RECONSTRUCTING LANDSCAPES ACROSS THE EARLY TO LATE CRETACEOUS TRANSITION – EVALUATING BASE LEVEL, CLIMATE AND SEQUENCE STRATIGRAPHY FROM POTOMAC FORMATION SEDIMENTS IN NEW JERSEY AND DELAWARE

By

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ABSTRACT OF THE DISSERTATION

Reconstructing Landscapes Across the Early to Late Cretaceous Transition – Evaluating Base Level, Climate and Sequence Stratigraphy from Potomac Formation Sediments in New Jersey and Delaware

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The mid-Cretaceous (Barremian/Aptian/Albian/Cenomanian stages) marks the transition to global greenhouse climatic conditions. The mid-Cretaceous Potomac Formation, deposited on the North American coastal plain, offers the potential to study a nonmarine fluvial/deltaic deposit that experienced changes in climate and sea level. This study involves three coreholes from New Jersey (Fort Mott and Medford) and Delaware (Summit Marina) that were used to evaluate the landscape evolution through this time interval and to develop an enhanced method of correlation between these sites.

Paleosols offer excellent records of terrestrial conditions during their formation. 103 total paleosols were identified and analyzed from all three sites and grouped into five pedotypes ranging in pedogenic maturity: Gray and Gray-Red Types are weakly developed, immature soils formed under poor drainage conditions; Red and Purple Types are moderately developed soils formed under alternating wet/dry conditions; Brown Type are well-developed, mature soils formed under well drained conditions. A morphology index and two geochemical proxies (Nb and Ba/Sr) provide further information on paleoprecipitation, and drainage conditions. A conceptual model was developed linking the Nb paleoprecipitation proxy and Ba/Sr drainage proxy to determine landscape changes as a result of precipitation/evaporation versus base level. Potomac Formation Unit I displays varying dry to wet conditions up section from the unit base. The morphology index and geochemical proxies provide evidence that Unit I was sub-humid with episodes of saturation and overall drier conditions relative to overlying units. Paleoprecipitation was the main control on the formation of these paleosols. Units II (lower Albian to lower Cenomanian) and III (lower Cenomanian) have similar wet and dry conditions upsection through both units. Paleoprecipitation played a role lower in Unit II although upsection base level exerts more influence on landscape conditions. The morphology index and geochemical proxies provide evidence Units II and III were deposited under wetter conditions, experiencing sub-humid to humid conditions, with episodes of drying.

Palynology also provides a correlation tool, and was analyzed here to try and establish a higher resolution of correlation. This was attempted using angiosperm diversity patterns, specifically Monocots-Magnoliids, Eudicots and the ratio of Eudicots to Monocots-Magnoliids. The inconsistent sample material as well as sparse angiosperm populations did not allow for a higher resolved correlation.

A sequence stratigraphic framework was developed for the Potomac Formation. The Potomac Formation units were subdivided into packages known as Fluvial Aggradation Cycles (FACs). An analysis of FAC stacking patterns reveals potential sequence boundaries and systems tracts. FACs support the identification of unit boundaries as sequence boundaries. FACs also indicate tentative higher order sequence boundaries and provide potential additional correlative surfaces among Potomac Formation sites.

This study reconstructed the landscape showing the variability in climate (precipitation/evaporation) and base-level through time that had a significant influence the formation of coastal plain paleosols. This enhances the overall understanding of how coastal plain landscapes evolve in transitions towards greenhouse climates during overall transgressions. The use of FACs has provided a potentially novel method to correlate sites at a higher resolution, creating tie points within these lithologic units. It also provided further information on the landscape evolution through this time interval, offering information on base-level and accommodation.

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Chapter 1

Introduction

The Early (Barremian/Aptian/Albian) to Late (Cenomanian) Cretaceous marks a time of significant global transition into peak greenhouse conditions globally. Climatic conditions such as these have an immediate and direct influence on coastal locations because sea level plays a major role in sediment deposition and preservation. The Potomac Formation represents a thick wedge of coastal plain strata from North Carolina to New York (Olsson et al., 1997). Deposition of these sediments occurred from the Barremian to early Cenomanian Stages of the Cretaceous and thus provides a significant record of this climatic transition towards global greenhouse conditions.

This study incorporates three sites in the updip portion of the Delaware and New Jersey coastal plains targeting the Potomac Formation (Fig. 1.1). The Fort Mott (39°36´19.956"N, 75°33´07.175"W; Delaware City U.S. Geological Survey [USGS] 7.5´ quadrangle; Fort Mott State Park, Salem County, New Jersey) and Medford (39°53´48.815N, 74°49´15.904"W; Mount Holly USGS 7.5' quadrangle; Medford Township, Burlington County, New Jersey) coreholes provide good recovery (79% and 62% respectively) of Potomac Formation sediments from New Jersey. The Summit Marina (39°32'43.31"N, 75°42'16.70"W; St. Georges USGS 7.5' quadrangle; New Castle, New Castle County, Delaware) corehole provides good recovery (70%) of Potomac Formation sediments from Delaware.

There are two primary goals of this study. The first is to provide an enhanced understanding of the coastal plain landscape response during the transition to global

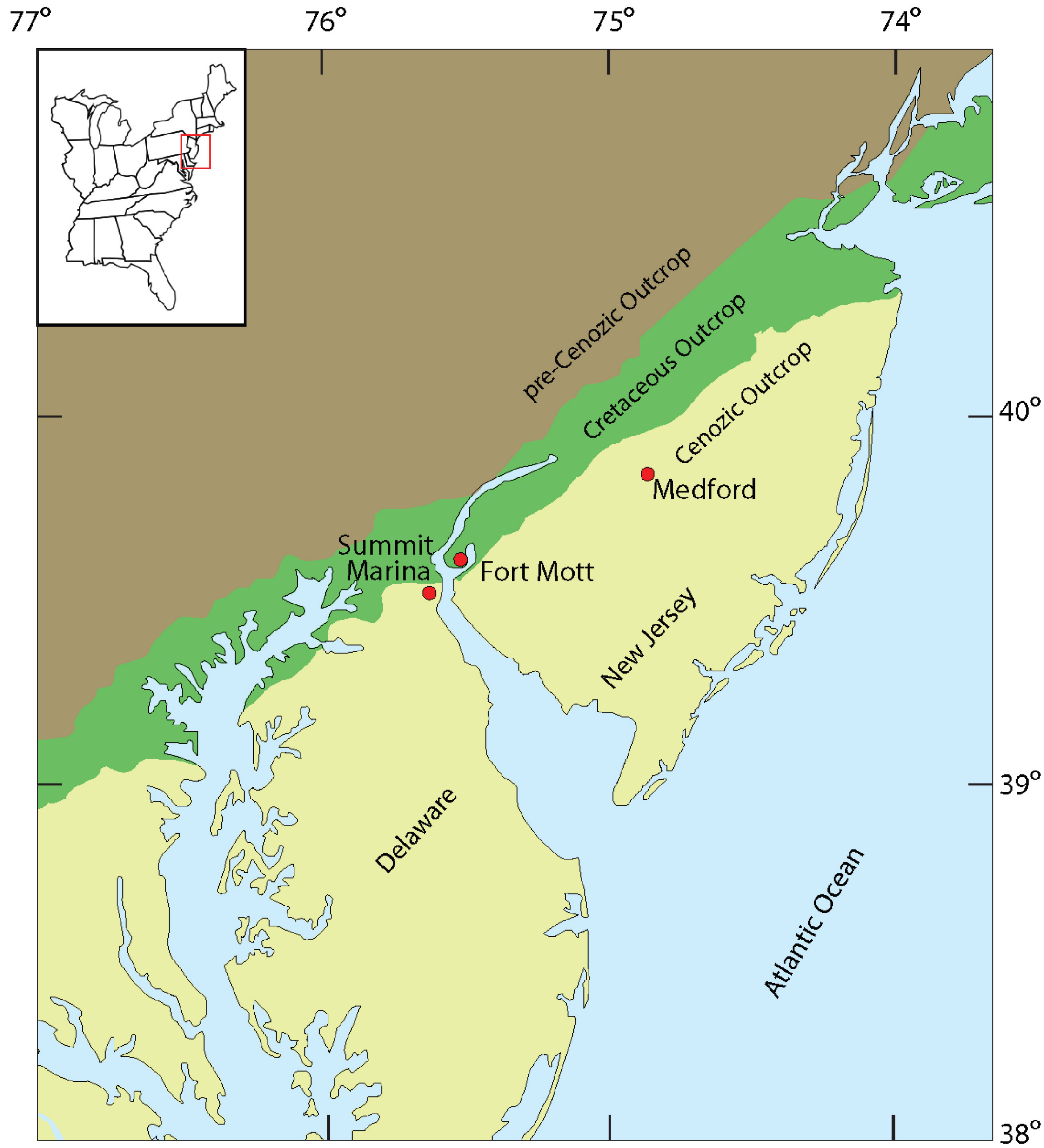

Figure 1.1 - Map of the study area in the Northeastern coast of North America. Drill sites are labeled in red (modified from Sugarman et al., 2004).

greenhouse conditions. Variability in climate or sea level influences the maturity and morphology of coastal plain soils during their formation. Evaluation of soils provides insight into the character of the landscape at different points in time and its evolution through this transition. I want to evaluate whether the climatic response of soils was steady and unchanging, changed in one direction uniformly or if changes were variable and fluctuating. Additionally, previous correlation of the Potomac Formation among sites was accomplished primarily using lithology and broad pollen zonation, with three distinct lithologic units (I, II, and III) and zones occupying large durations with coarse age resolution. Therefore, a second aim of this study is to provide a higher resolution of correlation between Potomac Formation sites, offering tie points that occur within these lithologic units.

To achieve this, the following four chapter will each address some aspect related to these goals. The chapter 2 is a major contribution towards the first goal and deals with the deposition and formation of paleosols found within the Potomac Formation. The paleosol deposits represent formation on stable portions of the landscape and their development records the landscape conditions during formation. Their formation is influenced by this landscape stability, how long they sit on the landscape subjected to pedogenic conditions, and by the drainage conditions of the landscape. Drainage is controlled both by climate (precipitation/evaporation) and base-level; in the coastal plain location base-level is tied directly to sea level. Information used from these preserved soils include the maturity and morphology. Further information was drawn from the geochemical data (measures of barium, strontium, and niobium) that offer proxies for paleodrainage and paleoprecipitation. These paleosols provide an incredible record of these landscape conditions and their progression through time, and the tools to evaluate these conditions also provide information on the major controls (base-level and climate) of these conditions.

Chapter Three looks at a secondary aspect of this project to see if further information can be discerned from this material. Chapter Three attempts to analyze palynological material from these sediments. The goal of this chapter was to attempt a higher resolution of correlation between corehole sites using spore and pollen diversity patterns. To this end the amount of Monocots-Magnoliids, and Eudicots were identified, and the ratio between which were used to try and correlate. An attempt was also made to link diversity of spore and pollen types to landscape conditions.

Chapter Four is the second major contribution of this work. This chapter synthesizes paleosol and geochemical data from Chapter One and uses a sequence stratigraphic paradigm developed for fluvial settings by Atchley et al. (2004, 2013). The paleosol deposits and associated fluvial sands were grouped into fluvial sedimentary packages known as fluvial aggradational cycles (FACs; sensu Atchley et al., 2004). The stacking patterns of these packages are analyzed to determine changes in accommodation and base level. By applying this method, I interpret a potential means of identifying systems tract equivalents and higher order sequence boundaries (few Myr scale). This sequence stratigraphic framework creates a more complete regional picture of landscape and climate evolution through time as well as offering the potential for higher order correlation among Potomac Formation sites.

Chapter 2

Paleopedology and Landscape Reconstruction of the Early to Late Cretaceous Atlantic Coastal Plain

Abstract

Potomac Formation paleosols were identified and described from three coreholes in New Jersey and Delaware to interpret the depositional history and reconstruct the regional landscape, as environmental and climatic conditions changed through the transition from Early to Late Cretaceous. In total, 103 identified paleosol profiles were described and grouped into five pedotypes ranging in pedogenic maturity: 1) weakly developed, immature soils formed under poor drainage conditions; 2) moderately developed soils formed under alternating wet/dry conditions; and 3) well-developed, mature soils formed under well drained conditions. We use a morphology index and two geochemical proxies (Nb and Ba/Sr) to provide further information on paleoprecipitation, lessivage, and drainage conditions. A conceptual model is developed linking the Nb paleoprecipitation proxy and Ba/Sr drainage proxy to determine landscape changes as a result of paleoclimate versus base level. Potomac Formation Unit I (Barremian to lower Albian) displays varying dry to wet conditions up section from the unit base. Paleoprecipitation was the main control on the formation of these paleosols. Unit II (lower Albian to lower Cenomanian) and III (lower Cenomanian) have similar wet and dry conditions upsection through both units. Paleoprecipitation played a role lower in Unit II although upsection base level exerts more influence on landscape conditions. The morphology index and geochemical proxies provide evidence that Unit I was sub-humid with episodes of saturation and overall drier

conditions relative to overlying units. Units II and III were deposited under wetter conditions, experiencing sub-humid to humid conditions, with episodes of drying. The use of these proxies matches the interpretations made using the macro- and micro-features of the paleosols, and emphasizes that the main environmental control on landscape development during this period was base-level with climatic factors having a secondary influence.

2.1 Introduction

Paleosols record nonmarine environmental and climatic information during their formation (Kraus, 1999). Soil formation is a function of contemporaneous physical, chemical, and biological processes, and is controlled locally by climate, organisms, relief, parent material, and exposure time; these factors influence the morphology, maturity, mineralogy and chemistry that are preserved in a paleosol (Jenny, 1941; Kraus, 1999; Retallack, 2001). An understanding of paleosols and by extension the processes that led to their formation provide insight into how the landscape of a region evolved.

This study identifies and analyzes nonmarine sediments from the mid-Cretaceous Potomac Formation of the New Jersey and Delaware coastal plain. This includes targeting paleosols that act as sensitive climate and landscape proxies. The Potomac Formation was deposited during a period where the global climate was significantly warmer than present (Francis and Frakes, 1993). The goal of this study is to understand the landscape response under these conditions as any variability in climate or sea level will influence the formation of coastal plain paleosols. This will provide insight into the character of this landscape and its evolution through time to understand if it was steady and unchanging, changed in one direction uniformly or if changes were variable and fluctuating.

The mid Cretaceous has been described through proxy evidence as being a greenhouse world with high levels of atmospheric CO_2 (2-10x present CO2), high average global temperatures (~6°C higher than present), high global sea-level, with an enhanced north to south atmospheric heat transport that influenced the North American hydrologic cycle (Barron, 1983; Berner, 2006, 2009; Royer et al., 2004; Ufnar et al., 2004; White et al., 2001; Haq, 2014; Miller et al., 2005; Suarez et al., 2011; Spicer and Corfield, 1992; Wolfe and Upchurch, 1987). Previous studies of palynology and leaf morphology indicate warmth and provide evidence that the Atlantic Coastal Plain was at times a sub-humid to humid, sub-tropical environment (Doyle and Hickey, 1976; Hickey and Doyle, 1977).

The transition from late Early Cretaceous into early Late Cretaceous was a period of continental realignment including the early connection between the northern Atlantic and southern Atlantic basins that created new regional circulation patterns (Scotese et al., 1988; Poulsen, 1999; Norris et al., 2002). Altered circulation patterns are significant because oceanic circulation is one of the major controls on atmospheric conditions and climate (Poulsen, 1999; Norris et al., 2002). Changes in both landmass and oceanic geometry and position must certainly have played a central role in determining climate during this period; this changing climate was recorded in the Potomac Formation sediments from this period.

The Cretaceous Western Interior Seaway (KWIS) had a significant effect on continental climate, with a potentially great latent heat transport capacity by atmospheric water vapor (Poulsen et al., 1999; Ufnar et al., 2004a). Increased atmospheric latent heat transport would have transferred heat from the equator to pole and reduced the temperature gradient (Poulsen et al., 1999; Ufnar et al., 2004a). This increased latent heat flux would also explain the intensified hydrologic cycle (increased rainout) that is recorded in sediments found along the former coast of the WIS, including proxy constrained models that give mid- and high-latitude WIS coastal precipitation rates of 2600-3300 mm/yr and 560 mm/yr respectively (Poulsen et al., 1999; Ufnar et al., 2001, 2004b). Features preserved within paleosols record changes in precipitation/evaporation and Potomac Formation paleosols should offer insight into whether an intensified hydrologic cycle also occurred along the eastern margin of North America.

A likely factor in the Cretaceous greenhouse climate is increased atmospheric CO_2 (2-10 times present atmospheric level), that has been inferred from carbon isotopic data and both carbon-climate and general circulation models (Berner, 1991, 1994; Berner and Kothavala, 2001; Royer et al., 2001; Freeman and Hayes, 1992; Cerling, 1991; Bice and Norris, 2002). However, proxy data from stomatal densities/indices, $\delta^{13}C$ values from haptophytic algae, and $\delta^{11}B$ values from marine carbonates indicate that atmospheric CO_2 during the Early Cretaceous was more variable than the consistently high levels previously inferred (Royer, 2006). If CO_2 levels were the controlling factor of global mean temperature, then these latter proxies indicate that climate may have been variable during this period (Royer, 2006). Evidence of this variability has been observed in the Aptian by Royer (2006) and Dumitrescu et al. (2006) in ancient Pacific SSTs, where temperatures averaged 20-26^{o} C, but include two prominent drops of up to 4^{o} C. This instability led to short term glacio-eustatic controls on sea level, supported by short, rapid fluctuation in the sea-level record (Stoll and Schrag, 2000; Miller et al., 2003, 2004, 2005b). Variability in both climate and sea level would have an impact on North American Coastal Plain and evidence of this should be preserved in the Potomac Formation sediments.

A single preserved paleosol provides a wealth of information regarding the conditions during its formation; a vertical succession of multiple preserved paleosols from a single core allow trends to be discerned at a particular location through time. Vertical changes in paleosol profiles provide information on the balance between pedogenesis, sedimentation, and erosion. Weakly developed stacked thin profiles form compound paleosols that develop on unstable landscapes with rapid sedimentation. Thick, more mature profiles develop on stable landscapes and form cumulative or composite paleosols. The identification, analysis, and correlation of paleosol profiles can be used to reconstruct the climate and landscape, including changes in base-level. This study incorporates data from coreholes in 3 locations recovered from the Atlantic Coastal Plain in New Jersey and Delaware to determine local changes from those changes that are regional in scope. Ultimately, the aim of this study is to further enhance understanding of coastal landscape response to changes through time as global conditions moved towards peak greenhouse conditions.

This study uses a multi-proxy approach. This includes describing the general morphology of the paleosols to infer the conditions of soil formation, as well as two geochemical climofunctions to expand on these interpretations. Each proxy individually has limits and associated uncertainty. Disagreements among these proxies and associated paleosol type reflect these limitations. When used together in a multi-proxy approach, they provide a more complete representation of the landscape and its evolution through time. The general paleosol morphology was also used in an index as a proxy for paleoprecipitation. The geochemical analyses measured niobium (Nb), which acts as a proxy for paleoprecipitation and the ratio of barium to strontium (Ba/Sr) that acts as a proxy for the overall drainage condition during soil formation. One advantage of using multiple proxies is the ability to reveal variation within paleosols that are grouped into the same general morphology type. Subtle changes in drainage and precipitation can be accounted for even if this is not apparent in the paleosol morphology. Here, we use Nb and Ba/Sr to discriminate between wet/dry conditions attributed to changes in mean annual precipitation (MAP) from those attributable to base level rise and fall. Our conceptual model is based on the assumption that a waterlogged soil mainly influenced by precipitation should have high Nb values that correspond to high MAP. This is in contrast to a waterlogged soil resulting from a rise in base level not from precipitation will only be reflected by lower Ba/Sr values and not a rise in Nb values. When these two proxies are in agreement it would suggest that precipitation is influencing the drainage conditions, wetting/drying resulting in poor/good drainage. When there are changes in Ba/Sr with opposing or no changes in Nb then it is possible that this variation in drainage is due to changes in base level: rising/falling base level results in good/poor drainage (Fig. 2.1).

2.2 Background

The Coastal Plain Drilling project (Ocean Drilling Program (ODP), Leg 174A), drilled a series of onshore continuous coreholes in New Jersey and Delaware to study the sea-level history of the past 110 My (Fig. 1.1; Browning et al., 2008; Miller et al., 2005a). As part of this program, the Fort Mott (39°36′19.956"N, 75°33′07.175"W; Delaware City U.S. Geological Survey [USGS] 7.5′ quadrangle; Fort Mott State Park, Salem County,

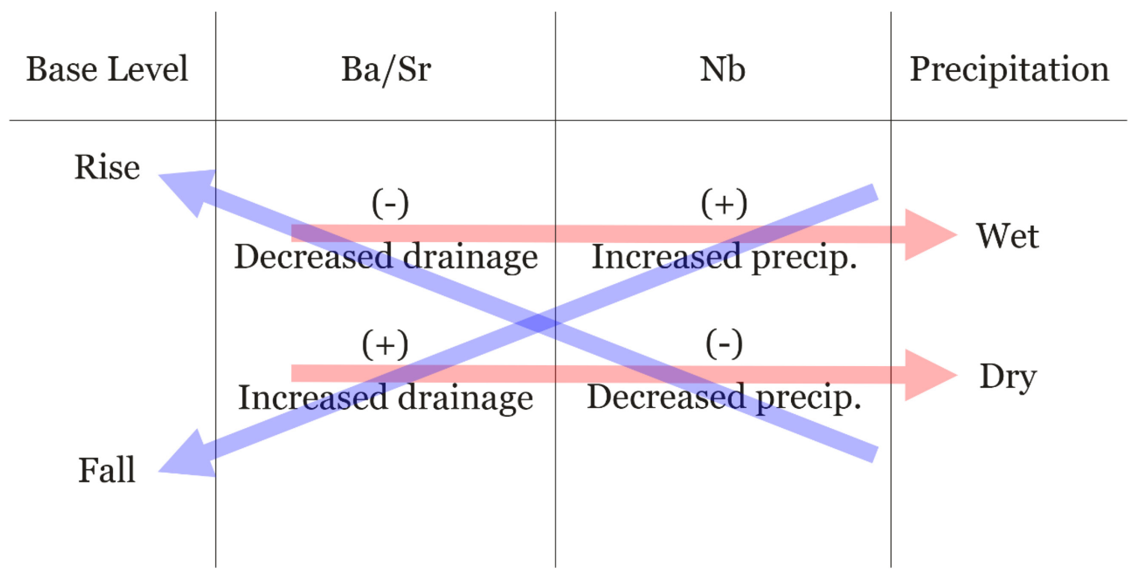

Figure 2.1 - Conceptual Model of geochemical paleosol proxies on the influence of climate vs. base level on the paleolandscape. Increased Nb values corresponding to decreased Ba/Sr values results from increased paleoprecipitation. Decreased Nb values corresponding to Ba/Sr values results from high base level conditions. Nb = niobium, Ba = barium, Sr = Strontium.

New Jersey) and Medford (39°53′48.815N, 74°49′15.904”W; Mount Holly USGS 7.5’ quadrangle; Medford Township, Burlington County, New Jersey) coreholes provide good recovery (79% and 62% respectively) of Potomac Formation sediments from New Jersey (Fig. 1.1; Browning et al., 2008; Sugarman et al., 2004; Sugarman et al., 2010). The Summit Marina (39°32'43.31"N, 75°42'16.70"W; St. Georges USGS 7.5’ quadrangle; New Castle, New Castle County, Delaware) core was drilled in 2009 by the Delaware Geological Survey, and provides good recovery (70%) of Potomac Formation sediments from Delaware (Fig. 1.1). These three sites were chosen to assess changes in local conditions between two closely spaced sites (Summit Marina and Fort Mott) with a more distant site (Medford) to distinguish those changes that are likely regional in nature.

The Atlantic Coastal Plain contains Lower Cretaceous to Holocene strata where deposition was controlled by a combination of changes in sea-level and subsidence (Olsson et al., 1988; Kominz et al., 1998; Browning et al., 2008). The Potomac Formation, found at the base of this section, is composed of fluvial/deltaic sediments of interbedded fine to medium sands, described at Fort Mott and Medford by Sugarman et al. (2004, 2010) as channel sands, and clay-rich sediments described at Fort Mott and Medford by Sugarman et al. (2004, 2010) as paleosols, deposited during the transition from the Early to Late Cretaceous (Barremian-Aptian-Albian-Cenomanian). The Potomac Formation found in these cores is underlain unconformably by crystalline basement rocks, and are unconformably overlain by lower delta plain/estuarine swamp sediments of the upper Turonian Magothy Formation at Summit Marina and Fort Mott and upper Cenomanian Raritan Formation at Medford (Browning et al., 2008; Sugarman et al., 2004, 2005, 2010; Zullo, 2012). The formation boundary between the Potomac and overlying units are placed using lithology and geophysical well log data (gamma and resistivity); the Potomac Formation is subdivided into three units established by the succession of lower medium to fine sand bodies overlain by finer grained clay and silt units (Sugarman et al., 2004, 2010; Browning et al., 2008).

Biostratigraphic zones were assigned using the palynological zonation developed in Cretaceous Atlantic Coastal plain continental sections (Brenner, 1963; Doyle and Robbins, 1977). Age assignments have been made using pollen and spore biostratigraphy, relying on established correlations with well-dated marine sections in England and Portugal, and placed into the establish Atlantic Coastal Plain palynological zonal framework (Brenner, 1963; Doyle and Robbins, 1977; Hochuli et al., 2006; Sugarman et al., 2005). The Potomac Formation is assigned to Zones I-III. Brenner (1963) initially established this zonation with Zones I and II; it was expanded by Doyle and Robbins (1977) to include Zone III. Hochuli et al. (2006) revised these zone ages: Zone I is Aptian to early Albian, Zone II is middle Albian to early Cenomanian, and Zone III is early to middle Cenomanian.

Accommodation was high during this time due to the thermo-flexural subsidence along this margin (Kominz et al., 2008). The Potomac Formation is found along much of the Eastern United States (New York to North Carolina) and has been previously described as a thick clastic sedimentary wedge thinning east to west across the Coastal Plain towards the Piedmont (Lindholm, 1978; Benson and McLaughlin, 2006). Deposition, however, was at times a complex, locally controlled process that created deposits that vary in thickness and lithology, making some facies distinctions ambiguous and laterally discontinuous (Lindholm, 1978; Jordan, 1983; Zullo, 2012).

2.3 Methods

2.3.1 Stratigraphic Control Units

Previous studies (Sugarman et al., 2004, 2005, 2010) identified 3 distinct lithologic units (I, II, and III) in the Potomac Formation at Fort Mott and Medford, NJ. Sugarman et al. (2005) noted that these 3 lithologic units were distinct fluvial-deltaic successions with typical sands at the base and clays (typically soils) at the top. Correlation between sites was made using these defined lithologic units aided by geophysical (gamma and resistivity) logs.

Age control is entirely reliant on pollen biostratigraphy that are poorly calibrated to the Geological Time Scale (GTS) and are long in duration (3 zones in ~25 Myr). Each Potomac unit corresponds with a distinct pollen zone: 1) Unit III is placed in pollen Zone III, assigned by various authors to the early Cenomanian (Doyle and Robbins, 1977; Hochuli et al., 2006) with an age of ~96-100 Ma according to the Geological time scale 2012 [GTS2012; Gradstein et al., 2012); 2) Unit II is placed in pollen Zone II, assigned to the middle to late Albian (Doyle and Robbins, 1977), though it possibly extends to the earliest Cenomanian (Hochuli et al., 2006); the age is ~100-111 Ma (GTS2012); 3) Unit I is placed in pollen Zone I, the Aptian (Hochuli et al., 2006), though it may extend to the Barremian (Doyle and Robbins, 1977); the age is ~111-126 Ma (Fig. 2.2). Pollen is not able to discern hiatuses between the units, but Sugarman et al. (2004, 2005) used physical stratigraphy (erosional break associated with facies stacking patterns) to infer that each unit was a distinct sequence (sensu Vail et al., 1977) associated with base level falls. This implies that hiatuses occurred between deposition of the units, though the hiatuses are within the broad age resolution of pollen biostratigraphy (e.g., Units I, II, and III are at

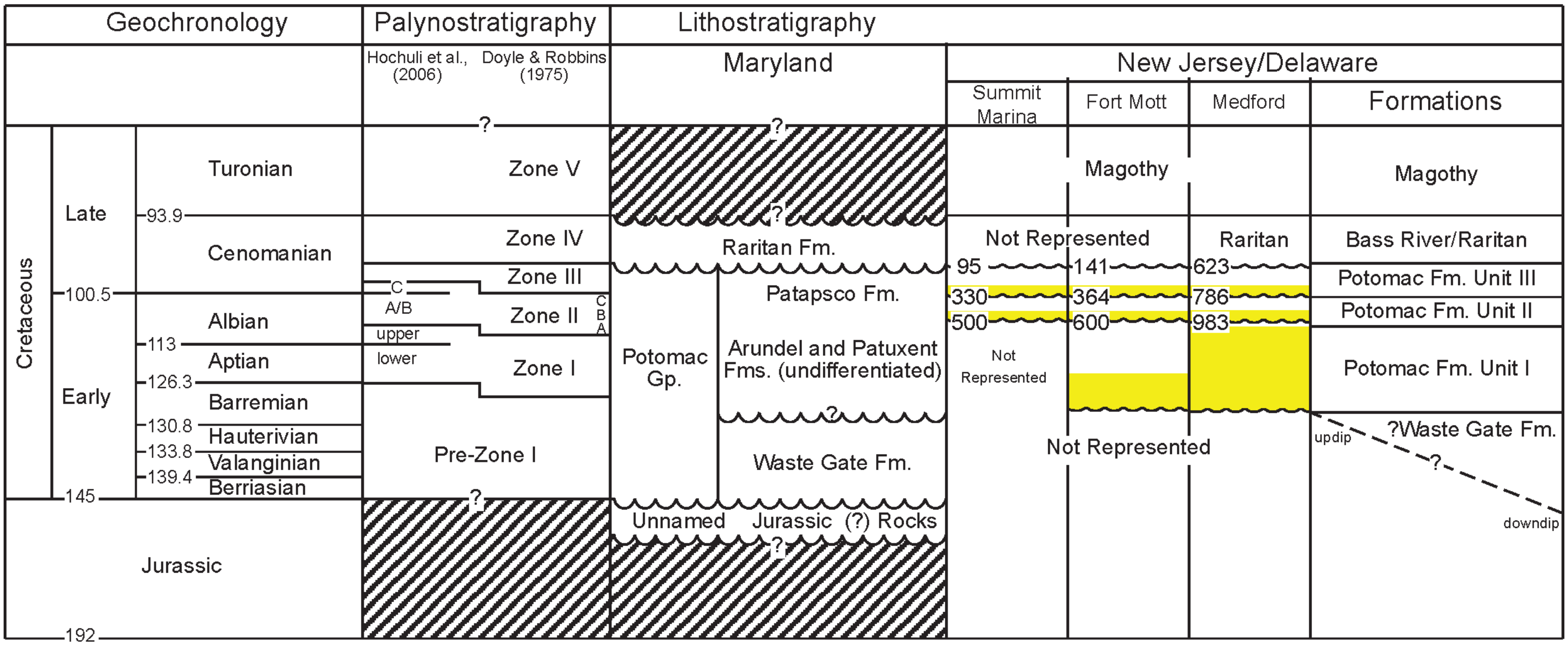

Figure 2.2 - Stratigraphic correlation chart for Potomac Formation in New Jersey and Delaware with GTS 2012 and Maryland equivalents (yellow = sands; modified from Sugarman et al., 2010 and Doyle and Robbins, 1977).

most ~15, ~10, and ~4 Myr in duration, respectively). The correlations presented below indicate similar lithostratigraphic successions (especially within Units II and III) among the three coreholes, with similar soil profiles and inferred climate change within successions; these correlations imply that the units are regional and support the inference of Sugarman et al., (2004, 2005, 2010) that Units I, II, and III are, in fact, distinct sequences. Unit I is represented at Fort Mott and Medford in fundamentally different environments (anastomosing vs. braided) and we cannot establish that this is one correlatable unit or sequence. All three sites examined here are updip and do not extend older than the ?Barremian. Downdip sites sample older units assigned to pre-Zone I (?Barremian to ?Berriasian) and to the Waste Gate Formation in Maryland (Fig. 2.2; Hansen, 1982); this unit apparently extends into Delaware and New Jersey in downdip sections (Olsson et al., 1987).

2.3.2 Core Observations

Macroscopic observations made on paleosol profiles, include grain size, ped structure, root structure, color, soil horizonation, hydro- and redoximorphic features (Fig. 2.3). Color was recorded from dry, unaltered surfaces using the Munsell System (Munsell, 2000). Horizon designation criteria (Table 2.1) modified from modern USDA Soil Taxonomy (Soil Survey Staff, 1999). All other field descriptions were made following the National Soil Survey Center field book for describing and sampling soils (Schoeneberger et al., 2002).

Soil micromorphology features were observed on oriented samples, collected and prepared at Temple University using methods outlined by Brewer (1964) (Fig. 2.4). The samples were first impregnated under vacuum with epoxy before being dry cut and polished, after which they were mounted to slides, cut and polished to a thickness of 30μm. Thin section analysis was completed to detail soil mineralogical and micromorphological features using a Nikon E600 Polarizing Microscope. Micromorphology features were defined and classified following Brewer (1964) and Fitzpatrick (1993).

All paleosols were described and grouped using a pedotype approach (after Retallack, 1994, 2001). This method of nongenetic classification focuses on an individual, representative paleosol profile and allows similar profiles to be grouped with this representative paleosol (Retallack, 1994). Pedotype grouping is used to group large numbers of paleosol profiles into a classification scheme which is based on lithology and pedogenic features including macromorphology, micromorphology, and clay mineralogy (Fig. 2.5; Tables 2.2-2.4).

2.3.3 Paleosol Morphology Index

This index uses morphological features of the paleosol to assess soil wetness and the relative drainage conditions between paleosols. This semi-quantitative method has been shown to be a proxy for paleoprecipitation (Adams et al., 2011; Kraus et al., 2013). The features evaluated include the chroma value, the presence or absence of calcium carbonate, and the presence or absence of yellow-brown ferruginous nodules. Values are assigned to these features within the B horizon, applicable if the horizon is approximately greater than 1m (See Table 2.1 for horizon designation criteria; Table 2.5). If the horizon can be subdivided based on morphologic properties then the subdivision values are multiplied by the horizon subdivision thickness, all subdivisions are summed, and then divided by the horizon thickness to provide a paleosol morphology index value (Eq. 1) (after Adams et al., 2011).

Figure 2.3 - Macroscopic paleosol features. A – Large, vertical clay-filled root trace from the A horizon of a Unit I Brown Type paleosol (Fort Mott, 780 ft). B – Bioturbation with large vertical silt filled burrows from Unit III (Medford, 644.0 ft). C – Bioturbation found within the A horizon of a Unit III Gray Type paleosol (Fort Mott, 255 ft). D – Sphaerosiderites concentrated along a root trace in the B horizon of a Unit I Red Type paleosol (Fort Mott, 765 ft). E – Bioturbation and burrow fills found in Unit III (Fort Mott, 295.5 ft). F – Large, vertical clay-filled root trace from the B horizon of a Unit III Brown Type paleosol (Summit Marina, 200 ft).

Table 2.1 - Horizon designation criteria (modified Soil Survey Staff, 1999).

Horizon	Criteria
A	When preserved will be uppermost in profile, darkened (from organics) in appearance compared with underlying horizons. Root traces are rare to common. Occasional traces of organic material preserved as charcoal or lignite.
AB	Gradual transition between A and B horizons. Darker in appearance then underlying horizons. Roots will be rare to common. Redoximorphic features that include faint to distinct mottling, drab halo root traces, and iron-staining. Occasional evidence of translocated clays. Submillimeter to millimeter scale sphaerosiderites are rare to common.
Bt	Horizon defined by the appearance of illuvial clay features. Clay films and clay lamellae are rare to few. Millimeter to centimeter scale clay-filled root traces and cracks are rare to common. Redoximorphic features. Faint to distinct mottles. Faint to distinct iron stained roots and cracks. Submillimeter to millimeter scale sphaerosiderites are rare to common.
AC	Transition between A and C horizon, with no B horizon. Faint evidence of redoximorphic features. Rare iron stained root traces. Submillimeter scale sphaerosiderites are rare to few. Faint relict bedding is rare.
BC	Transition between B and C horizon. Distinct redoximorphic features. Distinct iron stained root traces and cracks are few to common. Submillimeter to millimeter scale sphaerosiderites are rare to common. Faint relict bedding is few to common.
C	Parent material with relatively little evidence of pedogenesis. Lighter in appearance than overlying horizons. Relict bedding is common.

Diagnostic Horizons	
Argillic	Subsurface horizon accumulating clay from illuviation, evidenced by clay films, clay lamellae, and clay-filled root traces. Significant increase in clay content from overlying horizons. Thickness greater than 7.5 cm.

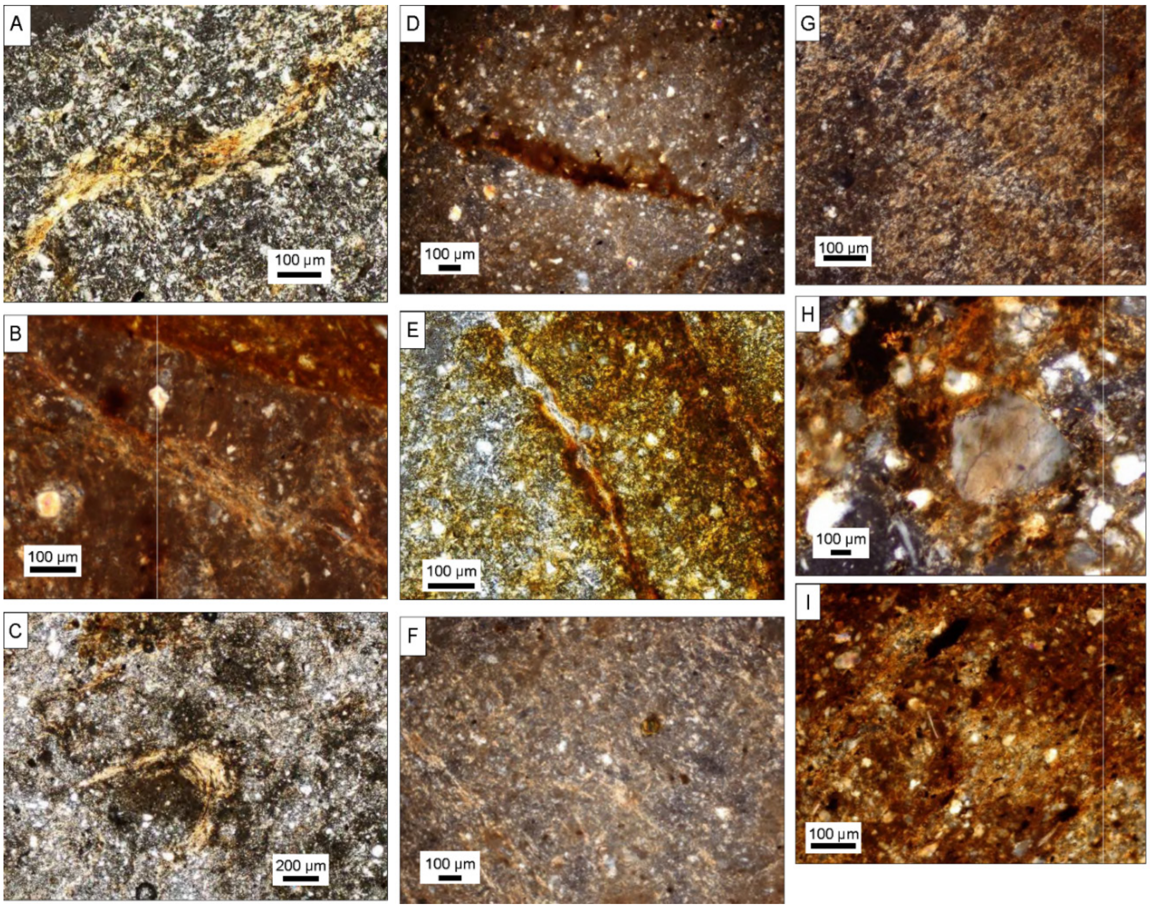

Figure 2.4 - Microscopic features observed of thin sections from corea; all photos are in cross polarized light. A, B, C – Argillans from translocation of clay are common in the B horizon of Purple, Red and Brown Type soils; 10x (A – Purple Type, Summit Marina, 380 ft; B – Red Type, Medford, 705 ft; C[20x] – Purple Type, Medford, 742 ft). D, E – Iron-staining is common, including these root traces; 10x (D – Red Type, Medford, 705 ft; E – Purple Type, Summit Marina, 380 ft). F, G – Clino-bisepic and Lattisepic clay fabrics are present in Gray-Red, Purple and Red Type paleosols, indicating wetting and drying during pedogenesis; 10x (both from a Red Type, Medford, 705 ft). H, I – Other clay fabrics, including skelsepic, masepic and random orientations, indicative of more water logged conditions are present in the Gray and Gray-Red Type paleosols; 10x (G – skelsepic in a Gray Type paleosol, Fort Mott, 475 ft; H – maesepic to random in a Gray Type paleosol, Fort Mott, 475 ft).

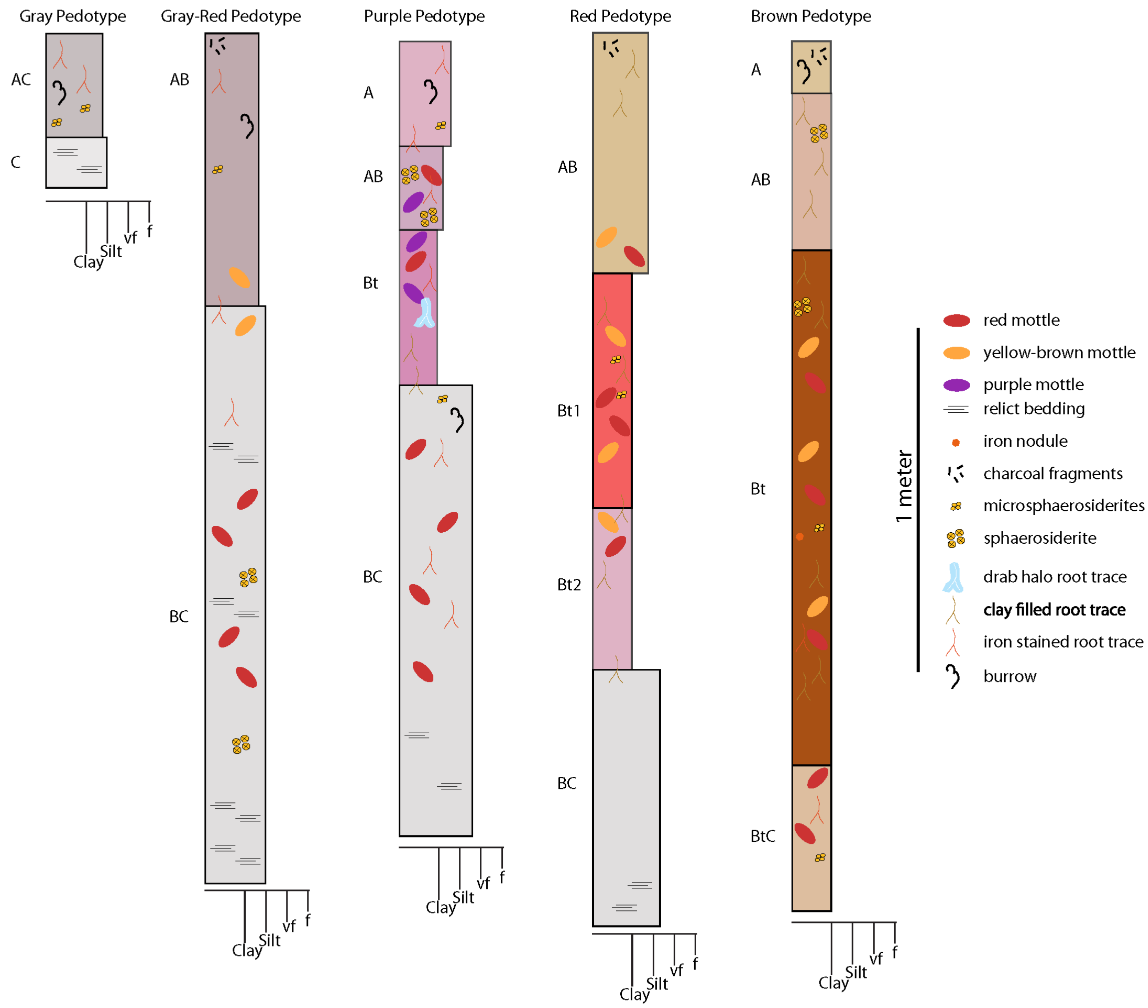

Figure 2.5 - Diagrammatic stratigraphic sections for the type paleosols of each representative pedotype.

Table 2.2 - Occurrences and classification of defined pedotypes.

Pedotype	Occurrences				Classification	Classification
	Total	Fort Mott	Medford	Summit Marina	Mack et al., 1993	USDA, 1999
Gray	19	10	2	7	Protosol	Inceptisol
Gray-Red	18	5	4	9	Gleysol	Inceptisol
Purple	24	11	2	11	Gleyed Argillisol	Alfisol
Red	32	22	3	7	Ferric Argillisol	Alfisol
Brown	10	4	1	5	Argillisol	Alfisol
Total		52	12	39		

Table 2.3 - Description of type paleosol horizons for each defined pedotype, including relevant macro- and micromorphological features and dominant clay mineralogy.

Pedotype	Type Profile and Depth	Horizon, Boundary and Depth (cm)		Dominant Color	Subordinate Color(s)	Macromorphology	Micromorphology	Dominant <2 um clay mineralogy
Gray	Fort Mott 50.29m (165ft)	AC	0 – 30.5	10YR 6/6	10R 4/6	Fairly featureless Few, faint root traces	Clino-Bisepic to Masepic clay fabrics	Kaolinite Illite Quartz
		Diffuse						
		C	30.5 – 48.8	N7				
Gray-Red	Fort Mott 54.86m (180ft)	AB	0 – 70.1	10YR 5/4	10R 7/4 10YR 8/2	Few faint to distinct fine to medium mottles – light brown to light red Redoximorphic features including: zones of iron concentrations	Iron Staining Clino-Bisepic to Masepic clay fabrics	Kaolinite Illite Quartz
		Gradual						
		BC	70.1 – 243.8	5R 3/4	5P 6/2 N8			

Table 2.3 (cont.)

Purple	Summit Marina 128.02m (420ft)	A	0 – 30.5	5Y 8/1	2.5Y 8/2 10R 4/6	Many prominent coarse to extremely coarse mottles – red and purple in color Many iron stained root traces Sphaerosiderites present	Clino-Bisepic and lattisepic clay fabric Iron Staining	Kaolinite Illite Quartz Goethite
		Clear/Wavy to Irregular						
		AB	30.5 – 54.9	5Y 8/1	10R 4/6 10R 7/3			
		Clear/Smooth						
		Bt	54.9 – 100.6	10R 4/6	10R 7/3 10R 7/4			
		Gradual/Wavy						
		BC	100.6 – 231.7	10R 7/3	10R 4/8 5Y 4/3			
Red	Fort Mott 70.10m (230ft)	AB	0 – 45.7	5Y 6/1		Many prominent coarse to extremely coarse mottles – red in color Many iron stained and clay filled root traces Sphaerosiderites present	Clino-Bispeic and lattisepic clay fabric Translocated clay	Kaolinite Illite Quartz Goethite
		Clear/Wavy						
		Bt1	45.7 – 112.8	5Y 8/1	10YR 7/4			
		Gradual/Smooth						
		Bt2	112.8 – 271.3	5R 4/6	5Y 6/1			
		Gradual/Smooth						
		BC	271.3 – 329.2	10YR 8/2	5R 3/4 5P 4/2			

Table 2.3 (cont.)

Brown	Medford 259.08m (850ft)	AB	0 – 45.7	2.5YR 4/6	10YR 8/3	Many prominent coarse to extremely coarse mottles – brown and red in color	Clino-Bisepic clay fabric	Kaolinite
		Clear/Smooth					Translocated clays	Goethite
		Bt	45.7 – 289.6	2.5YR 4/6	10R 4/6 5Y 6/1	Many clay filled root traces		
		Clear to Gradual						
		CB	289.6 – 332.2	2.5YR 4/6	10YR 7/1 10R 4/6			

Table 2.4 - Description of diagnostic features for the defined pedotypes.

Pedotype	Horizonation	Development/Maturity	Rooting	Other
Gray	Diffuse to Absent	Very Weak	• Small, Fine • Occasional drab halos	
Gray - Red	Diffuse to Gradual	Weak to Moderate	• Small, vertical • Clay-filled • Fe-stained	• Occasional sphaerosiderite • Few to common mottles
Purple	Clear	Moderate	• Fine, horizontal mats • Fe-stained • Drab halos	• Many, coarse mottles • Common Fe-staining • Common Sphaerosiderites
Red	Clear	Moderate to Well	• Small, vertical • Clay-filled	• Common fine to medium mottles • Occasional Fe-staining • Occasional Sphaerosiderites
Brown	Clear	Moderate to Well	• Small, vertical • Clay-filled	• Many, medium to coarse mottles

$$\text{Morphology Index} = \left(\frac{\sum(\text{Subdivision Chroma x Subdivision thickness})}{\text{Horizon thickness}}\right) + \left(\frac{\sum(\text{Subdivision properties value x Subdivision thickness})}{\text{Horizon thickness}}\right)$$

Eq. 1

Table 2.5 - Determined morphology index values, lower values correspond to wet conditions, higher values correspond to dry conditions (FM = Fort Mott; SM = Summit Marina; MT = Medford.

Soil ID	Index Value	Soil ID	Index Value	Soil ID	Index Value
SM110	5.3	FM152	7.0	MT690	5.2
SM160	4.3	FM170	8.1	MT700	2.5
SM165	5.0	FM180	2.4	MT705	4.2
SM170	4.5	FM190	6.7	MT742	6.1
SM195	3.7	FM220	7.7	MT747	4.1
SM200	7.1	FM230	7.5	MT790	4.5
SM220	2.3	FM250	5.9	MT795	5.0
SM230	1.5	FM260	5.9	MT800	4.0
SM285	4.6	FM270	7.0	MT850	3.5
SM345	4.7	FM370	5.3	MT955	6.9
SM352	4.7	FM380	6.0		
SM365	7.9	FM415	5.2		
SM375	5.2	FM510	4.4		
SM380	6.4	FM520	7.8		
SM385	4.3	FM530	5.9		
SM420	6.3	FM540	4.0		
SM430	3.9	FM550	8.6		
SM445	10.1	FM615	5.3		
SM450	4.9	FM660	8.3		
SM460	6.9	FM670	3.6		
SM480	7.5	FM680	4.8		
		FM685	5.6		
		FM700	2.3		
		FM705	2.6		
		FM725	4.8		
		FM730	6.0		
		FM760	5.7		
		FM780	4.1		
		FM790	2.7		

Chroma values were described using the Munsell color charts on dry samples, and range from 1-6, with lower chroma values corresponding to wetter paleosols. Paleosol color has been used previously to identify poorly drained versus well drained conditions, and although post-burial alteration does occur, relative differences should remain apparent (Driese and Ober, 2005).

The presence of ferruginous nodules is scored as 0 for common to abundant nodules, 3 when common to sparse, and 6 when absent; the presence of these nodules indicates soil under more saturated conditions. Calcium carbonate which is present commonly under drier conditions has an inverse scoring, with 0 when absent, 3 when there are small (<mm) rhizoliths and 6 for larger (>mm) nodules.

2.3.4 Clay mineralogy

Clay minerals were identified via X-ray diffraction (XRD) pattern analysis using a Rigaku DMAX/B horizontal diffractometer at Temple University. Samples were run for analysis at 35 kV and 15 mA using CuKα radiation, scanning from 2-40^{o} 2θ at a rate of 1.2^{o} per minute. Data were then processed with Material Data Incorporated's (MDI) Jade 9.1 powder diffraction data analysis acquisition software. Pattern peaks were identified using the International Center for Diffraction Data (ICDD) XRD patterns. A quartz standard was used at the start and finish of each run for quality control producing characteristic 2θ peaks at 20.8° and 26.6°. Each sample was analyzed twice: once when untreated and once when glycolated. Glycolated samples were prepared in a desiccator with ethylene glycol for at least 24 hours to remove ambient environmental effects and allow the distinction between swelling and non-swelling clays.

A total of 25 samples were processed for XRD analysis, this includes a representative sample from the every horizon of each pedotype (Fig. 2.6). The clay fraction (<2 μm) of each sample was prepared by disaggregation of bulk materials by soaking in a bath of deionized and distilled water. Disaggregated samples were then spun down by centrifuge at 500 RPM for 12 minutes to separate the clay-sized fraction. The samples were then removed using a Millipore® Filter Transfer Method prescribed by Moore and Reynolds (1997) and mounted on a glass slide.

2.3.5 Bulk Geochemistry

The geochemistry, specifically Niobium (Nb) and ratio of Barium to Strontium (Ba/Sr), of the paleosol profiles was measured to provide to proxy record of paleoprecipitation, and leaching/drainage conditions (Kahmann, 2008; Retallack, 2001; Sheldon and Tabor, 2009).

Bulk samples of 100 g were taken from B horizons (multiple samples for thicker horizons) of 88 samples from 44 profiles for geochemical analysis by x-ray fluorescence (XRF) (Table 2.6). Samples were dried, ground using an agate mortar and pestle to create a uniform size, split using a micro-splitter to avoid density sampling bias, and placed into 32 mm XRF sample cells and covered with 6 μm Mylar® X-Ray film. Three lab standards (SiO2 180-428; RCRA As, Ba, Cd, Se, Ag 180-436; NCS 73308 180-600) were used as quality control to ensure the proper calibration of the XRF instrument. Precision was routinely between 0.01-0.1% of reported values. Major, minor and trace elements (Barium, Strontium, Niobium, Rubidium, Bismuth, Arsenic, Selenium, Lead, Tungsten, Zinc, Copper, Nickel, Cobalt, Iron, Manganese, Chromium, Vanadium, Titanium, Calcium, Potassium, Aluminum, Phosphorous, Silicon, Chlorine, Magnesium) within each sample

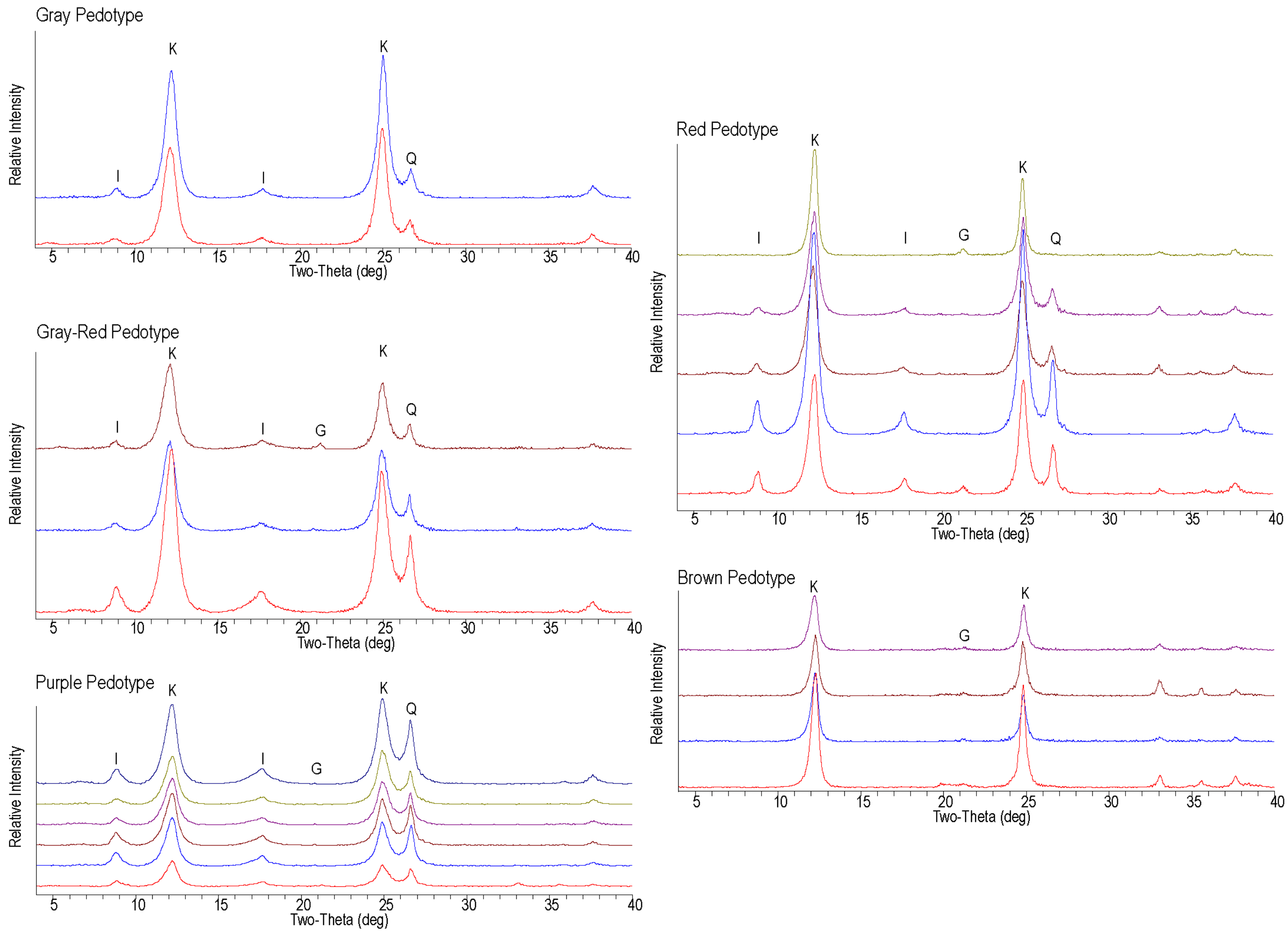

Figure 2.6 - X-ray diffraction patterns of represented paleosols for each pedotype. Patterns are from glycolated samples and stacked according to relative depth in the profile, with lower horizons at the base of the overlay. K = Kaolinite, I = Illite, G = Goethite, Q = Quartz.

Table 2.6 - Calculated geochemical proxy values; lower Ba/Sr values correspond to decreased leaching, higher values correspond to increased leaching; lower Nb values correspond to increased paleoprecipitation, lower Nb values correspond to decreased paleoprecipitation. All values reported in ppm (FM = Fort Mott; SM = Summit Marina; MT = Medford).

Soil ID	Nb	Ba/Sr	Soil ID	Nb	Ba/Sr	Soil ID	Nb	Ba/Sr
SM110	24.3	3.9	FM170	29.1	2.5	MT690	28.6	1.9
SM160	26.5	5.5	FM180	24.5	2.2	MT705	32.2	2.6
SM165	24.6	5.4	FM190	26.7	3.8	MT742	27.4	1.4
SM170	29.6	2.2	FM210	30.5	2.1	MT747	26.9	2.9
SM200	21.3	3.8	FM250	23.7	4.2	MT790	28.7	1.7
SM345	20.8	7.2	FM260	23.5	2.1	MT795	27.1	2.3
SM365	23.8	3.3	FM270	23.9	3.0	MT800	32.8	1.6
SM385	25.8	4.2	FM315	27.0	2.5	MT850	22.6	3.4
SM420	24.7	2.5	FM370	24.5	1.7			
SM440	26.2	4.4	FM380	25.7	2.0			
SM445	25.8	3.5	FM395	23.3	1.7			
SM460	21.0	2.1	FM415	34.1	1.8			
SM480	29.3	2.5	FM510	29.1	1.8			
			FM520	23.2	2.8			
			FM530	23.5	2.9			
			FM540	29.9	1.3			
			FM650	31.1	1.0			
			FM700	20.4	2.0			
			FM705	25.0	1.0			
			FM730	17.0	6.0			
			FM750	27.2	5.4			
			FM760	30.3	1.4			
			FM770	17.9	6.4			
			FM780	21.6	5.9			

were measured in triplicate using XRF analysis with a bench mounted Thermo Niton XL3t-900 in a shielded lab stand at Temple University and purged with Helium (He) gas to decrease signal attenuation.

2.3.6 Compaction

Compaction of paleosols was accounted for and determined using the method of Sheldon and Retallack (2001). This method developed the following equation to determine total compaction (C) paleosols from original thickness. This equation as follows:

$$C = -S_i/[(F_0/e^{Dk})-1] \tag{eq. 2}$$

Where S_i represents the initial solidity, F_0 the initial porosity, D the burial depth in km and k a curve fitting constant (determined from the relationship between initial and burial porosities (Sheldon and Retallack, 2001). Compaction varies based on soil type, in the case of this chapter, Alfisols and Inceptisols, and uses predetermined values from Sheldon and Retallack (2001) and Soil Survey Staff, (1999).

2.4 Results

A total of 103 paleosols were identified and described across the three sites. At Fort Mott, 52 total profiles were identified; 19 in Unit III, 12 in Unit II, 1 in Unit I/II, and 20 in Unit I (Figs. 2.7, 2.8; Appendix 1-2). At Summit Marina, 39 total profiles were identified; 15 in Unit III, and 24 in Unit II (Figs. 2.7, 2.9; Appendix 1-2). At Medford, 12 total profiles were identified; 6 from Unit III and 6 for Unit II (Figs. 2.7, 2.10; Appendix 1-2).

2.4.1 Pedotypes

Five pedotypes were defined from the Potomac Formation in this study: Gray, Gray-Red, Purple, Red and Brown. The Gray Type and Gray-Red Type of paleosols are Protosols, similar to modern Inceptisols, with weak horizon development (A and C with occasional development of a B horizon in the Gray-Red Type) reflecting rapid formation from parent material (Tables 2.2-2.4; Mack et al., 1993; Retallack, 2001; Soil Survey Staff, 1999), The Purple, Red, and Brown Type paleosols are Argillosols, similar to modern Alfisols, that formed over a longer period of time (Tables 2.2-2.4; Mack et al., 1993; Retallack, 2001; Soil Survey Staff, 1999).

The Gray Type of paleosol was identified in cores at all three sites [Fort Mott (n=10), Summit Marina (n=7), and Medford (n=2)]. This pedotype is the least mature with little pedogenic modification, including initial weak horizonation, and few, faint to distinct, small (mm-scale) mottling (Fig. 2.5; Table 2.4). This weakly developed soil displays features of water-logged, poor-drainage conditions including drab halo root traces, low chroma values (ranges between 0-4), skelsepic and masepic clay fabrics, and iron nodules as well as microsphaerosiderites that are found in several of the profiles of this type (Figs. 2.3-2.5).

The Gray-Red Type of paleosol has increased pedogenic modification relative to the gray type, with more distinct horizonation, including the development of a BC horizon [Summit Marina (n=9), Fort Mott (n=5), and Medford (n=4)]. However this type is still weakly developed overall (Fig. 2.5; Table 2.4).

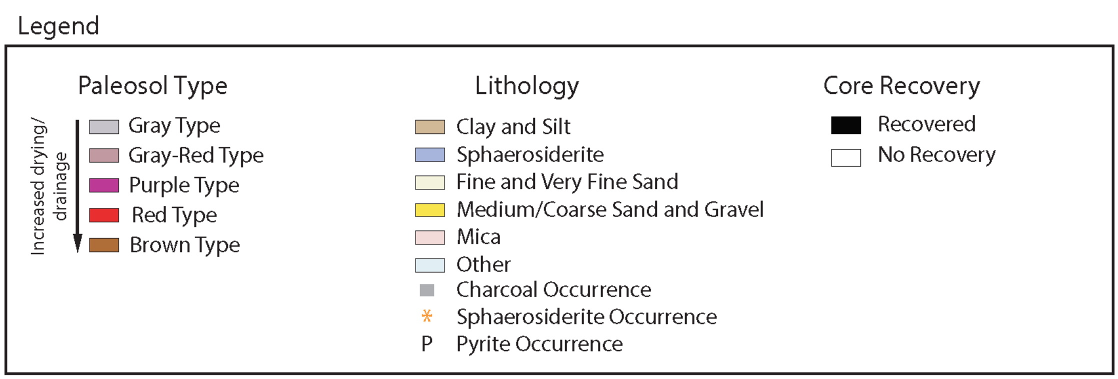

Figure 2.7 - Legend for corehole figures 2.8-2.10.

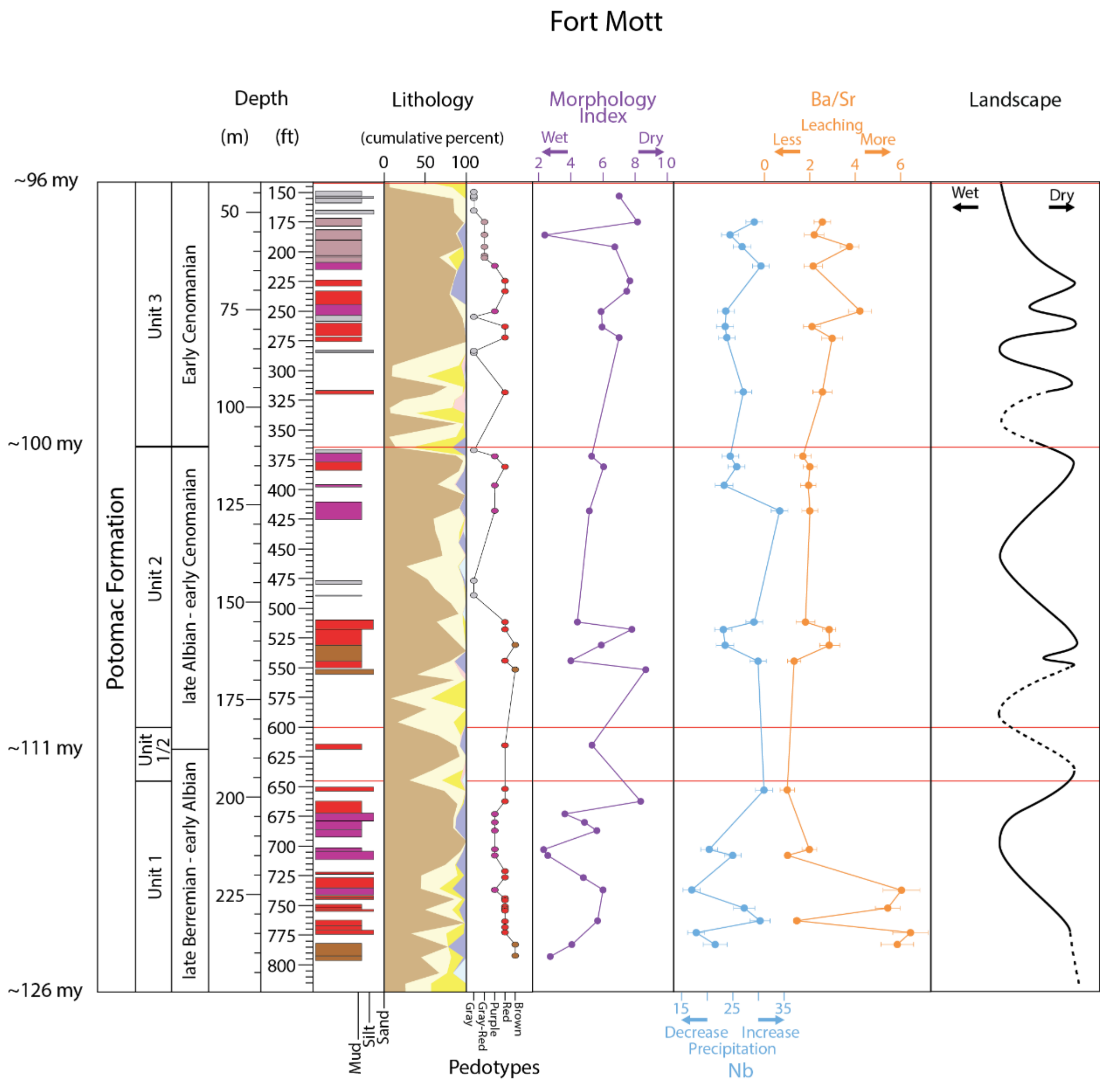

Figure 2.8 - Fort Mott - Cumulative lithology, gamma, resistivity, paleosol pedotype, paleosol morphology index, Niobium, and Barium/Strontium ratio distribution for the Potomac Formation.

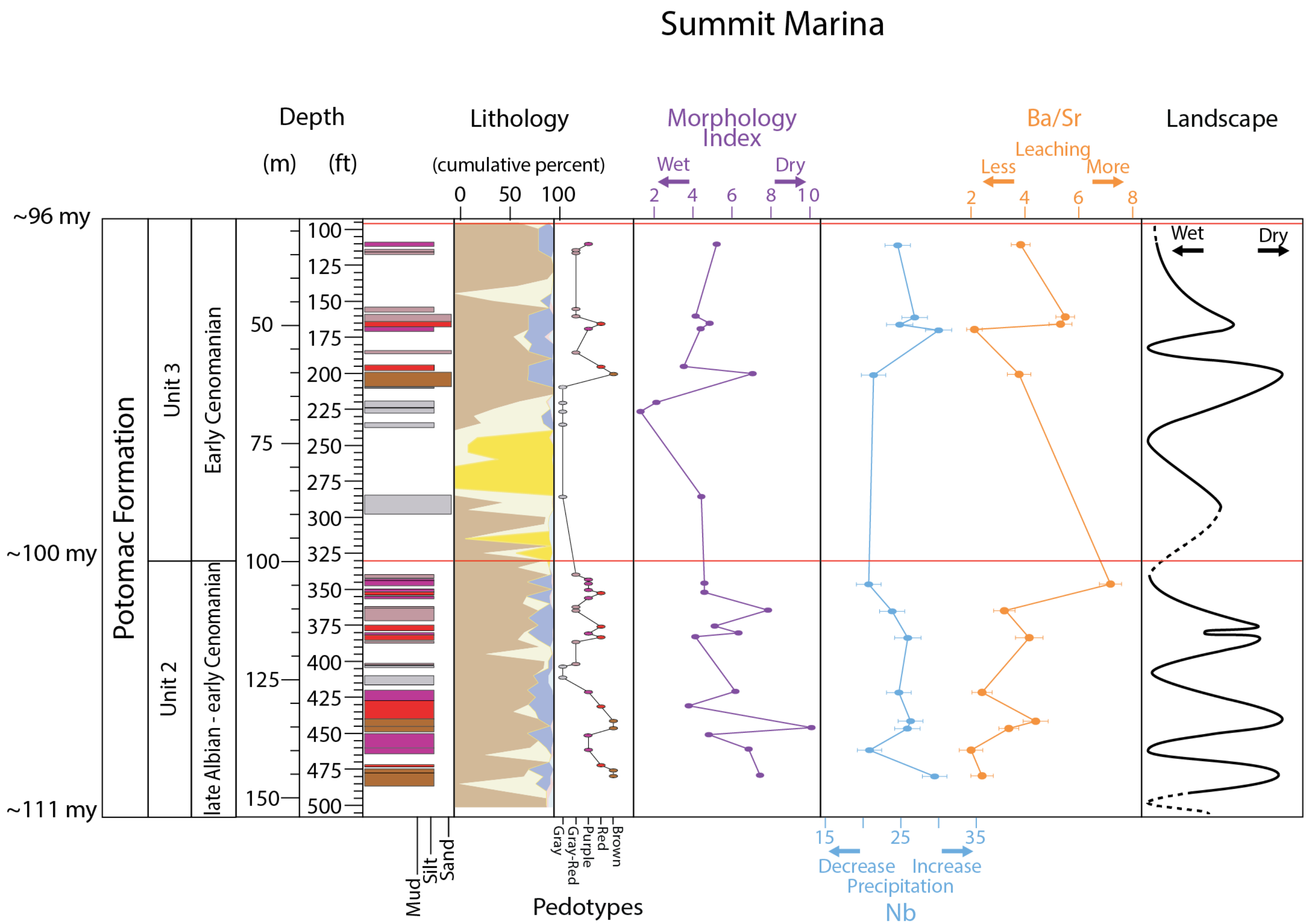

Figure 2.9 - Summit Marina - Cumulative lithology, gamma, resistivity, paleosol pedotype, paleosol morphology index, Niobium, and Barium/Strontium ratio distribution for the Potomac Formation.

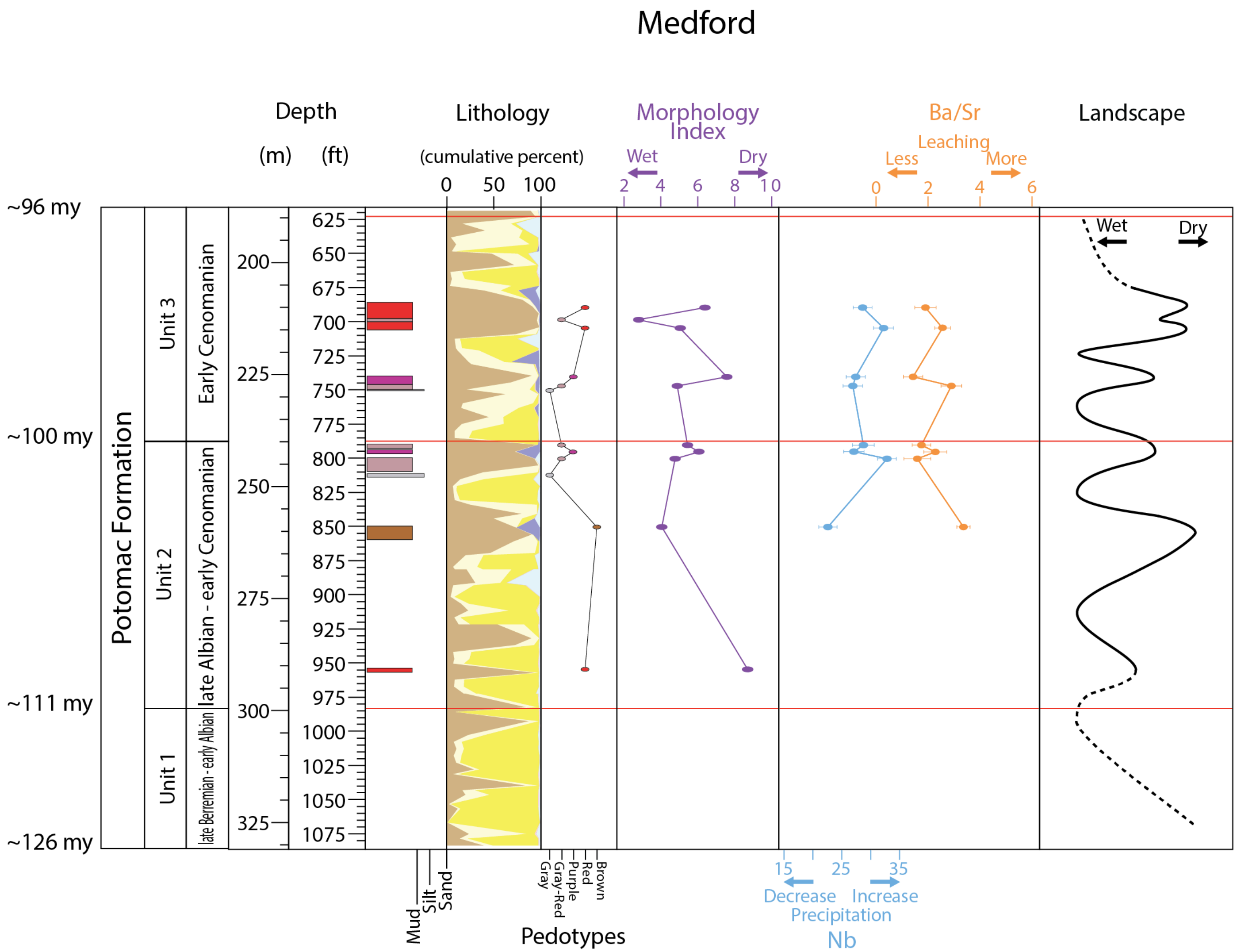

Figure 2.10 - Medford - Cumulative lithology, gamma, resistivity, paleosol pedotype, paleosol morphology index, Niobium, and Barium/Strontium ratio distribution for the Potomac Formation.

Pedogenic development features include higher chroma values (4-6) in the upper soil horizons relative to the lower soil horizons (1-4), suggesting drying in the upper horizons after a period of saturation. This is supported by bisepic clay fabrics and mottling present with translocated iron (stained root traces and cracks) as well as sphaerosiderites that are found in the lower horizons of several profiles of this type (Fig. 2.3-2.5).

The Purple Type exhibits features of mature pedogenic development with distinct horizons including an argillic horizon [Summit Marina (n=11), Fort Mott (n=11), and Medford (n=2)]. However, pedogenic development was either inhibited or ceased at times due to saturated conditions, this suggests the possibility of seasonal wet/dry cycles during formation (Fig. 2.5; Table 2.4). Waterlogged condition is evidenced by lower chroma values (2-4), fine root mats and drab halo root traces. However, the presence of many, large (cm-scale) mottles, clay skins, sphaerosiderites, iron staining, and bisepic clay fabrics attest to breaks in saturated conditions (Figs. 2.3-2.5). Similar modern Alfisols form in semi-arid to humid areas usually under forest cover.

The Red Type of paleosol is mature, more so than the Purple Type, with well-developed horizons, including an argillic horizon, and moderate chroma values (3-6) [Fort Mott (n=22), Summit Marina (n=7) and Medford (n=3)] (Fig. 2.5; Table 2.4). Features suggest enhanced drainage with occasional periods of water-logged conditions. Clay-filled root traces and iron staining are found along root traces and cracks throughout; sphaerosiderites are also present in several profiles. Many, large (cm-scale) mottles are present. Argillians and bisepic clay fabrics are observed in thin section (Figs. 2.3-2.5).

The Brown Type of paleosol is the most mature and well-developed paleosol, with distinct horizonation, an argillic horizon and translocated clay features including large (cm-scale), vertical roots that are preserved through clay-infilling, indicating well drained conditions [Fort Mott (n=4), Summit Marina (n=5) and Medford (n=1)] (Fig. 2.5; Table 2.4). Higher chroma values (4-6) are found throughout the profile as well as many, large (cm-scale) red and brown mottles. Rare iron staining and sphaerosiderites are found in some profiles (Figs. 2.3-2.5). All soil profiles are reported in the appendices 1 and 2.

The occurrences of pedotypes can be placed in a stratigraphic context. The Gray and Gray-Red Types of paleosol are best developed in Units II and III at Summit Marina, Fort Mott and Medford. The Purple and Red Types of paleosols are found in Unit I at Fort Mott and in Units II and III at Summit Marina, Fort Mott and Medford. The Brown Type is found in Unit I at Fort Mott, in Unit II at Summit Marina, Fort Mott and Medford, and in Unit III at Summit Marina.

2.4.2 Clay Mineralogy

Kaolinite is the major clay mineral present in all 25 samples, with lesser amounts of smectite and illite (Fig. 2.6). The kaolinite crystallinity in both the <2 μm and <0.2 μm size fraction suggest that it is mostly authigenic. The presence of smectite is supported by sink/swell features in some of the paleosol profiles (Fig. 2.6). The illite is mostly allogenic having formed elsewhere and only deposited at these sites, although it is possible some smectite did undergo illitization during pedogenesis for in-situ formation, however, these soils did not reach burial depths/pressures great enough to transform the majority of smectite into illite. Quartz and goethite also are present in several of the paleosols in the clay-sized fraction (Fig. 2.6).

2.4.3 Paleosol Compaction

Given the geologic history and stratigraphy, burial depth was assumed to be no deeper than cored depth, with most compaction occurring with the deeper Medford paleosols. Overall, compaction was low and similar at all three sites and values of original thickness ranged from 99.7-97.8% in the Alfisols to 99.1-94.2% in the Inceptisols (Appendix 3). As such, compaction was not considered to play a major role in influencing observed paleosol morphology and measure geochemical values.

2.4.4 Paleosol Morphology Index

The use of the morphology index of Adams et al. (2011) was applied to appropriate paleosol profiles as a proxy for paleoprecipitation. This index was originally applied on soils with calcium carbonate as a function of this index; all soils from this study contain no calcium carbonate and therefore this index may not be as robust or sensitive an indicator of changing precipitation. In this index higher values indicate drier conditions, while lower values correspond to wetter conditions; the ranges for each site are given to show variability both through time and across the region.

At Fort Mott, morphology index values were obtained from 29 paleosol profiles from Units I through III of the Potomac Formation, and range between 2.3 (wetter) & 8.6 (drier) (Fig. 2.9; Table 2.5). At Summit Marina, index values were obtained from 21 paleosol profiles for Units II and III of the Potomac Formation, and range from 1.5 (wetter) to 10.1 (drier) (Fig. 2.9; Table 2.5). At Medford, index values were obtained from 10 paleosol profiles for Units II and III of the Potomac Formation, and range from 2.5 (wetter) to 6.9 (drier) (Fig. 2.10; Table 2.5).

Fort Mott is the only site with paleosols preserved from Unit I. From the base of this unit up-section values show drying, the middle of the unit has lower (wetter) values with several shifts between wet and dry conditions before drying at the unit top (Figs. 2.8, 2.11; Table 2.5). There is a minimum wet value of 2.3 and a maximum dry value of 8.3. Across the unit boundary, conditions become relatively wetter as values drop to 5.3 in the undifferentiated portion of Unit I/II.

Unit II is preserved at all three sites displaying variability at all sites. Fort Mott and Summit Marina show the same general shifts with a landscape that alternates up section between generally drier and wetter conditions. Minimum (wetter) values of 4.0 at Fort Mott and 3.9 at Summit Marina, and maximum (drier) values of 8.6 at Fort Mott and 10.1 at Summit Marina (Figs. 2.8-2.9, 2.12; Table 2.5). At Summit Marina there is a general decrease upsection from 7.5 in soil 480 to 4.9 in soil 450 before spiking to 10.1 in soil 445. The middle of this unit has relative fluctuations between lower and higher values before increasing upsection to 7.9 in soil 365. Nearing the top of the unit values decrease again. At Fort Mott there is variability lower in Unit II with a value of 8.6 in soil 550 that decreases to 4.0 in soil 540, rising to 7.8 in soil 520 before decreasing again to 4.4 in soil 510. The middle of this unit at Fort Mott has no values, while the upper unit has little variability with values between 5.2 in soil 415, 6.0 in soil 380, and 5.3 in soil 370. Medford displays little variability in range with a minimum (wetter) value of 3.5 and a maximum (drier) value of 6.9 (Figs. 2.10, 2.12; Table 2.5). Two widely spaced values show a decrease from 6.9 in soil 955 near the unit base to the 3.5 in soil 850 in the unit middle. The top of the unit there is less variability with values between 4.0 in soil 800 to 5.0 in soil 795 and 4.5 in soil 790.

Unit III is preserved at all three sites, displays variability at each site (Fig. 2.13). At Fort Mott there are distinct up section shifts between wet and dry conditions. The unit has a maximum dry value of 7.7 and minimum wet value of 2.4 (Figs. 2.8, 2.13; Table 5). Summit Marina is similar to Fort Mott alternating between wet and dry, including a similar range, with a max dry value of 7.1 and minimum wet value of 1.5 (Figs. 2.9, 2.13; Table 5). Medford has slightly less variability, with maximum dry value of 6.1 and minimum wet value of 2.5 (Figs. 2.10, 2.13; Table 5).

2.4.5 Geochemistry

The geochemistry of paleosol profiles was measured, as they act as proxy records. Niobium (Nb) serves as a proxy for paleoprecipitation, with higher values of Nb (reported in parts per million (ppm)) corresponding to increased mean annual precipitation, with lower values corresponding to the decreased precipitation (Kahmann, 2008; Retallack, 2001; Sheldon and Tabor, 2009). The ratio of Barium to Strontium (Ba/Sr) provides a proxy for leaching and drainage conditions during pedogenesis (Retallack, 2001; Sheldon and Tabor, 2009). Lower Ba/Sr values correspond to more saturated, poorly drained conditions and higher values to well-drained conditions. The ranges for each site (Figs. 2.8-2.10; Table 2.6) are given to show variability both through time and across the region. All measured geochemical values are reported in Table 2.6. All sampled soil profiles are listed according to their soil id, profile and horizons depths are reported in Appendix 1 and 2.

At Fort Mott, Nb and Ba/Sr data were collected from 23 paleosol profiles from Units I through III (Fig. 2.8; Table 2.6. Nb values range from 17.0 (semi-humid; e.g. >1000 mm/yr) to 34.1 (humid; e.g. >2000 mm/yr). Ba/Sr values range from 1.0 (poorly drained) to 6.4 (well drained). At Summit Marina, Nb and Ba/Sr data were collected from 13 paleosol profiles from Units II and III (Fig. 2.9; Table 2.6). Nb values ranged from 20.8 (semi-humid) to 29.6 (humid). Ba/Sr values range from 2.1 (poorly drained) to 7.2 (well drained). At Medford, Nb and Ba/Sr data were collected from 8 paleosol profiles from Units II and III (Fig. 2.10; Table 2.6). Nb values range from 22.6 (semi-humid) to 32.8 (humid). Ba/Sr values range from 1.4 (poorly drained) to 3.4 (poorly drained).

Unit I Ba/Sr values, reported in Table 6, are measured only at Fort Mott, with a maximum value of 6.4 and minimum of 1.0 (Fig. 2.11). The lower half of Unit I exhibits generally higher (enhanced drainage) values including the unit maximum value of 6.4 in soil profile 770, the only exception is a shift to 1.4 in soil profile 760. The upper half of this unit exhibits generally lower (decreased drainage) values including the unit minimum value of 1.0 in soil profiles 705 and 650.

Nb values in Unit I, reported in Table 6, are measured only at Fort Mott (Fig. 2.12). Values range from a maximum of 31.1 to a minimum of 17.0 (Fig. 2.8, 2.12). Lower values (decreased precipitation) are found near the unit base before increasing to higher values (increased precipitation) upsection from 17.9 in profile 770 to 30.3 in profile 760. This is followed upsection by a decrease to the unit minimum of 17.0 in profile 730 before increasing to the unit maximum value of 31.1 in profile 650 at the top of the unit.

Ba/Sr values, reported in Table 2.6, are measured from Unit II at all three sites (Fig. 2.13). Values at Summit Marina range from a maximum value of 7.2 to a minimum of 2.1. From the bottom of the corehole moving upsection there is a general increase from 2.5 in soil profile 480 to 4.4 in profile 440. The middle of this unit has sparse overage with generally lower values before a spike from 3.3 in profile 365 to the unit maximum of 7.2

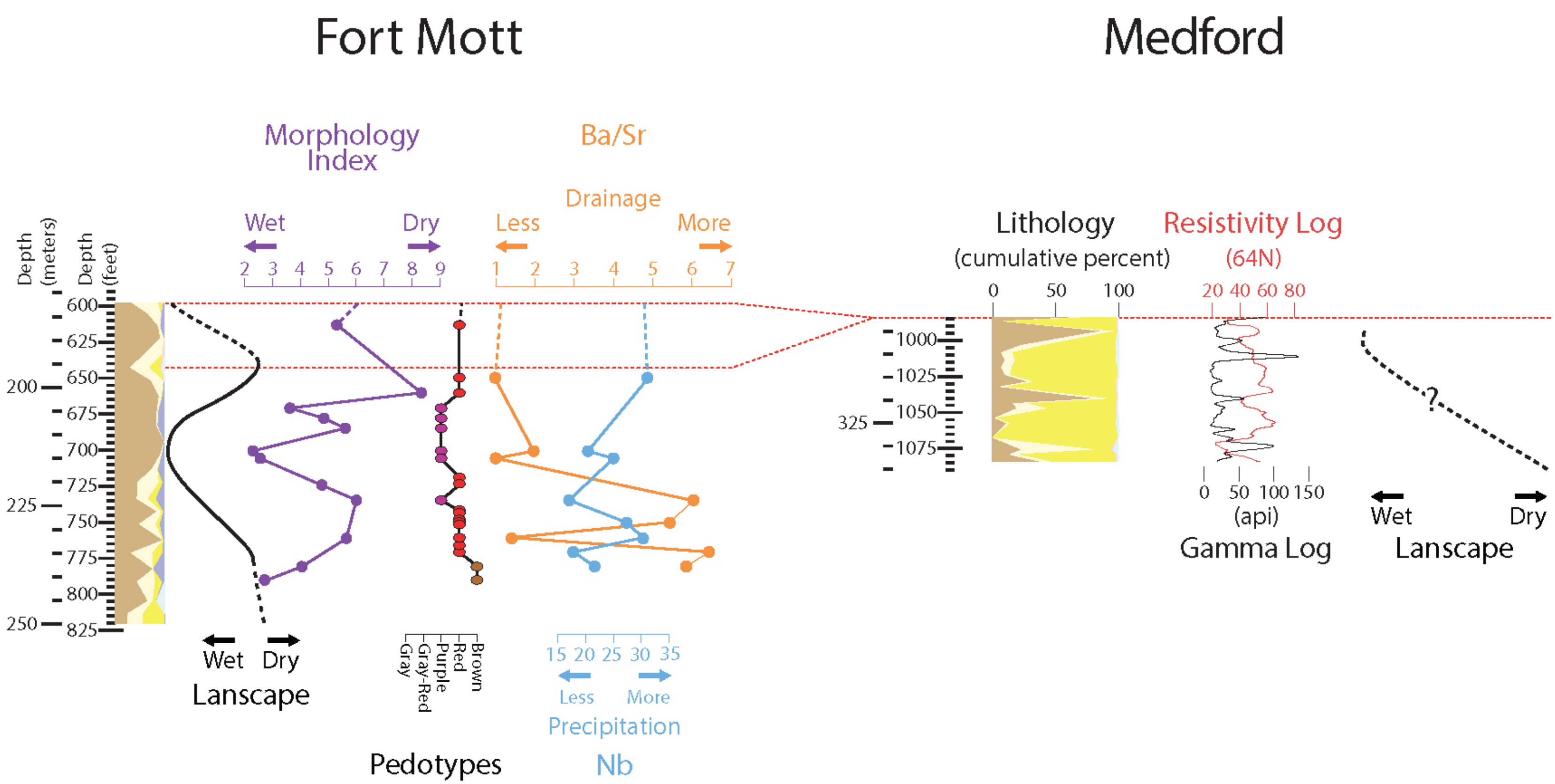

Figure 2.11 - Proxy data for Unit I at sites and a curve of general landscape condition through time at each site inferred from these proxies at Fort Mott, with Medford the curve is speculative. Note the scale differences between sites.

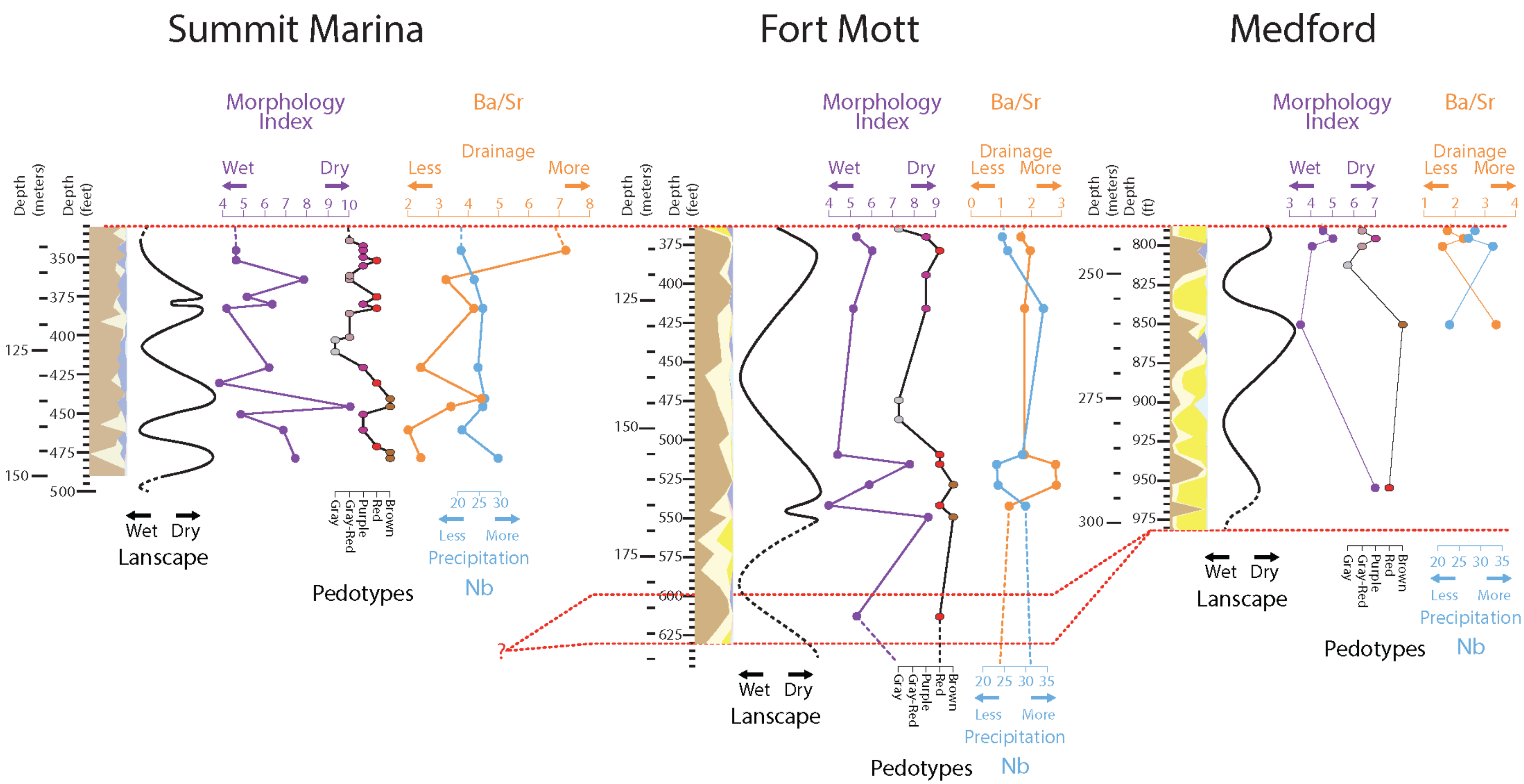

Figure 2.12 - Proxy data for Unit II at all 3 sites and a curve of general landscape condition through time at each site inferred from these proxies. Note the scale differences between sites

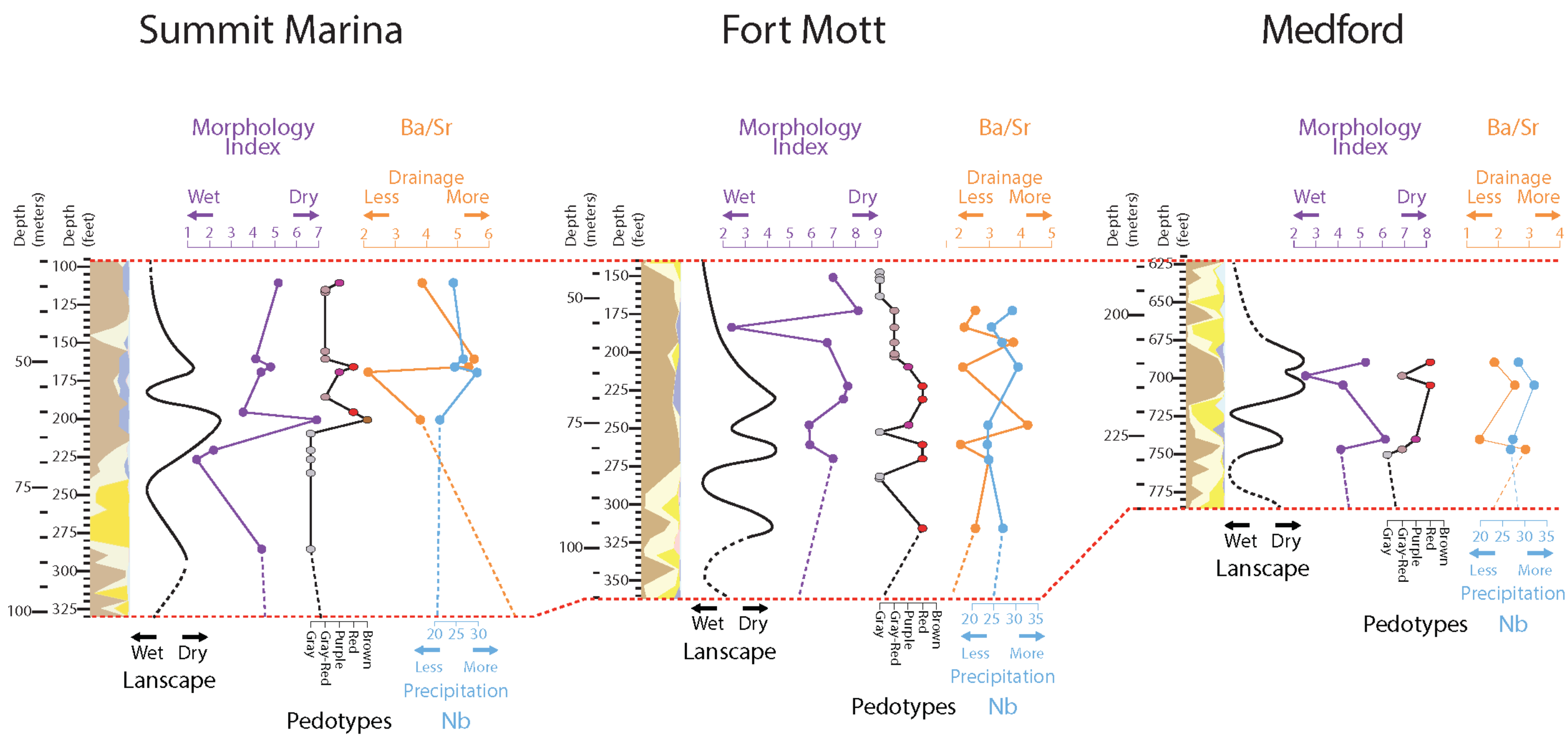

Figure 2.13 - Proxy data for Unit III at all 3 sites and a curve of general landscape condition through time at each site inferred from these proxies. Note the scale differences between sites.

in profile 345 near the top of the unit. At Fort Mott, values are generally low throughout, although sampled profiles are clustered into two groups, with a maximum value of 2.9 and minimum of 1.3. Of note, in the lower half of this unit, there is an increase from the unit minimum of 1.3 in profile 540 to the unit maximum of 2.9 in profile 530 and 2.8 in profile 520 before decreasing to 1.8 in profile 510. At Medford values are only obtained from the upper half of this unit with a maximum value of 3.4 and minimum of 1.6. There is a decrease upsection from the unit maximum of 3.4 in profile 850 to 1.7 in profile 790 at the top of the unit.

Unit II Nb values, reported in Table 2.6, are found at all three sites (Fig. 2.12). At Summit Marina Unit II values range from a maximum of 29.3 and a minimum of 20.8. The base of the unit shows a decrease from the unit maximum of 29.3 in profile 480 near the corehole base upsection to 21.0 in profile 460. There is a slight increase upsection with the unit middle showing little variability in Nb values. There is a decrease from 25.8 in profile 385 to 20.8 in profile 345 near the top of the unit. At Fort Mott values cluster into a group in the lower half of the unit and a group near the top of the unit. At Fort Mott the unit maximum is 34.1 and minimum is 23.2. Of note, in the lower half of Unit II is an upsection decrease from 29.9 in profile 540 to 23.5 in profile 530 to the unit minimum of 23.2 in profile 520 before increasing to 29.1 in profile 510. This increase continues upsection to the upper half of the unit with the maximum value of 34.1 in profile 415. Nb values then decrease to 24.5 in profile 370 near the top of the unit. At Medford values are found only in upper portion of this unit and range from a maximum of 32.2 and a minimum of 26.9. The lowest Unit II profile, 747, has the unit minimum of 26.9 and increases upsection the unit maximum of 32.2 in profile 705. Values then decrease to 28.6 in profile 690 near the top of the unit.

Unit III Ba/Sr values, reported in Table 2.6, are measured at all three sites (Fig. 2.13). Values at Summit Marina range from a maximum value of 5.5 to a minimum of 2.2. Values are measured from the upper half of this unit and show variability upsection to the unit top. The unit minimum of 2.2 is found in soil profile 170, and increases upsection to the unit maximum of 5.5 in profile 160 before decreasing to 3.9 in profile 110 near the unit top. At Fort Mott values range from a maximum of 4.2 to a minimum of 2.1. There is some relative variability upsection. Of note, is an increase from the unit minimum of 2.1 in profile 260 to the unit maximum of 4.2 in profile 250. This is followed upsection by a subsequent decrease to the unit minimum of 2.1 in profile 210, and another upsection increase to 3.8 in profile 190 before decreasing to the unit top. At Medford values are obtained from the lower half of this unit and are generally low, with a maximum value of 2.9 and minimum of 1.4. The lowest sampled profile, 747 exhibits the unit maximum of 2.9 before decreasing upsection in profile 742 to the unit minimum of 1.4.

Unit III Nb values, reported in Table 2.6, are found at all three sites (Fig. 2.13). At Summit Marina, values are found in the upper half of this unit, with a maximum value of 29.6 and minimum of 21.3. The only notable variability in this unit at Summit Marina is upsection from the minimum of 21.3 in profile 200 to the unit maximum of 29.6 in profile 170. At Fort Mott values range from a maximum of 30.5 to a minimum of 23.5. A slight upsection decrease from 27 in profile 315 to 23.9 in profile 270. These relatively lower values continue upsection with little variability in the lower half of this unit. In the upper half of Unit II there is an increase to the unit maximum of 30.5 in profile 210 before decreasing again to the top of the unit. At Medford values are found in the lower half of this unit, and range from a maximum of 32.2 and minimum of 26.9. Values from this unit show little variability, there is a slight increase upsection from 26.9 in profile 747 to 32.2 in profile 705.

2.5 Discussion

The Gray and Gray-Red Type paleosols have weak horizon development and are interpreted to have developed on unstable landscape surfaces where there is rapid sedimentation and/or a consistent saturation to inhibit pedogenesis (Fig. 2.5). The Gray Type formed under poorly drained, saturated conditions, while the Gray-Red Type experienced episodic periods of relatively enhanced drainage. Both soil types likely formed in environments such as proximal floodplains, lower delta plains, or tidal flats.

The Purple, Red, and Brown Type paleosols have greater horizon development, with pedogenic maturity increasing respectively. Soil formation is interpreted to have occurred on more stable landscapes, with increased time of formation allowing for greater pedogenic development (Fig. 2.5). The Purple and Red Type experienced periods of poor drainage with extended saturation that may have resulted from rises in base-level or increased seasonal precipitation; in contrast, the Brown Type exhibits evidence of persistent well-drained conditions. Potential environments of formation for these three soil types include distal floodplains, interfluves, and upper delta plains.

Although the paleosol deposits are generally discontinuous within units, they provide an overall picture of landscape conditions within and between units. Up section changes of paleosol maturity within units may reflect shifts in channel positions (Kraus, 2002). Changes in paleosol morphology features, as opposed to paleosol maturity, reflect changes in the drainage state of the landscape (Platt and Keller, 1992; Kraus, 2002).

Aside from the general interpretations made from the lithology and paleosol morphologies found at these three sites, three proxy data sets are employed to complement the interpretations and provide further insight. The paleosol morphology index (PMI) of Adams et al. (2011) is a proxy for mean annual precipitation (MAP), and uses the appearance or absence of pedogenic features that are sensitive to changes in rainfall. This method has shown correlation to the established chemical index of alteration minus potash (CIA-K) and CALMAG paleoprecipitation proxies (Adams et al., 2011).

While paleosol morphology provides information on conditions of formation. Geochemical measurements used in this study, Nb and Ba/Sr, act as paleoprecipitation and paleodrainage proxies to provide a higher resolution of conditions on these landscape helping to differentiate between factors of soil formation. For example, the Purple Type of paleosol is considered here to form under extended periods of waterlogged conditions. These waterlogged conditions could be a result of increased precipitation, and should be reflected by increased Nb values. In contrast, if the waterlogged conditions are caused by a rise in base level, lower Ba/Sr values would be anticipated over an increase in Nb values (Fig. 2.1). It is noted that that geochemical measurements are not applicable on all identified paleosols and therefore the record is incomplete.

Several factors influencing paleosol morphology during formation are considered here: parent material, relief, time, climate, and base level. Parent material is assumed to be consistent at these locations as no large differences in clay mineralogy are observed. Relief is considered to play a role in paleosol formation, but given the location of these sites on a low gradient coastal plain the role of any significant topography influence is unlikely. Subtle changes in topography can influence the features of a single soil; these should be negated both by subsequent deposition and the use of multiple paleosols through the section. The time component is related to landscape stability: Alfisols form over longer periods of time on stable landscapes when deposition is slow and episodic; Inceptisols form in short periods of time on relatively unstable surfaces with rapid and unsteady deposition. The time of formation can be quantified to some extent; although genesis can span a range that is often several orders of magnitude (Retallack, 2001; Schaetzl and Anderson, 2005). Alfisols, the Purple, Red and Brown Type soils form over 10^3 to 10^6 years, with the more mature Red and Brown types likely falling towards the higher end of this range (Retallack, 2001; Schaetzl and Anderson, 2005). Inceptisols, the Gray and Gray-Red Type soils form over 10 to 10^4 years, while generally immature the paleosols from these sites are relatively mature enough to suggest longer formation times (Retallack, 2001; Schaetzl and Anderson, 2005).

The role of evolving flora on landscape evolution was considered. Pollen shows that the evolution of angiosperms was rapid during deposition of the Potomac Formation (Berner, 1963; Doyle and Robbins, 1977; Hochuli et al., 2006). However the effects of this do not appear in this region as we see no changes in landscape evolutions based on the trends in angiosperm proportion in relation to soil type. The results of this are presented in the following chapter.

Climate, specifically precipitation and evaporation, influences morphology by changing hydrologic and drainage conditions. The Paleosol Morphology Index (PMI) and concentration of Nb provide a way to assess the influence of climate on these paleosols.

Changes in base level influence drainage through in hydrology or, given this coastal plain location, sea level. The measure of Ba/Sr provides a proxy of the drainage condition during the formation of the paleosol, and when taken with the PMI and Nb proxies a method is developed to distinguish the influence of climate from the influence of regional base level changes.

In general, there is a relationship between this landscape, base level, and soil formation. A regional rise in base level causes an overall decrease in drainage. This increases the potential of higher avulsion frequency, leading to the formation of more distributary channels, lakes, and swamps commonly observed on lower portions of a delta plain. Although avulsions can occur due to a number of factors, the rise of base level on a coastal plain creates favorable conditions for such, and has been documented to increase the frequency of avulsions (Makaske, 2001; Autin and Aslan, 2001; McCarthy and Plint, 1998; Törnqvist, 1994).

Any soil formation in the interdistributary areas on a coastal plain during a base level rise occurs as isolated or compound profiles that are weakly developed with features that show evidence of waterlogged conditions during pedogenesis. A subsequent fall in base level causing an overall increase in drainage conditions would result in formation of more composite and cumulative soil profiles that are mature and well developed.

The type of fluvial system also plays a role in influencing pedogenesis. Lateral movement of the channel affects sedimentation and the hydrology of the landscape. Proximal to a channel, poorly developed, compound and cumulative soils will form (Kraus, 1999; Kraus and Aslan, 1999). Distally from the channel, soils grow increasingly more mature, cumulative types, and this relationship increases as a channel migrates away

(Kraus, 1999; Kraus and Aslan, 1999). Lateral migration should then produce a vertical stepwise progression of increasing soil maturity as the channel migrates away and decreasing soil maturity as the channel migrates back towards a particular location (Kraus, 1999, 1987; Kraus and Aslan, 1999). Lateral migration of the channel does not appear to play a large role in influencing the soils of this landscape as this trend in soil maturity is not observed.

Sugarman et al. (2004, 2010) previously interpreted the fluvial style at Fort Mott as anastomosing. This interpretation is expanded here to include Summit Marina. An anastomosing system fits the landscape location of these sites on an inferred low gradient coastal plain. Anastomosing systems form on low gradient floodplains with high floodplain aggradation at the lower reaches of fluvial systems and comprise interconnected channels enclosing flood basin (Makaske, 2001). These flood basins are bounded by levees, and save for any topography, are low-lying depressions with poor drainage (Makaske, 2001). Channel migration in an anastomosing systems is mainly through avulsion with little lateral migration. Kraus and Aslan (1999) interpreted thick sand deposits as trunk channels while within an avulsion belt heterolithic intervals with weakly developed paleosols form due to the rapid and unsteady nature of deposition. Distally from the channel, normal flooding results in slow and episodic deposition resulting in moderate to well-developed paleosols (Kraus and Aslan, 1999). The relationship of paleosol development with respect to the channel, plays a role in the profile maturity, and the overall morphology of paleosols on a coastal plain setting has been shown to be greatly influenced by drainage condition (i.e. water table depth) (McCarthy and Plint, 1998; Autin and Aslan, 2001).

The following discussion breaks the Potomac Formation into its constituent lithologic units. All depths rely on core observations, interpretations from Sugarman et al. (2004, 2010), and geophysical data to fill in coring gaps. Profile IDs refer to the approximate depth of a profile, refer to Appendix 1 for complete profile depth ranges. Paleosol interval depths refer to the multiple profiles potentially including coring gaps and unaltered overbank material, refer to figures for illustration of intervals; complete paleosol depth data is available in Appendix 1 and 2.

2.5.1 Unit I

Only the Fort Mott and Medford coreholes reach Unit I of the Potomac Formation, assigned to pollen Zone I (?Barremian to Aptian) (Fig. 2.8, 2.10, 2.11; Sugarman et al., 2004, 2010). The preserved sediments reveal different depositional environments between the two sites. However, possible regional connections can still be attempted. No paleosols are present in Unit I at the Medford site; sands and gravels dominate this section with two thin clay beds. These deposits have been interpreted by Sugarman et al. (2010) as representing a braided fluvial environment. This interpretation based on coarse-grained gravel and sand lithology compared to the medium to fine sand and silt lithology found at sites representing an anastomosing fluvial environment (e.g. Fort Mott). The interpretation of Sugarman et al. (2010) of a braided fluvial environment is supported by the location of Medford along strike to the northeast, which is more proximal to the uplands and the sediment source area (Poag and Sevon, 1989; Klitgord et al., 1986).

At Fort Mott, there was a more stable, well-drained landscape with multiple preserved Red and Brown Type paleosol profiles dominating Unit I; however, the appearance of several sand bodies and Purple Type paleosols show that the landscape was periodically waterlogged and occasionally unstable. Sugarman et al. (2004) has interpreted deposits from this unit at Fort Mott as representing an anastomosing fluvial system, with sand bodies representing levee, splay, and channel fill deposits. Unlike the braided system at Medford, an anastomosing fluvial system has multiple channels each with good lateral stability, and an overall environment that produces a larger proportion of overbank muds to channel sands (Makaske, 2001). These overbank deposits are overprinted by pedogenesis, and soil development can potentially be related to sedimentation rate and landscape position (Makaske, 2001). Simple, immature paleosol profiles surrounded by thin sand bodies potentially form proximal to avulsion-belts and levees, cumulative mature profiles form further from active channels (Kraus, 1996; 2002; Kraus and Wells, 1999; Makaske, 2001).

The paleosols at Fort Mott reveal that conditions at the base of Unit I were dry and well-drained (Brown Type) or usually dry and well-drained although experiencing periods of saturation (Red Type, Fig. 2.8, 2.11, 2.14). The paleosols upsection become more waterlogged with periods of drying (Purple Type, Fig. 2.8, 2.11, 2.14). Direct correlation between Fort Mott and Medford is broad; the unit designation is based on general lithology, though this is supported by pollen biostratigraphic correlation to Zone I (Sugarman et al., 2005; 2010). A higher resolution of correlation within the unit is speculative and undetermined.

Geochemical proxy data are available for Unit I at Fort Mott, but not at Medford (Figs. 2.11, 2.14; Table 2.6). Higher Ba/Sr values of 5.9 and 6.4 are found at the unit base, corresponding to well-drained profiles at 780.0 ft and 769.2 ft, respectively (Figs. 2.11, 2.14). Ba/Sr values decrease upsection indicating that drainage decreases from the well-drained profile at 734.7 ft with Ba/Sr value of 6.0 to the poorly-drained profile at 702.9 ft with a Ba/Sr value of 1.0. The PMI is in general agreement with these proxies, values decrease over this interval from 6.0 at profile 734.7 to 2.3 at profile 700.0. Profiles upsection are mainly Purple Types, showing continued hydromorphic conditions persisting (Figs. 2.11, 2.14). The PMI does show an increase from profile 700.0 to 5.6 at profile 684.7, indicating some drying has occurred even though the paleosol type has not varied. Nb values are higher in these sections of decreased drainage, suggesting that these profiles formed under water-logged conditions due to increased precipitation, with the overall condition of Unit I described as sub-humid. As an example, the well-drained profile at 734.7 ft has an Nb value of 17.0 while upsection poorly drained profiles at 702.9 ft, 700.0 ft, and 649.2 ft have Nb values of 25.0, 20.4, and 31.1 respectively.

The proxy data here illustrate that climate, specifically changes in the amount of precipitation, played a major role in the formation of these soils profiles at Fort Mott without necessarily fluctuating base level (Fig. 2.11, 2.14). The increase in Nb values reflects greater precipitation associated with wetter soils. Decreases in drainage inferred from a drop in Ba/Sr align with increases in Nb, suggesting that this poor drainage is from paleoprecipitation, and thus does not require a base level change within the unit to explain observed paleosol trends.

2.5.2 Unit II

Unit II is preserved at all three sites (Figs. 2.12, 2.15). The base of Unit II at Fort Mott (555.1 to 599.7 ft) contains sand deposits interpreted by Sugarman et al. (2004) as mainly channel fill deposits. This transitions up-section to well-drained, Red and Brown

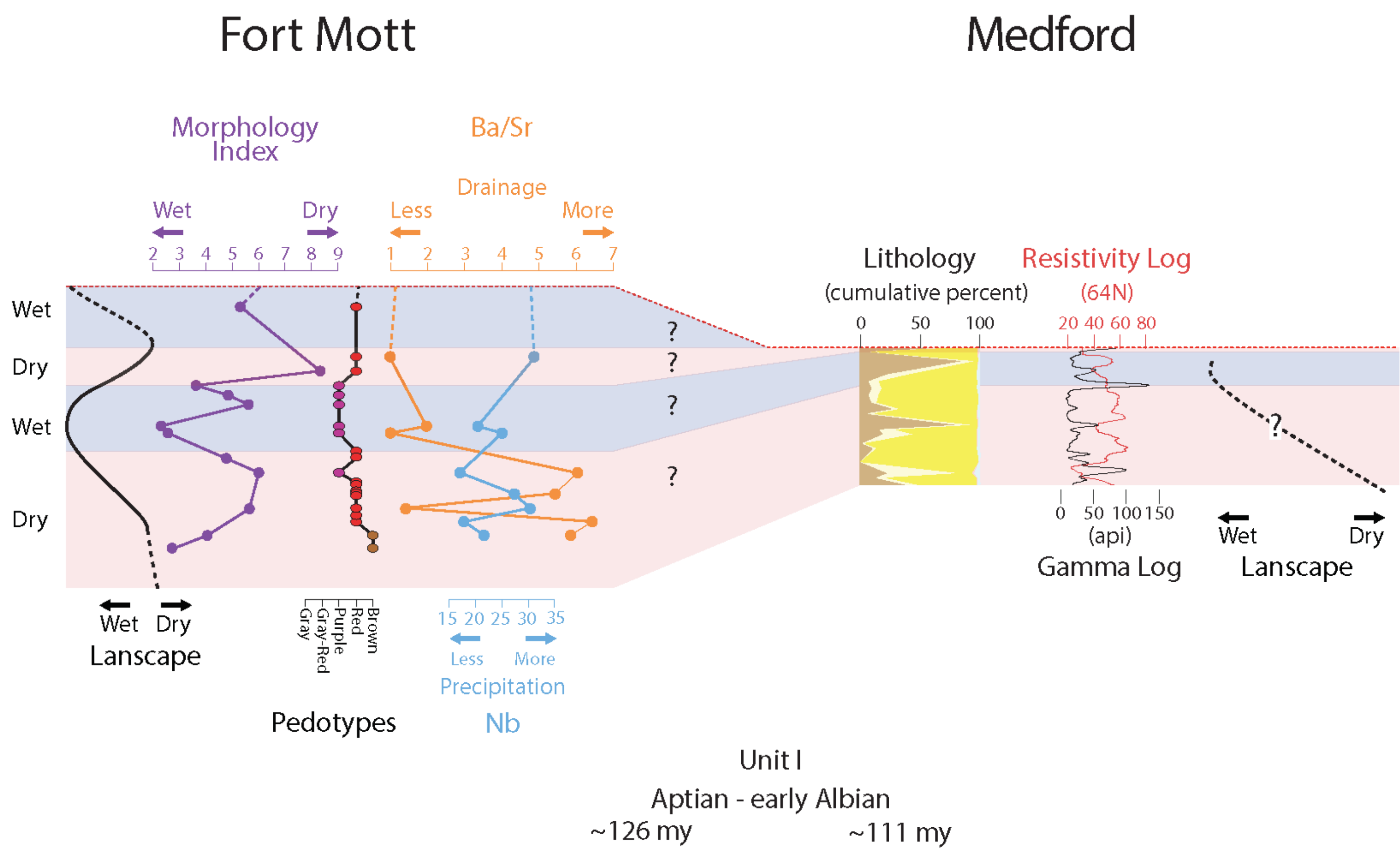

Figure 2.14 - Correlation of Unit I among sites at Fort Mott, and Medford; unit boundaries have been correlated using general lithology as described in the text; correlations within the unit are made on the basis of paleosol morphology and proxy trends. Note the scale differences between sites.

Type compound paleosols (508.2 to 554.0 ft) that formed on a more stable landscape (Fig. 2.12, 2.15). The Summit Marina borehole reaches into Unit II but not to the basement (Fig. 2.12, 2.15). However, given the depth, proximity and grain characteristics, sands at the bottom of the Summit Marina hole (485 to 500 ft), although not as clean, with interbeds of silt and clay, are here interpreted as roughly correlatable to those sands at the base of Unit II at Fort Mott (Fig. 2.12, 2.15). The base of unit II at Fort Mott and Medford has been interpreted by Sugarman et al. (2004; 2005; 2010) as forming on an anastomosing fluvial landscape, or possibly on a delta plain (Sugarman et al., 2005). The extent to which an anastomosing system is separate, occurs on, or overlaps with a deltaic system, including the classification of distributary deltaic fluvial systems, is ambiguous (Makaske, 2001 and references therein). Regardless of this distinction and the exact location of these sites on the coastal landscape, the paleosols still offer a picture of precipitation/evaporation and base level conditions of the landscape on which they formed.

The succession of deposits above these sands at Summit Marina, with the occurrence of Brown, Red, and Purple Type compound paleosols (427.6 to 485.7 ft) indicating a shift in landscape position to interfluvial environments, suggests an abrupt change to more stable and well-drained landscapes, similar to the change noted at Fort Mott. Ba/Sr values at Summit Marina increase from 2.5 to 4.4 from profile 485.7 to profile 440.0, indicating increased drainage. The Nb values over this same interval fall from 29.3 to 26.2, indicating a decrease in paleoprecipitation. Similarly at Fort Mott, profiles from 515.2 to 542.0 ft are composed of Red and Brown profiles and produce a decrease in Nb from 29.9 to 23.2, and Ba/Sr values, while still low, do increase slightly from 1.3 to 2.8. This correspondence between decreasing Nb and increasing Ba/Sr suggest the control of climate on the lower part of Unit II at both Summit Marina and Fort Mott (Figs. 2.12, 2.15).

Medford, along strike but more proximal to the source area, has a more ambiguous record at the base of Unit II. Sand deposits are primarily preserved, interbedded with several silty-clay deposits (869.3 to 983.15 ft) and one Red Type paleosol (954.0 to 957.0 ft) (Figs. 2.12, 2.15). This interval was interpreted Sugarman et al. (2010) as fluvial channel fill with lacustrine deposits. There is a single well-drained Brown Type soil (850.0-860.0 ft) overlying these sandy deposits, representing a period characterized by a stable, well-drained landscape (Figs. 2.13, 2.16). A high Ba/Sr value coupled with low Nb value suggest that climate played a role in the formation of this profile.

The features in basal Unit II indicative of stable well-drained landscapes give way up section to features associated with water logged, poorly drained conditions likely forming on an avulsion belt. Kraus and Aslan (1999) interpreted deposits within an avulsion belt to consist of heterolithic intervals with thin, weakly developed paleosols forming due to the rapid and unsteady nature of deposition during an avulsion. This description fits a generally heterolithic interval at Fort Mott (424.0 to 515.2 ft) including immature Gray Type paleosol profiles (475.0 and 487.4). A similar heteorlithic interval is found at Summit Marina (386.5 to 420.0 ft) with several weak, immature paleosol profiles (386.5, 401.0, 403.65, and 410.0). This up section change could be explained by increased avulsion resulting from rising base level (Figs. 2.12, 2.15).

The change in soil types can be tied to a decrease in Ba/Sr leading into this interval from profiles 440.0 and 420.0 with values of 4.4 to 2.5 at Summit Marina and at Fort Mott profiles 515.2 and 508.2 produce values decreasing from 2.8 to 1.8 (Figs. 2.12, 2.15).

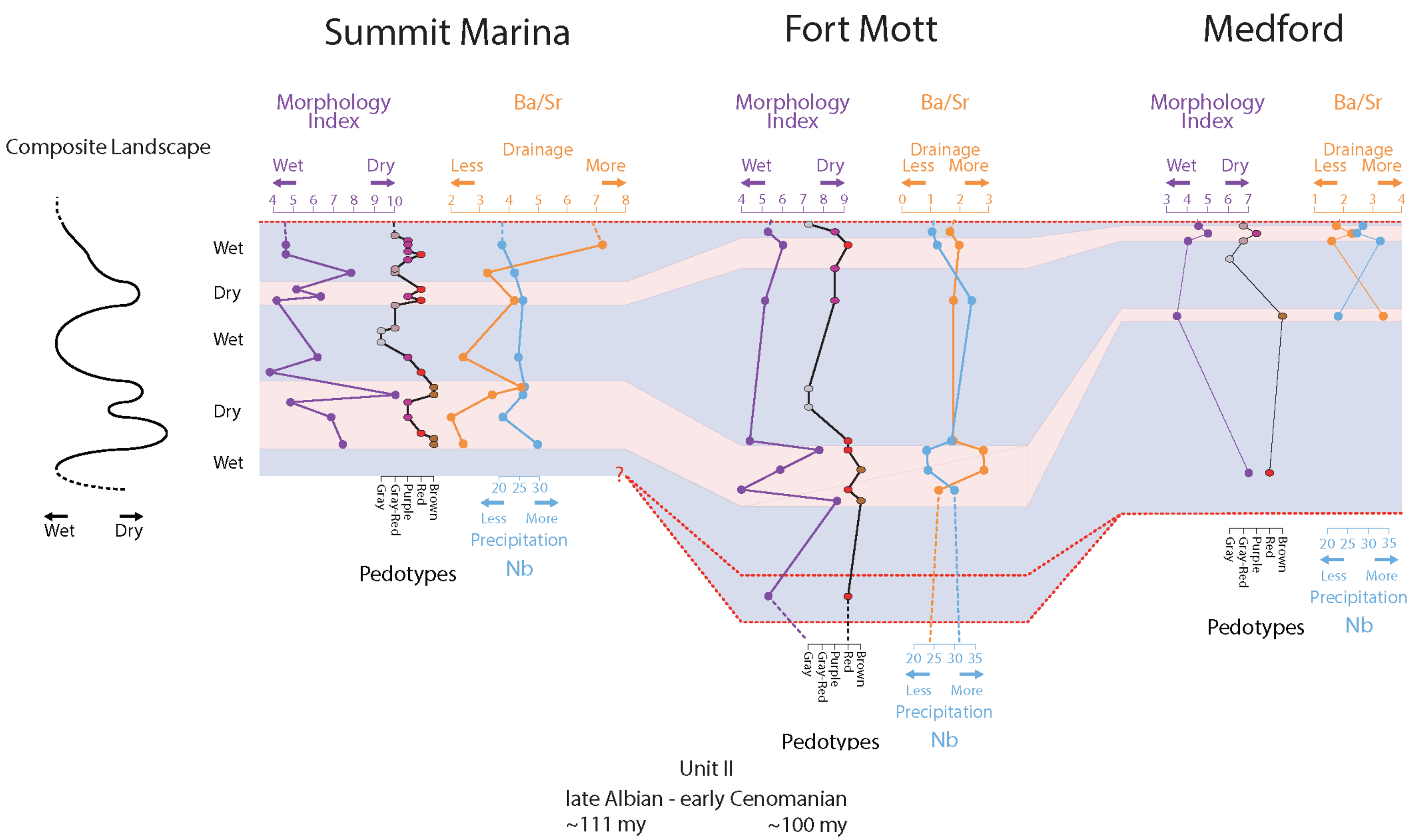

Figure 2.15 - Correlation of Unit II among sites at Summit Marina, Fort Mott, and Medford; unit boundaries have been correlated using general lithology as described in the text; correlations within the unit are made on basis of paleosol morphology and proxy trends. Note the scale differences between sites.

A decrease in Nb across this same interval indicates decreased precipitation. This suggests increasing water-logged conditions, resulting from a rise in base-level (Fig. 2.15).

It is also worth noting that the lithofacies present could reflect a marine influence on deposition across this same interval, with evidence including very fine to fine sands, heavy mineral concentrations on bedding planes, and occurrences of pyrite. This shift to more waterlogged conditions with possible marginal marine influences offers a likely correlatable section between Fort Mott and Summit Marina (Fig. 2.15). A tentative link can be made with these sites to Medford, where cross-bedded, bioturbated fine sands and pyrite is found (816.0 to 844.7 ft) in sediments deposited above a Brown Type paleosol (850.0 to 860.0 ft) and inferred stable, well-drained landscape (Figs. 2.12, 2.15).

There are some similarities among the three sites within the upper part of Unit II (Fort Mott 375.0 to 424.0 ft, Summit Marina 362.5 to 385.85 ft, and Medford 794.0 to 814.25 ft), where there are preserved composite and cumulative paleosols. These profiles are mainly hydromorphic in nature; however, there appears to be some drying up section with a period of some increased landscape stability, including better profile development with enhanced relative drainage. The Ba/Sr proxy data provides some indication of this increased drainage with values increasing from 2.5 to 4.2 at Summit Marina (profiles 420.0 and 382.9), only slightly from 1.6 to 2.3 at Medford (profiles 800.0 and 794.0), and 1.8 to 2.0 at Fort Mott (profiles 408.6 and 375.0) (Figs. 2.12, 2.15). The Nb values from these profiles decrease upsection at all three sites: at Summit Marina 25.8 to 23.8 (profiles 382.9 to 362.5), at Fort Mott 34.1 to 25.7 (profiles 408.6 to 375.0), and at Medford 32.8 to 27.1 (profiles 800.0 to 794.0) (Figs. 2.12, 2.15).

Upsection approaching the Unit II boundary at each site, there are weakly developed, compound paleosols forming under waterlogged conditions: Summit Marina profiles 340.2, 343.75, 344.8, 350.0, 351.8, 355.0, 361.5, and 362.5; Fort Mott profiles 365.0 and 367.0; Medford profile 790.0 (Figs. 2.12, 2.15). The transition to this boundary includes the development of waterlogged paleosols that occasionally experienced periods of drying (Purple Type). The Ba/Sr data at Fort Mott and Medford show a decrease at the unit boundary, while only slight, does support this interpretation of more poorly drained, saturated conditions (Figs. 2.12, 2.15). Only at Medford is there an increase in Nb to suggest these saturated conditions were from increased precipitation; Nb values drop at both Summit Marina and Fort Mott suggestive of a rise in base level. Summit Marina exhibits a transition from waterlogged, unstable surface (Gray and Red-Gray Type) to more stable, periods of wetting/drying (Purple and Red Type) before a move towards the waterlogged, saturated conditions at the unit boundary. This is likely an artifact of local landscape positioning with respect to the fluvial system, as the maturity of the paleosol profiles is related to the lateral distance to the channel.

2.5.3 Unit III

A body of sand marks the Unit II/III boundary at all three sites: 310.0 to 330.1 ft at Summit Marina, 320.4 to 363.6 ft at Fort Mott, and 760.9 to 786.8 ft at Medford (Figs. 2.13, 2.16). The deposition of these sands was followed by a period of soil formation at all three locations. A weakly developed compound Gray Type soil is found at the Summit Marina site (profile 285.0), a Red Type soil is found at the Fort Mott site (profile 315.0). At Medford, a Purple, Gray-Red, and Gray Type compound profiles (740.6, 747.1, and 750.0) are found to have formed under varying levels of saturation. A second body of sands overlies these paleosols at all three sites: Summit Marina (238.0 to 285.0 ft), Fort Mott (290.0 to 315.0 ft), and Medford (710.0 to 721.7 ft) (Figs. 2.14, 2.17). At all three sites, this sand body lies above an interpreted erosional contact with scattered pyrite, organics, burrows, and cross-bedding.

These sands at Fort Mott and Medford are similar to the basal sands in Unit II, and have been described by Sugarman et al. (2004; 2010) as channel fill from an anastomosing fluvial system. Avulsion is a likely explanation for the deposition of these heterolithic sands/silts/clays. The weakly developed Gray and Gray-Red paleosols fit this scenario. However this explanation is more problematic for the Purple Type (Medford profile 740.6) and Red (Fort Mott profile 315.0) soils given the greater degree of development. A possible explanation would be the avulsions carrying the respective channel at each site to a more distal location. This would allow time for these soils to form. In the delta scenario from above, this could represent a shift in delta plain due to fluctuating sea level or due to lobe switching, although this is unlikely given the nature of the formation of the paleosol, which lower on a delta plain should feature more evidence of forming under saturated conditions.

Upsection from these sands at all three sites, there is evidence of base level rising with weakly developed compound paleosols formed under waterlogged conditions at Summit Marina (profiles 210.0, 220.0, 225.0, and 235.0), Fort Mott (profiles 281.5 and 282.5), and Medford (profiles 697.4 and 700.0) (Figs. 2.13, 2.16). Decreasing Ba/Sr and Nb values at Medford support a base level lowering. Overlying this interval there are preserved well-developed cumulative and composite Red and Brown Type paleosols at all

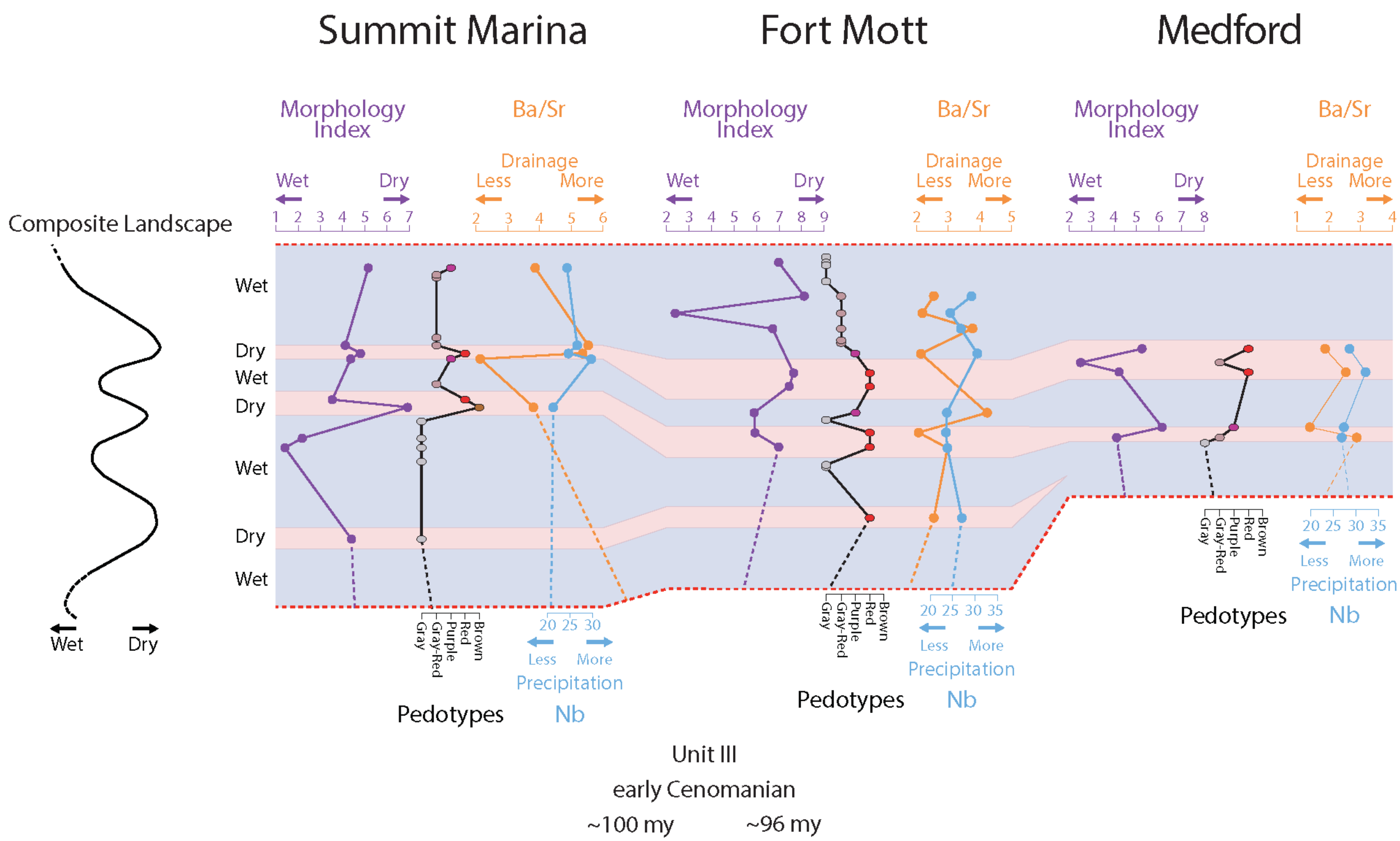

Figure 2.16 - Correlation of Unit III among sites at Summit Marina, Fort Mott, and Medford; unit boundaries have been correlated using general lithology as described in the text; correlations within the unit are made on basis of paleosol morphology and proxy trends. Note the scale differences between sites.

sites: Summit Marina (profiles 195.0 and 200.0), Fort Mott (profiles 258.9 and 270.0), and Medford (profile 688.5). The paleosol morphology illustrates the more landscape stability with good drainage possibly due to a fall in base level at these sites, although at Medford this link is somewhat more speculative given the only one paleosol (Figs. 2.13, 2.16).

Overlying this section of stability, there is again the return of features indicative of landscape flooding that may reflect a rise in base level. Evidence of saturation appears at all three sites, with fine sands and poorly developed compound paleosols (Gray and Gray-Red Type) at Summit Marina (profiles 185.0) and Fort Mott (profile 251.2) and sand with organic rich silts and clays at Medford (623.8 to 681.2 ft) indicative of lake/swamp and channel fill (Figs. 2.13, 2.16). Ba/Sr values decrease from 3.0 to 2.1 at Fort Mott (profiles 270.0 and 258.9) with a slight decrease in the Nb values illustrating that this decrease in drainage not associated with an increase in precipitation (Fig. 2.13), indicating a possible rise in regional base level. This rise would potentially increase the rate of avulsion in an anastomosing system responsible for the channel fill deposits. Alternatively, in the deltaic scenario this rise in base level would result in a flooding event that would result in the deposition of organic rich sands and muds along with the formation of the poorly developed waterlogged compound paleosols.

Upsection at Summit Marina (profile 164.6 and 168.4) and Fort Mott (profiles 223.8, 230.2, and 242), well-developed Purple to Red Type paleosols formed on a surface with improved drainage. An associated Ba/Sr value increase upsection of 2.2 to 5.5 at Summit Marina (profile 168.4 to 160.0) and 2.1 to 4.2 at Fort Mott (profile 258.9 to 242.0) supports this interpretation (Figs. 2.13, 2.16). Nb values at Summit Marina decrease upsection from 29.6 to 26.5 (profile 168.4 to 160.0) while at Fort Mott there is minimal Nb change from 23.5 to 23.7 (profile 258.9 to 242.0). This indicates that paleoprecipitation was not a factor in this change. There are no preserved paleosol or obvious lithologic trends at Medford that reflect this apparent drop in base-level and would offer potential correlatable positions to Summit Marina and Fort Mott.

Upsection to the Unit II top at Summit Marina and Fort Mott there is a change in paleosol character with weakly developed compound profiles forming under saturated conditions. There are also heterolithic sands found within this interval, and a likely scenario of an avulsing anastomosing system responsible for these deposits. At both sites the Ba/Sr and Nb values decrease that suggests a rise in base level. This scenario would also create the conditions favorable for avlusion and result in the deposition of heteorlithic sands/silts/clays and weakly developed paleosols.

Unconformably overlying the Potomac Formation at Medford is the Raritan Formation that is also Cenomanian in age. The Raritan Formation at Medford is interpreted to have been deposited on the lower delta plain and bay/backswamp environments (Sugarman et al., 2010). The Raritan Formation is not found at Summit Marina and Fort Mott. The Potomac Formation at these sites is overlain by sediments of the Magothy Formation, which are Coniacian, suggesting a more significant unconformity. The depositional environment of these sediments are interpreted as estuarine at Fort Mott (Sugarman et al., 2004).

Using trends within preserved paleosol deposits and associated sediments, the following sedimentary environments are inferred: Unit I is predominately fluvial, Units II and III are fluvially dominated delta plain, with possible shifts between the upper and lower position on the delta plain. This agrees with previous interpretations at Fort Mott by

Sugarman et al. (2004; 2005), where the possibility of a delta plain environment in Unit III was noted based on the lithology and corresponding geophysical logs showing laterally continuous sediments with the typical geometry indicative of a delta plain depositional environment is especially evident in New Jersey and less so in Delaware (e.g. Sugarman et al., 2005). The distribution of sediments from these 3 cores has also been described as being deposited in an anastomosing fluvial setting (Sugarman et al., 2004; 2005). Anastomosing fluvial morphology features relatively stable channels separated by islands and bars stabilized by vegetation and fine grained sediments (Makase, 2001). Formation occurs mainly in low-gradient settings featuring floodplain deposits of fine, organic rich sediments. Much of the Potomac Formation fits this descriptions. There remains a question of distinguishing an anastomosing system from the upper delta plain environment (e.g. Makase, 2001).

The lack of marine or marginal marine fossils at these sites precludes a definitive interpretation of a delta plain facies. However, this interpretation noted by Sugarman et al. (2005), is supported by previous studies of the Potomac Formation in Maryland, Virginia and New Jersey where marine and marginal marine elements (glauconitic sands, dinoflagellates, fish, mollusk and ostracod fossils) are present in down-dip subsurface samples (Anderson, 1948; Richards, 1957, 1967; Glaser 1969; Hansen, 1969, 1982; Owens et al., 1969; Reinhardt et al., 1980; Owens and Gohn, 1985; Olsson et al., 1988; Dalton et al., 1999). This includes foraminifera (*Favusella washitensis*; a species restricted to the late Albian-early Cenomanian) identified by Richards (1957) from a well drilled at Port Penn, DE, a site less than 10 miles downdip from both Fort Mott and Summit Marina. A well drilled at Ancora, NJ reached the Unit III/IV transition of the Potomac Formation. At this site Unit III is divided into three intervals: the upper interval is poorly sorted medium to very coarse sand with very lignitic clay, and a very large (0.5 ft) pyritized burrow; the middle interval is composed primarily of shelly (pelecypod), slightly glauconitic clays; the lower interval contains very lignitic sands and clays with slight cross-bedding. A 1 ft. bed of lignitic, slightly glauconitic clay is found in this lower interval. The base of the cored unit contains bioturbated clayey silt and flaser bedding. The upper interval was interpreted by Miller et al. (1999) as deposited in marginal marine to estuarine setting, while the middle interval was deposited in an inner-middle neritic setting. The lower interval was interpreted by Miller et al. (1999) as estuarine with the 1 ft layer of clay within this interval representing a marine component of the estuary or possible marine interfinger. Breaks between these intervals have been describe by Miller et al. (1999) as possible sequence boundaries.

The evidence of apparent rising/falling base-level in the Potomac Formation and its location on the coastal plain offers the potential to explain these trends with transgressive and regressive events during this period. These changes in base level in Units II and III appear related and regional in extent (affecting all three core sites). This could potentially correlate to two major transgressive events recorded in the sea-level record at the Albian/Cenomanian boundary and early Cenomanian (Glaser, 1969; Haq, 2014). However, care must be taken in assigning these to global events, as minor fluctuations in relative sea level could potentially influence large areas, given the broad, shallow topography of the coastal plain in this region. Additionally, a drop in base-level, increasing drainage and resulting stabilization of the landscape following these flooding events presents the opportunity to assign sequence boundaries leaving open the future potential for regionally correlatable positions.

2.6 Conclusions

We analyzed Potomac Formation paleosols from two sites in New Jersey (Fort Mott and Medford) and one in Delaware (Summit Marina) to understand the landscape evolution along part of the eastern margin of North America during the transition from Early to Late Cretaceous (Aptian-Albian-Cenomanian). An analysis of morphological features, both micro- and macro-, allows these paleosols to be grouped into five general pedotypes. These range in pedogenic maturity from weakly developed, poorly drained, Inceptisol-like Gray and Gray-Red Type soils, moderately developed, Alfisol-like, hydromorphic Purple and Red Type soils, and well developed, well drained, Alfisol-like soils Brown Type.

A paleosol morphology index and two geochemical (Nb and Ba/Sr) proxies were applied to aid in this landscape reconstruction, and all were in generally good agreement with interpretations made using the paleosol profile morphology and maturity. These proxies provide information on paleodrainage (Ba/Sr) and paleoprecipitation (Nb), revealing the cause of landscape conditions either due to a rise/fall in base-level or from climate (increase/decrease precipitation). The paleoclimate is inferred at the base of Unit I to be sub-humid, and relatively drier than Units II and III. These units are generally wetter, with sub-humid to humid conditions with limited episodes of drying.

Paleosols at the Unit I base of the Potomac Formation at Fort Mott display features of a relatively well-drained landscape with extended periods of drying. There is an upsection change to palesols that form under alternating wet/dry conditions with extended periods of water saturation. Proxy data from the paleosol profiles attest to a large climate influence on soil formation, including increased paleoprecipitation upsection. Bodies of sand separate the preserved paleosols that formed under poorly drained, waterlogged conditions; this landscape has been interpreted as an anastomosing system at Fort Mott. At Medford, no paleosols are preserved, with mainly sand separated by silt and clay interbeds; this landscape is interpreted as being dominated by a braided fluvial system.

Paleosols are preserved in Unit II at all three sites. The base of this unit is dominated by fluvial sands that have been interpreted as an anastomosing system. Upsection, paleosols show relative shifts between well-drained, relatively drier conditions to poorly-drained, relatively wetter conditions. Paleosol and proxy show that conditions fluctuate between reduced and enhanced drainage upsection before ultimately becoming saturated at the unit boundary, with paleoprecipitation conditions fluctuating slightly compared with base level.

The base of Unit III is marked by a large package of sands that is present at all three sites. As in Unit II, this landscape is interpreted as an anastomosing fluvial system. However the thickness of this sandy interval and its apparent lateral continuity within New Jersey has led to the possible scenario of deposition on a delta plain. Upsection paleosol profiles show that drainage conditions fluctuate between poorly-drained and well-drained. Paleosol morphology and proxy data show that these fluctuations were driven mainly by changes in base level, with a lesser influence from paleoprecipitation. There is an upsection change in the sand deposits, as they appear thinner and more heterogeneously mixed with silts and organic material. This change is interpreted as the result of fluctuating base level conditions leading to increases in the avulsion frequency of this anastomosing fluvial system.

Regardless of this depositional landscape distinction, the paleosol and proxy data illustrate the role of base level and climate during paleosol formation. Ba/Sr provides a proxy of drainage conditions and the Nb a proxy for paleoprecipitation. When these two proxies are in agreement it appears that precipitation is influencing the drainage conditions, with increasing/decreasing precipitation causing wetting/drying resulting in poor/good drainage respectively. When there are changes in Ba/Sr with opposing or no changes in Nb then it is possible that this change in drainage is due to changes in base level; rising/falling base level results in good/poor drainage respectively.

This study offers data between these sites that provides insight into the changing landscape and climate conditions (base level and paleoprecipitation) through the mid-Cretaceous. Further work is needed to fully develop a picture of the overall depositional environment of this coastal plain. The coastal plain location of the Potomac Formation has the potential to link base level changes to changing sea levels and the application of potential sequence boundaries.

Chapter 3

Spore and Pollen Diversity and Landscape Connections of the Potomac Formation in New Jersey and Delaware

Abstract

The Potomac Formation was deposited within a fluvial-deltaic system on the coastal plain of eastern North America during the transition from the Early to Late Cretaceous. These deposits are notable for their preservation of palynomorph material that has documented a major period of angiosperm pollen radiation. Palynology also provides a correlation tool, and an age zonation has been established and refined from this formation. This age resolution of this zonation is coarse but it is necessary to aid lithologic correlations. This project has two goals, first is the establishment of a higher resolution of correlation between three corehole sites located in New Jersey and Delaware. This higher order resolution was attempted using angiosperm diversity patterns, specifically Monocots-Magnoliids, Eudicots and the ratio of Eudicots to Monocots-Magnoliids. Inconsistent sediment for sampling as well as sparse angiosperm populations did not allow for a higher resolved correlation. The second goal was to evaluate the connection between changes in the character of the landscape related to angiosperm diversity. Two hypotheses were tested, the first involved a positive feedback loop of angiosperm diversity related to wildfires proposed by Bond and Scott (2010). We did not see any consistent connection between fire deposits (charcoal) and angiosperm diversity. This may be a function of limited preservation at these sites and further study is warranted. The expansion of angiosperm diversity in riparian settings was also tested. The fluvial/deltaic depositional environment

of the Potomac Formation is ideal for addressing this hypothesis. A connection is observed between unstable landscapes, due to avulsion, and increases in angiosperm diversity. This hypothesis seems more likely at this location although because sampling was inconsistently spaced this is not definitive.

3.1 Introduction

Potomac Formation sediments are found along the Atlantic Coastal Plain from North Carolina to New York. Aside from limited up dip exposures, the majority of the Potomac Formation resides in the subsurface, because of this, access is mainly limited to well-logs and coreholes. The utilization of these coreholes for a proper understanding of the mid-Cretaceous coastal plain landscape can only be completed with good correlations between sites. New data from three coreholes in New Jersey and Delaware is presented here and compared with previous palynological data to create a more complete regional picture of this landscape.

The deposition of the Potomac Formation occurred on a fluvial-deltaic coastal plain landscape during the transition from the early to late Cretaceous (Barremian to Cenomanian). This was a period of global greenhouse conditions, this includes a climate defined by globally higher than present average temperatures, atmospheric CO_2 and sea levels (Barron, 1983; Berner, 2006, 2009; Royer et al., 2004; Ufnar et al., 2004; White et al., 2001; Haq, 2014; Miller et al., 2005; Suarez et al., 2011; Spicer and Corfield, 1992; Wolfe and Upchurch, 1987). This greenhouse climate and its influence on the coastal plain should be reflected in the sediments deposited during this time interval. Correlation between corehole sites provides the opportunity to reconstruct the landscape along the eastern margin of North America during this transition.

Here we provide a brief review of previous researchers work on Potomac Formation palynology, including correlations with other locations globally. The ratio of angiosperm pollen (Eudicot: Monocots and Magnoliids) will be used to attempted to correlate these three sites at a higher resolution. We will evaluate the potential relationship between landscape disturbances and the expansion of angiosperms.

3.2 Background

The transition from Early to Late Cretaceous (Aptian, Albian and Cenomanian ages) is of particular interest to palynological studies because it represents the major diversification and radiation of angiosperm pollen globally. This change resulted in the eventual global domination of these angiosperm plants. The first definitive forms appear in the earliest Cretaceous, the Neocomian (Berriasian/Valanginian/Hauterivian), Barremian and Aptian of England and the Valanginian and Hauterivian of Israel (Brenner, 1996; Kemp, 1968; Hughes et al., 1979; Hughes 1984; Traverse, 2007).

3.2.1 Potomac Formation/Group

Brenner (1963) carried out the first detailed palynological investigation of the Potomac Group and was responsible for creating the first workable biostratigraphic zonation. This systematic palynological study identified 130 distinct spore and pollen palynomorphs, including 125 different species, 65 of which were considered new forms. These specimens were obtained from 21 surface and 22 subsurface samples from the Potomac Group (Patuxent Fm., Arundel Clay Fm., and Patapsco Fm.) all within Maryland.

Brenner (1963) divided the Potomac Group into two major zones, I and II, based on species appearance and species frequency. Zone I incorporates the combined Patuxent and Arundel Formations, while Zone II covers the Patapsco Formation. Zone I contains only four index specimens and Brenner (1963) has stated that identification is based mainly on the absence of the 33 index species of Zone II. Brenner (1963) went on to subdivide Zone II into two subzones, A and B, based on the appearance of several distinctive forms in the upper part of Zone II. Subzone IIB was further subdivided into upper and lower parts based on the appearance of *Rugubivesiculites reductus*. Brenner also did not identify any angiosperms in Zone I, however subsequent studies have shown their rare presence in Zone I (Doyle and Robbins, 1977). It should be noted that the Brenner (1963) relied on Potomac Group sediments from Maryland while the Doyle and Robbins (1977) study relied on sediments from two coreholes in Delaware where the Potomac is a formation in rank due to lack of differentiation between the Patuxent, Arundel and Patapsco Formations observed in Maryland. This suggests a possible difference in preserved lithofacies between sites that may result in this difference between studies. Although the trends between two sites appear to be similar.

This study also assigned ages based on the appearance of equivalent forms from the age-constrained Wealden and Lower Greensand Formations of England (Brenner, 1963). The Patuxent and Arundel Formations were assigned as upper Barremian or slightly older, and the Patapsco is Albian in age.

Doyle and Robbins (1977) used two new subsurface coreholes combined with the angiosperm pollen data of Brenner (1963) to refine the zonation scheme. This included the addition of subzone IIC on the appearance of cf. *Rugubivesiculites rugosus*, cf.

Tricolporoidites subtilis, aff. *T. sp. A.*, cf. *T. minimus*, cf. *"Tricoloporopollenites" distinctus*, cf. *"T." triangulus*, as well as changes in relative abundances of characteristic Subzone IIB sporomorphae. A new zone was also added, Zone III based on the appearance of a variety of tricolpates and tricolporoidates palynomorph forms (Doyle and Robbins, 1977). Within this new Zone III it was noted a possible separation into an upper and lower part based on the appearance of several species (Doyle and Robbins 1977).

The age designations were revised by Doyle and Robbins (1977), again using comparisons with marine sections of England. Zone I was reassigned to a Barremian to early Albian age. Zone IIA was placed at the early-middle Albian boundary; Zone IIB was assigned to middle-late Albian, and IIC as latest Albian. Zone III was early Cenomanian in age on the basis of several correlations including with well-dated flora and palynology from North America and Europe and marine sections in France (Doyle and Robbins, 1977).

Recent work by Hochuli et al. (2006) used ages from two well constrained sections from southern Portugal for correlation with the Potomac to adjust the ages of these pollen zones. This correlation did not rely solely on direct species comparisons, but rather used angiosperm diversity and abundance patterns of monocolpate (monocots and magnoliids) and poly-(tri)-aperturate (eudicots) forms (Hochuli et al., 2006).

This reassigned lower Zone I found at the Potomac (Patuxent Formation) to an Aptian age based on the occurrence of the Pennipollis Group pollen (Hochuli et al., 2006). This time period is also marked by a gradual increase in relative pollen abundance and diversity. The Aptian/Albian boundary has a distinct increase of monocolpates in both diversity and abundance, including the first appearance of eudicots, with the ratio of eudicots to monocots is less than 0.5 (Hochuli et al., 2006).

Forms from Upper Zone I found at the Potomac (Arundel Clay Formation) correspond to late Aptian/early Albian of Portugal, although other independently dated sections place it into the mid- to late Albian (Hochuli et al., 2006). Other studies of carbon isotope curves from the Arundel Clay are ambiguous between an age of either early to mid-Aptian or early Albian.

Subzone IIA was placed in the mid-Albian based on the presence of *Tricolpites crassimurus*, while IIB was placed into the late Albian based on the documented range of *Cupuliferoidaepollenites parvulus*. The base of IIA has a eudicot to monocot ratio of 0.3 to 1.3 which rises to 2.0 in subzone IIB (Hochuli et al., 2006). Subzone IIC was early Cenomanian in age based on the appearance of *Tricolporoidites distinctus* and *T. triangulus* (Hochuli et al., 2006). Based on these observations Zone III can be assigned an early to mid-Cenomanian age, with the ratio of eudicots to monocots above Zone III is 3.0 or greater (Hochuli et al., 2006).

3.2.2 Fort Mott

The Potomac Formation was recovered from a corehole at Fort Mott, NJ from 141.1 to the bottom of the corehole at a depth of 820.0 ft. Palynological study by Brenner and McLaughlin in Sugarman et al. (2004) reported palynomorphs in 11 of 16 samples. The Fort Mott core contains all three of zones of the Potomac Formation. Zone III is defined by the appearance of the angiosperm species *Tricolporoidites sp. A* and *T. sp. B* from sample 162 ft; Zone IIC is marked by the several angiosperms including *Tricolporopollenites triangulus* and *T. distinctus* from sample 465 ft; Zone IIB contained poor recovery, but has the marker spore *Cicatricosisporites patapscoensis* from sample 556 ft (Sugarman et al., 2004). There is no evidence of Zone IIA markers in the sampled sections, although one sample at 599.3 ft (182.7 m) contains forms from both Zones I and II. Below this interval, samples produced species that are restricted to Zone I including *Cicatricosisporites dorogenesis* (Sugarman et al., 2004).

Sugarman et al. (2004) shows that overall there is a general trend of increasing angiosperm diversity through time at Fort Mott, with fluctuations in the diversity of gymnosperms and spores. Although it should be noted that Sugarman et al. (2004) focused on biostratigrapically useful forms and thus may not represent fully the upsection change in diversity. This may be partially due to the limited available material produced from sampled intervals. This current study resampled Fort Mott 17 times with the goal of a higher resolution of these diversity changes, these samples were also spiked for counting purposes to provide a quantitative understanding of the changes in diversity.

3.2.3 Medford

The Potomac Formation was recovered from a corehole at Medford, NJ from 623.8 to the bottom of the corehole at a depth of 1090.0 ft. The paplynomorphs in this corehole were analyzed by Brenner and McLaughlin in Sugarman et al. (2010) for pollen and spores to assign biostratigraphic zones. Recovery of palynomorphs was poor, although all three zones appear to be present (Sugarman et al., 2010). Zone III is noted by the appearance of *Tricolporoidites sp. A*, *Tricolpites nemejci, Foveotricolporites rhombohedralis, Tricolporopollenites sp. A*, and *T. sp. B* (Sugarman et al., 2010). Zone IIC assigned by the appearance of *Tricolporoidites subtilis* and *Rugubivesiulites rugosus*; Zone IIB by the appearance of the spores *Neoraistrickia robusta* and *Cicatricosisporites patapscoensis* (Sugarman et al., 2010). Like Fort Mott, no species restricted to Zone IIA was observed by Sugarman et al. (2010); a Zone I assignment was based on the occurrence of forms that more commonly occur in Zone I, rather than any identified index fossils.

At Medford, similar to Fort Mott, with the same caveats as Fort Mott, there is an increase in diversity of angiosperm pollen, and this increase included several rises and falls relative to the diversity of gymnosperms and spores. This current study resampled Medford 11 times to asses these changes in diversity.

3.2.4 North America Correlations

Similar assemblages of spores and pollen have been documented throughout North America and serve as correlative tools to help date the range of species found within the Potomac Group. This includes the Fredricksburg Group found in Oklahoma and Texas, and has been dated as late middle Albian using correlating ammonites in Texas; assemblages in this group correspond to those found in middle Zone II of the Potomac (Hedlund and Norris, 1968). The Glen Rose Fm. in Oklahoma produces Zone II forms with Clavatipollenites and Retimonocolpites monosulcates being the most common and diverse (Tanrikulu and Doyle, 2015). The Glen Rose Fm. is also notable for contrasting with Potomac flora and suggests a significant hiatus between Zone I and Zone II in the Potomac (Tanrikulu and Doyle, 2015). The Red Branch Member of the Woodbine Formation in Southern Oklahoma has produced assemblages similar to middle/upper Zone III in the Potomac, with a Cenomanian age based on late Cenomanian/early Turonian marine sediments that overlie this formation (Hedlund, 1966). The late Albian Thermopolis and Mowry Shales of Montana have palynomorphs that are correlatable to late Zone II forms (Tschudy and Veach, 1965). The Albian-Cenomanian boundary is often poorly defined. It is inferred in the Colorado Group of central Alberta as this section overlies (albeit unconformably) marine fauna that has been dated as middle Albian, it contains assemblages similar to those found in the latest Zone II/earliest Zone III (Norris, 1967). The Dakota Formation found throughout the Rocky Mountain and Great Plains region offers much similarity to the Potomac in terms of lithology, facies and assemblage types (Pierce, 1961; Retallack and Dilcher, 1981; Dilcher and Crane, 1984). Much like the Potomac it is poorly dated, relying on correlative formations (most closely is the Red Branch Member), it has the best flora diversity of this group allowing a better correlation with the Potomac Group (Pierce, 1961; Retallack and Dilcher, 1981; Dilcher and Crane, 1984).

3.2.5 Europe Correlations

Brenner (1963) initially used correlations with formations in England including the Valanginian to Barremian aged Wealden Group to place ages on his zonal scheme. The lower-middle Albian lower Greensand, Gault and upper Greensand Formations were found to contain assemblages correlatable to the Zone I/II boundary (Kemp, 1968). The Peruc Formaiton in the former Czechoslovakia has a similar assemblage to Zone III and is overlain by upper Cenomanian sediments dated by marine fauna.

Other localities in Europe, including Portugal (an area that factors heavily in the revised timeline of Hochuli et al., 2006), was initially studied by Groot and Groot (1962) and found to have undifferentiated Aptian sediments correlatable to Zone I. The Aptian/Albian boundary is similar to early Zone II forms and a Cenomanian age for Zone III assemblages (Groot and Groot, 1962).

3.2.6 Age Data

Previous studies by Sugarman et al. (2004; 2005; 2010) identified 3 distinct lithologic units (I, II, III) in the Potomac Formation at Fort Mott and Medford, NJ. Sugarman et al. (2005) noted that these three lithologic units were distinct fluvial-deltaic successions with typical sands at the base and clays (typically soils) at the top. Age control is entirely reliant on pollen biostratigraphy that is poorly calibrated to the Geological Time Scale (GTS) and are long in duration (3 zones in ~25 Myr). Each Potomac unit corresponds generally with a distinct pollen zone (See Ch. 2 Fig 2.2): 1) Unit III is placed in pollen Zone III, assigned by various authors to the early Cenomanian (Doyle and Robbins, 1977; Hochuli et al., 2006) with an age of ~96-100 Ma according to the Geological time scale 2012 [GTS2012; Gradstein et al., 2012); 2) Unit II is placed in pollen Zone II, assigned to the middle to late Albian (Doyle and Robbins, 1977), though it possibly extends to the earliest Cenomanian (Hochuli et al., 2006); the age is ~100-111 Ma (GTS2012); 3) Unit I is placed in pollen Zone I the Aptian (Hochuli et al., 2006), though it may extend to the Barremian (Doyle and Robbins, 1977); the age is ~111-126 Ma.

3.3 Methods

A total of 42 samples were collected from continuous coreholes at Fort Mott, NJ (17 samples), Medford, NJ (11 samples), Summit Marina, DE (6 samples). Samples taken and processed by Sugarman et al. (2004) from Fort Mott, NJ (6 samples) and by Sugarman et al. (2010) from Medford, NJ (6 samples) were also re-examined.

Sampled sediments were prepared using procedures developed by the Delaware Geological Survey (DGS) and processed at DGS facilities. Samples were dried in an oven at 100°C for 24hrs. Samples are then washed in 37% hydrochloric acid (HCl) solution to remove any carbonates, after which they are brought to neutral. Sand and larger grains are then removed via swirling and pouring off. Next 48% hydrofluoric acid (HF) is added to remove all silicates; this solution is allowed to sit for up to a week before being decanted. Followed by 20% HCl is added to neutralize the HF before being brought back to neutral. Samples are then oxidized with 35% Nitric Acid (HNO_3) and again brought back to neutral. Once neutral, 5% ammonium hydroxide (NH_4OH) is added to remove any humic acid. The samples are again neutralized before dehydration with acetic acid ($C_2H_4O_2$). Cellulose material is removed by the addition of 2ml sulfuric acid (H_2SO_4) and18ml acetic anhydride $(CH_3CO)_2O$ in a boiling water bath. Samples are then rewashed with acetic acid, centrifuged, and decanted until neutral, before being finally washed in 2% HCl to the remove excess acetic acid.

Pollen is then floated from the sample by heavy liquid separation using zinc chloride (ZnCl). Once ZnCl is added, the sample is centrifuged and palynomorph material is removed with a pipette to a 15ml vial. It is treated once more with 2% HCl to remove the heavy liquid, centrifuged and washed until neutral. After separation, pollen grains are mounted to a glass slide using glycerol (Faegri et al., 1989). Identifications of palynomorphs were made based on the morphology and as these features can be subtle, the samples will be stained (Safranin red) to increase contrast (exines absorb stains preferentially) from any surrounding material.

Pollen analysis will also include the additional of an exotic marker spike, in this case, polystyrene spheres, for quantitative measurement of absolute pollen grains. The marker technique involves adding 15 μm polystyrene microspheres with a known density (between $7x10^4$ and $10x10^4$ spheres/ml) at the end of pollen processing before the bromoform/ethanol separation (P. McLaughlin Jr., personal communication, August, 2011; Faegri et al., 1989). Species identification was done using a Nikon Eclipse LV100 light microscope at 300 to 1000 times magnification. Samples were processed and examined to count the diversity of species, including the amount of different species of spores, gymnosperms, and angiosperms (Eudicots and Monocots-Magnoliids). Diversity plots were created by counting at least 100 palynomorphs (more if applicable), this includes the artificial spike. Although it should be noted that this study produced low number of palynomorphs grains compared to previous studies from other locations. All identifiable pollen and spore were recorded at a genus and species level when possible. Otherwise the count was made to determine simply whether a form was spore, gymnosperm, Monocot-Mangnoliid or Eudicot.

3.4 Results

At Summit Marina, 6 depths were sampled for pollen (Fig. 3.1). All data and calculations are presented in Figs. 3.4-3.6, 3.8 and Tables 3.1, 3.2. The lowest sampled depth was at 470.7 ft (143.5 m) producing 7 different gymnosperms forms (58% of the total), 3 different spore types (25% of total), 2 different angiosperms, both Monocots-Magnoliids (17% of total). The next sample was upsection at a depth of 406.1 ft (123.8 m). This sample includes 5 different types of spore, (24% of total), 6 different gymnosperms (29% of total), and 10 different angiosperms, 4 Monocots-Magnoliids (19% of total), and 6 Eudicots (29% of total). Continuing upsection at a depth of 395.9 ft (120.7 m) produces 5 spore types (22% of total), 8 gymnosperm types (35% of total), 10

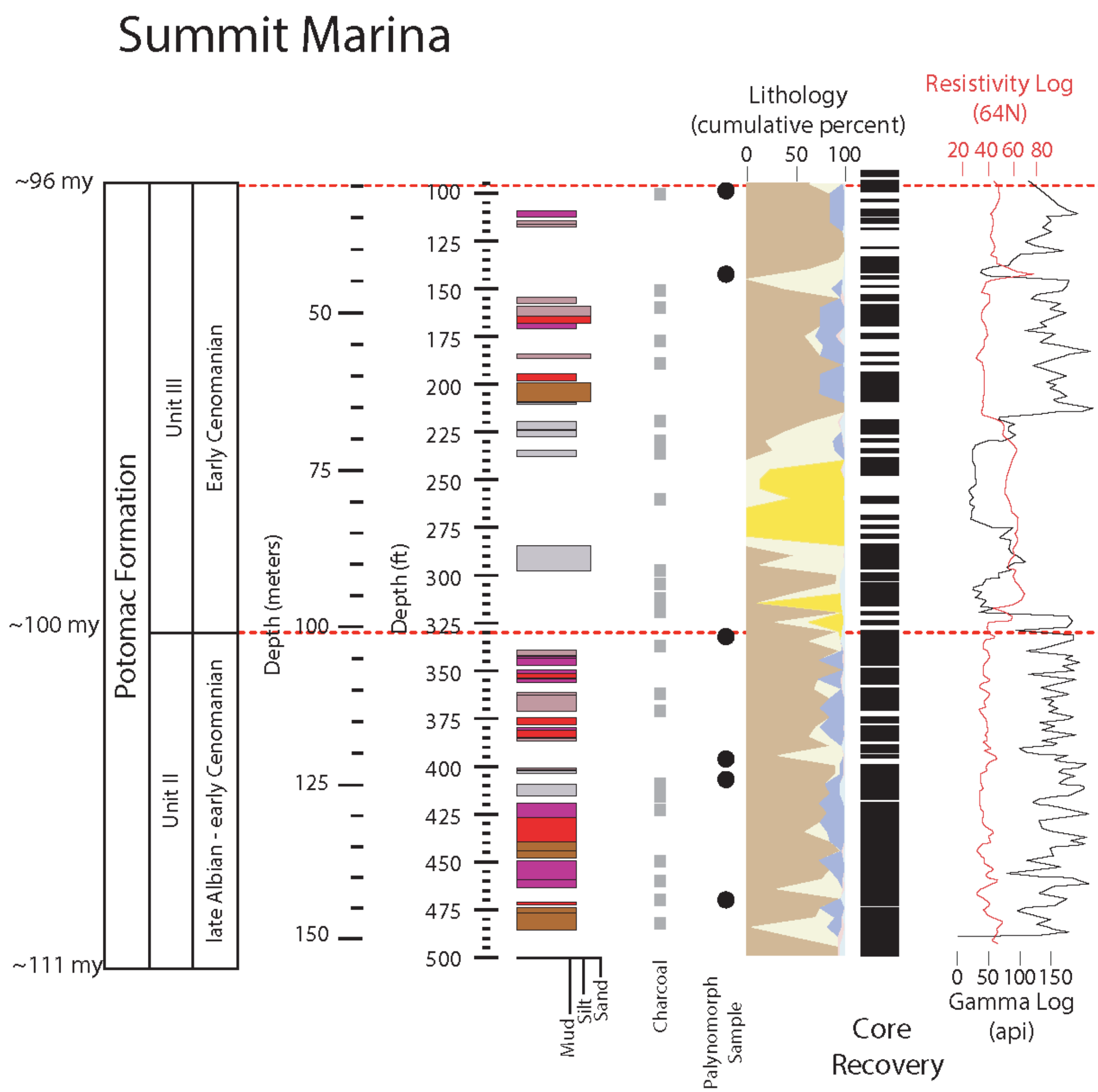

Figure 3.1 - Summit Marina corehole data illustrating palynomorph sample depths with respect to total lithology and geophysical data with location of paleosol profiles and occurrences of charcoal. Refer to Fig. 2.7 for legend.

angiosperm forms consisting of 4 Monocots-Magnoliids (17% of total), and 6 Eudicots (26% of total). The sample at a depth of 331.0 ft (100.9 m) has 5 spore types (18% of total), 10 gymnosperm types (36% of total), 13 angiosperm forms consisting of 5 Monocots-Magnoliids (18% of total), and 8 Eudicots (29% of total). At a depth of 142.5 ft (43.4 m) has 7 spore types (22% of total), 8 gymnosperm types (25% of total), 17 angiosperm forms consisting of 4 Monocots-Magnoliids (13% of total), and 13 Eudicots (10% of total). At a depth of 99.4 ft (30.3 m) has 3 spore types (16% of total), 7 gymnosperm types (37% of total), 9 angiosperm forms consisting of 3 Monocots-Magnoliids (16% of total), and 6 Eudicots (32% of total).

At Fort Mott, 23 depths were sampled or resampled for pollen (Fig. 3.2). All data and calculations are presented in Figs. 3.4-3.6, 3.8 and Tables 3.1, 3.2. The lowest depth, 806.0 ft (245.7 m), contains Zone I palynomorphs including 4 types of spore (80% of total), 1 type of gymnosperm (20% of total) and no angiosperm pollen. The next upsection sample at 765.5 ft (233.3 m) was essentially barren. A sample at 641.1 ft (195.4 m) produced Zone II palynomorphs including 6 spore types (67% of total), 2 types of gymnosperm (22% of total) and 1 angiosperm form, a Monocot-Magnoliid (11% of total). At a depth of 599.3 ft (182.7 m) 5 spore types were identified (71% of total), 1 gymnosperm type (14% of total) and 1 angiosperm, a Monocot-Magnoliid (14% of total). Upsection several samples produced sparse results at a depth of 577.2 ft (175.9 m) 2 spore types were identified (33% of total), 3 types of gymnosperm (50% of total) and 1 type of angiosperm, a Monocot-Magnoliid (17% of total). At a depth of 556.2 ft (169.5 m) 4 spore types were identified (80% of total), 1 types of gymnosperm (20% of total) and no angiosperm pollen was observed. At a depth of 500.0 ft (152.4 m) 1 spore type was identified (17% of total), 2

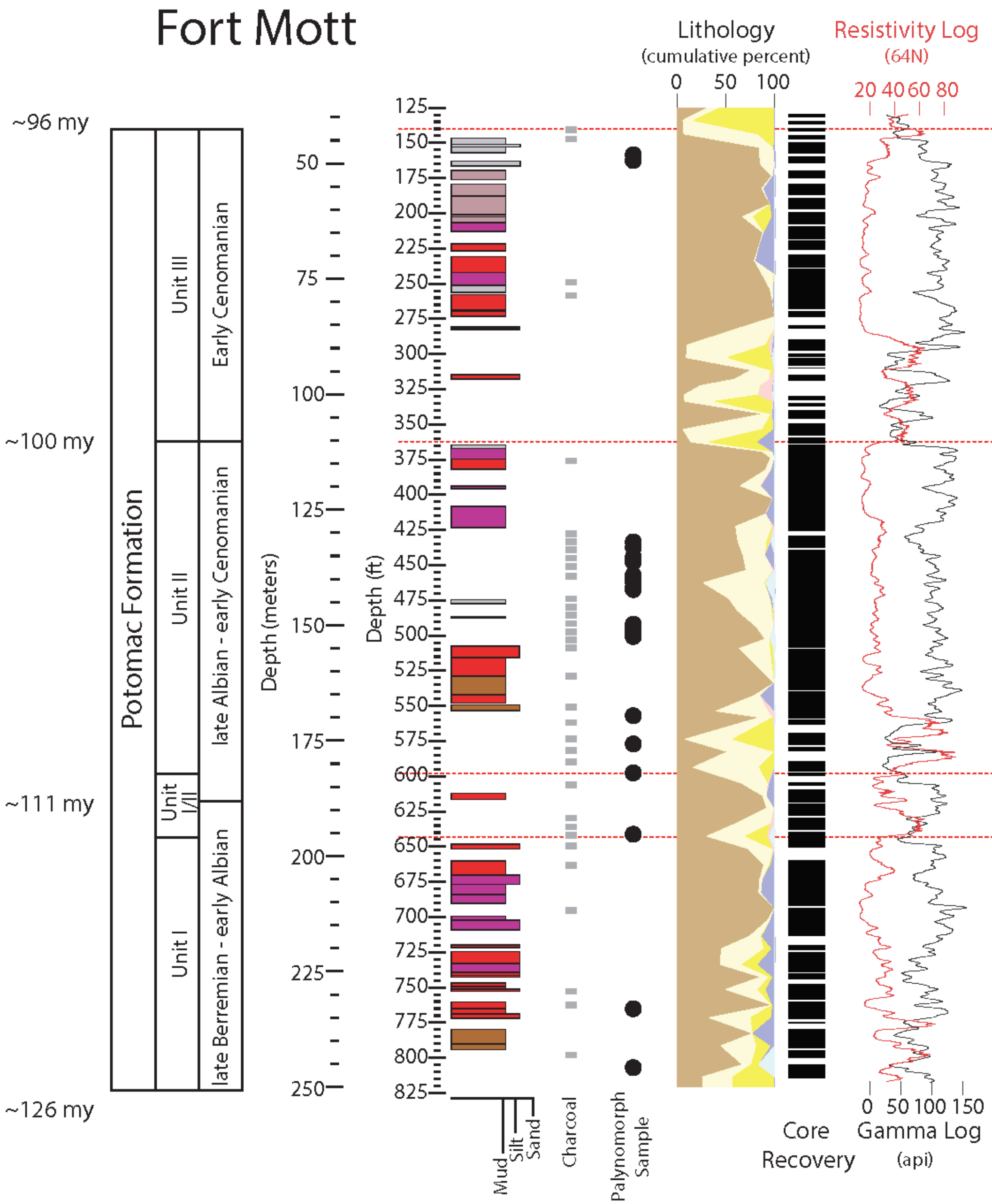

Figure 3.2 - Fort Mott corehole data illustrating palynomorph sample depths with respect to total lithology and geophysical data with location of paleosol profiles and occurrences of charcoal. Refer to Fig. 2.7 for legend.

types of gymnosperm (33% of total) and 3 types of angiosperm, all Eudicots (50% of total). At a depth of 497.9 ft (151.8 m) 3 spore types were identified (17% of total), 6 types of gymnosperm (33% of total) and 9 types of angiosperm, 3 Monocots-Magnoliids (17% of total) and 6 Eudicots (33% of total). At a depth of 497.3 ft (151.6 m) 15 spore types were identified (48% of total), 6 types of gymnosperm (19% of total) and 10 types of angiosperm, 6 Monocots-Magnoliids (19% of total) and 4 Eudicots (13% of total). At a depth of 496.3 ft (151.3 m) 3 spore types were identified (75% of total), 1 type of gymnosperm (25% of total) and no angiosperm pollen was identified. At a depth of 467.5 ft (142.5 m) 4 spore types were identified (27% of total), 7 types of gymnosperm (47% of total) and 4 types of angiosperm, 3 Monocots-Magnoliids (20% of total) and 1 Eudicots (7% of total). A barren sample at a depth of 466.0 ft (142.0 m). At a depth of 465.3 ft (141.8 m) no spores were identified, 2 types of gymnosperm (33% of total) and 4 types of angiosperm, all Eudicots (67% of total) were identified. A barren sample at 464.9 ft (141.7 m). At a depth of 463.9 ft (141.4 m) 11 spore types were identified (35% of total), 8 types of gymnosperm (26% of total) and 12 types of angiosperm, 6 Monocots-Magnoliids (19% of total) and 6 Eudicots (19% of total). At a depth of 460.5 ft (140.4 m) 8 spore types were identified (33% of total), 6 types of gymnosperm (25% of total) and 10 types of angiosperm, 3 Monocots-Magnoliids (13% of total) and 7 Eudicots (29% of total). At a depth of 455.6 ft (138.9 m) 4 spore types were identified (44% of total), 1 types of gymnosperm (11% of total) and 4 types of angiosperm, 2 Monocots-Magnoliids (22% of total) and 2 Eudicots (22% of total). At a depth of 449.1 ft (136.9 m) 14 spore types were identified (47% of total), 4 types of gymnosperm (13% of total) and 12 types of angiosperm, 3 Monocots-Magnoliids (10% of total) and 9 Eudicots (30% of total) were identified. At a depth of 447.6 ft (136.4 m) identifications include: 2 types of spore (33% of total), 3 types of gymnosperm (50% of total) and 1 type of angiosperm, a Eudicot (17% of total). At a depth of 435.9 ft (132.8 m) 5 spore types were identified (24% of total), 9 types of gymnosperm (43% of total) and 7 types of angiosperm, 3 Monocots-Magnoliids (14% of total) and 4 Eudicots (19% of total) were identified. At a depth of 435.4 ft (132.7 m) identifications include: 4 types of spore (80% of total), 1 types of gymnosperm (20% of total) and no angiosperm pollen. At a depth of 434.5 ft (132.4 m) identifications include: 6 types of spore (30% of total), 5 types of gymnosperm (25% of total) and 9 types of angiosperm, 3 types of Monocot-Magnoliid (15% of total), and 6 types of Eudicot (30% of total). At a depth of 162.8 ft (49.6 m) identifications include Zone III types including: 1 type of spore (20% of total), no observed gymnosperms, 4 types of angiosperm, 1 types of Monocot-Magnoliid (20% of total) and 3 types of Eudicot (60% of total). At a depth of 157.0 ft (47.9 m) identifications include: 2 type of spore (25% of total), 2 types of gymnosperms (25% of total), 4 types of angiosperm, 1 types of Monocot-Magnoliid (13% of total) and 3 types of Eudicot (38% of total).

At Medford, 17 depths were sampled or resampled for pollen (Fig. 3.3). All data and calculations are presented in Figs. 3.4-3.6, 3.8 and Table 3.1, 3.2. The lowest depth, 1043 ft (318.1 m), contains Zone I palynomorphs including 10 types of spore (67% of total), 4 type of gymnosperm (27% of total) and 1 type of angiosperm pollen, a Monocot-Magnoliid (7% of total). A sample at a depth of 1039.1 ft (316.7 m) was essentially barren with only 3 types of spore identified. A depth of 982.2 ft (299.4 m) was also essentially barren with only one type of spore identifiable. At a depth of 957.95 ft (291.98 m) Zone II forms are observed, identifications include: 2 type of spore (14% of total), 3 types of

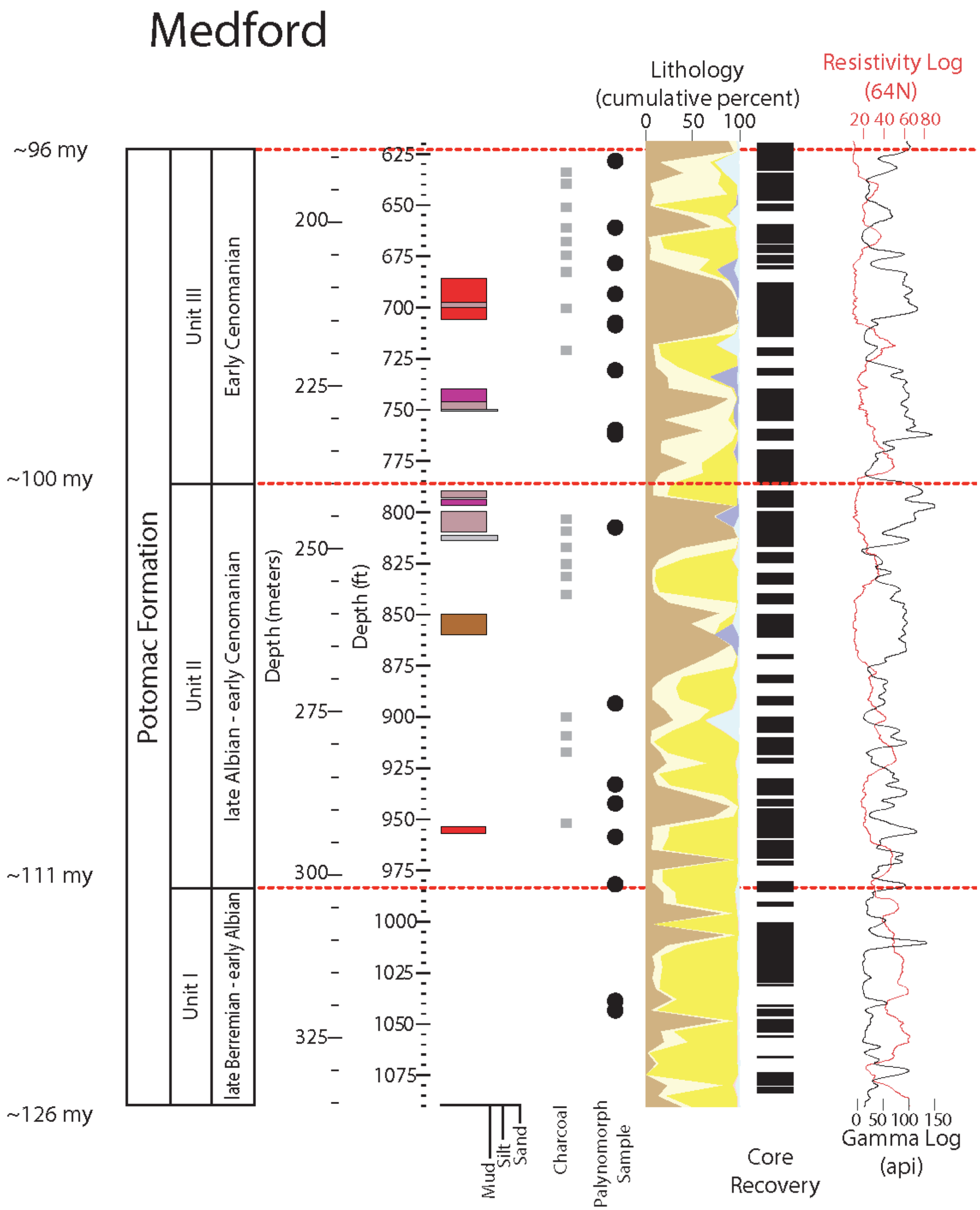

Figure 3.3 - Medford corehole data illustrating palynomorph sample depths with respect to total lithology and geophysical data with location of paleosol profiles and occurrences of charcoal. Refer to Fig. 2.7 for legend.

gymnosperms (21% of total), 9 types of angiosperm, 4 types of Monocot-Magnoliid (29% of total) and 5 types of Eudicot (36% of total). At a depth of 942.5 ft (287.3 m) identifications include: 6 type of spore (43% of total), 4 types of gymnosperms (29% of total), 4 types of angiosperm, 2 types of Monocot-Magnoliid (14% oftotal) and 2 types of Eudicot (14% of total). At a depth of 933.8 ft (284.6 m) identifications include: 8 type of spore (50% of total), 4 types of gymnosperms (25% of total), 4 types of angiosperm, 3 types of Monocot-Magnoliid (19% of total) and 1 types of Eudicot (6% of total). At a depth of 893.4 ft (272.3 m) identifications include: 7 type of spore (50% of total), 7 types of gymnosperms (36% of total), 2 types of angiosperm, 1 type of Monocot-Magnoliid (7% of total) and 1 types of Eudicot (7% of total). At a depth of 761.1 ft (232.0 m) identifications include: 1 type of spore (17% of total), 3 types of gymnosperms (50% of total), 2 types of angiosperm, 1 type of Monocot-Magnoliid (17% of total) and 1 type of Eudicot (17% of total). At a depth of 760.2 ft (231.7 m) likely within Zone III, identifications include: 5 type of spore (26% of total), 7 types of gymnosperms (37% of total), 7 types of angiosperm, 3 types of Monocot-Magnoliid (16% of total) and 4 types of Eudicot (21% of total). At a depth of 730.0 ft (222.5 m) identifications include: 9 type of spore (41% of total), 6 types of gymnosperms (27% of total), 7 types of angiosperm, 1 type of Monocot-Magnoliid (5% of total) and 6 types of Eudicot (27% of total). At a depth of 709.5 ft (216.3 m) identifications include: 1 type of spore (10% of total), 1 types of gymnosperms (10% of total), 8 types of angiosperm, 1 type of Monocot-Magnoliid (10% of total) and 7 types of Eudicot (70% of total). At a depth of a 708.0 ft (215.8 m) an essentially barren sample with only 1 type of spore identified. A barren sample at 693.1 ft (211.3 m). At a depth of 678.7 ft (206.9 m) identifications include: 4 type of spore (24%

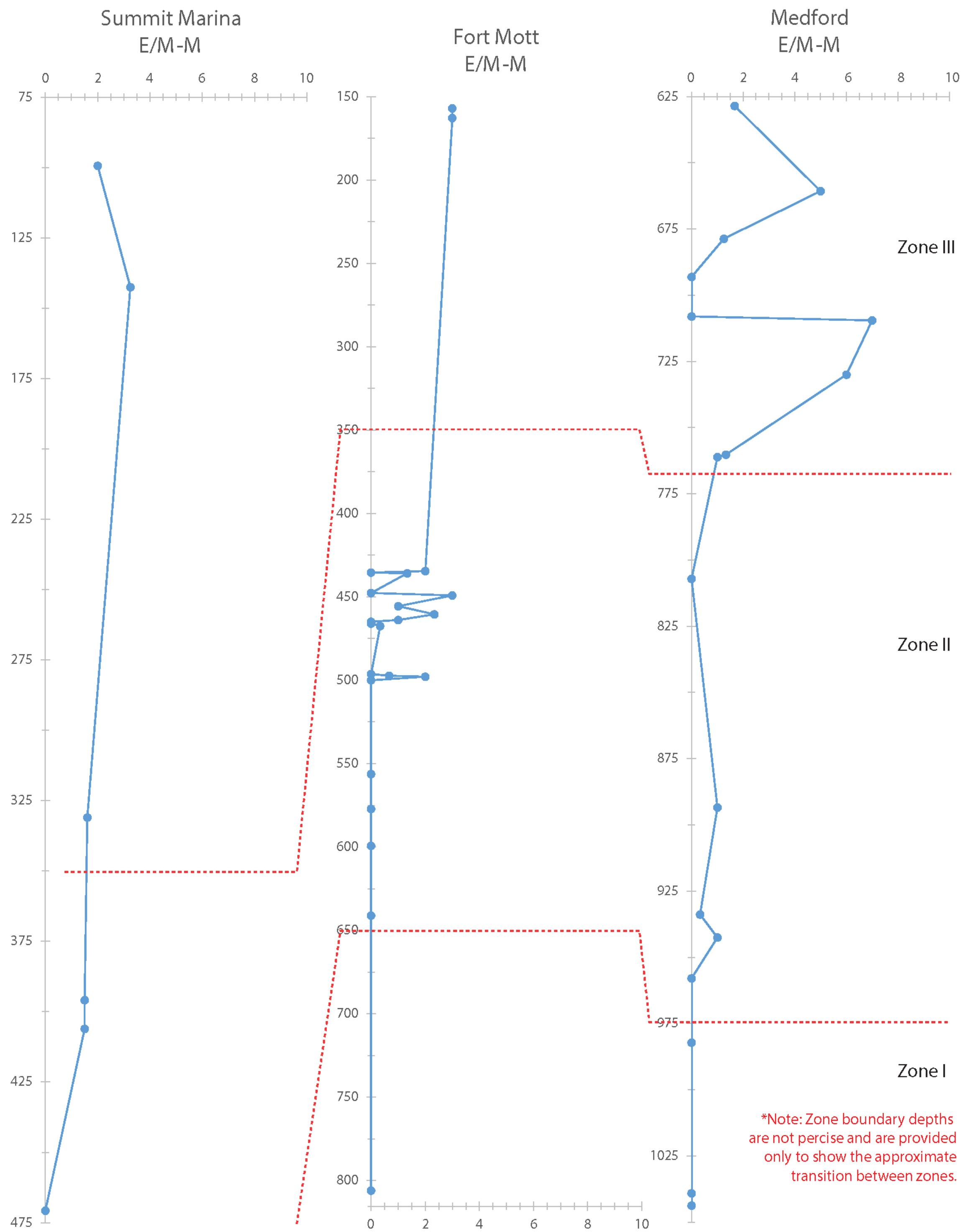

Figure 3.4 - Ratio of diversity of Eudicots to Magnoliids-Monocots for each of the three coreholes. Diversity calculation made on number of different species for each group.

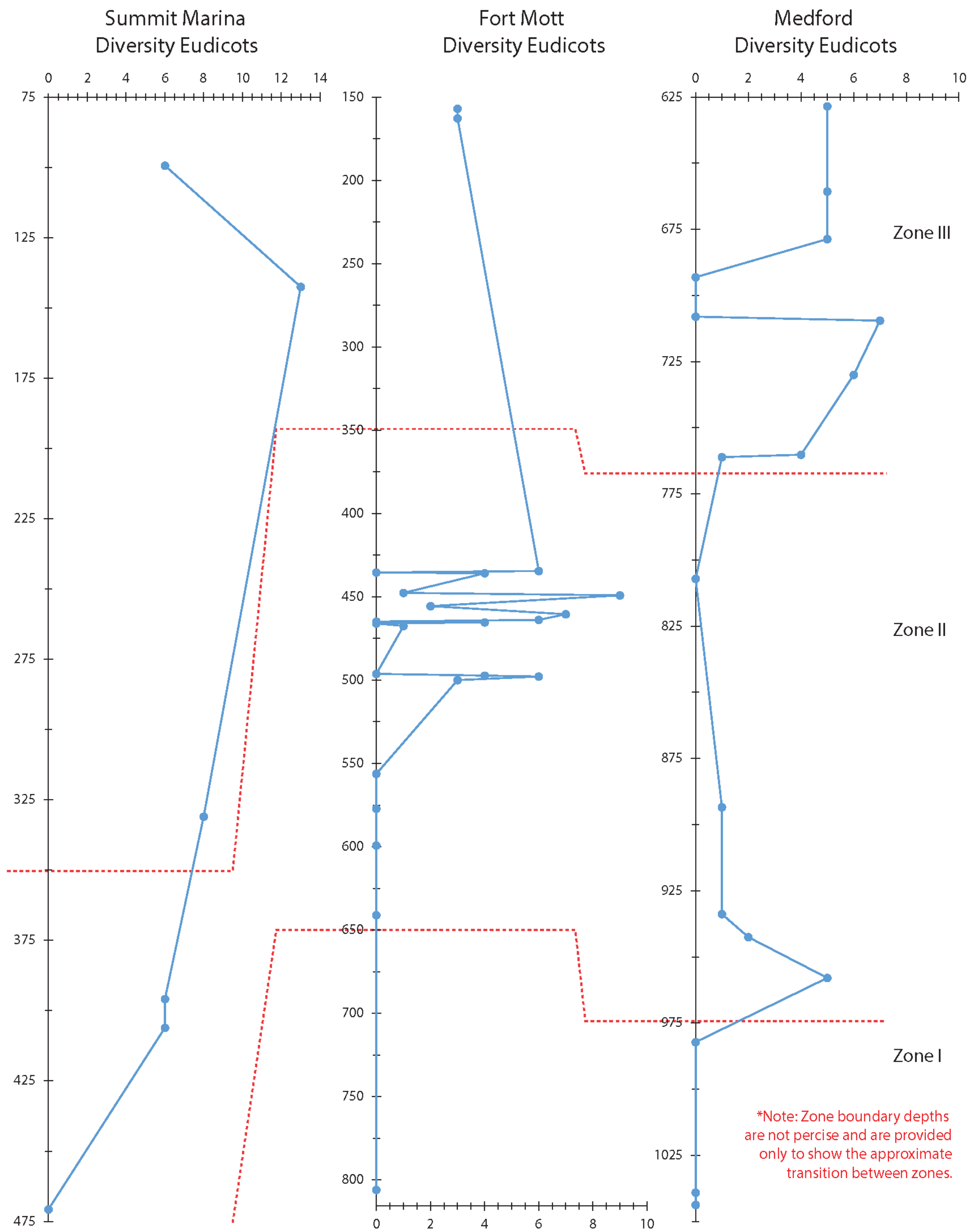

Figure 3.5 - Diversity of Eudicots for each of the three coreholes. Diversity calculation made on number of different species.

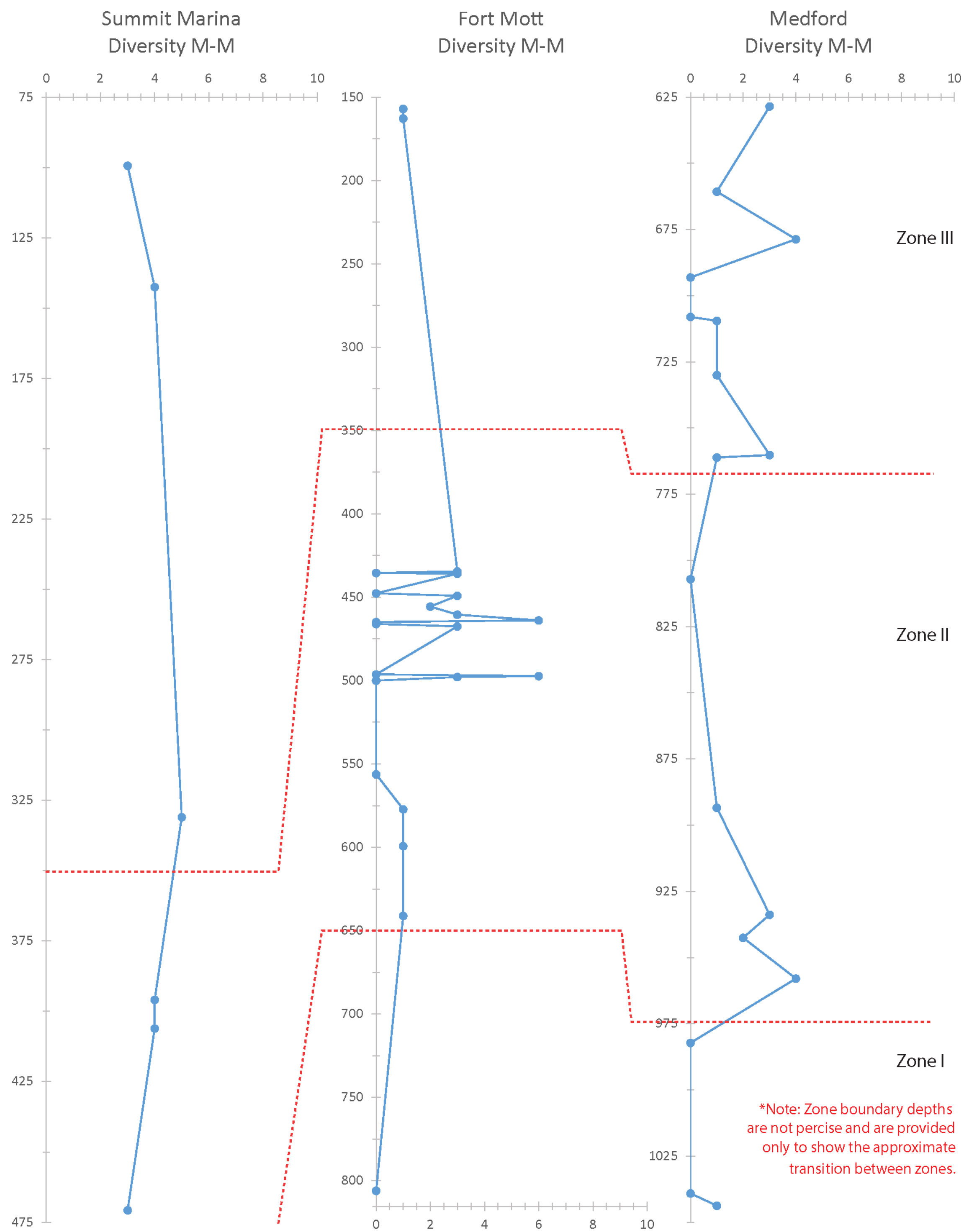

Figure 3.6 - Diversity of Magnoliids-Monocots for each of the three coreholes. Diversity calculation made on number of different species.

Table 3.1 - Angiosperm occurrence data for sampled palynomorph material for three coreholes. Note: horizontal black line represents zonal boundaries with III at the top.

Summit Marina - Angiosperm Pollen

	Monocot-Magnoliid										Eudicot																			
Depth (ft.)	Clavtipollenites tenellis	Clavatipollenites hughesii	Clavatipollenites minutus	Stellapollenites barghoornii	Stellatopollis spp.	Retimonocolpites sp. A	Liliacidites sp. E	Liliacidites sp. D	Retimonocolpites peroreticulatus	Liliacidites sp. F	Tricolpites cf albiensis	Tricolpites aff. Fragosus	Tricolpites sagax	Tricolpites micromunus	Tricolpites minutus	Tricolpites sp. B	Tricolpopollenites parvulus	Tricolporoidites cf subtilis	Tricolporoidites sp. A	Tricolporopollenites aff triangulus	Tricolporopollenites sp. B	Ajatipollis sp. A	Clavatipollenites parvulus	Striatopollis spp.	Rousea georgensis	Striatipollis paranus	Striatipollis sp. B	Tricolporopollenites bohemicus	Dicotetradites sp. A	Tricolpites vulgaris
99.4			x			x				x								x	x	x	x	x	x							
142.5			x				x	x		x				x	x	x	x	x	x	x	x		x			x	x	x		x
331.0		x	x	x	x		x						x		x	x		x		x				x	x				x	
395.9	x	x	x						x			x	x	x	x					x				x						
406.1		x	x	x						x	x				x			x		x						x			x	
470.7	x																													

Fort Mott - Angiosperm Pollen

	Monocot-Magnoliid								Eudicot															
Depth (ft.)	Clavatipollenites hughesi	Monosulcites scabrous	Monosulcites chaloneri	Monosulcites sp.	Retimonocolpites dividuus	Stellatopollis barghoornii	Liliacidites dividuus	Spheripollenites perinatus	Tricolpites albiensis	Tricolporoidites subtillis	Tricolporoidites sp. A	Tricolporopollenites distinctus	Tricolporopollenites triangulus	Tricolpopollenites minutus	Tricolpopollenites micromunus	Tricolporopollenites sp. B	Tricolporoidites sp. B	Ajatipollis sp. A	Tricolporoidites minimus	Penetetrapites mollis	Rousea aff. Georgensis	aff. Tricolporopollenites triangulus	aff. Ajatipollis sp. A	aff. Striatopollis vermimura
157.0										x	x					x								
162.8	x															x	x	x						
434.5				x			x	x		x		x		x						x		x	x	
435.4																								
435.9		x	x	x						x			x							x			x	
447.6														x										
449.1	x	x		x					x	x		x	x						x	x		x	x	x
465.3												x	x	x	x									
497.9	x				x	x				x			x		x				x	x	x			
500.0									x	x			x											
556.2																								
577.2	x																							
599.3	x																							
641.1	x																							
806.0																								

Table 3.1 (cont.)

Summit Marina - Angiosperm Pollen

Depth (ft.)	Monocot-Magnoliid										Eudicot																			
	Clavtipollenites tenellis	Clavatipollenites hughesii	Clavatipollenites minutus	Stellapollenites barghoornii	Stellatopollis spp.	Retimonocolpites sp. A	Liliacidites sp. E	Liliacidites sp. D	Retimonocolpites peroreticulatus	Liliacidites sp. F	Tricolpites cf albiensis	Tricolpites aff. Fragosus	Tricolpites sagax	Tricolpites micromunus	Tricolpites minutus	Tricolpites sp. B	Tricolpopollenites parvulus	Tricolporoidites cf subtilis	Tricolporoidites sp. A	Tricolporopollenites aff triangulus	Tricolporopollenites sp. B	Ajatipollis sp. A	Clavatipollenites parvulus	Striatopollis spp.	Rousea georgensis	Striatipollis paranus	Striatipollis sp. B	Tricolporopollenites bohemicus	Dicotetradites sp. A	Tricolpites vulgaris
99.4			x			x				x								x	x	x	x	x	x							
142.5			x				x	x		x				x	x	x	x	x	x	x	x		x			x	x	x		x
331.0		x	x	x	x		x						x		x	x		x		x				x	x				x	
395.9	x	x	x						x			x	x	x	x					x				x						
406.1		x	x	x						x	x				x			x		x						x			x	
470.7	x																													

Fort Mott - Angiosperm Pollen

Depth (ft.)	Monocot-Magnoliid								Eudicot															
	Clavatipollenites hughesi	Monosulcites scabrous	Monosulcites chaloneri	Monosulcites sp.	Retimonocolpites dividuus	Stellatopollis barghoornii	Liliacidites dividuus	Spheripollenites perinatus	Tricolpites albiensis	Tricolporoidites subtillis	Tricolporoidites sp. A	Tricolporopollenites distinctus	Tricolporopollenites triangulus	Tricolpopollenites minutus	Tricolpopollenites micromunus	Tricolporopollenites sp. B	Tricolporoidites sp. B	Ajatipollis sp. A	Tricolporoidites minimus	Penetetrapites mollis	Rousea aff. Georgensis	aff. Tricolporopollenites triangulus	aff. Ajatipollis sp. A	aff. Striatopollis vermimura
157.0										x	x					x								
162.8	x															x	x	x						
434.5				x			x	x		x		x		x						x		x	x	
435.4																								
435.9		x	x	x						x			x							x			x	
447.6														x										
449.1	x	x		x					x	x		x	x						x	x		x	x	x
465.3												x	x	x	x									
497.9	x				x	x				x			x		x				x	x	x			
500.0									x	x			x											
556.2																								
577.2	x																							
599.3	x																							
641.1	x																							
806.0																								

Table 3.2 - Total diversity data for occurrences of different species for each palynomorph group. Note: horizontal black line represents zonal boundaries with III at the top.

Summit Marina		Diversity Spores	Diversity Gymnosperm	Diversity Monocot-Magnoliid	Diversity Eudicot	Eudicot/Monocot-Magnoliid
	99.4	3	7	3	6	2.0
	142.5	7	8	4	13	3.3
	331.0	5	10	5	8	1.6
	395.9	5	8	4	6	1.5
	406.1	5	6	4	6	1.5
	470.7	3	14	1	0	0.0
Fort Mott						
	157.0	2	2	0	3	0.0
	162.8	1	0	1	3	3.0
	434.5	6	5	3	6	2.0
	435.4	4	1	0	0	0.0
	435.9	5	9	3	4	1.3
	447.6	2	3	0	1	0.0
	449.1	14	4	3	9	3.0
	465.3	0	2	0	4	0.0
	497.9	3	6	3	6	2.0
	500.0	1	2	0	3	0.0
	556.2	4	1	0	0	0.0
	577.2	2	3	1	0	0.0
	599.3	5	1	1	0	0.0
	641.1	6	2	1	0	0.0
	806.0	4	1	0	0	0.0
Medford						
	628.5	3	5	2	5	2.5
	660.7	4	2	1	5	5.0
	678.7	4	4	3	5	1.7
	693.1	0	0	0	0	0.0
	708.0	1	0	0	0	0.0
	709.5	1	1	1	7	7.0
	730.0	9	6	1	6	6.0
	760.2	5	7	2	5	2.5
	761.1	1	3	1	1	1.0
	807.1	0	0	0	0	0.0
	893.4	7	5	1	1	1.0
	933.8	8	4	2	1	0.5
	942.5	6	4	2	2	1.0
	958.0	2	3	4	5	1.3
	982.2	1	0	0	0	0.0
	1039.1	3	0	0	0	0.0
	1043.7	10	4	1	0	0.0

of total), 4 types of gymnosperms (24% of total), 9 types of angiosperm, 4 types of Monocot-Magnoliid (24% of total) and 5 types of Eudicot (29% of total). At a depth of 660.7 ft (201.4 m) identifications include: 4 types of spore (33% of total), 2 types of gymnosperms (17% of total), 6 types ofangiosperm, 1 type of Monocot-Magnoliid (8% of total) and 5 types of Eudicot (42% of total). At a depth of 628.5 ft (191.6 m) identifications include: 3 type of spore (19% of total), 5 types of gymnosperms (31% of total), 8 types of angiosperm, 3 types of Monocot-Magnoliid (19% of total) and 5 types of Eudicot (31% of total).

3.5 Discussion

3.5.1 Correlation

The correlation technique of Hochuli et al. (2006) was attempted to see any changes in angiosperm diversity and abundance patterns of monocolpate (monocots and magnoliids) and poly-(tri)-aperturate (eudicots) forms within the lithologic units of the Potomac Formation. This would potentially offer a higher order of resolution between these sites. Unfortunately the sampled sediments often produced sparse angiosperm available on processed slides to provide any data with definitive trends within the units. The variability does not allow for any reasonable tie points between sites. Hochuli et al. (2006), noted an increase in E/M-M from <0.5 in Zone I to 1.3 in Zone IIA, 2.0 in IIB, and rising continuously to >3.0 in Zone III (Fig. 3.7). Hochuli et al. (2006) applied this increase in the ratio of E/M-M to a composite of the two coreholes (Delaware City sites D12 and D13) from the Doyle and Robbins (1977) study to refine the Potomac Fm. age data. This increase in E/M-M is not present at these sites, even though they relatively close, Summit

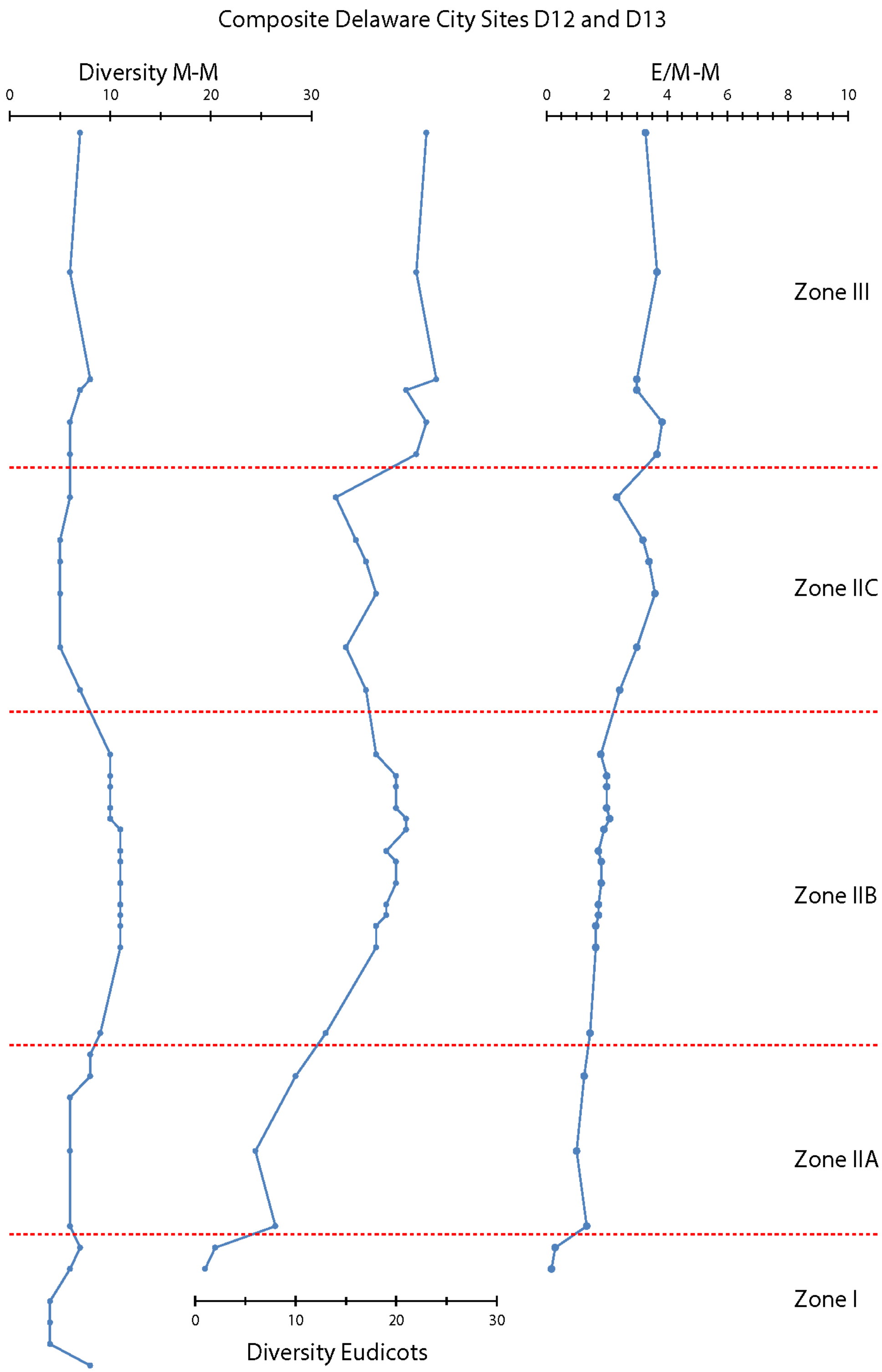

Figure 3.7 - Diversity and Ratio of Eudicots and Magnoliids-Monocots for the Delaware City coreholes of Doyle and Robbins (1977) and utilized by Hochouli et al. (2006) for comparison with the three coreholes of this study (modified from Doyle and Robbins (1977) and Hochuli et al. (2006)).

Marina and Fort Mott are less than 10 miles away (Figs. 3.4, 3.7). Although it is noted that the number of specimens recovered and counted in the Doyle and Robbins (1977) is much greater than found and recovered at the sites in this study. Even in the known assigned Zones at Fort Mott and Medford there was variations in the E/M-M ratio, and between sites these variations did not appear related. It should be noted that this variability is not the continuously increasing values upsection that Hochuli et al. (2006) noted at the Delaware City sites. This may be a function of the limited availability of material at all three of our sites that does not allow regular closely spaced sampling upsection. All recovered and processed samples produced slides with very limited amount of palynomorphs material compared to those from the Delaware City sites. Trends, data and calculations are presented in Figs. 3.4-3.8 and tables 3.1-3.2.

With this in mind a note is made here on lithologic bias. Care must be taken with using palynological data for assessing diversity, abundance and stratigraphic relationships. This is due to the inherent bias that occurs during the deposition of palynomorphs. Pollen and spores are silt-sized particles, and there deposition can be restricted due to this, areas of higher energy and with well-sorted sands or clays will often lack palynomorphs (Traverse, 1988). Although these specimens are resistant to most chemical weathering, they are susceptible to periods of oxidation and/or high alkalinity that will degrade the specimens (Traverse, 1988). In the Potomac Formation this leaves gaps in sampling and must be taken into account when trying to analyze any potential trends in diversity and abundance through time, this is illustrated in the lithology columns (Figs. 3.2-3.4).

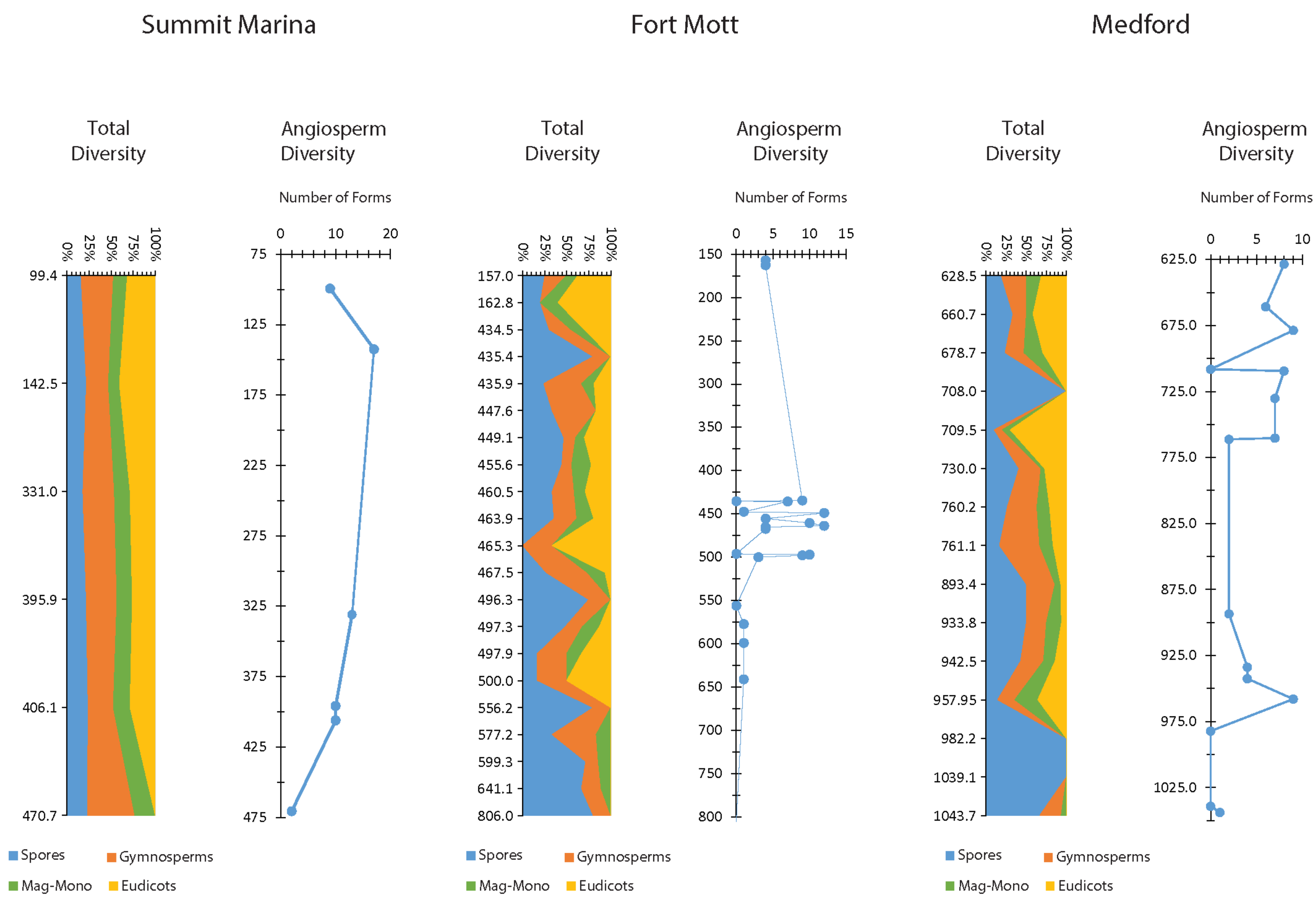

Figure 3.8 - Diversity of total angiosperm pollen with respect to total diversity of all palynomorphs identified in sampled material. Diversity refers to the total number of identified different species.

These samples were also used in conjunction with sediment data to evaluate changes in overall diversity (angiosperm, gymnosperm and spore) with changes in surface conditions. With the above on bias in mind, sampling is usually restricted to those sediments deposited in lower energy that is not particularly well-sorted sands or clays. Well sorted sediments, or coarser grain sizes, indicative of higher energy or any areas of significant oxidization (e.g. red beds) are all usually poor sites for preservation of palynomorphs and were disregarded during sampling.

3.5.2 Habitat Disturbances

A secondary goal of this project was to test two hypotheses regarding the radiation of angiosperm pollen related to disturbances in landscape conditions. Habitat disturbance has been often cited as being related to angiosperm radiation, the first hypothesis proposed by Bond and Scott (2010) looks at habitat disturbances from wildfires promoting and the second put forth by various researchers looks at disturbances from fluvial or coastal influences (Bakker, 1978; Hickey and Doyle, 1977; Retallack and Dilcher, 1981, 1986; Wing and Bouchner, 1998; Royer et al., 2010; Bond and Scott, 2010).

Large scale changes inducing the radiation of angiosperms includes that of Bakker (1978) proposing the rise of ornithischians causing dinoturbation to clear the land. This however does not seem sufficient to account for the rapid diversification and global spread of angiosperms. Global changes in climate and oceanographic perturbations during the Early to Late Cretaceous have been cited by Heimhofer et al. (2005) as the driver of angiosperm diversity. This cannot be tested here, aside from observing that the rise of angiosperms occurred the same time as these global changes.

A more local (and thus testable here) possible cause in the rise of angiosperms, other than the angiosperm-fire cycle of Bond and Scott (2010), links diversification to habitat disruption. A riparian environment where habitat disturbances are from a fluvial system is favored by researchers such as Hickey and Doyle (1977), Wing and Bouchner (1998), and Royer et al., (2010). The depositional environment of the Potomac Formation has been previously described as fluvial-deltaic occurring on a coastal plain setting. Given this, and the occurrence of angiosperms, this seems to hold the most promise regarding the increase in angiosperm occurrence found at these sites. Aside from this interpretation, Retallack and Dilcher (1981, 1986) explained this radiation using a coastal hypothesis where environmental stresses, such as transgressions and regression, occur frequently over time. These stresses create the habitat disturbances necessary for angiosperms to evolve and radiate.

Below each site is examined with the palynomorph diversity compared with the surrounding lithology. The purpose of this is to test the riparian hypothesis to see if any relationship presents itself between the nature fluvial sediments deposits and angiosperm diversity. This lithology was previously described at Fort Mott and Medford by Sugarman et al. (2004, 2005, and 2010) with the interpretation of sand body deposition occurring from an anastomosing fluvial system. The finer grain deposits have often experienced periods of pedogenesis (described in the detail in chapter 2) and provide insight as to the stability of landscape conditions (e.g. stable for long periods producing well-developed soils). Sugarman et al. (2005) did suggest that the large deposits of sand found at the base of Potomac Formation Unit II and III are possible delta front sands. While this scenario is unlikely, it offers the chance explore an alternative hypothesis of Retallack and Dilcher

(1981, 1986) to see if there is any change in angiosperm diversity above or below these sands.

3.5.3 Angiosperms and Fire

The first landscape disturbance hypothesis is an angiosperm-fire cycle that has been promoted as a possible positive feedback (Bond and Scott, 2010). This feedback lead to the rapid expansion and diversification of angiosperms during the early Cretaceous (Bond and Scott, 2010). The fire regime (frequency, severity, and spatial extent) plays a role in how the vegetation of an ecosystem is structured as well as influencing the traits of an individual plant species (Bond and Scott, 2010). Evidence abounds for the presence of Cretaceous wildfires globally, including with the presence of fusain (fossil charcoal) providing direct evidence, as well as inertinite (coal) and geochemical traces of polyaromatic hydrocarbons (PAHs) that act as fire proxies (Brown et al., 2010; Bond and Scott, 2010; Glasspool and Scott, 2010; 2013).

Conditions for the spread of wildfires include sufficient biomass, periodic dry conditions, climates conductive to lightning and sufficient atmospheric oxygen. Oxygen levels above 15% are believed the lower limit to allow ignition and higher values permit ignition of wetter material (Bond and Midgley, 2012; Bond and Scott, 2010; Glasspool and Scott, 2010; 2013). Modeling and proxy data place atmospheric oxygen during this time between 17 and 25% (Belcher, 2010; Bond and Midgley, 2012; Bond and Scott, 2010).

Current data suggests that if these conditions are satisfied, fires would clear land and allow for the appearance of the highly productive, rapidly growing angiosperms (Bond and Scott, 2010; Brown et al., 2013). Attributes of fossil features compared with modern forms suggest that early angiosperms were small, weed to shrub-like in nature (Bond and

Scott, 2010). The appearance and volume of this low growing flora would have created an abundance of biomass that provided the fuel source for wildfires. This created a novel fire regime and produced a positive feedback loop of increased biomass enhancing the frequency between fires, which cleared new areas to be populated by the highly productive angiosperms. Frequent fires clearing land also provided habitats that were open and exposed to sunlight, this is a preferential habitat for angiosperms with adaptations for increased rates of photosynthesis, reproduction and maturation.

Global increase in extent and frequency of wildfires, as evidenced through charcoal and other proxies provides a more satisfactory explanation for both their colonization and producing of a positive feedback of rapid growth creating a novel fire regime to clear further land (Bond and Midgley, 2012; Bond and Scott, 2010; Brown et al., 2013).

The following looks at each individual site to evaluate any changes in angiosperm abundance related to charcoal deposits. Detailed counts of individual species will provide an enhanced picture of potential increases in angiosperm diversity (Fig. 3.8).

At Medford the first increase in angiosperm diversity occurs at 942.5 ft. and is preceded by charcoal rich sediments at 950-953 ft. Upsection from this spike in diversity there is a deposit with charcoal fragments at 914-920 ft. and 900-906 ft. which could roughly follow the angiosperm/fire hypothesis of Bond and Scott (2010). Although not as a continuous trend upsection as the diversity of angiosperms at sample 893.4 ft. drops. There are several intervals with fragments from charcoal above this at 844 ft., 830-834ft., 824 ft., 814-816 ft., and 800-804 ft., however the next sample containing palynomorphs upsection at 761.1 ft., so no assessment within this section can be made of these charcoal deposits. This sample at 761.1 ft as well as a sample at 730.0 ft both contain angiosperm pollen, but neither sample is dominated by this type.

A layer of charcoal fragments is found at 706-709 ft. and occurs with a spike in angiosperm diversity in a sample at 709.5 ft. Similarly charcoal fragments are found upsection between 662-674 ft. and 628-639 ft. that occur with increases in angiosperm pollen at 628.5 ft., 678.7 ft. and 660.7 ft.

At Fort Mott, angiosperm diversity increases in Unit II with dramatic peaks at, 465.3 ft., 497.9 ft., and 500.0 ft. Each of these can be associated with charcoal fragments preceding and following these spikes that can be explained by the angiosperm-fire hypothesis. However there is ambiguity as to just how related these two factors appear. This ambiguity is compounded by focus of this study on changes in diversity with generally low counts made per sample. A more detailed count of individual specimens might possibly shed further light on abundance changes with regard to charcoal deposits. There are charcoal fragments surrounding other samples within this interval that show no similar increases in diversity of angiosperm pollen, in fact at times, some of these samples (496.3 ft. and 497.3 ft) show the diversity drops.

Palynomorph recovery was poor in both Zones I and III. With this paucity of data in mind there are still several occurrences of charcoal with angiosperms that occur in Zones I, I/II and lower II. Charcoal rich deposits occur, from 651-640 ft. that correspond to the rise in angiosperm diversity at 641.1 ft. This is followed upsection by more charcoal at 638-630 ft. There are only few fragments of charcoal observed at 620 and 615 ft. before the next recovered sample of palynomorphs showing increased diversity at 599.3 ft., with charcoal deposits found upsection at 598-598 ft.

There is an increase in angiosperm diversity in Zone III at 162.8 ft, this is not preceded by any significant deposits of charcoal (the nearest deposit is downsection at 255 ft.) with the nearest upsection interval containing any charcoal from 130-140 ft. The diversity drops upsection before this however at sample from 157.0 ft. The variability of the increases and decreases do not at least at this site seem to be related to the charcoal, again this may be a function of the limited sampling. The evaluation of this hypothesis is hampered by the abundance of charcoal fragments found throughout this site, with a question of how much is in situ versus how much was transported to this site.

As at Fort Mott, Summit Marina offers an ambiguous at best record. In Zone II there are charcoal deposits at 475.0 ft with samples containing no angiosperm pollen at 470.7 ft. However sediments with charcoal at 410.0 ft could possibly be associated with samples containing angiosperm pollen at 406.1 and 395.9 ft, although there are no nearby charcoal rich sediments upsection that would be expected with an increase in fire from angiosperms radiating.

In Zone III at Summit Marina, there are charcoal deposits (100.5 ft, 150.0 ft, and 340.2 ft) associated with samples containing angiosperm pollen (99.4 ft, 142.5 ft, and 336.0 ft). These instances of angiosperm pollen are not dominating the sample and they do not even continuously increase upsection.

This hypothesis cannot be discounted completely but it is not overly apparent at these sites and a connection made between fire and angiosperm radiation is speculative at best. This may be due to the irregular spacing of sampling and lack of any direct connection between charcoal rich deposits and spikes in angiosperm pollen does not permit any good evaluation of this relationship. The other variables associated with preservation of sediments and limited lateral resolution also should be taken into account, and possible future sampling to extract palynomorphs from the charcoal may provide further insights into this potential link.

3.5.4 Riparian and Coastal Disturbances

Below we look at the second hypothesis related to habitat disturbance, with angiosperm diversity as it relates to landscape conditions to judge the riparian hypothesis for radiation, and also consider the coastal hypothesis.

At Medford Unit I materials were mostly to coarse for palynomorphs preservation and sampling. The base of Unit II is marked by a large sand deposit, interpreted as deposited within an anastomosing fluvial system. Within these deposits a spike in pollen diversity occurs at 957.95 associated with a brief period of landscape stability that is noted by the formation of moderate to well-developed paleosol deposits. Upsection there is a return avulsion deposits, several samples from this interval show angiosperm diversity decreases. This is interesting as this landscape is highly unstable and disturbed during this period of avulsion; however, the aquic nature of the landscape might not permit the angiosperms to flourish. A rise in spore diversity is observed over this same interval.

The base of Unit III at 786.8 ft is marked again by a large interval of sand. As in Unit II, there is a relative period of landscape stability with paleosols, preceding this, samples at 760.2 and 761.1 ft show an increase in angiosperm diversity. Upsection is more sands deposited during avulsions from this anastomosing system. A sample from this interval shows as in Unit II a decrease in diversity, and an increase in spore diversity that would be anticipated under wet conditions. Upsection from this interval of instability a sample at 709.5 ft shows another increase in angiosperm diversity that is followed upsection by a period of landscape stability. This is of note from the information at this site it appears that not only does the landscape need disruption from the fluvial system (as show by the sand deposits) but one the landscape is disrupted there needs to be relative stability to allow radiation.

There is only one sample from Unit I at Fort Mott so no connections between the landscape and palynomorphs can be made with reasonable certainty. The base of Unit II is marked by fluvial sands, through which the diversity of angiosperms remains low, upsection preceding landscape stability at a sample at 556.2 ft does not show an increase in angiosperm radiation as at Medford.

Upsection from this stable interval (marked by paleosols) is an interval of instability resulting in avulsion deposits. Several samples show spikes in angiosperm diversity, however just as many samples show similar drops in angiosperm diversity. This variability is potentially due to the nature of deposition under aquic conditions, each decrease is marked by an increase in spores as evidence of this explanation.

Samples at Fort Mott from the top of Unit III (157.0 ft and 162.5 ft) depositing under similarly poorly drained conditions where there was rapid deposition. At both sample depths angiosperms account for the majority of the identified forms and may reflect the favorable conditions created by disruption of the landscape.

The base of the corehole at Summit Marina, within Unit II, is marked by a stable landscape, and a sample from 470.7 ft has very low angiosperm diversity. Upsection during a more unstable interval with poorly developed paleosol and avulsion deposits angiosperm diversity increases at 406.1 and 395.9 ft. At the top of this unit, again marked by an unstable landscape, shows a further increase in angiosperm diversity.

Unfortunately there are no samples within or directly overlying the sand at the base of Unit III. The only samples from Unit III are at the top of this unit, within two intervals deposited during avulsions and both show relatively high angiosperm diversities.

Although there is variability from the sites regarding angiosperm diversity within the lithologic units there appears to be consistent increases associated with landscape disturbances when compared with the lithology which shows that at times this landscape unstable dominated either by the fluvial channel or avulsion deposits. Some of variability, especially during unstable intervals expected to have high angiosperm diversity can be explained by a landscape that has become too unstable for angiosperms to flourish. If we take an alternative approach and suppose the basal unit sand intervals are delta front sands representing transgression deposits with overlying sediments would represent regression deposits. In the coastal hypothesis of Retallack and Dilcher (1981, 1986) these transgressions and regressions were responsible for landscape disturbances clearing the land for angiosperm radiation. However, while there is an increase after these unit basal sands, upsection trends should favor a decrease in diversity as the landscape stabilizes during regression and forest cover is established. This is not observed and this alternative scenario is unlikely here. The data and interpretations here support the riparian hypothesis of angiosperm radiation.

3.6 Conclusion

Palynology has provided a key means to correlate the strata of the nonmarine Potomac Formation. However this zonation offers only a coarse resolution between sites. The Potomac Formation is noted for its preservation of the early radiation of angiosperm pollen. Here we attempted to use diversity patterns, specifically changes in Monocots-Magnoliids, Eudicots, and the ratio between the Eudicots to Monocots-Magnoliids to see if a higher resolution of correlation was attainable. The large separation between available materials did not allow for closely spaced sampling and produced variable results in the diversity patterns. These factors did not allow for a higher resolution correlation between sites. The potential exists for possible trends to be discerned when using higher counts focused on changes in the number of individual species.

A second goal of this study was to use these changes in angiosperm diversity to compare with previously interpreted changes in the landscape conditions. This was done to evaluate the influence of landscape with diversity changes and test the fire-angiosperm and riparian hypotheses for angiosperm radiation. The connection between fires (as evidenced by charcoal deposits) and angiosperm radiation in this study was inconsistent and variable. There was no direct connection between the two, with agreement in some samples but disagreement in others, so no definitive evaluation can be made regarding the link between fires and the rise of angiosperms. Again, future work looking at the number of individual species present might shed further light on this connection. Regardless, there appears to be a greater connection to the landscapes disturbed in the riparian zone along fluvial channels. There were increases in angiosperm diversity associated with avulsion deposits and preceding intervals of landscape stability. The fluvial-deltaic setting responsible for the deposition of the Potomac Formation is key to its role in preserving the rise of angiosperm pollen. But this setting is also the reason sample preservation is inconsistent and variable, leading to the variability seen throughout these three sites.

Chapter 4

Sequence Stratigraphic Framework of the Early to Late Cretaceous Nonmarine Potomac Formation, New Jersey and Delaware

Abstract

We developed a sequence stratigraphic framework for the ?Barremian to lower Cenomanian of the fluvial-deltaic Potomac Formation in the Medford, NJ, Fort Mott, NJ, and Summit Marina, DE coreholes. Previous correlations have matched distinctive lithologic units associated with distinct pollen zones and identified tentative sequence boundaries between lithologic units I (?Barremian to lower Aptian, pollen Zone I), II (Aptian to ?lowermost Cenomanian, pollen Zone II), and III (lower Cenomanian, pollen Zone III) at all three sites. Here, we further subdivide these units into packages known as Fluvial Aggradation Cycles (FACs). An analysis of FAC stacking patterns reveals potential sequence boundaries and systems tracts. FACs support the identification of unit boundaries as sequence boundaries. FACs also indicate tentative higher order sequence boundaries and provide potential additional correlative surfaces among Potomac Formation sites.

4.1 Introduction

The mid-Cretaceous Potomac Formation[1] is found along the Atlantic Coastal Plain from North Carolina to New York. Because outcrop exposures are generally thin and limited in lateral extent, this unit is best studied in the subsurface using well-logs and

[1] Also termed a group in Maryland

coreholes. The use of coreholes to understand the mid-Cretaceous coastal plain landscape and climate evolution requires reliable correlation among sites. New data from three coreholes in New Jersey and Delaware (presented in the preceding chapters) are synthesized here to apply a sequence stratigraphic framework creating a more complete regional picture of landscape and climate evolution. This framework also offers the potential for higher order correlation among Potomac Formation sites.

Deposition of the Potomac Formation occurred on a fluvial-deltaic coastal plain landscape during the transition from the late Early to early Late Cretaceous (Barremian to Cenomanian). This was a period of global greenhouse conditions, with a climate defined by globally high temperatures (~5°C higher than present), atmospheric CO_2 (2-8x pre-anthropogenic), and sea levels (Barron, 1983; Berner, 2006, 2009; Royer et al., 2004; Ufnar et al., 2004; White et al., 2001; Haq, 2014; Miller et al., 2005; Suarez et al., 2011; Spicer and Corfield, 1992; Wolfe and Upchurch, 1987). This greenhouse climate and its influence on the coastal plain should be reflected in the sediments deposited during this time. Correlation among coreholes provides the opportunity to reconstruct landscape and climate along the eastern margin of North America during this transition.

The Potomac Formation was continuously cored at three sites in the updip portion of the Delaware and New Jersey coastal plains. Ocean Drilling Program (ODP) Leg 174AX) drilled a series of onshore continuous coreholes in New Jersey (NJ) and Delaware to study the sea-level history of the past 110 Myr (Fig. 1.1; Browning et al., 2008; Miller et al., 2005). As part of this program, the Fort Mott (39°36′19.956"N, 75°33′07.175"W; Delaware City U.S. Geological Survey [USGS] 7.5′ quadrangle; Fort Mott State Park, Salem County, New Jersey) and Medford (39°53′48.815N, 74°49′15.904"W; Mount Holly

USGS 7.5' quadrangle; Medford Township, Burlington County, New Jersey) coreholes provide good recovery (79% and 62% respectively) of Potomac Formation sediments from New Jersey (Fig. 1.1; Browning et al., 2008; Sugarman et al., 2004, 2010). The Summit Marina (39°32'43.31"N, 75°42'16.70"W; St. Georges USGS 7.5' quadrangle; New Castle, New Castle County, Delaware) core was drilled in 2009 by the Delaware Geological Survey, and provides good recovery (70%) of Potomac Formation sediments from Delaware (Fig. 1.1).

The Potomac Formation is found at the base of these coreholes and is likely unconformably underlain by crystalline basement rocks, and is unconformably overlain by lower delta plain/estuarine swamp sediments of the upper Turonian Magothy Formation at Summit Marina and Fort Mott and the upper Cenomanian Raritan Formation at Medford (Browning et al., 2008; Sugarman et al., 2004, 2005, 2010; Zullo, 2012). The formation boundary between the Potomac and overlying units is placed using lithology and geophysical well log data (gamma and resistivity).

Correlation of the Potomac Formation among sites is accomplished primarily using lithology and pollen biostratigraphy. Previous studies by Sugarman et al. (2004, 2005, 2010) and the preceding chapters, identified three distinct lithologic units (I, II, and III) in the Potomac Formation at Fort Mott and Medford, NJ. Sugarman et al. (2005) noted that these 3 lithologic units were distinct fluvial-deltaic successions with typical medium to fine sands at the base and silts and clays (typically paleosols) at the top. While this relationship in the upper units (II and III) of the Potomac Formation is well-defined, facies relationships in the bottom unit (I) are less well defined, because it is dominantly coarse grained.

Age control of these non-marine sediments is relies primarily on pollen biostratigraphy, with zones that are poorly calibrated to the Geological Time Scale (GTS2012; Gradstein et al., 2012) and are long in duration (3 zones in ~30 Myr). Each Potomac unit corresponds to a distinct pollen zone (Fig. 2.3): 1) Unit I is placed in pollen Zone I assigned to the Aptian (Hochuli et al., 2006), though it may extend to the Barremian (Doyle and Robbins, 1977); the age is ~111-126 Ma (GTS2012); 2) Unit II is placed in pollen Zone II, assigned to the middle to late Albian to the earliest Cenomanian (Doyle and Robbins, 1977; Hochuli et al., 2006); the age is ~100-111 Ma (GTS2012); 3) Unit III is placed in pollen Zone III, assigned to the early Cenomanian (Doyle and Robbins, 1977; Hochuli et al., 2006) with an age of ~96-100 Ma (GTS2012);

This paper synthesizes previously reported (chapter 2) paleosol and geochemical data using a sequence stratigraphic paradigm developed for fluvial settings by Atchley et al. (2004, 2013). The paradigm focuses on fluvial sedimentary packages known as fluvial aggradational cycles (FACs; sensu Atchley et al., 2004) and their stacking patterns. By applying this method, we interpret a potential means of identifying systems tract equivalents and higher order sequence boundaries (few Myr scale) that offer correlative surfaces.

4.2 Previous Work

The following is an overview of previous work (presented in the preceding chapters) that is used to identify and assess fluvial aggradation cycles at these sites. 103 paleosols were described in the three coreholes. These paleosols were placed into one of five paleosol groups based on paleosol morphology and its relationship to the soil formation. The paleosol groups are:

1) Gray Type, a Protosol that is a weakly developed immature soil forming under poorly drained, waterlogged conditions.
2) The Gray-Red Type, a Protosol forming under water-logged conditions; this soil is also weakly developed although with relatively increased pedogenesis relative to the Gray Type, including minimal periods of drying. Both Gray and Gray-Red are similar to modern Inceptisols, with weak horizon development (A and C with occasional development of a B horizon in the Gray-Red Type). These types are interpreted to have developed on unstable landscape surfaces where there is rapid sedimentation and/or a consistent saturation to inhibit pedogenesis.
3) The Purple Type, an Argillisol that is a moderately developed, water logged soil that experienced extended periods of drying.
4) The Red Type is also an Argillisol that is moderately developed, forming under comparatively drier conditions with extended periods of water logged saturation.
5) The Brown Type, is a well-developed Argillisol that formed under well-drained conditions, although some profiles do exhibits features present during periods of water saturation. The Purple, Red, and Brown Type are similar to modern Alfisols, with pedogenic development increasing due to increasing landscape stability respectively.

We use stacking patterns of paleosol morphologies and geochemical proxies to distinguish the influence of landscape position versus climate during soil formation. Assignment and assessment of FACs and FAC sets requires evaluation of the landscape position of each site through time, including proximity to channel. Upsection changes of paleosol maturity (e.g. an Inceptisol vs. an Alfisol) have been shown previously to primarily reflect landscape position with respect to channel position (Kraus, 2002l; e.g. a succession of paleosols with increasing to decreasing maturity, reflects a channel shifting first away before returning to a more proximal location). Vertical changes in profile maturity and/or morphological character provide evidence to reconstruct the nature of the landscape position through time (Kraus, 1987; Bown and Kraus, 1987; Kraus, 2002). In contrast, changes in paleosol morphologic character (e.g., gley features), as opposed to paleosol maturity, likely reflect changes in the drainage state of the landscape and not simply landscape position (Platt and Keller, 1992; Kraus, 2002). The main influences on drainage conditions are climate (specifically precipitation and evaporation) and base level.

In addition to the general interpretations made from the lithology and paleosol maturities and morphologies found at these three sites, three proxy data sets (a morphology index, Niobium, and Barium/Strontium; described in detail in Chapter 1) are employed to complement interpretations made from the preserved paleosol profiles and provide further insight into this region at this time. The morphology index and concentration of Nb act as a proxy for paleoprecipitation. They are used in conjunction with the measure of Ba/Sr ratio that provides a proxy for drainage conditions during soil formation. Discrete geochemical measurements of Nb and Ba/Sr may not correlate from site to site. However, there appears to be similar patterns of landscape wetting/drying from site to site.

Overall general morphology and morphology index values provide insight into the nature of the landscape, whether generally wet/dry and stable/unstable. The two geochemical proxies allow inferences about the possible causes of these conditions. Our conceptual model is that if Niobium is inverse to Barium/Strontium (i.e., if Nb increases, Ba/Sr decrease), then the landscape changes are due mainly to climate; if changes in Barium/Strontium covary with or correspond with no change in Niobium landscape changes are due mainly to changes in base level (See chapter 1 for detailed information).

Collectively using paleosol morphology, maturity, and related proxies, the general composite landscape condition upsection in these units is inferred to be wet near the unit base and alternating between episodes of wet and dry conditions before wet conditions persist across the Unit III top (See Chapter 2 for detail). Overall, the morphology and proxy data suggest that base level lowering is the main control on these drying trends. However, a climate (precipitation-evaporation) overprint is indicated by geochemical data at individual sites, suggesting that this deposition of thick flood deposits, including thick, laterally extensive, heterogeneous sands and poorly developed paleosols, are a result of frequent deposition from fluvial avulsion.

4.3 Fluvial Aggradation Cycle Strategy

Sequence stratigraphy is an attempt to divide the stratigraphic record into genetically related packages known as sequences (Posamentier and Vail, 1988). In marine siliciclastic sediments, sequences are generally recognized by a regional basal unconformity above which the section generally coarsens upsection in the lowstand systems tract (LST), fines in the transgressive systems tract (TST), and then coarsens again in the highstand systems tract (HST) to another regional unconformity on top; the LST are often not preserved in updip settings (e.g., the New Jersey coastal plain; see summary in Miller et al., 2013). The surface where sediments change from fining up to coarsening upsection is known as the Maximum Flooding Surface (MFS). The sequence boundary and sediment changes within sequences are the result of changing accommodation that can be related to several factors: uplift/subsidence, sea-level, and climate change.

Atchley et al. (2013) have demonstrated the applicability of sequence stratigraphy to fluvial sequences and noted that thick successions of alluvial and overbank deposits may contain a cyclic hierarchy relationship that is influenced by autogenic and allogenic processes (Atchley et al., 2004, 2013). They noted that their analysis should be confined to conformable alluvial successions characterized by rapid and variable rates of long-term subsidence and is best confined to settings without tectonism. The NJ and Delaware coastal plains in the mid Cretaceous were part of a passive margin following the post-rift unconformity beginning at about 180 Ma. Accommodation on the margin was largely controlled by a thermoflexural response to offshore simple thermal subsidence, loading, and compaction (Kominz et al., 1996) that was overprinted by more frequent changes in base level. Given that deposition occurred on a low gradient passive margin coastal plain, it is assumed that changes in base level were caused by fluctuations in sea level. The influence of sea level on coastal fluvial systems has been observed up to 200 km from the shoreline (Blum and Tornqvist, 2000; Atchley et al., 2004).

Stacking pattern analysis of these fluvial successions recorded fluvial system response to rising and falling base level (Atchley et al., 2004; 2013). Any given stacking pattern can be attributed to effects other than base level change; however, even in alluvial successions, regional correlation of stacking patterns argue for regional changes in base level. Base-level changes result in deposition of sedimentary packages of varying thickness within the vertical succession. The smallest units, known as FACs, are recognized as typically fining-upward sediment packages usually with a paleosol at the upper boundary, representing large overbank deposition or avulsion and subsequent weathering during channel stability (Atchley et al., 2004, 2013). FACs, as originally defined by Atchely et al. (2013) from the Upper Triassic of New Mexico, are meter-scale packages (FACs; sensu Atchley et al., 2004), similar in size to the packages described here.

These FACs are records of episodic floodplain aggradation with a typical pattern of a fining upward succession topped with a paleosol deposit. At larger scales, comprising longer time intervals, FACs are components within decameter-scale FAC sets that record fluvial stability and avulsion. The criteria for a FAC set includes a series of stacking FACs that usually fine upward, and either demonstrate a gradual upward increase in paleosol maturity and drainage or a somewhat symmetric upward increase to decrease in paleosol maturity with associated good to poor drainage (Atchley et al., 2004).

Episodes of base level rise induce alluvial aggradation that result in more frequent avulsions, flooding, and the development of immature, poorly drained paleosol profiles and are associated with typically thicker FACs. As base level rise slows and then falls, accommodation is reduced and alluvial aggradation gives way to more mature paleosols that have enhanced drainage associated with thinner FACs. Sequence boundaries can thus be placed above the mature paleosols with the best drainage before base level rise begins to again increase the frequency of avulsions and flooding events. These sequence boundaries are typically associated with an inflection from thinning FACs to thickening FACs, and by extension the MFS equivalent is placed at the inflection from thickening FACs to thinning FACs (Fig. 4.1; Atchley et al., 2004, 2013).

Decreasing accommodation favors the preservation of thin floodplain deposits and will result in the formation of well-drained, increasingly mature paleosols, and creating

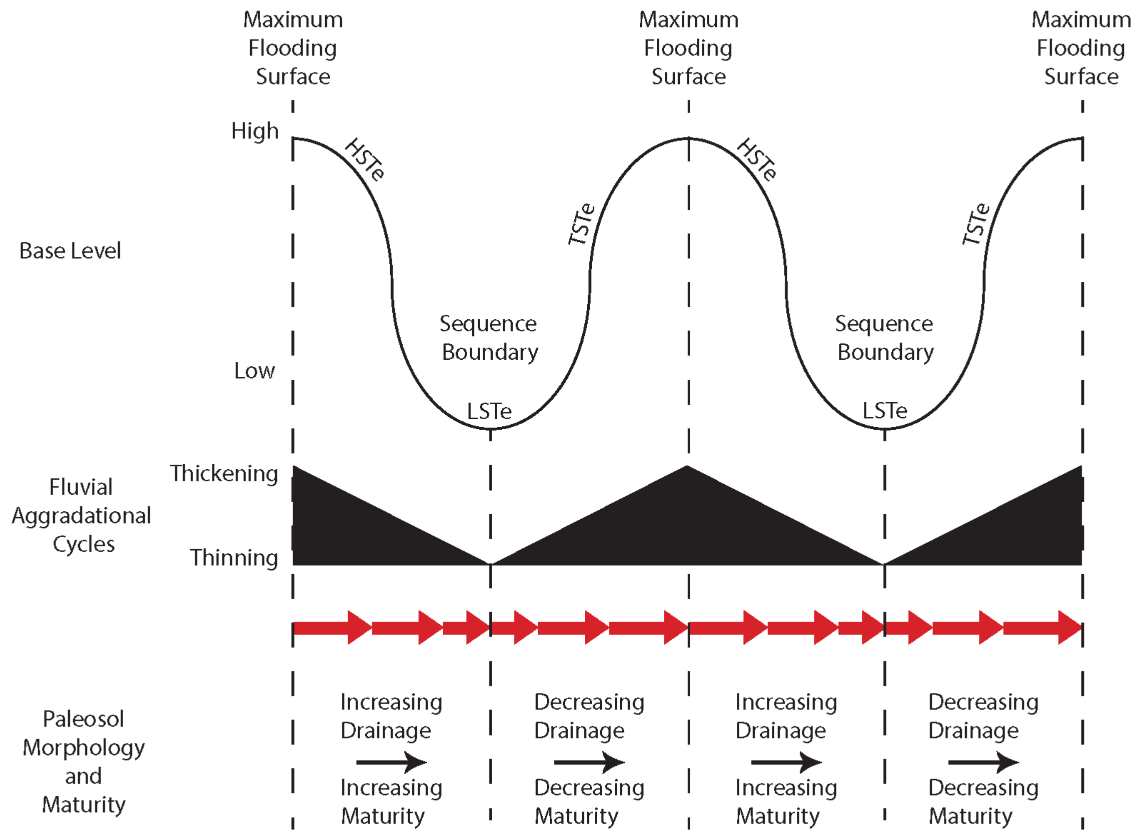

Figure 4.1 - Model of fluvial aggradation cycles (FACs) and the relation to an equivalent sequence stratigraphic framework.

FACs that are generally thinner. The decrease in accommodation is related to lowering base level and is equivalent to HSTs. Falling base level results in the formation of well-drained mature paleosols that are found within many of these related FACs.

The inflection between thinning and thickening FACs represents base level change from falling to rising and a sequence boundary can be placed at this level. This boundary is usually placed above the most mature paleosols, formed during base level fall and a period of landscape stability, and below those paleosols exhibiting more gley features forming under water-logged conditions as base level rises. By extension the point where thickening FACs with immature poorly drained paleosols begin to thin with paleosols exhibiting increased maturity and enhanced drainage would then represent a MFS.

FAC sets occur within larger (hectometer-scale) alluvial sequences that have been described as disconformity-bounded successions, and are recognized here using the guidelines outlined by Atchley et al. (2004, 2013) of FAC thickness, paleosol maturity, and drainage. FACs and FAC sets generally thin and paleosols increase upsection in maturity and drainage from within a fluvial sequence. Atchley et al. (2004) tentatively linked fluvial sequences from Cretaceous coastal Western Interior Seaway sites to third-order global sea-level changes. FAC sets are related to autocyclic fluvial processes, and at our coastal plain sites, changes are directly influenced by allocyclic base-level changes, with adjustments in sea-level affecting accommodation and the fluvial dynamics. Therefore they are defined here as equivalent to sequence stratigraphy terminologies (e.g. TST equivalent, HST equivalent, and MFS equivalent).

4.4 Results

The following results are presented in stratigraphic order starting with Potomac Formation Unit I and moving up section to Unit III. The unit designations and correlations have been outline in the preceding chapters and by Sugarman et al. (2004, 2005, 2010). The depositional environment of Unit I at Medford has been interpreted as a braided fluvial system by Sugarman et al. (2010) and at Fort Mott as an anastomosing fluvial system. Units II and III have been interpreted at Fort Mott and Medford by Sugarman et al., (2004, 2010) and expanded here to include Summit Marina, as an anastomosing fluvial system. Anastomosing fluvial systems are defined by multiple channels with cohesive banks separated by stable bars (Smith and Smith, 1980; Makaske, 2001). Bank and bar stability is a prominent feature of this fluvial system and is aided by vegetation and/or fine-grained overbank sedimentation (Smith and Smith, 1980; Makaske, 2001). The depositional landscape is likely comparable to the modern Orinoco delta (Fig. 4.2), with the notable difference of this delta forming at a latitude of 9^{o}S and the Potomac Formation depositing at a paleolatitude of ~30^{o}N (Barron, 1987; Hay et al., 1999).

4.4.1 Fluvial aggradation cyclic hierarchy

FACs represent channel avulsion and overbank events with subsequent pedogenesis. Defining FACs in overbank mud facies requires finding fining- or coarsening-upward successions capped by a paleosol as upper boundary; the lower boundary is placed above the underlying paleosol or at an apparent disconformable surface. Definition of FACs is more challenging in channel sand facies, because channels may be amalgamated. When no paleosols were present, FACs were assigned on the basis of fining upward successions, with the upper boundary defined by the sharp transition to coarser grained sediment. Data including criteria for each identified FACs are tabulated (Table 4.1).

At Fort Mott, 23 FACs are identified in Unit I that show an upsection pattern of decreasing and increasing thickness. These FACs are placed into 3 FAC sets that represents a partial sequence (Fig. 4.3). Unit I at Medford has been previously described by Sugarman et al. (2004) as a braided fluvial system; the varying deposition and heterolithic nature of sediments in this unit do not allow identification of fluvial aggradational cycles. Unit I was not sampled at Summit Marina.

At Summit Marina, Unit II is separated into 27 FACs with paleosols becoming thinner upsection. These FACs are placed into 3 FAC sets that comprise one partial and one complete fluvial sequence (Fig. 4.4). At Fort Mott, this unit is separated into 20 FACs with a general upsection decrease in paleosol drainage. These FACs are placed into 4 FAC sets comprising two complete fluvial sequences (Fig. 4.3). At Medford, 20 FACs are identified with an upsection decrease in FAC thickness. These FACs are placed into 3 FAC sets that represents two complete fluvial sequences (Fig. 4.5).

At Summit Marina, 19 FACs are identified in Unit III where FAC thickness decreases then increases upsection. These FACs are placed into 4 FAC sets that comprise one complete and one partial fluvial sequence (Fig. 4.4). At Fort Mott, 24 FACs were identified within this unit, with an upsection decrease in FAC thickness and paleosol drainage and maturity. These FACs are placed into 3 FAC sets comprising one complete and one partial fluvial sequence (Fig. 4.3). At Medford, 15 FACs are identified, decreasing and increasing upsection. These FACs are placed into 3 FAC sets that represents one complete and one partial fluvial sequence (Fig. 4.5).

Figure 4.2 - Cartoon of modern Orinoco River delta. This modern system offers a depositional analog for the Potomac Formation that likely formed under similar environmental conditions. The red box represents a probable area in which formation of Potomac type paleosols occurs, with the more mature types forming on the landward side of the box and less mature forming on the basinward side of the box.

Table 4.1 - Fluvial aggradation cycle (FAC) depths. Note: These depths encompass some intervals not recovered during drilling and were grouped into a FAC based on inferred lithology from above/below and geophysical log data.

Fort Mott

FAC	TOP (FT)	BOTTOM (FT)	FAC	TOP (FT)	BOTTOM (FT)
68	141.1	147.9	34	475.0	487.4
67	147.9	151.3	33	487.4	508.2
66	151.3	153.6	32	508.2	515.2
65	153.6	164.2	31	515.2	529.5
64	164.2	170.0	30	529.5	542.0
63	170.0	180.0	29	542.0	550.3
62	180.0	188.0	28	550.3	574.0
61	188.0	200.4	27	574.0	577.6
60	200.4	203.0	26	577.6	611.2
59	203.0	206.0	25	611.2	620.1
58	206.0	223.8	24	620.1	644.1
57	223.8	230.2	23	644.1	649.2
56	230.2	242.0	22	649.2	660.0
55	242.0	251.2	21	660.0	670.1
54	251.2	258.9	20	670.1	676.1
53	258.9	270.0	19	676.1	684.7
52	270.0	281.5	18	684.7	700.0
51	281.5	293.6	17	700.0	702.9
50	293.6	315.0	16	702.9	720.0
49	315.0	337.9	15	720.0	725.0
48	337.9	340.7	14	725.0	734.7
47	340.7	342.9	13	734.7	740.0
46	342.9	345.9	12	740.0	741.9
45	345.9	351.4	11	741.9	748.0
44	351.4	360.0	10	748.0	749.9
43	360.0	363.6	9	749.9	751.3
42	365.0	367.0	8	751.3	755.7
41	367.0	375.0	7	755.7	760.6
40	375.0	394.0	6	760.6	765.0
39	394.0	408.6	5	765.0	769.2
38	408.6	432.1	4	769.2	780.0
37	432.1	449.4	3	780.0	790.3
36	449.4	467.4	2	790.3	808.8
35	467.4	475.0	1	808.8	820.0

Table 4.1 (cont.)

Summit Marina

FAC	TOP (FT)	BOTTOM (FT)	FAC	TOP (FT)	BOTTOM (FT)
46	99.5	110.0	23	350.0	351.8
45	110.0	115.0	22	351.8	355.0
44	115.0	117.5	21	355.0	361.0
43	117.5	143.6	20	361.0	362.5
42	143.6	155.0	19	362.5	375.0
41	155.0	160.0	18	375.0	380.0
40	160.0	164.6	17	380.0	382.9
39	164.6	168.4	16	382.9	386.5
38	168.4	185.0	15	386.5	392.3
37	185.0	195.0	14	392.3	401.0
36	195.0	200.0	13	401.0	403.7
35	200.0	210.0	12	403.7	410.0
34	210.0	220.0	11	410.0	420.0
33	220.0	225.0	10	420.0	427.6
32	225.0	235.0	9	427.6	440.0
31	235.0	285.0	8	440.0	445.0
30	285.0	305.0	7	445.0	450.0
29	305.0	325.9	6	450.0	460.4
28	325.9	330.0	5	460.4	471.9
27	330.0	340.2	4	471.9	475.0
26	340.2	343.8	3	475.0	478.8
25	343.8	344.8	2	478.8	495.0
24	344.8	350.0	1	495.0	500.0

Table 4.1 (cont.)

Medford

FAC	TOP (FT)	BOTTOM (FT)	FAC	TOP (FT)	BOTTOM (FT)
35	623.8	635.0	17	811.6	823.4
34	635.0	646.2	16	823.4	830.0
33	646.2	660.6	15	830.0	834.0
32	660.6	677.0	14	834.0	840.0
31	677.0	686.3	13	840.0	844.7
30	686.3	697.4	12	844.7	850.0
29	697.4	700.0	11	850.0	860.8
28	700.0	706.9	10	860.8	881.5
27	706.9	710.8	9	881.5	892.5
26	710.8	730.0	8	892.5	907.6
25	730.0	740.6	7	907.6	922.5
24	740.6	747.1	6	922.5	930.6
23	747.1	750.0	5	930.6	932.6
22	750.0	764.5	4	932.6	944.5
21	764.5	790.0	3	944.5	954.0
20	790.0	794.0	2	954.0	980.3
19	794.0	800.0	1	980.3	983.2
18	800.0	811.6			

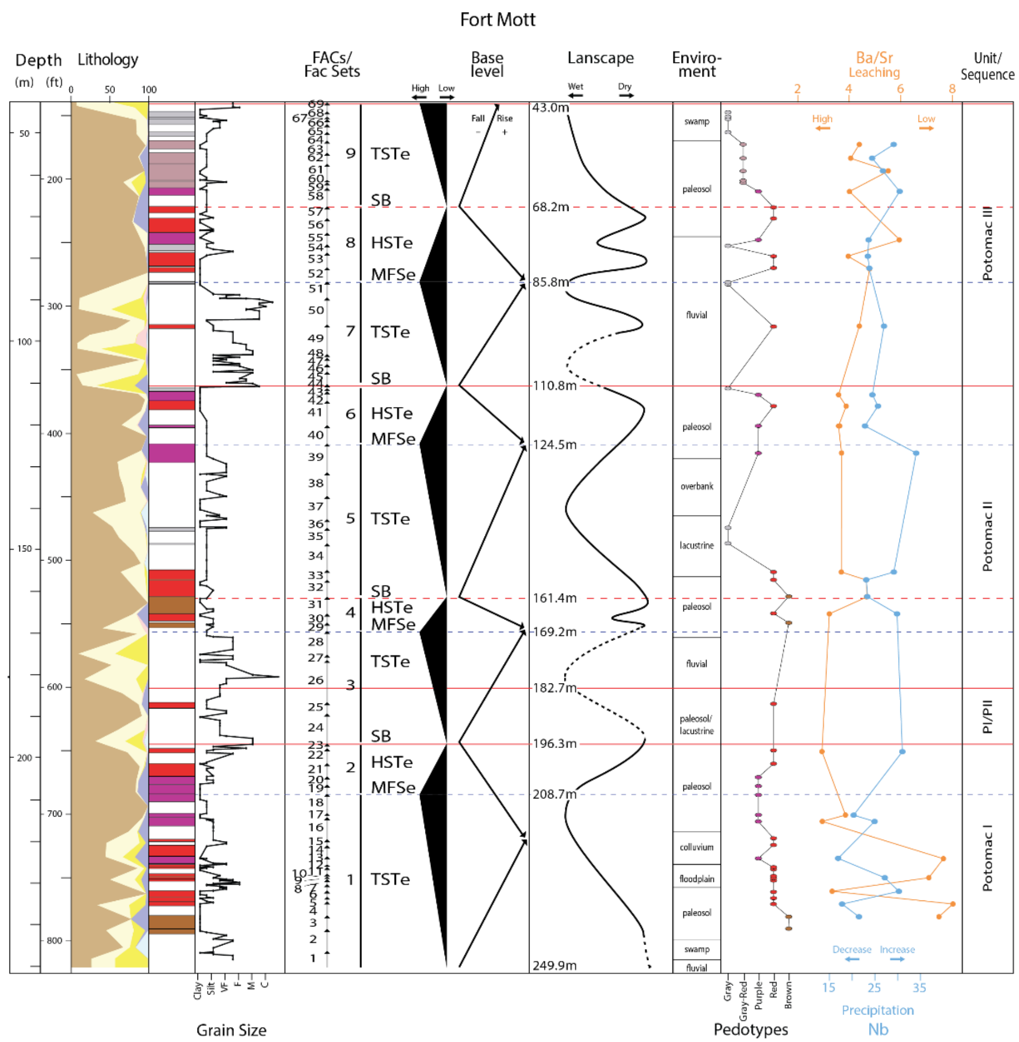

Figure 4.3 - FACs and sequence stratigraphic framework for the Potomac Formation section of the Fort Mott site, inferred landscape conditions was determined using paleosol deposits and geochemical data discussed in preceding chapters. Refer to Fig. 2.7 for legend.

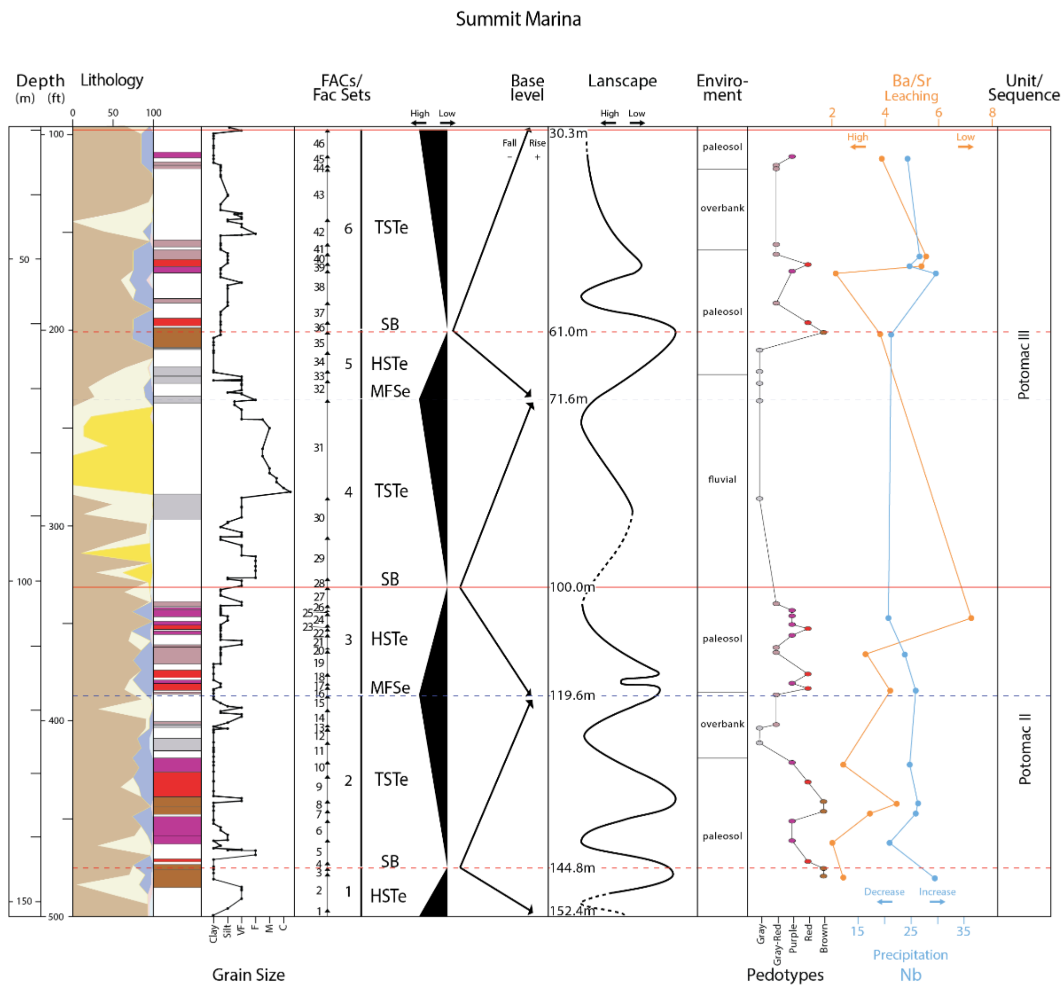

Figure 4.4 - FACs and sequence stratigraphic framework for the Potomac Formation section of the Summit Marina site, inferred landscape conditions was determined using paleosol deposits and geochemical data discussed in preceding chapters. Refer to Fig. 2.7 for legend.

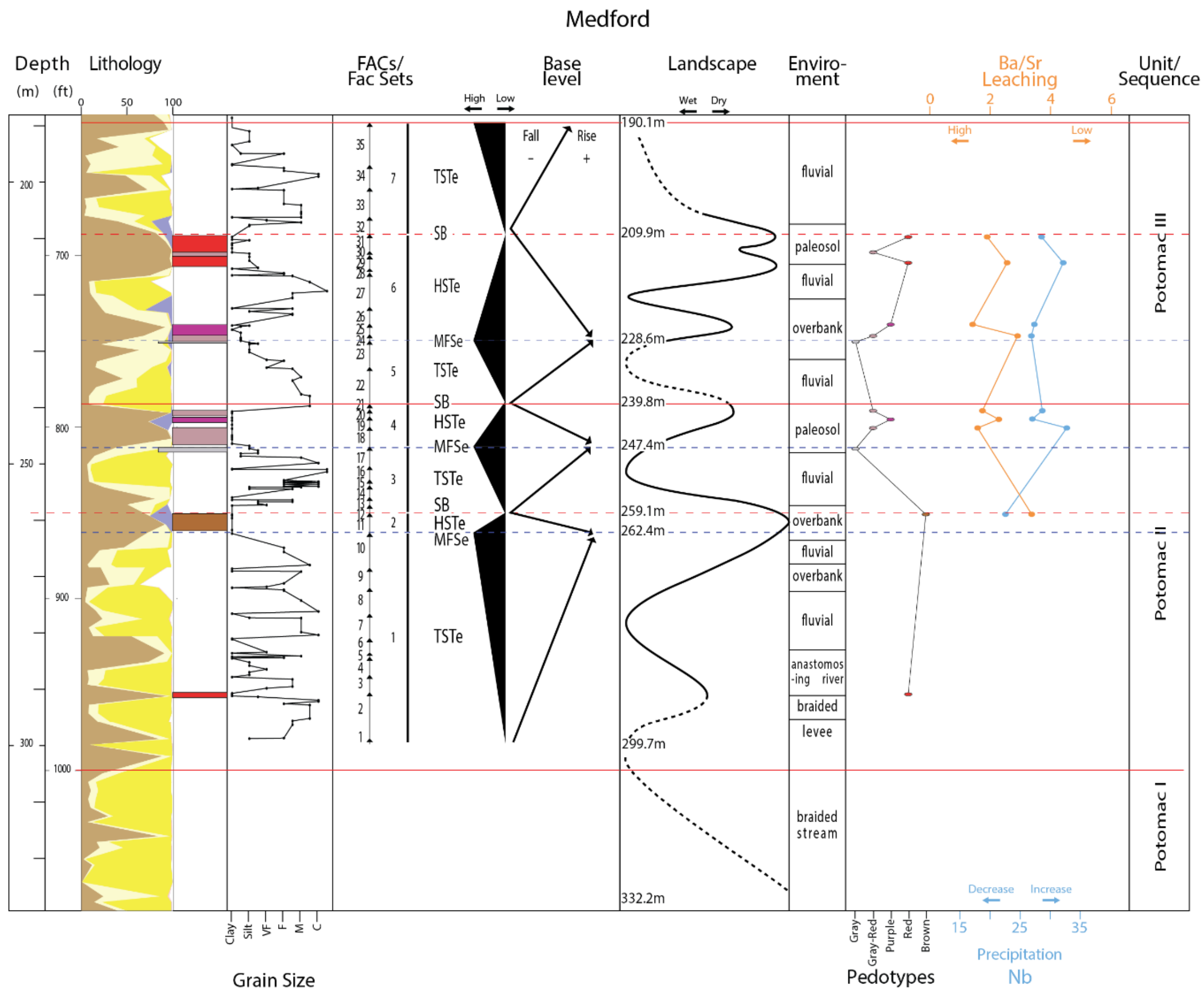

Figure 4.5 - FACs and sequence stratigraphic framework for the Potomac Formation section of the Medford site, inferred landscape conditions was determined using paleosol deposits and geochemical data discussed in preceding chapters. Refer to Fig. 2.7 for legend.

4.4.2 Sequence stratigraphic framework

At Fort Mott, one sequence is preserved in Unit I (Fig. 4.3). Upsection from the base of the corehole at 249.9 m (820 ft), sandy deposits accompany paleosol profiles exhibiting decreasing drainage and maturity, representing a TST equivalent. A MFS is placed on FAC 18 at 208.7 m (684.7 ft) that is 4.7 m (15.3 ft) thick, above this FACs thin with paleosol maturity and drainage increasing, representing a HST equivalent upsection to the top of the unit. Based on thinning of the FACs and increased maturity of the paleosols, a sequence boundary is placed at the unit I/II boundary at 196.3 m (644.1 ft), supporting the interpretations of Sugarman et al. (2005) based on gross lithologic and pollen correlations.

Unit I is also preserved at Medford. However, given the lack of paleosol deposits, coupled with the heterolithic nature of the sediments, previously interpreted by Sugarman et al. (2010) as being deposited in a braided fluvial system, makes application of fluvial aggradation cycles impossible.

At Summit Marina, the basal sand of Unit II apparently was not reached, but a higher order sequence boundary is placed immediately above several well-developed, well-drained paleosol profiles in FAC 3 at 144.8 m (475.0 ft) (Fig. 4.4). FAC 3 is 1.1 m (3.8 ft) thick and though the overlying FAC 4 is thinner (1.0 m (3.1 ft)), the sequence boundary is tentatively placed due to the well-developed/drained nature of the paleosol in FAC 3. Upsection from this boundary, FACs in general thicker, and associated paleosol deposits are thin, weakly developed, poorly drained profiles. These FACs are likely equivalent to LST to TST equivalents that transition upwards to a MFS equivalent at FAC 14 that is 2.6 m (8.7 ft) thick at 119.6 m (392.3 ft). The MFS sediments are overlain by FACs with more mature paleosols forming under better drainage and equivalent to a HST. A sequence boundary placed at the top of the unit at FAC 27 that is relatively thick (3.1 m (10.2 ft)) at 100.6 m (330 ft) on the basis of lithostratigraphy (similar to the unit boundaries at Fort Mott). This placement is supported by overlying thickening FACs that have no or minimally developed paleosol profiles.

The interval of Fort Mott from 196.3-182.8 m (644.1 ft-599.7 ft) is described by Sugarman et al. (2004) as undifferentiated Unit I/II. It could be possible to interpret a single preserved paleosol found in FAC 25 (2.7 m, 8.9 ft thick) at 186.3 m (611.2 ft) as a possible sequence boundary. However, given the limited information from preserved sediments and on the basis of the heterolithic nature of sediments, including relatively thick FACs, we have placed this interval into Unit II.

Unit II at Fort Mott (196.3-110.8 m; 644.1-363.6 ft) is a distinct sequence that can be subdivided into one higher order sequence based on FACs. At the base of the Unit II (196.3 m (644.1 ft)), thick FACs are dominated by fining upward packages of channel sands that we interpret as to a TST equivalent with a MFS equivalent placed on FAC 28 with a thickness of 5.8 m (18.9 ft) at 169.2 m (555.1 ft) (Fig. 4.3). Above this surface, well-drained, well-developed paleosol profiles represent a HST with a sequence boundary tentatively placed at 161.4 m (529.5 ft) in FAC 31 with a thickness of 3.8 m (12.5 ft). A sequence boundary is placed directly below a thick, mature, well-drained paleosol that overlies a relatively thin underlying HST FACs. Upsection, thicker FACs with thin, poorly drained, and weakly developed paleosol profiles represent a TST equivalent with a MFS equivalent placed above a thick (7.2 m (23.5 ft)) FAC 39 at 124.5 m (408.6 ft). This surface is placed here based on the thinning of the FACs upsection to the top of the unit at 110.8

m (363.6 ft), this interval is interpreted as a HST equivalent with a sequence boundary placed at the unit boundary that is part of FAC 44. This sequence boundary of Sugarman et al. (2004) is supported by a thin FAC, only 0.6 m (2.0 ft) thick, with underlying FACs thinning to this level and overlying FACs ultimately thickening upsection.

In Unit II at Medford, trends are again less apparent due to a lack of preserved paleosol profiles (Fig. 4.5). FACs can still be assigned, and the trends between FAC thickening and thinning related to accommodation used to assign boundaries. Upsection from the Unit boundary at 299.7 m (983.2 m), FACs are generally thicker, heterolithic sediments with only one discernible paleosol. A MFS equivalent is placed above the thick FAC 10 (6.3 m (20.7 ft thick) at 262.4 m (860.8 ft). Directly overlying this, a higher order sequence boundary is tentatively placed on the relatively thick (3.3 m 910.8 ft)) FAC 11; this placement is based on a well-drained, well developed paleosol capping this FAC at 259.1 m (850.0 ft). Above this higher order sequence boundary, a FACs composed of sand beds thicken only slightly upsection, capped in FAC 17 at 247.4 m (811.6 ft) with a thin, immature, poorly drained paleosol. This, 3.6 m (11.8 f) thick FAC represents a MFS equivalent because FACs thin upsection above this and are capped by relatively more mature paleosols. These FACs above the MFS represent a HST equivalent, with a sequence boundary placed at the upper unit boundary at 239.8 m (786.8 ft), and is represented by FAC 21 that is 1.0 m (3.2 ft) thick. As at Fort Mott, this sequence boundary of Sugarman et al. (2004) is supported by underlying FACs thinning to this level and the abrupt overlying thick FACs.

At Summit Marina, the base of Unit III at 100.6 m (330.0 ft) is dominated by fluvial sands and poorly drained, simple paleosols (Fig. 4.4). This heterolithic interval is composed of FACs 28-31, that thicken upsection, with FAC 31 that is 15.3 m (50.0 ft) thick. The top of this thick FAC at 71.6 m (235.0 ft) represents the MFS equivalent. This gives way upsection to thinning FACs with well-developed paleosols with enhanced drainage in FACs 32-35. The most mature, well drained Brown Type paleosol occurs in FAC 35. A sequence boundary is placed at the top of FAC 35 at 61.0 m (200.0 ft) on the basis of the paleosol profile. Upsection from this sequence boundary FACs thicken slightly, these FACs contain associated paleosols that become increasingly thin, poorly drained and weakly developed, and are TST equivalent deposit up to the unit boundary (30.3 m (99.5 ft)).

At Fort Mott, the base of Unit III at 110.8 m (363.6 ft) is composed of FACs 44-51 made up of thick sand bodies with thin, weakly developed paleosol deposits that represent overbank deposition in the TST equivalent (Fig. 4.3). A MFS equivalent is placed at 85.8 m (281.5 ft) on FAC 51, a heterolithic interval that is 3.7 m (12.1 ft) thick. This surface is placed on top of this FAC due to the heterolithic nature of sediments and thin, poorly drained paleosols that developed. Above this, FACs 52-57 thin, and relative more mature paleosols develop. These better developed paleosols are forming under enhanced drainage indicating a falling stage system tract; a higher order sequence boundary is tentatively placed on thinnest FAC 57 (2.0 m (6.4 ft) thick) at 68.2 m (223.8 ft). This boundary is placed on the basis of this paleosol with good development and enhanced drainage, as well as a decrease in the overlying abrupt increase in FAC thickness and decrease paleosol maturities and drainage. These upsection FACs, 58-69, are of variable thickness although the paleosols do exhibit features of decreased drainage that results in weakly developed, simple paleosol profiles. This section is inferred to be a TST equivalent and extends to the unit boundary at 43.0 m (141.1 ft).

At Medford, Unit III spans from 239.8-190.1 m (786.8-623.8 ft), although the record is slightly more ambiguous due to the paucity of preserved paleosol profiles (Fig. 4.5). This does not preclude the placement of FACs, FAC-sets, and sequences. As at Fort Mott and Summit Marina, the base of this unit is dominated by thick sand beds, FACs 22 and 23 are relatively thick, with a MFS equivalent placed on FAC 23 (4.4 m (14.5 ft) thick). FAC 23 and the overlying FACs 24-25 are capped by paleosols exhibiting features of increasing drainage. The flooding surface is placed given the decrease in overlying FAC thickness, but also the increase in paleosol drainage. There is an abrupt transition back to thicker sands up section (FACs 24-28), before being overlain by moderately drained and developed paleosols, and there is a possibility that FAC 27 represents the MFS based on its thickness (5.8 m (19.2 ft)). A sequence boundary at 209.2 m (686.3 ft) above FAC 31 (2.7 m (8.9 ft) thick) is placed on account of FAC thinning and is above the most mature, moderately drained paleosol in this interval. Upsection, thickening FACs 32-35 are composed of preserved fluvial sands formed from increased flooding/avulsion deposits and are interpreted as a TST equivalent.

4.5 Discussion

Previous attempts at correlation have shown that biostratigraphy is not able to discern hiatuses between Potomac units I-III, though Sugarman et al. (2004, 2005) used physical stratigraphy (erosional breaks associated with facies stacking patterns) to infer that each unit was a distinct sequence (sensu Mitchum et al., 1977) associated with base level falls. This implies that hiatuses occurred between the deposition of each unit, though the hiatuses are within the broad age resolution of pollen biostratigraphy (e.g., Units I, II, and III are at most ~16, ~10, and ~4 Myr in duration, respectively).

Regional well log correlations indicate similar lithostratigraphic successions (mainly within Units II and III) among the three coreholes, with similar soil profiles and inferred climate change within successions. Sugarman et al. (2005) and Monteverde et al., (2011) used well log correlations of Potomac Units II and III to argue for the regional continuity of these units. A subset of well logs from the Potomac Formation are presented to illustrate these regional correlations (Fig. 4.6):

1) Unit I geophysical logs present the most variability (Fig. 4.6). Sites in New Jersey and Delaware display characteristic inconsistencies indicative of a heterolithic sandy unit. Downdip locations show more uniform and thick blocky structures representing sand deposits (Sugarman et al., 2005; 2011; Monteverde et al., 2011).
2) Unit II basal sands show variability both along strike and along dip, but remain mappable in this region (Fig. 4.6; Sugarman et al., 2005; 2010; Monteverde et al., 2011). At Fort Mott and along strike as far north as Clayton, NJ, this sand body appears as one or two blocky, thick beds (Sugarman et al., 2005; 2010; Monteverde et al., 2011). At Medford and further along strike to the north there is more variability with multiple apparent sand beds. Downdip geophysical logs at several sites in New Jersey (Anchor Dickenson and Island Beach) show lower portion of Unit II appearing as either as one, two or three distinct, thick sand bodies (Sugarman et al., 2005; 2010; Monteverde et al., 2011).

3) The Unit III basal sand bed proves traceable along strike in New Jersey from Fort Mott to the north at Freehold, NJ. It is also found to thicken downdip to over 86.9 m (285 ft) at Anchor Dickenson, NJ (Fig. 4.7; Sugarman et al., 2005; 2010; Monteverde et al., 2011). To the south this sand is apparent at Summit Marina and in the Delaware City D12 log; however, at other locations in Delaware this sand body is less apparent with more variability. As noted by Sugarman et al. (2005) the lateral extent of the Unit III sands in New Jersey may not be adequately explained by deposition in an anastomosing fluvial system. An alternative explanation to this deposition is one occurring within a deltaic system which has been applied by previous researchers (e.g. Owens et al., 1970), although there is no direct evidence in the three coreholes of marine conditions (Sugarman et al., 2005). The extent to which an anastomosing fluvial system and the delta plain depositional environment overlap is not well defined (Makaske, 2001).

These correlations imply that the units are regional and support the inference of Sugarman et al. (2004, 2005, 2010) that Units I, II, and III are, in fact, distinct sequences. Unit I is represented at Fort Mott and Medford in fundamentally different environments (anastomosing vs. braided) and we cannot establish that this is one correlatable unit or sequence.

Potomac Formation is distinguished by a mix of sediments consisting of a basal sand bed interpreted as channel sand facies overlain by heterogeneous muds interpreted as overbank clay facies (Sugarman 2004, 2005, 2010). A significant portion of these heterogeneous muds have been subjected to pedogenesis. Differences in overbank clay facies are reflected in paleosol maturity and drainage, defined in previous chapters as paleosol type (similar to the pedofacies concept of Kraus, 1987).

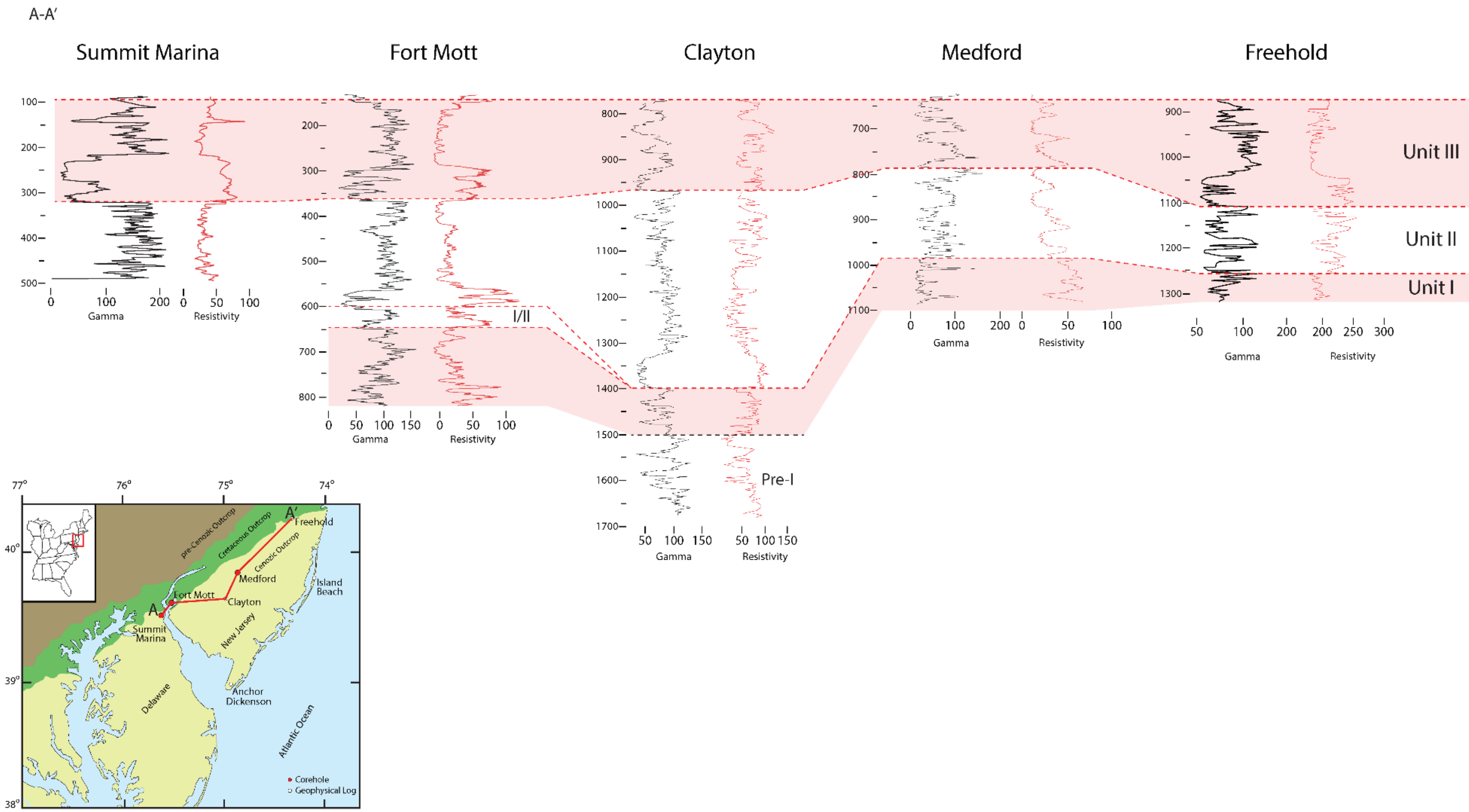

Figure 4.6 - Gamma and resistivity logs showing correlation between sites on the New Jersey and Delaware coastal plain (modified from Sugarman et al., 2005; Monteverde et al., 2011). A) Correlation between sites along strike, B) Correlation between sites along dip.

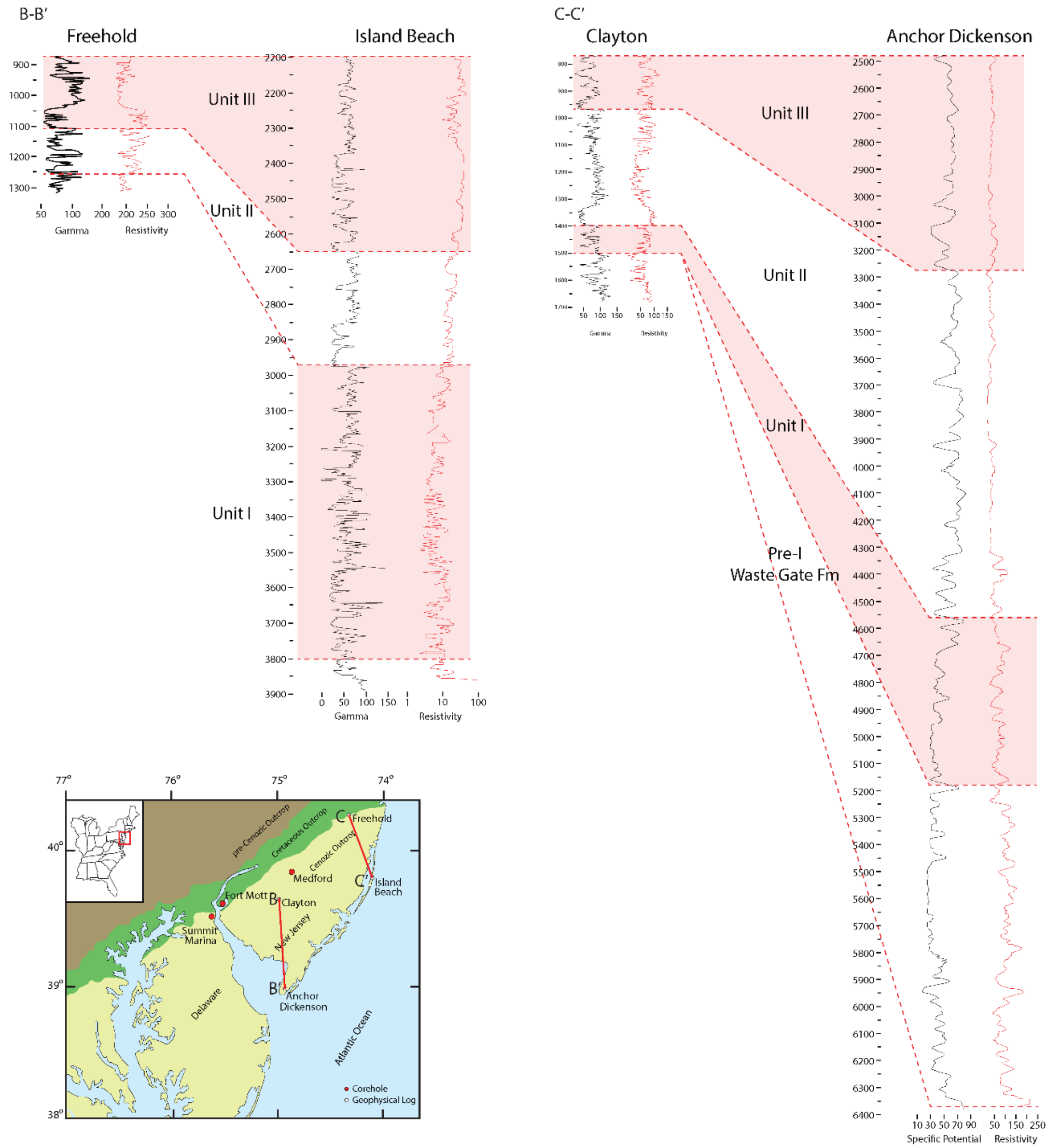

Figure 4.7 - Gamma and resistivity logs showing correlation between sites on the New Jersey and Delaware coastal plain (modified from Sugarman et al., 2005; Monteverde et al., 2011). A) Correlation between sites along strike, B) Correlation between sites along dip.

These sediments are placed into fining upward FACs, usually with a paleosol at its upper boundary.

We use FAC and paleosol relationships to place systems tract equivalents and sequence boundaries in Potomac Formation Units I to III (Figs. 4.3-4.5), supporting and expanding on the inferences from well log correlations. Our sequence stratigraphic framework provides correlative surfaces to tie sites together (Fig. 4.8). The assignment of systems tract equivalents allows potential placement of higher order sequence boundaries and thus higher resolution tie points within the units of the Potomac Formation. Unit I, reached only at Fort Mott and Medford, is not well sampled nor correlatable due to a lack of paleosol deposits and its heterogeneous nature (Figs. 4.3, 4.5). The use of FACs to place a sequence stratigraphic framework supports the previously designated unit boundaries as the basal sequence boundaries II and III of Sugarman et al., (2004, 2005, 2010).

It is important to note that we do not rely on correlations of beds, but rather rely on similar stacking patterns exemplified by FAC. FACs with increasing thickness upsection result from increasing accommodation due to base level rise and are interpreted as TST equivalents. FACs that thin upward, accompanied by an increase in paleosol maturity and drainage, are interpreted as HST equivalents. A shift in stacking pattern from thickening to thinning upsection, accompanied by a decrease in paleosol maturity and drainage indicates a MFS equivalent. A shift from thinning to thickening indicates a candidate sequence boundary.

Our study provides new tools to decipher sequences in a fluvial setting. Sequence boundaries associated with the bases of Units II and III have shown to be laterally extensive in New Jersey (Fig. 4.6; Sugarman et al. 2005; Monteverde et al., 2011); the assignment of

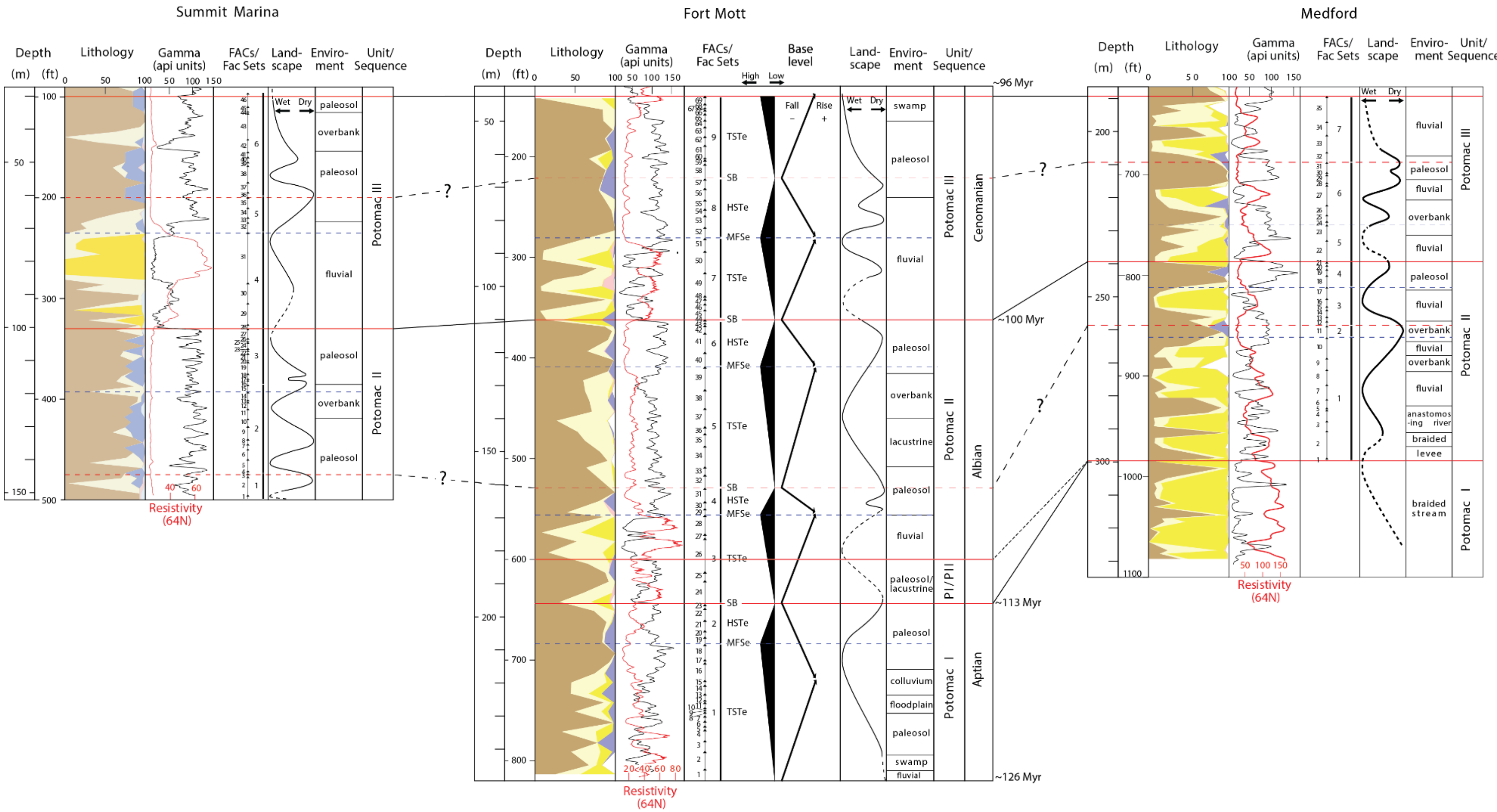

Figure 4.8 - Correlation of three coreholes utilizing FAC stacking patterns. This method confirms the Potomac Formation units as regional sequence boundaries, as well as illustrating potential higher order boundaries with the units of the Potomac Formation apparent at all three sites.

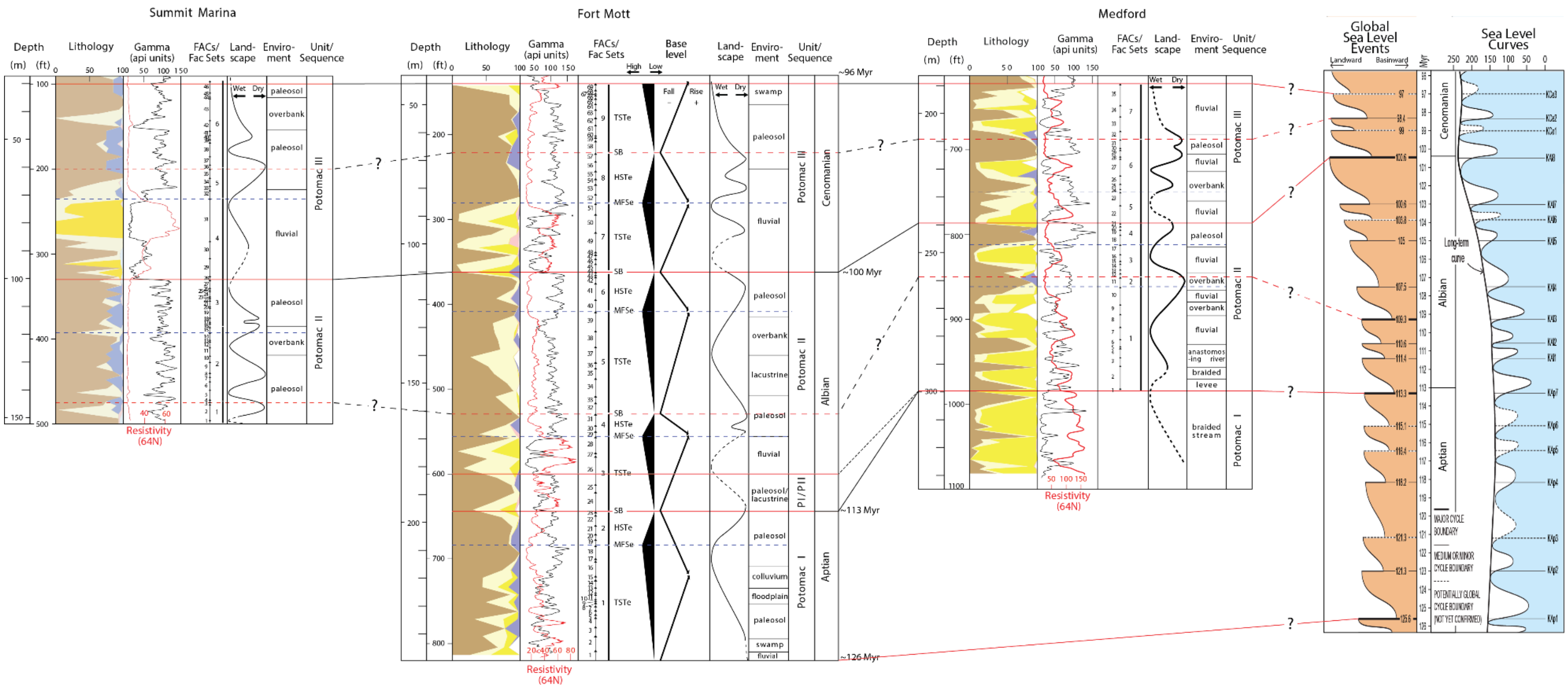

Figure 4.9 - Correlation of three coreholes utilizing FAC stacking patterns with sequences tied to onlap and sea-level curves of Haq (2014).

fluvial aggradation cycles combined with paleosol proxies confirms these units as distinct sequences. The use of FACs also allows the placement of higher order sequence boundaries that are tentatively found within Units II and III. This potentially creates a new, additional method to correlate these sites within the units of the Potomac Formation.

4.6 Conclusion

We develop a nonmarine sequence stratigraphic framework for the Potomac Formation among three corehole sites in New Jersey and Delaware. Sequences were identified and system tracts assigned within Potomac Formation units by analyzing paleosol morphologies, proxies, and the stacking patterns of FACs.

Placement of FACs, FAC sets, and sequences boundaries was accomplished using the stacking pattern of paleosol and related sediment deposits, following a paradigm developed for fluvial settings by Atchley et al. (2004, 2013). The low gradient coastal setting of these sites along a passive margin allows the assumption that fluvial deposition is controlled by accommodation space created or lost by changes in base level; these are in turn related to changes in relative sea level. At Fort Mott, a higher order sequence boundary was tentatively placed within Unit I though its presence at Medford cannot be determined. Units II and III have tentative higher order sequence boundaries at all three sites and are placed based on the FACs and paleosol morphologies.

Sugarman et al. (2005) proposed that lithologic unit boundaries I-III are also sequence boundaries, likely associated with significant hiatuses. The use of FACs to place sequence boundaries supports these as sequence boundaries and show they may be widely correlated. The placement of higher order sequence boundaries within the Potomac units offers potential for future regional correlations. The correlation of these sites presented here using soil morphology, proxies, and fluvial aggradation cycles suggest that integration of these datasets has great potential for reconstruction of coastal plain landscapes as they evolves through time.

Chapter 5

Conclusion

This study incorporated data from three sites from New Jersey (Fort Mott and Medford) and Delaware (Summit Marina) to evaluate Potomac Formation sediments. These sites offer both a local and regional picture of a coastal plain during the mid-Cretaceous. There are two primary goals of this study: 1) to understand the landscape response during the transition to global greenhouse conditions of the mid-Cretaceous; 2) to provide a higher resolution of correlation between Potomac Formation sites.

5.1 Summary of Results

In chapter two Potomac Formation paleosols were analyzed to understand the landscape evolution along part of the eastern margin of North America during the transition from Early to Late Cretaceous (Barremian-Aptian-Albian-Cenomanian). This included evaluating morphological features that allowed these paleosols to be grouped into five general pedotypes. These range in pedogenic maturity from weakly developed, poorly drained, Inceptisol-like Gray and Gray-Red Type soils, moderately developed, Alfisol-like, hydromorphic Purple and Red Type soils, and well developed, well drained, Alfisol-like soils Brown Type.

A paleosol morphology index and two geochemical (Nb and Ba/Sr) values were measured to act as proxies and applied to aid in this landscape reconstruction. All were in generally good agreement with interpretations made using the paleosol profile morphology and maturity. These proxies provided information on paleodrainage (Ba/Sr) and paleoprecipitation (Nb). Taken together, a conceptual model was developed to reveal the cause of landscape conditions as either due to changing base-level or changing climate. When these two proxies are in agreement it appears that precipitation is exerting the main control on influencing the drainage conditions. When there are changes in Ba/Sr with opposing or no changes in Nb then it is possible that this change in drainage is due to changes mainly in base level. The landscape is inferred at the base of Unit I to be sub-humid, and relatively drier than Units II and III, with climate playing a larger role than base-level. Units II and III are generally wetter, with sub-humid to humid conditions with limited episodes of drying, and base-level exerting a greater influence on landscape conditions.

Chapter three attempted to use diversity patterns, specifically changes in Monocots-Magnoliids, Eudicots, and the ratio between the Eudicots to Monocots-Magnoliids to see if a higher resolution of correlation was attainable. The large separation between available materials did not allow for continuous sampling and those horizons sampled produced only a paucity of identifiable material. This resulted in gaps and variability in the diversity patterns. These factors did not allow for a higher resolution correlation between sites.

Chapter four sought to create a higher resolution of correlation through the lithology. The major Potomac Formation lithologic units (I-III) were subdivided into packages known as Fluvial Aggradation Cycles (FACs). Placement of FACs was accomplished using the stacking pattern of paleosol and related sediment deposits, following a paradigm developed for fluvial settings by Atchley et al. (2004, 2013). An analysis of FAC stacking patterns reveals potential sequence boundaries and systems tracts. FACs also support the previous identification of Sugarman et al. (2005) that unit boundaries act also as sequence boundaries. FACs also indicate tentative higher order sequence boundaries. At Fort Mott, a higher order sequence boundary was tentatively placed within Unit I, though its presence at Medford cannot be determined. Units II and III have tentative higher order sequence boundaries at all three sites and are placed based on the FACs and paleosol morphologies. The placement of higher order sequence boundaries within the units provide potential additional correlative surfaces among Potomac Formation sites.

5.2 Implications and Contributions

The deposition of the Potomac Formation occurred during the mid-Cretaceous transition towards global greenhouse conditions, and its location on the coastal plain place it in an environment likely to experience these changes directly. The Potomac Formation sediments were therefore evaluated to understand the depositional landscape and its evolution during this transition as the world warmed and sea-levels rose. This study reconstructed the landscape showing the variability in climate and base-level through time that had a significant influence the formation of coastal plain paleosols. This enhances the overall understanding of how coastal plain landscapes evolve in transitions towards greenhouse climates during overall transgressions.

Additionally, the deposition of the Potomac Formation has been described as occurring on a primarily nonmarine, fluvial/deltaic landscape. As such, there is only coarse age control available, and correlation between sites is done primarily through lithology with three distinct lithologic units. This study has provided a potential novel method to correlate sites at a higher resolution, creating tie points within these lithologic units. This method offers the potential to correlate between sites when limited material, such as a singular Potomac Formation unit, is available. It has also provided further information on the overall evaluation of landscape evolution through this time interval, offering further information on base-level and accommodation.

5.3 Limitation and Future Research

The majority of Potomac Formation sediments are found in the subsurface, and ultimately this study was limited by the number of sites with recovered sediments. These sites were chosen for their good recovery as well as providing local and regional understanding of the coastal plain. Any future coreholes recovering Potomac Formation sediments will aid in this overall picture of landscape. While outcrops of Potomac Formation sediments are limited, any correlations to these outcrops will provide a better lateral understanding of facies relationships and will only enhance these landscape reconstructions.

These three coreholes contain several sphaerosiderite horizons that were not analyzed. Future work includes analyzing these sphaerosiderites to enhance the overall isotopic picture of the Potomac Formation. This includes a more complete hydrologic evolution through the mid-Cretaceous and the connection to the paleosol profiles these sphaerosiderites are found within.

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Appendix 1 - Paleosol profile depths

Summit Marina

Soil ID	Soil Type	Profile Top Depth ft (m)	Profile Bottom Depth ft (m)	
110	Purple	110.00 (33.53)	113.60 (34.63)	
115	Gray-Red	115.00 (35.05)	116.20 (35.42)	
116	Gray-Red	116.20 (35.42)	117.50 (35.81)	
155	Gray-Red	155.00 (47.24)	158.10 (48.19)	
160	Purple	160.00 (48.77)	164.60 (50.17)	
165	Red	164.60 (50.17)	168.40 (51.33)	
170	Purple	168.40 (51.33)	171.10 (52.15)	
185	Gray-Red	185.00 (56.39)	186.80 (56.94)	
195	Red	195.00 (59.44)	199.40 (60.78)	
200	Brown	200.00 (60.96)	209.80 (63.95)	**Note:** 12.6 feet recovered from 200-210
210	Gray	210.00 (64.01)	210.90 (64.28)	Run 200-205 recovered 7.8 feet
220	Gray	220.00 (67.06)	224.50 (68.43)	Run 205-210 recovered 4.8 feet
230	Gray	225.00 (68.58)	227.40 (69.31)	
235	Gray	235.00 (71.63)	237.50 (72.39)	
285	Gray	285.00 (86.87)	297.5 (90.68)	**Note:** 389.6-290.0 Not recovered during drilling
340	Gray-Red	340.20 (103.69)	343.35 (104.65)	**Note:** 389.6-290.0 Not recovered during drilling
344	Purple	343.75 (104.78)	344.80 (105.10)	
345	Purple	344.80 (105.10)	347.70 (105.98)	
350	Purple	350.00 (106.68)	351.80 (107.23)	
352	Red	351.80 (107.23)	354.60 (108.08)	
355	Purple	355.00 (108.20)	356.30 (108.60)	
360	Gray-Red	361.00 (110.03)	362.50 (110.49)	
365	Gray-Red	362.50 (110.49)	371.70 (113.29)	**Note:** 369.9-370.0 Not recovered during drilling
375	Red	375.00 (114.30)	378.40 (115.34)	**Note:** 369.9-370.0 Not recovered during drilling
380	Purple	380.00 (115.82)	382.90 (116.71)	
385	Red	382.90 (116.71)	385.85 (117.61)	
387	Gray-Red	386.50 (117.81)	387.45 (118.09)	
400	Gray-Red	401.00 (122.22)	403.55 (123.00)	
403	Gray	403.65 (123.03)	404.60 (123.32)	
410	Gray	410.00 (124.97)	415.40 (126.61)	
420	Purple	420.00 (128.02)	427.60 (130.33)	

Appendix 1 - Paleosol profile depths

Summit Marina

Soil ID	Soil Type	Profile Top Depth ft (m)	Profile Bottom Depth ft (m)
430	Red	427.60 (130.33)	440.00 (134.11)
440	Brown	440.00 (134.11)	445.00 (135.64)
445	Brown	445.00 (135.64)	449.40 (136.98)
450	Purple	450.00 (137.16)	460.40 (140.33)
460	Purple	460.40 (140.33)	464.60 (141.61)
470	Red	471.90 (143.84)	473.55 (144.34)
475	Brown	475.00 (144.78)	478.80 (145.94)
480	Brown	478.80 (145.94)	485.70 (148.04)

Fort Mott

Soil ID	Soil Type	Profile Top Depth ft (m)	Profile Bottom Depth ft (m)	
149	Gray	147.90 (45.08)	151.30 (46.12)	**Note:** 149.0-150.0 Not recovered during drilling
152	Gray	151.30 (46.12)	153.30 (46.73)	
155	Gray	153.60 (46.82)	156.00 (47.55)	
165	Gray	164.20 (50.05)	165.80 (50.54)	
170	Gray-Red	170.00 (51.82)	176.60 (53.83)	
180	Gray-Red	180.00 (54.86)	188.00 (57.30)	
190	Gray-Red	188.00 (57.30)	200.40 (61.08)	**Note:** 188.4-190.0 Not recovered during drilling
200	Gray-Red	200.40 (61.08)	203.00 (61.87)	198.5-200.0 Not recovered during drilling
205	Gray-Red	203.00 (61.87)	206.00 (62.79)	
210	Purple	206.00 (62.79)	214.60 (65.41)	**Note:** 209.0-210.0 Not recovered during drilling
220	Red	223.80 (68.21)	227.50 (69.34)	
230	Red	230.20 (70.16)	242.00 (73.76)	**Note:** 239.8-240.0 Not recovered during drilling
250	Purple	242.00 (73.76)	251.20 (76.57)	
255	Gray	251.20 (76.57)	256.00 (78.03)	
260	Red	258.90 (78.91)	269.65 (82.19)	
270	Red	270.00 (82.30)	274.80 (83.76)	
280	Gray	281.50 (85.80)	282.50 (86.11)	
282	Gray	282.50 (86.11)	282.80 (86.20)	
315	Red	315.00 (96.01)	318.25 (97.00)	

Appendix 1- Paleosol profile depths

Fort Mott

Soil ID	Soil Type	Profile Top Depth ft (m)	Profile Bottom Depth ft (m)	
360	Gray	365.00 (111.25)	367.00 (111.86)	**Note:** 364.25-365.0 Not recovered during drilling
370	Purple	367.00 (11.86)	375.00 (114.30)	
380	Red	375.00 (114.30)	382.00 (116.43)	
395	Purple	394.00 (120.09)	395.35 (120.50)	
415	Purple	408.60 (124.54)	424.00 (129.24)	
475	Gray	475.00 (144.78)	477.00 (145.39)	
480	Gray	478.40 (145.82)	488.00 (148.74)	
510	Red	508.20 (154.90)	515.20 (157.03)	**Note:** 508.5-510.0 Not recovered during drilling
520	Red	515.20 (157.03)	529.50 (161.39)	
530	Brown	529.50 (161.39)	542.00 (165.20)	**Note:** 529.9-530.0 Not recovered during drilling
540	Red	542.00 (165.20)	549.40 (167.46)	539.0-540.0 Not recovered during drilling
550	Brown	550.30 (167.73)	554.00 (168.86)	
615	Red	611.20 (186.29)	616.00 (187.76)	
650	Red	649.20 (197.88)	652.85 (198.99)	
660	Red	660.00 (201.17)	670.10 (204.25)	
670	Purple	670.10 (204.25)	676.10 (206.08)	**Note:** 674.7-675.0 Not recovered during drilling
680	Purple	676.10 (206.08)	684.70 (208.70)	**Note:** 679.7-680.0 Not recovered during drilling
685	Purple	684.70 (208.70)	690.00 (210.31)	
700	Purple	700.00 (213.36)	702.90 (214.24)	
705	Purple	702.90 (214.24)	710.60 (216.59)	
720	Red	720.00 (219.46)	722.70 (220.28)	
725	Red	725.00 (220.98)	734.70 (223.94)	
730	Purple	734.70 (223.94)	739.10 (225.28)	
740	Red	740.00 (225.55)	741.85 (226.12)	
742	Red	741.85 (226.12)	742.60 (226.34)	
748	Red	748.00 (227.99)	749.85 (228.55)	
750	Red	749.85 (228.55)	751.30 (229.00)	
752	Red	751.30 (229.00)	752.80 (229.45)	
760	Red	760.60 (231.83)	765.00 (233.17)	
765	Red	765.00 (233.17)	769.20 (234.45)	
770	Red	769.20 (234.45)	772.30 (235.40)	
780	Brown	780.00 (237.74)	790.30 (240.88)	
790	Brown	790.30 (240.88)	792.70 (241.61)	

Appendix 1 - Paleosol profile depths

Medford

Soil ID	Soil Type	Profile Top Depth ft (m)	Profile Bottom Depth ft (m)
690	Red	686.30 (209.18)	697.40 (212.57)
700	Gray-Red	697.40 (212.57)	700.00 (213.36)
705	Red	700.00 (213.36)	706.00 (215.19)
742	Purple	740.60 (225.73)	747.10 (227.72)
749	Gray-Red	747.10 (227.72)	750.00 (228.60)
750	Gray	750.00 (228.60)	750.90 (228.87)
790	Gray-Red	790.00 (240.79)	793.70 (241.92)
795	Purple	794.00 (242.01)	797.70 (243.14)
800	Gray-Red	800.00 (243.84)	810.00 (246.89)
810	Gray	811.60 (247.38)	814.25 (248.18)
850	Brown	850.00 (259.08)	860.00 (262.13)
955	Red	954.00 (290.78)	956.60 (291.57)

Appendix 2 - Paleosol Horizons

Summit Marina

Soil ID	Top Depth (ft)	Bottom Depth (ft)	Soil Horizon	Pedotype
110	110.00	111.70	Bt1	purple
	111.70	113.60	Bt2	
115	115.00	115.65	AB	gray-red
	115.65	116.20	C	
116	116.20	117.00	AB	gray-red
	117.00	117.50	C	
155	155.00	155.90	A	gray-red
	155.90	157.70	AB	
	157.70	158.10	BC	
160	160.00	161.40	ABs	purple
	161.40	163.40	Bs	
	163.40	164.60	C	
165	164.60	167.70	ABo	red
	167.00	168.40	Bo	
170	168.40	170.45	BoA	purple
	170.45	171.10	BC	
185	185.00	185.55	AC	gray-red
	185.55	186.80	C	
195	195.00	196.35	BA	red
	196.35	199.40	Bs	
200	200.00	201.65	A	brown
	201.65	203.30	Bo	
	203.30	205.50	Bt1	
	205.50	207.00	Bt2	
	207.00	210.30	Bt2C	
	210.30	211.60	C	
210	210.00	210.90	AC	gray
220	220.00	220.80	AB	gray
	220.80	223.00	Bw	
	223.00	224.50	CB	

Appendix 2 - Paleosol Horizons

Summit Marina

Soil ID	Top Depth (ft)	Bottom Depth (ft)	Soil Horizon	Pedotype
230	225.00	225.80	AC	gray
	225.80	227.40	C	
235	236.50	237.50	AC	gray
285	285.00	289.60	AC	gray
	289.60	295.00	Cg	
	295.00	297.50	Cg	
340	340.20	340.55	Bw	gray-red
	340.55	340.95	CB	
	340.95	341.45	Bw	
	341.45	342.30	CB	
	342.30	343.10	Bw	
	343.10	343.35	CB	
344	343.75	344.20	Bo	purple
	344.20	344.80	CB	
345	344.80	345.60	Bs1	purple
	345.60	347.70	Bs2	
350	350.00	351.10	Bs	purple
	351.10	351.40	BC	
	351.40	351.80	CB	
352	351.80	352.80	ABs	red
	352.80	354.60	Bs	
355	355.00	356.30	BC	purple
360	361.50	362.50	Abg	gray-red
365	362.50	364.20	AB	gray-red
	364.20	366.50	Bw1	
	366.50	370.70	Bw2	
	370.70	371.70	CB	
375	375.00	376.80	ABo	red
	376.80	378.40	BC	
380	380.00	381.70	Bo	purple
	381.70	382.90	CB	

Appendix 2 - Paleosol Horizons

Summit Marina

Soil ID	Top Depth (ft)	Bottom Depth (ft)	Soil Horizon	Pedotype
385	382.90	383.50	AB	red
	383.50	385.00	Bo	
	385.00	385.85	CB	
387	386.50	386.70	A	gray-red
	386.70	386.90	AB	
	386.90	387.20	BA	
	387.20	387.45	C	
400	401.00	402.30	A	gray-red
	402.30	402.80	Bw	
	402.80	403.55	CB	
403	403.65	404.00	A	gray
	404.00	404.60	C	
410	410.00	412.80	A	gray
	412.80	414	AC	
	414.00	415.4	C	
420	420.00	421.00	A	purple
	421.00	421.80	AB	
	421.80	423.30	Bt	
	423.30	427.60	BCg	
430	427.60	430.00	AB	red
	430.00	434.40	AB	
	434.00	437.50	Bo	
	437.50	438.30	BC	
	438.30	440.00	Cg	
440	440.00	441.00	A	brown
	441.00	442.80	Bt	
	442.80	445.00	C	
445	445.00	445.60	A	brown
	445.60	447.60	Abt	
	447.60	449.00	Bt	
	449.00	449.40	BC	

Appendix 2 - Paleosol Horizons

Summit Marina

Soil ID	Top Depth (ft)	Bottom Depth (ft)	Soil Horizon	Pedotype
450	450.00	450.15	O	purple
	450.15	450.50	A	
	450.50	451.60	AB	
	451.60	453.50	BC	
	453.50	457.30	BsC	
	457.30	460.40	C	
460	460.40	461.10	BA	purple
	461.10	462.30	Bo	
	462.30	463.80	BC	
	463.80	464.60	C	
470	471.90	473.55	AB	red
475	475.00	476.90	Bt	brown
	476.90	478.80	C	
480	478.80	484.00	Bt	brown
	484.00	485.70	C	
	484.00	485.70	C	
	484.00	485.70	C	
	484.00	485.70	C	

Fort Mott

Soil ID	Top Depth (ft)	Bottom Depth (ft)	Soil Horizon	Pedotype
149	147.9	149.0	A	Gray
	150.0	151.3	Cg	
152	151.3	153.1	AC	Gray
	153.1	153.3	Cg	
155	153.6	154.45	AC	Gray
	154.45	156.0	Cg	
165	164.2	165.2	AC	Gray
	165.2	165.8	Cg	

Appendix 2 - Paleosol Horizons

Fort Mott

Soil ID	Top Depth (ft)	Bottom Depth (ft)	Soil Horizon	Pedotype
170	170.0	171.1	AB	Gray-Red
	171.1	173.3	Bth	
	173.3	175.7	Bt	
	175.7	176.6	C	
180	180.0	182.3	AB	Gray-Red
	182.3	188.0	BCg	
190	188	191.1	AB	Gray-Red
	191.1	192.5	CB	
	192.5	195.5	Bt	
	195.5	197.6	BtC	
	197.6	198.5	C	
	200.0	200.4	C	
200	200.4	202.0	AB	Gray-Red
	202.0	203.0	C	
205	203.0	204.0	AB	Gray-Red
	204.0	206.0	CB	
210	206.0	208.5	Abt	Purple
	208.5	214.6	CB	
220	223.8	227.5	AB	Red
230	230.2	231.7	AB	Red
	231.7	233.9	Bt1	
	233.9	239.1	Bt2	
	239.1	242	BC	
250	242	245.8	Abt	Purple
	245.8	250.1	Bt	
	250.1	251.2	C	

Appendix 2 - Paleosol Horizons

Fort Mott

Soil ID	Top Depth (ft)	Bottom Depth (ft)	Soil Horizon	Pedotype
255	251.2	253.3	A	Gray
	253.3	256	CA	
260	258.9	260	Oa	Red
	260	263	AB	
	263	268.6	Bt	
	268.6	269.65	C/Bt	
270	270	274.8	Bt/A	Red
280	281.5	282.5	AC	Gray
282	282.5	282.8	AC	Gray
315	315	316.2	A	Red
	316.2	317.25	Bw	
	317.25	318.25	C	
360	365	365.8	Ag	Gray
	365.8	367	Cg	
370	367	367.9	A/Bt1	Purple
	367.9	372.4	Bt2	
	372.4	375	CBs	
380	375	375.9	AB	Red
	375.9	382	Bto	
395	394	395.35	Bss/C	Purple
415	408.6	416	AB	Purple
	416	417.6	Bo	
	417.6	424	CBg	
475	475	477	AC	Gray
480	487.4	488	AC	Gray
510	508.2	508.55	AB(?)	Red
	510	512.3	Bss	
	512.3	515.2	BgC	
520	515.2	520	Bt	Red
	520	523.5	Bo	
	523.5	529.5	C	

Appendix 2 - Paleosol Horizons

Fort Mott

Soil ID	Top Depth (ft)	Bottom Depth (ft)	Soil Horizon	Pedotype
530	529.5	532.9	BA	Brown
	532.9	538.2	Btss	
	538.2	542	BCs	
540	542	545.6	Bt	Red
	545.6	546.5	BC	
	546.5	549.4	C	
550	550.3	551.1	BC	Brown
	551.1	554	CB	
615	611.2	613.5	BC1	Red
	613.5	615.4	BC2	
	615.4	616	C	
650	649.2	649.8	A/Bo	Red
	649.8	651.3	Bt	
	651.3	652.85	C	
660	660	666.2	Bo	Red
	666.2	670.1	C	
670	670.1	672	Abo	Purple
	672	673.6	Bts	
	673.6	676.1	C	
680	676.1	683.6	BAs	Purple
	683.6	684.7	BCo	
685	684.7	688.15	Bo	Purple
	688.15	689.45	BC	
	689.45	690	BCss	
700	700	700.45	AB1	Purple
	700.45	701.1	BA1	
	701.1	702.6	AB2	
	702.6	702.9	BA2	
705	702.9	704	A/Bss	Purple
	704	705.6	Bo	
	705.6	710.6	CB	

Appendix 2 - Paleosol Horizons

Fort Mott

Soil ID	Top Depth (ft)	Bottom Depth (ft)	Soil Horizon	Pedotype
720	720	722	A/Bo	Red
	722	722.7	Bg/C	
725	725	734.3	Bto	Red
	734.3	734.7	CBs	
730	734.7	738.75	Bs	Purple
	738.75	739.1	C	
740	740	741.4	A/Bt	Red
	741.4	741.85	C	
742	741.85	742.25	A/Bt	Red
	742.25	742.6	C	
748	748	749.85	ABs	Red
750	749.85	750.1	A/Bo	Red
	750.1	750.95	Bts	
	750.95	751.3	C	
752	751.3	751.95	A	Red
	751.95	752.1	A/B	
	752.1	752.6	Bts/C	
	752.6	752.8	C	
760	760.6	763	A/B	Red
	763	764.9	Bt	
	764.9	765	BC	
765	765	765.6	Aa	
	765.6	766.85	ABa	
	766.85	768.2	Bo	
	768.2	769.2	Cg	Red
770	769.2	770.3	A/Bss	Red
	770.3	771.7	Bo/C	
	771.7	772.3	Cg	
780	780	781.5	A	Brown
	781.5	782.4	AB	
	782.4	788.45	Bt	
	788.45	789.05	BC	
	789.05	790.3	C	

Appendix 2 - Paleosol Horizons

Fort Mott

Soil ID	Top Depth (ft)	Bottom Depth (ft)	Soil Horizon	Pedotype
790	790.3	791.6	Bts	Brown
	791.6	792.7	CBs	

Medford

Soil ID	Top Depth (ft)	Bottom Depth (ft)	Soil Horizon	Pedotype
690	688.5	690.10	Bgs	Red
	690.1	696.30	Bt	
	696.3	697.40	C	
700	697.4	699.00	Bws	Gray-Red
	699	700.00	C	
705	700	702.30	Bs1	Red
	702.3	704.80	Bs2	
	704.8	706.00	C	
742	740.6	742.40	Abs	Purple
	742.4	744.20	Bt	
	744.2	747.10	Cbo	
749	747.1	748.00	Abw	Gray-Red
	748	748.90	Bw	
	748.9	750.00	CBw	
750	750	750.50	AC	Gray
	750.5	750.90	C	
790	790	791.00	Bwo	Gray-Red
	791	793.70	C	
795	793.7	795.20	Bt1	Purple
	795.2	796.80	Bt2	
	796.8	797.70	BtC	
800	800	803.90	O	Gray-Red
	803.9	804.90	Ao	
	804.9	806.10	Bts	
	806.1	808.70	Bt	
	808.7	810.00	C	

Appendix 2 - Paleosol Horizons

Medford

Soil ID	Top Depth (ft)	Bottom Depth (ft)	Soil Horizon	Pedotype
810	811.6	813.15	A	Gray
	813.15	814.25	C	
850	850	850.50	Abo	Brown
	850.5	852.00	Bt	
	852	860.00	CB	
955	954	954.70	A	Red
	954.7	955.50	Bt	
	955.5	956.60	Cg	

Appendix 3 - Paleosol Compaction

Fort Mott	Soil	Top (km)	Bottom (km)	Compaction – top (% of original)	Compaction - bottom (% of original)
149	Gray	0.045	0.046116	99.6%	99.6%
152	Gray	0.046	0.046726	99.6%	99.6%
155	Gray	0.047	0.047549	99.6%	99.6%
165	Gray	0.05	0.050536	99.6%	99.6%
170	Gray-Red	0.052	0.053828	99.6%	99.6%
180	Gray-Red	0.055	0.057302	99.6%	99.5%
//190	Gray-Red	0.057	0.061082	99.5%	99.5%
200	Gray-Red	0.061	0.061874	99.5%	99.5%
205	Gray-Red	0.062	0.062789	99.5%	99.5%
210	Purple	0.063	0.06541	99.5%	99.5%
220	Red	0.068	0.069342	99.5%	99.4%
230	Red	0.07	0.073762	99.4%	99.4%
250	Purple	0.074	0.076566	99.4%	99.4%
255	Gray	0.077	0.078029	99.4%	99.4%
260	Red	0.079	0.082189	99.4%	99.3%
270	Red	0.082	0.083759	99.3%	99.3%
280	Gray	0.086	0.086106	99.3%	99.3%
282	Gray	0.086	0.086197	99.3%	99.3%
315	Red	0.096	0.097003	99.2%	99.2%
360	Gray	0.111	0.111862	99.1%	99.1%
370	Purple	0.112	0.1143	99.1%	99.1%
380	Red	0.114	0.116434	99.1%	99.1%
395	Purple	0.12	0.120503	99.0%	99.0%
415	Purple	0.125	0.129235	99.0%	99.0%
475	Gray	0.145	0.14539	98.9%	98.9%
480	Gray	0.146	0.148742	98.8%	98.8%
510	Red	0.155	0.157033	98.8%	98.8%
520	Red	0.157	0.161392	98.8%	98.7%
530	Brown	0.161	0.165202	98.7%	98.7%
540	Red	0.165	0.167457	98.7%	98.7%
550	Brown	0.168	0.168859	98.7%	98.7%
615	Red	0.186	0.187757	98.5%	98.5%
650	Red	0.198	0.198989	98.4%	98.4%
660	Red	0.201	0.204246	95.2%	95.1%
670	Purple	0.204	0.206075	95.1%	95.1%

Appendix 3 - Paleosol Compaction

Fort Mott	Soil	Top (km)	Bottom (km)	Compaction – top (% of original)	Compaction - bottom (% of original)
680	Purple	0.206	0.208697	95.1%	95.0%
685	Purple	0.209	0.210312	95.0%	95.0%
700	Purple	0.213	0.214244	94.9%	94.9%
705	Purple	0.214	0.216591	94.9%	94.8%
720	Red	0.219	0.220279	94.8%	94.7%
725	Red	0.221	0.223937	94.7%	94.7%
730	Purple	0.224	0.225278	94.7%	94.6%
740	Red	0.226	0.226116	94.6%	94.6%
742	Red	0.226	0.226344	94.6%	94.6%
748	Red	0.228	0.228554	94.6%	94.6%
750	Red	0.229	0.228996	94.6%	94.6%
752	Red	0.229	0.229453	94.6%	94.5%
760	Red	0.232	0.233172	94.5%	94.5%
765	Red	0.233	0.234452	98.2%	98.2%
770	Red	0.234	0.235397	98.2%	98.2%
780	Brown	0.238	0.240883	98.1%	98.1%
790	Brown	0.241	0.241615	98.1%	98.1%

Summit Marina	Soil	Top (km)	Bottom (km)	Compaction - top (% of original)	Compaction - bottom (% of original)
110	purple	0.034	0.0346	99.7%	99.7%
115	gray-red	0.035	0.03542	99.1%	99.1%
116	gray-red	0.035	0.03581	99.1%	99.1%
155	gray-red	0.047	0.04819	98.8%	98.8%
160	purple	0.049	0.05017	99.6%	99.6%
165	red	0.050	0.05133	99.6%	99.6%
170	purple	0.051	0.05215	99.6%	99.6%
185	gray-red	0.056	0.05694	98.6%	98.6%
195	red	0.059	0.06078	99.5%	99.5%
200	brown	0.061	0.06395	99.5%	99.5%
210	gray	0.064	0.06428	98.4%	98.4%
220	gray	0.067	0.06842	98.3%	98.3%
230	gray	0.069	0.06931	98.3%	98.2%
235	gray	0.072	0.07239	98.2%	98.2%
285	gray	0.087	0.09068	97.8%	97.7%

Appendix 3 - Paleosol Compaction

Summit Marina	Soil	Top (km)	Bottom (km)	Compaction - top (% of original)	Compaction - bottom (% of original)
340	gray-red	0.104	0.1047	97.4%	97.4%
344	purple	0.105	0.1051	99.2%	99.2%
345	purple	0.105	0.1060	99.2%	99.2%
350	purple	0.107	0.1072	99.2%	99.1%
352	red	0.107	0.1081	99.1%	99.1%
355	purple	0.108	0.1086	99.1%	99.1%
360	gray-red	0.110	0.1105	97.3%	97.3%
365	gray-red	0.111	0.1133	97.3%	97.2%
375	red	0.114	0.1153	99.1%	99.1%
380	purple	0.116	0.1167	99.1%	99.1%
385	red	0.117	0.1176	99.1%	99.1%
387	gray-red	0.118	0.1181	97.1%	97.1%
400	gray-red	0.122	0.1230	97.0%	97.0%
403	gray	0.123	0.1233	97.0%	96.9%
410	gray	0.125	0.1266	96.9%	96.9%
420	purple	0.128	0.1303	99.0%	99.0%
430	red	0.130	0.1341	99.0%	98.9%
440	brown	0.134	0.1356	98.9%	98.9%
445	brown	0.136	0.1370	98.9%	98.9%
450	purple	0.137	0.1403	98.9%	98.9%
460	purple	0.140	0.1416	98.9%	98.9%
470	red	0.144	0.1443	98.9%	98.9%
475	brown	0.145	0.1459	98.9%	98.8%
480	brown	0.146	0.1480	98.8%	98.8%

Medford	Soil	Top (km)	Bottom (km)	Compaction - top (% of original)	Compaction - bottom (% of original)
690	Red	0.209	0.2126	98.4%	98.3%
700	Gray-Red	0.213	0.2134	94.9%	94.9%
705	Red	0.213	0.2152	98.3%	98.3%
742	Purple	0.226	0.2277	98.2%	98.2%
749	Gray-Red	0.228	0.2286	94.6%	94.6%
750	Gray	0.229	0.2289	94.6%	94.6%
790	Gray-Red	0.241	0.2419	94.3%	94.3%
795	Purple	0.242	0.2431	98.1%	98.1%

Appendix 3 - Paleosol Compaction

Medford	Soil	Top (km)	Bottom (km)	Compaction (top)	Compaction (bottom)
800	Gray-Red	0.244	0.2469	94.2%	94.2%
810	Gray	0.247	0.2482	94.2%	94.1%
850	Brown	0.259	0.2621	98.0%	98.0%
955	Red	0.291	0.2916	97.8%	97.7%