxa were present to allow for a detailed zonation (Figure 4.4).

Cousteadinium aubryae was found at the base of core Qj32-27 in the Calvert Formation at 1446 ft (440.74 m) and up to 1153 ft (351.43 m) in the middle Calvert, designating this section DN2-DN4. A *Palaeocystodinium golzowense* was identified in the upper Calvert Formation at approximately 969 ft (295.35 m), although this taxa has a wide range from DN2 up to DN8 and is not particularly informative. *Trinovantedinium glorianum* was observed near 570 ft (173.74 m), placing these upper Choptank sediments in mid-DN7. The sample at 524 ft (159.72 m) contains *Hystrichosphaeropsis obscura* and *Geonettia clinae*, placing these middle-to-upper Choptank sediments as DN8 (Miller et al., 2003; McLaughlin et al., 2008).

The Marshy Hope core dinoflagellate cyst zonation results correlate quite well to the dinocyst zonation of the Bethany Beach sediments. Using the age correlation and aquifer correlation log figures (Figure 2.3; 4.2), along with age determinations for dinocyst zonations by de Verteuil and Norris (1996), approximate depths and ages of the Bethany dinocyst zonations can be compared to the Marshy Hope core.

The DN2-DN4 zonation in Bethany at a depth of approximately 1446 ft (440.74 m) to 1153 ft (351.43 m) corresponds to deeper than the base of the Marshy Hope core to approximately 430 ft (131.06 m), using the boundary between the Cheswold sand and the lower Cheswold sand. The Marshy Hope DN2-DN5 zonation spans from 526 ft (160.33 m) to as high as 225 ft (68.58 m). Extrapolated ages of this depth section range from approximately 20.8 Ma to 16 Ma. Moreover, de Verteuil and

Norris (1996) designate the base of DN2 at 22.2 Ma and the top of DN4 at 15.2 Ma. This correlates to the DN2 to DN5 zonation at Marshy Hope.

The DN7 designation at Bethany Beach at approximately 570 ft (173.74 m) correlates to a depth of approximately 96 ft in the Marshy Hope core based upon the base of the St. Marys confining unit at the boundary between the Choptank and St. Marys Formations. This depth corresponds to the top of the DN7 zonation at Marshy Hope. Age at Marshy Hope is approximately 11.8 Ma which is in agreement with the strontium age of 11.7 Ma near the bottom of the St. Marys confining unit at Bethany Beach. Moreover, this age fits well with the DN7 zone age being no older than 12.4 Ma (de Verteuil and Norris, 1996).

Lastly, the DN8 zonation at Bethany Beach is located at approximately 524 ft (159.72 m), within the St. Marys confining unit. This depth correlates to approximately 75 ft (22.86 m) at the Marshy Hope core, well within the designated DN7-DN8 zonation. Correlated age of this zone at Marshy Hope is approximately 10.6 Ma, which falls within the approximate 8.6-11.2 Ma age range for DN8 given by de Verteuil and Norris (1996).

Correlation of two study areas using dinocysts has been found to be useful for this study. Although the dinocyst record at the Bethany Beach study site is sparse, enough information was available to substantiate the few correlating zonations at Marshy Hope. More dinocyst data from Bethany Beach would be needed to correlate more dinoflagellate events to Marshy Hope.

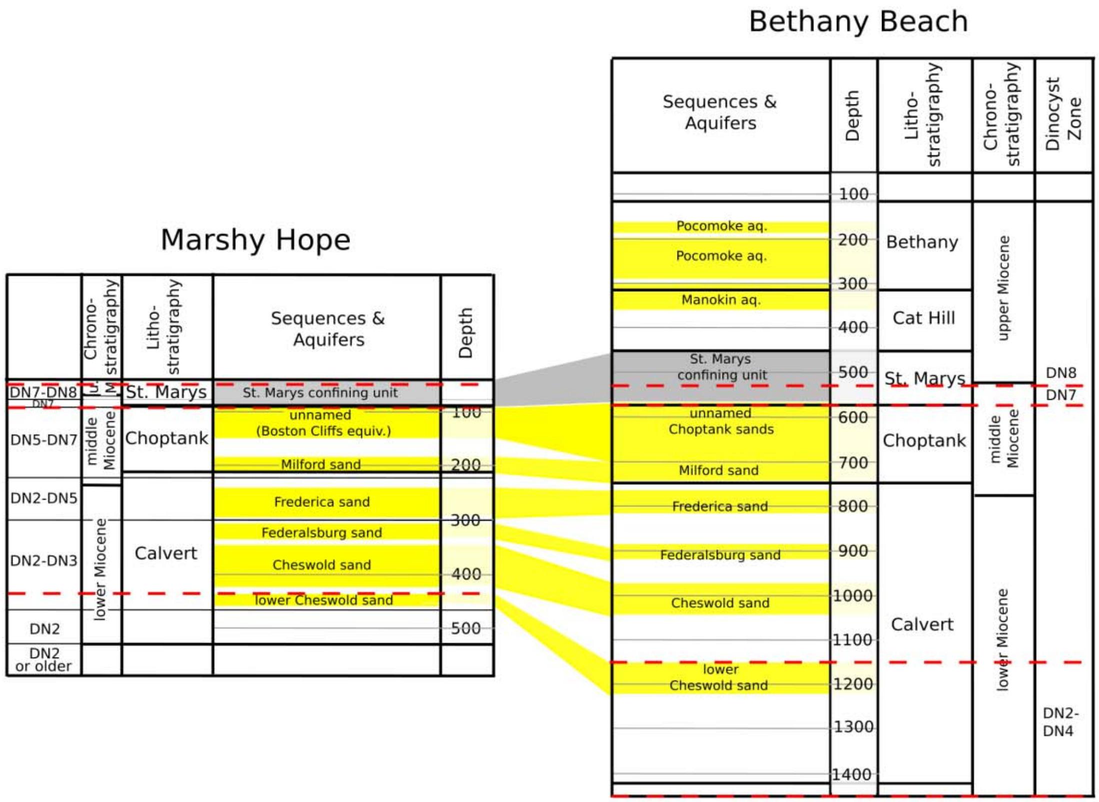

Figure 4.4: Correlation of dinocyst zones from the Marshy Hope borehole to the Bethany Beach borehole. Dashed red lines trace the relative positions of the Bethany Beach dinocyst zonation into the more detailed dinocyst horizons at Marshy Hope.

Chapter 5

CONCLUSIONS

This study of middle Miocene-age sediments from Marshy Hope, Delaware has yielded important information with implications for subsurface geology and correlation to other study sites in the region. Core lithology, sedimentology and micropaleontology have allowed for sequence stratigraphic and paleoenvironmental interpretations through the Calvert, Choptank and St. Marys Formations.

Miocene-age sediments at the Marshy Hope area depict a nearshore marine environment with many transgressions and regressions of the shoreline. The Calvert Formation is composed of clay and silt which coarsens upward with intermittent thin layers of shell material with coarser-grained sands. Depositional environments are interpreted as periodic episodes of offshore shallow-marine environments shoaling upwards into upper shoreface environments. The Choptank Formation is composed of medium- to coarse-grained sands with interbedded silt and clay, interpreted as cyclic packages of offshore or lower shoreface environments shoaling upwards to foreshore and estuarine/marsh environments The St. Marys Formation sediments consist of fine-grained sands and silts and clays which are interpreted as shaved sequences within an estuarine or marsh environment punctuated by a marine transgression to an offshore environment before returning to an estuary or marsh.

Examination of stratigraphic surfaces and interpretation of paleoenvironments allows for the identification and description of sequence stratigraphic units. Seven lithological units and seven stratigraphic sequences are recognized in the Miocene-age formations at Marshy Hope. The Calvert Formation consists of three complete coarsening-upward sequences and one half sequence which carries into the Choptank Formation. The Choptank Formation begins with the latter half of the sequence from the Calvert Formation and contains two more complete sequences. The last sequence within the Choptank is characterized by fining-upwards sediments, rather than the more common coarsening-upward sediments. The St. Marys Formation consists of one package of shaved sequences, consisting of only transgressive deposits. The seven sedimentary sections correlate to ten sequences of the Qj32-27 core sediments within eastern Sussex County, Delaware.

Fossil palynomorph assemblages in the Nb53-08 sediments yields information on paleoenvironments and allow for the correlation to other study sections in Sussex County. The flora is dominated by *Quercus, Carya,* and *Pinus*. Taxodiaceae/Cupressaceae/Taxaceae (TCT), *Ilex* and *Nyssa* are common occurrences, and "exotic" taxa such as *Engelhardia* and *Symplocos* are also present. The regional pollen record indicates a climate warmer than today and similar to the modern southern Atlantic Coastal Plain during the Calvert Formation and a slightly cooler warm-temperate climate during the Choptank Formation. Stratigraphically constrained cluster analysis of pollen assemblages within samples resulted in three distinct biozones, which has proven useful in the correlation of pollen zones to borehole Qj32-27 at Bethany Beach, Delaware. Dinoflagellate cyst analysis has resulted in seven subdivisions, which also allows for correlation to the Bethany Beach site.

The results of this study help to better understand the depositional history of northwest Sussex County, and allows for correlation to the Bethany Beach study site. Moreover, this study provides valuable information about the problematic regional correlation of the Calvert and Choptank formations, which also has implications for aquifer correlation within the region. Finally, this study provides another example of a rare shaved sequence, which exhibits a greater amount of a transgressive systems tract preserved within the estuarine sections of the St. Marys Formation.

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Appendix

SUPPLEMENTAL MATERIAL

Table A.1: Grain size weights and percentages for Nb53-08. Solid red lines indicate a formational boundary. Note: LITH SHELLS refers to a sample which contained only lithified shells, and no individual weights could be determined.

Sample #	Depth EF	Original Weight (g)	Weight after 63 µm sieve (g)	1 mm	500µm	250µm	125µm	>63µm	Total:	Silt/Clay Weight (g)	Final Weight	Percentage:	1mm	500µm	250µm	125µm	>63µm	Silt/Clay
105572-0.5	50.5	42.21	1.55	0	0.01	0.01	0.14	1.41	1.57	40.66	42.23		0.00%	0.02%	0.02%	0.33%	3.34%	96.33%
105573-0.5	55.5	57.13	17.53	0.03	0.08	0.1	4	13.13	17.34	39.6	56.94		0.05%	0.14%	0.18%	7.00%	22.98%	69.32%
105573-5.6	60.6	39.54	1.24	0.08	0.08	0.07	0.12	0.98	1.33	38.3	39.63		0.20%	0.20%	0.18%	0.30%	2.48%	96.86%
105574-0.5	65.5	32.88	1.03	0.05	0.03	0.03	0.13	0.81	1.05	31.85	32.9		0.15%	0.09%	0.09%	0.40%	2.46%	96.87%
105574-5.35	70.35	64.07	1.82	0.01	0.06	0.07	0.63	1.08	1.85	62.25	64.1		0.02%	0.09%	0.11%	0.98%	1.69%	97.16%
105575-0.2	75.2	36.43	0.93	0.03	0.07	0.1	0.26	0.61	1.07	35.5	36.57		0.08%	0.19%	0.27%	0.71%	1.67%	97.45%
105575-5.1	80.1	52.89	10.2	0.2	1.11	1.75	3.46	3.49	10.01	42.69	52.7		0.38%	2.10%	3.31%	6.54%	6.60%	80.71%
105576-0.0	85	38.11	0.52	0	0.01	0.03	0.03	0.46	0.53	37.59	38.12		0.00%	0.03%	0.08%	0.08%	1.21%	98.64%
105576-5.0	90	43.09	0.32	0	0.01	0.01	0.02	0.28	0.32	42.77	43.09		0.00%	0.02%	0.02%	0.05%	0.65%	99.26%
105577-0.7	95.7	48.44	5.79	0.02	0.02	0.03	0.07	5.66	5.8	42.65	48.45		0.04%	0.04%	0.06%	0.14%	11.68%	88.05%
105577-5.2	100.2	59.61	26.08	0.48	0.31	1.04	1.85	22.26	25.94	33.53	59.47		0.81%	0.52%	1.74%	3.10%	37.34%	56.25%
105578-3.6	108.6	59.44	34.58	2.95	1.43	6.82	9.75	13.39	34.34	24.86	59.2		4.96%	2.41%	11.47%	16.40%	22.53%	41.82%
105579-0.6	115.6	73.11	64.29	31.54	1.65	4.89	23.53	2.11	63.72	8.82	72.54		43.14%	2.26%	6.69%	32.18%	2.89%	12.06%
105579-5.5	120.5	54.57	35.48	4.85	2.28	5.74	17	5.47	35.34	19.09	54.43		8.89%	4.18%	10.52%	31.15%	10.02%	34.98%
105580-3.45	128.45	93.18	80.34	16.58	4.7	22.82	31.43	3.7	79.23	12.84	92.07		17.79%	5.04%	24.49%	33.73%	3.97%	13.78%
105581-3.55	138.55	76.91	68.7	21.94	8.94	24.23	11.31	2.03	68.45	8.21	76.66		28.53%	11.62%	31.50%	14.71%	2.64%	10.67%
105582-1.4	151.4	49.27	24.76	0.79	1.12	13.2	8.81	0.68	24.6	24.51	49.11		1.60%	2.27%	26.79%	17.88%	1.38%	49.75%
105582-6.3	156.3	44.74	25.27	3.78	3.46	11.68	5.09	1.2	25.21	19.47	44.68		8.45%	7.73%	26.11%	11.38%	2.68%	43.52%
105584-1.5	161.5	42.24	12.1	0.96	0.4	0.58	6.96	3.14	12.04	30.14	42.18		2.27%	0.95%	1.37%	16.48%	7.43%	71.35%
105584-5.95	165.95	45.82	6.67	2.98	0.75	0.78	0.76	1.41	6.68	39.15	45.83		6.50%	1.64%	1.70%	1.66%	3.08%	85.44%
105585-1.75	171.75	43.35	7.04	0.85	0.63	0.57	0.51	4.44	7	36.31	43.31		1.96%	1.45%	1.31%	1.18%	10.24%	83.76%
105586-0.8	180.8	43.35	0.26	0.01	0.02	0.01	0.02	0.2	0.26	43.09	43.35		0.02%	0.05%	0.02%	0.05%	0.46%	99.40%
105586-5.8	185.8	60.59	33.57	4.61	2.3	4.36	11.94	9.98	33.19	27.02	60.21		7.61%	3.80%	7.20%	19.71%	16.47%	44.59%
105587-0.55	190.55	46.61	27.7	1.43	0.46	0.81	7.91	17.11	27.72	18.91	46.63		3.07%	0.99%	1.74%	16.97%	36.71%	40.57%
105587-5.55	195.55	30.55	19.88	0.36	0.48	4.07	8.29	6.53	19.73	10.67	30.4		1.18%	1.57%	13.32%	27.14%	21.37%	34.93%
105588-0.95	200.95	52.32	28.83	6.15	4.15	5.8	8.28	4.4	28.78	23.49	52.27		11.75%	7.93%	11.09%	15.83%	8.41%	44.90%
105589-0.9	205.9	LITH SHELLS																
105590-4.45	219.45	26.32	8.98	1.15	1.26	3.82	1.61	1.16	9	17.34	26.34		4.37%	4.79%	14.51%	6.12%	4.41%	65.88%
105592-0.4	235.4	51.94	26.44	0.1	0.81	3.28	10.5	11.44	26.13	25.5	51.63		0.19%	1.56%	6.31%	20.22%	22.03%	49.10%
105592-5.5	240.5	52.81	41.92	3.69	4.87	14.11	13.28	5.61	41.56	10.89	52.45		6.99%	9.22%	26.72%	25.15%	10.62%	20.62%
105592-10.6	245.6	50	34.4	1.72	5.29	11.07	12.08	4.05	34.21	15.6	49.81		3.44%	10.58%	22.14%	24.16%	8.10%	31.20%
105594-1.25	256.25	68.53	64.39	2.3	20.78	37.25	3.08	0.65	64.06	4.14	68.2		3.36%	30.32%	54.36%	4.49%	0.95%	6.04%
105596-1.9	271.9	LITH SHELLS									0							

Table A.1: Continued.

105597-3.0	278	47.61	45.03	2.99	2.78	27.02	11.49	0.36	44.64	2.58	47.22	6.28%	5.84%	56.75%	24.13%	0.76%	5.42%
105599-2.6	287.6	35.47	9.86	0.07	0.08	0.08	0.54	9.16	9.93	25.61	35.54	0.20%	0.23%	0.23%	1.52%	25.82%	72.20%
105600-2.7	292.7	37.66	1.42	0.11	0.12	0.08	0.09	1.08	1.48	36.24	37.72	0.29%	0.32%	0.21%	0.24%	2.87%	96.23%
105601-2.9	297.9	45.37	13.65	0.02	0.02	0.5	2.09	11.39	14.02	31.72	45.74	0.04%	0.04%	1.10%	4.61%	25.10%	69.91%
105602-2.45	302.45	48.03	37.87	4.53	1.31	10.41	17.87	3.46	37.58	10.16	47.74	9.43%	2.73%	21.67%	37.21%	7.20%	21.15%
105604-0.5	310.5	LITH SHELLS							0		0						
105606-0.25	320.25	52.32	46.15	0.59	1.3	18.35	23.44	1.89	45.57	6.17	51.74	1.13%	2.48%	35.07%	44.80%	3.61%	11.79%
105607-2.9	327.9	47.01	43.74	0	0.05	5.35	35.86	2.04	43.3	3.27	46.57	0.00%	0.11%	11.38%	76.28%	4.34%	6.96%
105608-2.9	332.9	50.66	44.16	0.35	0.1	2.72	38.44	2.25	43.86	6.5	50.36	0.69%	0.20%	5.37%	75.88%	4.44%	12.83%
105619-1.7	396.7	41.31	27.34	0.05	0.05	0.26	13.17	13.42	26.95	13.97	40.92	0.12%	0.12%	0.63%	31.88%	32.49%	33.82%
105620-1.75	406.75	43	28.96	0.02	0.03	0.16	9.65	18.65	28.51	14.04	42.55	0.05%	0.07%	0.37%	22.44%	43.37%	32.65%
105620-6.8	411.8	36.19	22.44	0.02	0.03	0.09	6.79	15.31	22.24	13.75	35.99	0.06%	0.08%	0.25%	18.76%	42.30%	37.99%
105621-2.4	417.4	54.04	35.85	0.01	0.02	0.07	18.16	17.36	35.62	18.19	53.81	0.02%	0.04%	0.13%	33.60%	32.12%	33.66%
105621-7.4	422.4	44.47	30.82	0.04	0.03	0.13	19.42	10.77	30.39	13.65	44.04	0.09%	0.07%	0.29%	43.67%	24.22%	30.69%
105622-2.2	427.2	34.13	9.59	0.01	0.01	0.02	0.95	8.5	9.49	24.54	34.03	0.03%	0.03%	0.06%	2.78%	24.90%	71.90%
105622-7.2	432.2	45.2	29.75	9.29	3.17	4.97	5.61	6.63	29.67	15.45	45.12	20.55%	7.01%	11.00%	12.41%	14.67%	34.18%
105623-1.3	436.3	50.66	37.31	0.13	0.4	1.26	24	11.2	36.99	13.35	50.34	0.26%	0.79%	2.49%	47.37%	22.11%	26.35%
105624-0	440	80.85	44.74	12.63	7.96	8.93	9.56	5.18	31.63	36.11	67.74	34.98%	11.75%	13.18%	14.11%	7.65%	53.31%
105625-1.55	446.55	41.19	3.33	0.27	0.68	0.81	0.31	1.2	3.27	37.86	41.13	0.66%	1.65%	1.97%	0.75%	2.91%	91.92%
105626-3.5	458.5	77.06	56.34	1.25	10.25	26.92	11.18	5.84	55.44	20.72	76.16	1.62%	13.30%	34.93%	14.51%	7.58%	26.89%
105627-4.8	469.8	21.91	1.42	0	0.01	0.08	0.58	0.76	1.43	20.49	21.92	0.00%	0.05%	0.37%	2.65%	3.47%	93.52%
105627-9.8	474.8	55.54	42.51	0.77	4.07	26.02	8.63	2.38	41.87	13.03	54.9	1.39%	7.33%	46.85%	15.54%	4.29%	23.46%
105628-4.6	479.6	30.39	5.32	0.05	0.05	0.11	0.63	4.47	5.31	25.07	30.38	0.16%	0.16%	0.36%	2.07%	14.71%	82.49%
105628-9.6	484.6	31.23	0.16	0	0	0	0.05	0.13	0.18	31.07	31.25	0.00%	0.00%	0.00%	0.16%	0.42%	99.49%
105629-4.95	489.95	26.03	0.14	0	0	0.04	0.02	0.08	0.14	25.89	26.03	0.00%	0.00%	0.15%	0.08%	0.31%	99.46%
105629-10.0	495	25.86	0.07	0	0.02	0.02	0.01	0.02	0.07	25.79	25.86	0.00%	0.08%	0.08%	0.04%	0.08%	99.73%
105630-4.55	499.55	16.82	0.09	0	0	0	0.01	0.08	0.09	16.73	16.82	0.00%	0.00%	0.00%	0.06%	0.48%	99.46%
105630-9.45	504.45	23.39	0.33	0	0	0.01	0.05	0.18	0.24	23.06	23.3	0.00%	0.00%	0.04%	0.21%	0.77%	98.59%
105631-4.35	509.35	44.02	1.77	0.03	0.03	0.05	1.29	0.37	1.77	42.25	44.02	0.07%	0.07%	0.11%	2.93%	0.84%	95.98%
105631-9.25	514.25	26.82	0.17	0	0	0.02	0.02	0.13	0.17	26.65	26.82	0.00%	0.00%	0.07%	0.07%	0.48%	99.37%
105632-4.25	519.25	22.03	0.12	0	0.01	0.02	0.03	0.06	0.12	21.91	22.03	0.00%	0.05%	0.09%	0.14%	0.27%	99.46%
105632-9.35	524.35	15.61	2.06	0.07	0.05	0.13	0.21	1.68	2.14	13.55	15.69	0.45%	0.32%	0.83%	1.35%	10.76%	86.80%
105633-4	529	33.13	23.51	4.65	5.41	8.33	3.84	1.21	23.44	9.62	33.06	14.04%	16.33%	25.14%	11.59%	3.65%	29.04%
105634-4.45	534.45	36.22	27.78	0.7	3.21	14.23	7.58	1.77	27.49	8.44	35.93	1.93%	8.86%	39.29%	20.93%	4.89%	23.30%

Table A.2: Percentage of sediment components for Nb53-08. Solid red lines indicate a formational boundary. Note: MIXED refers to two samples which were accidentally mixed together and constituents of each sample could not be determined.

Sample #	Depth EF	Quartz	Glauconite	OHM	Mica	Carbonate	Feldspar	Forams	Phosphate	Total
105572-0.5	50.5	87%	0%	1%	2%	0%	10%	0%	0%	100%
105573-0.5	55.5	90%	1%	5%	1%	0%	2%	0%	1%	100%
105573-5.6	60.6	85%	0%	5%	0%	0%	10%	0%	0%	100%
105574-0.5	65.5	95%	0%	2%	2%	0%	1%	0%	0%	100%
105574-5.35	70.35	92%	1%	1%	0%	1%	5%	0%	0%	100%
105575-0.2	75.2	88%	5%	2%	5%	0%	0%	0%	0%	100%
105575-5.1	80.1	50%	40%	5%	5%	0%	0%	0%	0%	100%
105576-0.0	85	70%	20%	2%	2%	0%	1%	0%	5%	100%
105576-5.0	90	83%	5%	5%	5%	0%	0%	0%	2%	100%
105577-0.7	95.7	MIXED								
105577-5.2	100.2	95%	0%	3%	0%	1%	1%	0%	0%	100%
105578-3.6	108.6	78%	10%	2%	0%	10%	0%	0%	0%	100%
105579-0.6	115.6	51%	0%	1%	0%	48%	0%	0%	0%	100%
105579-5.5	120.5	MIXED								
105580-3.45	128.45	81%	0%	1%	0%	18%	0%	0%	0%	100%
105581-3.55	138.55	68%	0%	1%	0%	29%	0%	0%	2%	100%
105582-1.4	151.4	64%	30%	2%	0%	4%	0%	0%	0%	100%
105582-6.3	156.3	81%	5%	2%	1%	10%	1%	0%	0%	100%
105584-1.5	161.5	77%	5%	10%	1%	7%	0%	0%	0%	100%
105584-5.95	165.95	25%	1%	5%	2%	66%	1%	0%	0%	100%
105585-1.75	171.75	73%	4%	2%	2%	17%	2%	0%	0%	100%
105586-0.8	180.8	90%	1%	2%	0%	5%	2%	0%	0%	100%
105586-5.8	185.8	71%	5%	2%	2%	17%	1%	0%	2%	100%
105587-0.55	190.55	85%	1%	5%	0%	8%	1%	0%	0%	100%
105587-5.55	195.55	82%	5%	2%	0%	6%	1%	0%	4%	100%
105588-0.95	200.95	20%	10%	5%	1%	60%	0%	0%	4%	100%
105589-0.9	205.9	85%	0%	1%	1%	10%	3%	0%	0%	100%
105590-4.45	219.45	86%	1%	2%	0%	9%	2%	0%	0%	100%
105592-0.4	235.4	95%	1%	1%	1%	0%	2%	0%	0%	100%
105592-5.5	240.5	79%	2%	2%	0%	17%	0%	0%	0%	100%
105592-10.6	245.6	94%	0%	2%	0%	3%	1%	0%	0%	100%
105594-1.25	256.25	88%	1%	1%	0%	10%	0%	0%	0%	100%
105596-1.9	271.9	LITHIFIED								
105597-3.0	278	90%	0%	2%	2%	6%	0%	0%	0%	100%
105599-2.6	287.6	86%	2%	5%	2%	0%	5%	0%	0%	100%
105600-2.7	292.7	85%	2%	5%	5%	2%	1%	0%	0%	100%
105601-2.9	297.9	85%	10%	1%	2%	0%	2%	0%	0%	100%
105602-2.45	302.45	80%	5%	3%	0%	11%	1%	0%	0%	100%
105604-0.5	310.5	LITHIFIED								
105606-0.25	320.25	89%	0%	2%	1%	6%	0%	0%	2%	100%
105607-2.9	327.9	97%	0%	2%	1%	0%	0%	0%	0%	100%
105608-2.9	332.9	96%	1%	2%	0%	1%	0%	0%	0%	100%
105619-1.7	396.7	91%	1%	5%	2%	0%	1%	0%	0%	100%
105620-1.75	406.75	95%	1%	2%	2%	0%	0%	0%	0%	100%
105620-6.8	411.8	84%	0%	5%	10%	1%	0%	0%	0%	100%
105621-2.4	417.4	93%	2%	2%	1%	2%	0%	0%	0%	100%
105621-7.4	422.4	95%	1%	3%	1%	1%	0%	0%	0%	101%
105622-2.2	427.2	94%	1%	2%	2%	1%	0%	0%	0%	100%
105622-7.2	432.2	66%	1%	2%	1%	30%	0%	0%	0%	100%
105623-1.3	436.3	95%	1%	1%	0%	2%	1%	0%	0%	100%
105624-0	440	98%	0%	1%	1%	0%	0%	0%	0%	100%
105625-1.55	446.55	73%	10%	2%	5%	10%	0%	0%	0%	100%
105626-3.5	458.5	95%	0%	3%	0%	2%	0%	0%	0%	100%
105627-4.8	469.8	65%	20%	5%	3%	5%	2%	0%	0%	100%
105627-9.8	474.8	70%	5%	2%	0%	22%	1%	0%	0%	100%
105628-4.6	479.6	71%	15%	2%	2%	10%	0%	0%	0%	100%
105628-9.6	484.6	60%	0%	15%	20%	0%	5%	0%	0%	100%
105629-4.95	489.95	85%	1%	1%	10%	2%	1%	0%	0%	100%
105629-10.0	495	83%	0%	10%	5%	0%	2%	0%	0%	100%
105630-4.55	499.55	86%	5%	5%	2%	0%	2%	0%	0%	100%
105630-9.45	504.45	66%	20%	5%	5%	2%	2%	0%	0%	100%
105631-4.35	509.35	35%	60%	4%	1%	0%	0%	0%	0%	100%
105631-9.25	514.25	30%	5%	20%	0%	0%	5%	40%	0%	100%
105632-4.25	519.25	23%	5%	20%	0%	0%	2%	50%	0%	100%
105632-9.35	524.35	30%	40%	10%	16%	2%	2%	0%	0%	100%
105633-4	529	75%	20%	5%	0%	0%	0%	0%	0%	100%
105634-4.45	534.45	80%	10%	5%	0%	5%	0%	0%	0%	100%

Table A.3: Raw pollen counts for Nb53-08 samples which met the predetermined number of pollen grains. Solid red lines indicate a formational boundary.

Sample Number	Core Number	Depth	Formation	Slide	Abies	Alnus	Betula	Carya	Carpinus	Chenopod	Cornus	Corylus	Echinate Ball	Engelhardia	Ericaceae	Fagus	Fraxinus	Gramineae	Ilex	Cyperaceae (Type 1, Psilate Inap)	Cyperaceae (Type 2, Scabrate)	Juglans	Liquidambar	Liliaceae	Myrica	Nyssa	Periporopollenites
105573-4.85	Core 13	59.85	St. Marys	Y	0	5	2	29	3	0	0	0	1	0	0	1	0	3	6	4	26	0	11	0	0	2	0
105585-5.2	Core 25	175.2	Choptank	Y	0	6	0	48	4	1	2	4	0	16	0	0	0	0	2	3	5	1	1	0	0	1	0
105590-2.45	Core 30	217.45	Calvert	Y	0	1	0	5	3	0	2	0	0	8	0	1	1	0	5	0	15	0	5	2	0	12	0
105591-0.65	Core 31	225.65	Calvert	Y	5	2	2	29	0	0	7	0	0	3	1	5	1	0	5	0	7	2	4	0	1	16	0
105599-1.80	Core 39	286.8	Calvert	Y	0	1	4	6	0	0	11	0	0	11	0	19	2	0	8	6	7	0	1	1	0	13	3
105600-2.0	Core 40	292	Calvert	Y	0	6	5	5	0	0	4	0	0	11	0	3	0	0	10	16	22	0	0	0	0	10	0
105601-5.15	Core 41	300.15	Calvert	Y	0	4	2	11	0	0	3	0	0	6	0	3	3	0	9	5	6	0	0	1	0	3	0
105602-1.75	Core 42	301.75	Calvert	Y	0	5	3	10	0	0	12	4	0	3	1	0	1	0	19	5	6	1	2	0	0	13	0
105622-5.60	Core 62	430.6	Calvert	Y	0	1	0	12	1	0	2	1	0	50	0	0	0	0	3	3	14	1	0	0	0	1	0
105625-2.15	Core 65	447.15	Calvert	Y	0	2	0	16	0	0	0	1	0	29	0	0	0	0	4	7	12	1	3	0	0	1	0
105626-1.7	Core 66	456.7	Calvert	Y	0	3	0	23	2	0	3	0	0	19	1	0	1	0	10	4	20	0	2	0	0	2	0
105627-4.65	Core 67	469.65	Calvert	Y	0	0	0	16	0	0	5	1	0	34	0	1	1	0	10	0	10	0	0	0	0	5	0
105628-8.05	Core 68	483.05	Calvert	Y	0	2	1	15	0	0	4	0	0	6	0	1	3	0	6	4	4	0	2	0	1	15	0
105629-5.90	Core 69	490.9	Calvert	Y	0	1	0	14	1	0	5	0	0	1	0	2	0	0	5	5	10	2	0	0	0	11	0
105630-4.90	Core 70	499.9	Calvert	Y	0	1	0	11	0	0	3	0	0	1	0	6	0	0	5	9	19	0	4	0	0	6	0
105632-5.5	Core 72	520.5	Calvert	Y	0	3	2	15	0	0	1	1	0	2	0	7	0	0	2	1	44	1	0	0	0	1	0
105633-1.8	Core 73	526.8	Calvert	Y	0	1	0	26	0	0	1	0	0	13	0	0	0	0	6	2	12	0	0	0	0	4	0
					5	44	21	291	14	1	65	12	1	213	3	49	13	3	115	74	239	9	35	4	2	116	3

Table A.3: Continued.

Sample Number	Core Number	Depth	Formation	Slide	Abies	Alnus	Betula	Carya	Carpinus	Chenopod	Cornus	Corylus	Echinate Ball	Engelhardia	Ericaceae	Fagus	Fraxinus	Gramineae	Ilex	Polypodiaceae (Psilate Inap)	Inaperturpollenites (Scabrate)	Juglans	Liquidambar	Liliaceae	Myrica	Nyssa	Periporopollenites
105573-4.85	Core 13	59.85	St. Marys	Y	**0**	**5**	**2**	**29**	**3**	**0**	**0**	**0**	**1**	**0**	**0**	**1**	**0**	**3**	**6**	**4**	**26**	**0**	**11**	**0**	**0**	**2**	**0**
105585-5.2	Core 25	175.2	Choptank	Y	**0**	**6**	**0**	**48**	**4**	**1**	**2**	**4**	**0**	**16**	**0**	**0**	**0**	**0**	**2**	**3**	**5**	**1**	**1**	**0**	**0**	**1**	**0**
105590-2.45	Core 30	217.45	Calvert	Y	**0**	**1**	**0**	**5**	**3**	**0**	**2**	**0**	**0**	**8**	**0**	**1**	**1**	**0**	**5**	**0**	**15**	**0**	**5**	**2**	**0**	**12**	**0**
105591-0.65	Core 31	225.65	Calvert	Y	**5**	**2**	**2**	**29**	**0**	**0**	**7**	**0**	**0**	**3**	**1**	**5**	**1**	**0**	**5**	**0**	**7**	**2**	**4**	**0**	**1**	**16**	**0**
105599-1.80	Core 39	286.8	Calvert	Y	**0**	**1**	**4**	**6**	**0**	**0**	**11**	**0**	**0**	**11**	**0**	**19**	**2**	**0**	**8**	**6**	**7**	**0**	**1**	**1**	**0**	**13**	**3**
105600-2.0	Core 40	292	Calvert	Y	**0**	**6**	**5**	**5**	**0**	**0**	**4**	**0**	**0**	**11**	**0**	**3**	**0**	**0**	**10**	**16**	**22**	**0**	**0**	**0**	**0**	**10**	**0**
105601-5.15	Core 41	300.15	Calvert	Y	**0**	**4**	**2**	**11**	**0**	**0**	**3**	**0**	**0**	**6**	**0**	**3**	**3**	**0**	**9**	**5**	**6**	**0**	**0**	**1**	**0**	**3**	**0**
105602-1.75	Core 42	301.75	Calvert	Y	**0**	**5**	**3**	**10**	**0**	**0**	**12**	**4**	**0**	**3**	**1**	**0**	**1**	**0**	**19**	**5**	**6**	**1**	**2**	**0**	**0**	**13**	**0**
105622-5.60	Core 62	430.6	Calvert	Y	**0**	**1**	**0**	**12**	**1**	**0**	**2**	**1**	**0**	**50**	**0**	**0**	**0**	**0**	**3**	**3**	**14**	**1**	**0**	**0**	**0**	**1**	**0**
105625-2.15	Core 65	447.15	Calvert	Y	**0**	**2**	**0**	**16**	**0**	**0**	**0**	**1**	**0**	**29**	**0**	**0**	**0**	**0**	**4**	**7**	**12**	**1**	**3**	**0**	**0**	**1**	**0**
105626-1.7	Core 66	456.7	Calvert	Y	**0**	**3**	**0**	**23**	**2**	**0**	**3**	**0**	**0**	**19**	**1**	**0**	**1**	**0**	**10**	**4**	**20**	**0**	**2**	**0**	**0**	**2**	**0**
105627-4.65	Core 67	469.65	Calvert	Y	**0**	**0**	**0**	**16**	**0**	**0**	**5**	**1**	**0**	**34**	**0**	**1**	**1**	**0**	**10**	**0**	**10**	**0**	**0**	**0**	**0**	**5**	**0**
105628-8.05	Core 68	483.05	Calvert	Y	**0**	**2**	**1**	**15**	**0**	**0**	**4**	**0**	**0**	**6**	**0**	**1**	**3**	**0**	**6**	**4**	**4**	**0**	**2**	**0**	**1**	**15**	**0**
105629-5.90	Core 69	490.9	Calvert	Y	**0**	**1**	**0**	**14**	**1**	**0**	**5**	**0**	**0**	**1**	**0**	**2**	**0**	**0**	**5**	**5**	**10**	**2**	**0**	**0**	**0**	**11**	**0**
105630-4.90	Core 70	499.9	Calvert	Y	**0**	**1**	**0**	**11**	**0**	**0**	**3**	**0**	**0**	**1**	**0**	**6**	**0**	**0**	**5**	**9**	**19**	**0**	**4**	**0**	**0**	**6**	**0**
105631-8.05	Core 71	513.05	Calvert	Y	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
105632-5.5	Core 72	520.5	Calvert	Y	**0**	**3**	**2**	**15**	**0**	**0**	**1**	**1**	**0**	**2**	**0**	**7**	**0**	**0**	**2**	**1**	**44**	**1**	**0**	**0**	**0**	**1**	**0**
105633-1.8	Core 73	526.8	Piney Pt.	Y	**0**	**1**	**0**	**26**	**0**	**0**	**1**	**0**	**0**	**13**	**0**	**0**	**0**	**0**	**6**	**2**	**12**	**0**	**0**	**0**	**0**	**4**	**0**
					5	44	21	291	14	1	65	12	1	213	3	49	13	3	115	74	239	9	35	4	2	116	3

Figure A.1: Common pollen taxa found in the sediments of borehole Nb53-08.

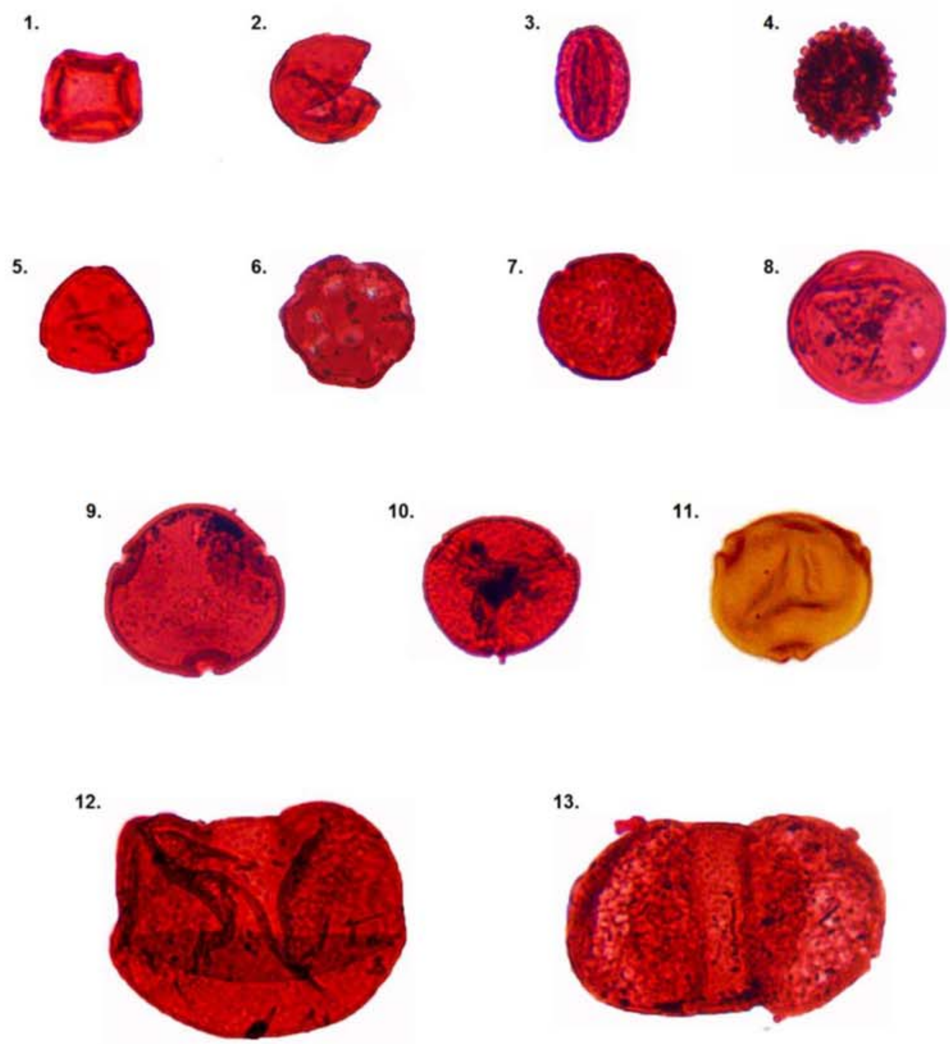

Plate 1

1. *Alnus* sp.
2. Taxodiaceae-Cupressaceae-Taxaceae
3. *Quercus* sp.
4. *Ilex* sp.
5. *Engelhardia* sp.
6. *Liquidambar* sp.
7. *Ulmus* sp.
8. *Carya* sp.
9. *Tilia* sp.
10. *Nyssa* sp.
11. *Carpinus* sp.
12. *Picea* sp.
13. *Pinus* sp.

Figure A.2: Common dinoflagellate cyst species found in the sediments of borehole Nb53-08.