CLEAR AS MUD:

ASSESSING THE PALEOSHELF ENVIRONMENT AND DEPOSITIONAL SETTING

AT MEDFORD, NEW JERSEY

DURING THE PALEOCENE-EOCENE THERMAL MAXIMUM

SUPPORT FOR AN APPALACHIAN AMAZON

By

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ABSTRACT OF THE THESIS

Clear as Mud: Assessing the Paleoshelf Environment and Depositional Setting at Medford, New Jersey during the Paleocene-Eocene Thermal Maximum Support for an Appalachian Amazon By: LUCA G. PODRECCA

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The Paleocene/Eocene boundary and attendant Paleocene-Eocene Thermal Maximum (PETM) marks a time of rapid global climatic change. New Jersey shelf sediments of the Marlboro Formation record the PETM with exceptionally thick preservation (up to ~15 m at Wilson Lake) during the period of global low carbon isotopic values ("the core") which requires minimum sedimentation rates near 10 cm/kyr. Rhythmic layers have previously been reported from both Wilson Lake & Millville, NJ (IODP Leg 174AX). These structures, dubbed 'couplets', consist of semi-periodic, 1-2 mm thick, raised laminations separated by typically homogenous sediment layers of varying width averaging 1.27 cm at Medford as opposed to nearly 2 cm at Wilson Lake and Millville. Previous studies have dismissed these structures as artifacts ('drilling biscuits') produced by drilling mud.

I report here on a series of shallow (<65 ft; ~19.81 m) auger cores drilled without using drilling fluid along a downdip transect at Medford, NJ. These cores show similar

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couplets on the ~1 - 2 cm scale, indicating that they are in fact primary depositional features. The mm-width laminae in the auger cores experienced remarkable swelling within minutes of splitting. XRD, XRF, bulk carbonate geochemistry, and grain size analysis were measured throughout the Medford auger cores. I analyzed differences in these parameters between the laminae and interspersing bulk material, and then made comparisons with data collected at other sites along the New Jersey Coastal Plain (NJCP). I find no uniform discernible difference in lithology between laminae and beds, other than a higher percentage of kaolinite in some laminae.

In general, the Marlboro Formation at this updip location consists of micaceous, lignitic, silty clay (mean size $< 2 \mu m$) with occasional organic debris indicating proximal deposition in a prodelta setting. A paleodepth of ~40 m is estimated from a paleoslope model and normal marine salinities are inferred from the presence of common, though not abundant, planktonic foraminifera. I propose a model of deposition for the Marlboro Formation as being driven by fluid mud (near-bed suspension flows) transport associated with the "Appalachian Amazon", implying that the extremely fine-grained Marlboro Clay was deposited at Medford as part of a sigmoidal shaped subaqueous clinoform. The clinoform model explains the differential preservation of the Vincentown Formation, transitional units, and the CIE onset, "core", recovery, and overlying units along a dip transect across the paleoshelf. The laminations discussed here have analogs in modern environments characterized by muddy continental shelves and are associated with episodic or possibly quasi seasonal events of increased riverine discharge and the attendant migration of the benthic salinity front.

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Introduction

The Paleocene-Eocene Thermal Maximum (PETM) was a brief period of intense global warming that occurred ~56 Ma and lasted <200kyr (McInerney & Wing, 2011). Determining the trigger mechanism as well as the speed and duration of the onset has been a hotly contested issue; constraining the speed and duration is needed to evaluate the causal processes for the PETM and to test its use as an analog for modern climate change. The PETM is characterized by a large (2-8%), rapid (<10 kyr) negative carbon isotope excursion (CIE) (<10kyr) (Kennett and Stott; 1991), extinction of benthic foraminifera taxa in the deep ocean, and a rapid increase in global temperatures estimated between 5-8°C (Zachos et al., 2006). These characteristics show a large-scale carbon cycle disruption via an enormous injection of carbon from a ¹³C depleted source (Bowen et al., 2006). The rapid onset of the CIE (<10 kyr) (Kennett & Stott; 1991) indicates that "the perturbation was initiated by an injection of ¹³C depleted carbon rather than a reduction of carbon burial which operates on a 100+ kyr timescale" (Kump and Arthur, 1999). The response recorded in the dissolved inorganic carbon (DIC) is measured as a negative δ^{13} C shift of 3-5‰ and the onset of this event is used globally to correlate the base of the Eocene (Dupuis et al., 2003; Aubry et al., 2007). The shape of the CIE has been used to correlate the PETM amongst terrestrial, shallow marine, and deep-sea sites (Röhl et al., 2007). The δ^{13} C record of the CIE is divided into three units (Fig. 1): 1) the sharp excursion dubbed the CIE onset; 2) an interval of remarkably constant δ^{13} C values dubbed the "core"; and 3) a period of exponential recovery of δ^{13} C to near pre-CIE δ^{13} C values (Röhl et al., 2007). In this study I examine the CIE record at various sites on the New Jersey Coastal Plain (NJCP) (Fig. 2) and use the shape of the CIE recorded at these

wells to correlate sites on a down-basin transect (Fig. 3). I use the Medford augers to anchor the most proximal facies possible on a paleoshelf transect in New Jersey to understand the NJCP's depositional environment during the PETM.

Medford, NJ is the furthest upbasin site on the NJCP that records the PETM (Fig. 2). Herein, I present data from cores that were collected at Medford in August 2016 during the Medford Augur Project (MAP) (Fig. 4). The notable stratigraphy encountered during this project includes the Upper Paleocene Vincentown Formation, a dark green glauconitic quartz silty sand, an uppermost Paleocene boundary transitional unit that ranges from sand- to clay- dominated, and the lowermost Eocene Marlboro Formation, a highly kaolinitic, smectite rich, gray-green, plastic clay deposited during the PETM found throughout a broad region of the Mid Atlantic Coastal Plain (e.g., Kopp et al., 2009). The geographic range, including a transect across the paleoshelf (Figs. 2, 3), coupled with the Marlboro's thickness (up to 15 m at Wilson Lake) creates a remarkable opportunity to study the carbon isotope excursion (CIE) and global warming event associated with the PETM. The dip transect of coreholes drilled in the NJCP (Fig. 2) also provides a unique perspective on the processes governing sedimentation on a continental shelf during a hyperthermal event, one that has been inferred to have experienced remarkably high rates of sedimentation (Kopp et al., 2009). Furthermore, the Medford, NJ site studied here is the furthest updip site on the NJCP and, as justified below, has provided one of the thickest known records of the initiation of the onset of the PETM CIE found in the marine realm.

Previous studies have placed special emphasis on describing a very notable set of structures found in several cores recovered on the NJCP termed 'couplets' (Wright and

Schaller, 2013; Miller et al., 2017). These couplets are comprised of rhythmic, mm-scale laminations and interspersed cm-scale, typically homogenous beds. These structures found in the Marlboro Formation, were first described in cores recovered from Wilson Lake (Lombardi, 2014) and at Millville (Wright and Schaller, 2013). They are now also recorded in cores recovered during the Medford Auger Project (MAP)(Fig. 4). These couplets have previously been interpreted as annual layers based on δ^{18} O cyclicity and the relationship between δ^{18} O and CaCO₃ records which have been interpreted to be triggered by sediment gravity flow deposits (Wright and Schaller, 2013). However, they have also been interpreted as artifacts of the drilling process with the cm-scale beds resulting from "biscuiting" and the laminations being produced by mud injection (Pearson and Thomas, 2015). Drilling at Millville and Wilson Lake used bentonite muds in the drilling process and injection of drilling mud was noted in the Millville site report and is associated with the high drilling pressures reported there (Sugarman et al., 2005). High pressures did not occur at Wilson Lake, and injection was considered less likely by the onsite geologists (Miller et al., 2017). In August 2016, a Rutgers team drilled at Medford, NJ the furthest updip section of the Salisbury Embayment in New Jersey as part of the MAP (Fig. 2). Six sites were drilled along a dip transect. Two holes, offset by 2.5 feet, were cored at each site. 4 of the 6 sites. Recovery exceeded 91%. Coring for the MAP used an auger, eschewing the use of drilling fluids. Thus, any laminations in the MAP must be primary and cannot be ascribed to injection by drilling fluids.

This study focuses on the upper Vincentown-Marlboro transition zone and the Marlboro Formation recovered during the MAP. These sections, while less thick than at Wilson Lake or Millville, are expanded enough to provide useful information on their depositional environment in the form of sedimentary structures (both primary and secondary), changes in clay mineralogy, overall grain size, and variations in the δ^{13} C record of the CIE between MAP sites and other locations along the NJCP. Through interpretation of these four data sets I have developed a depositional model for the area that supports the previously postulated "Appalachian Amazon" hypothesis (Kopp et al., 2009).

In this thesis, I use visual core description and correlation, fine-fraction grain size analysis, X-ray fluorescence and X-radiography, bulk carbonate stable isotope records, and clay mineral identification via qualitative and semi-quantitative X-ray diffraction to present the argument for a subaqueous clinoform depositional model for the regional deposition of the Marlboro formation. These data indicate that the Marlboro Formation was deposited in a fluid mud driven depositional environment.

The rapid change in climate catalyzed by the sudden warming associated with the PETM may have resulted in an enhanced hydrologic cycle along the NJCP (Kopp et al., 2009). General circulation and climate models of the PETM predict a "10-20% increase in precipitation in many continental areas" (Winguth et al., 2010; Huber and Sloan, 2000) and vegetation changes in the region support an increase in precipitation (Gibson et al., 1993). At the time of the PETM, the NJCP was a part of the Salisbury Embayment, an arm of the Atlantic Ocean which covered parts of northern Virginia, eastern Maryland, and Delaware, in addition to the NJCP (Fig. 5). The Salisbury Embayment was inundated by the Atlantic Ocean during the Cretaceous through the Miocene when sea level stood approximately 50-100 m higher than at present (Browning et al., 2008); thus, the shoreline of the embayment would have been found as far inland as the present-day fall

line (Fig. 5). During the PETM, deposition of the massive kaolinite rich clay of the Marlboro Formation can be traced 325 km north/south and 100 km east/west throughout the region (Figs. 5, 6) (Gibson et al., 2000; Kopp et al., 2009). Given its broad range and relative thickness, the Marlboro Formation provides an excellent opportunity to study a remarkably high-resolution section of the PETM along a paleoshelf transect (e.g. Makarova et al., 2017). Medford is unique and important because it anchors the paleoshelf transect of the NJCP on the shallow, proximal end.

Background

The MAP (see also: Methods) was conducted at Medford, NJ, due to its updip location on the NJCP, my research concentrated on Holes 3A and 3B due to their wellpreserved sedimentary structures (described below). When referencing the MAP cores in this study, I refer to their depths in units of adjusted core depths (acd), which is differentiated from drilling depth units (ft) in order to correlate between site 3 holes 3A and 3B as well as to compensate for core expansion.

Clay Mineralogy and Lithostratigraphy

Clays are sediments in the $< 4 \,\mu m$ size range, primarily formed through the chemical weathering of feldspars and other silicate minerals. These sheet-like minerals dominate the mineral assemblage in the size range under 2 μm because the physical weathering processes that work to break down quartz and feldspars becomes ineffective at such small grain sizes (Moore and Reynolds, 1989). Clay minerals tend to grow in low temperature environments wherein a great abundance of crystal imperfections are

created. These weaknesses in the structure of clay minerals work to destabilize them before growth can continue past their upper bounds (Moore and Reynolds, 1989).

In the $< 2 \mu m$ size range, clay mineral assemblages are dominated by hydrated alumino-silicates with layered structures. Of these hydrated alumino-silicates, most clay minerals fall into one of the following types: chlorite, illite, kaolinite, (hydrated) oxides, smectite, and vermiculite. Clay minerals may also be built of intergrown mixtures of two or more of these types. (Moore and Reynolds 1989)

Kaolinite is the prevalent mineral of these hydrated alumino-silicates found in regions associated with wet tropical climates, requiring intensive weathering under tropical to subtropical climatic conditions and the corresponding elevated rates of water percolation through source rocks of requisite composition, such as feldspars (Lyle et al., 2012; Robert and Kennett, 1994; Robert and Chamley, 1991). Thus, kaolinite is a characteristic mineral found in highly weathered soils such as those found throughout the Piedmont (Johnson, 1970). Smectite formation is very similar, however it is generally associated with environments controlled by an oscillating wet and dry season, and requires less water percolation than kaolinite (Robert and Kennett, 1994; Diester-Haass, 1993; Robert and Chamley, 1991)

Thus, changes in the dominant clay species of a mineralogical suite indicates a change in local climate.

(Illite)/Smectite \leftrightarrow Kaolinite

Lower temperature/precipitation; seasonal ↔ Higher year-round temperature/precipitation The hydrated oxides Al, Fe, and Mn are found to form in soils that have undergone the greatest degree of weathering (Moore, Reynolds 1989). In previous studies, the Upper Paleocene Vincentown Formation has been noted as having increasing kaolinite content up-section, a trend that continues to rise up to ~40% above the base of the Marlboro Formation, e.g., (Gibson et al., 2000).

X-ray Fluorescence (XRF) and X-radiography

XRF analysis provides a rapid, non-destructive means for analyzing the elemental composition of a given material; in this study I examined the archive half of core MAP Hole 3A Core #11 (1.5 m) and core MAP Hole 3B Core #12 (1.5 m). These two cores were selected for their excellent preservation of the laminae couples. Bombarding a sediment core with X-rays results in the ejection of one or more electrons; given that the energy of the x-ray is greater than the ionization energy of the constituent atoms of the material being bombarded.

If the X-ray carries enough energy, it will result in the ejection of electron(s) from inner orbitals; when this occurs, electron(s) from higher orbitals collapse into the vacancy left behind. This results in the release of energy via a photon, which carries energy equal to the difference in energy between the two orbitals involved in the event which is diagnostic of the type of atom in the material being bombarded.

The term fluorescence is used to define the phenomena by which the absorption of a specific quantity of energy via radiation by a material results in the re-emission of a photon characteristic of that material. Thus, XRF scanning produces a closely spaced (< 1 cm) record of the atomic abundances on the surface of a core. In addition to changes in atomic signature XRF also responds to changes in water content and porosity of unconsolidated sediment (Lyle et al., 2012).

Bulk Carbonate Stable Isotope Geochemistry (δ^{13} C and δ^{18} O)

Bulk carbonate is defined as all carbonates that are in the sample. It can be carried in by rivers, it can be biogenic and therefore representative of the phyto-planktonics (calcareous nannofossils) and faunal (usually dominated by foraminifera), it can be authigenic (formed in the water column) or diagenetic (formed after burial due to porewater changes. In fully marine settings, the bulk carbonate is dominated by the biogenic component. Thus, δ^{13} C values depend on the δ^{13} C of the dissolved inorganic carbonate in the surrounding water in which the carbonate forms, thus changes in the bulk carbonate record reflect changes in the carbon cycle. As such, the rapid (<10 kyr) and global negative shift in δ^{13} C values of the carbonates in the Marlboro Formation are indicative of a massive and rapid injection of isotopically depleted carbon entering into the carbon cycle system. The δ^{13} C values collected from the MAP cores are used in this study to correlate among several other sites on the NJCP.

Bulk carbonate δ^{18} O values depend on the paleotemperature and seawater δ^{18} O that reflect Rayleigh fractionation. However, my bulk carbonate δ^{18} O records show considerable variability that potentially can be ascribed to local seawater and/or minor diagenetic effects and are not interpreted here. It potentially could be used to indirectly estimate temperature of the water at time of formation although bulk δ^{18} O of a carbonate is also influenced by species effects (vs. analyses of individual species of test-building organisms).

Grain Size Analysis

The Malvern Mastersizer 3000 analyzes grain size via laser diffraction; measuring materials ranging in size from sub-micron to two millimeters. As dispersed particulate sample runs through the measurement area of the Malvern's optical bench, a laser beam illuminates the particles and a series of detectors measures the intensity of the scattered light in both red and blue wavelengths from many different angles. The angle of scattering by any particular particle has an inverse relationship with that particle's size. The particle size is calculated by analyzing the scattering pattern, implementing the Mie theory of light scattering (McCave et al., 1986). To produce a plotted curve depicting grain size distribution the Malvern measures each sample three separate times and also produces an average of the three separate scans.

The classic sieve and pipette grain size analysis experiment is based on Stoke's sedimentation rates for the fine fraction. The principle behind this analysis states that by a prescribed time, particles of a particular size that have been thoroughly suspended in a water column will settle out of suspension. Thus, any particles still left in suspension can be considered finer than the phi size assumed to have settled out. By sampling an aliquot of the suspended sediment at a particular time, evaporating the water off the sample, and then weighing it, the actual amount (mass in grams) of sediment that was in suspension at that time can be measured. It is then assumed that subtracting the sample weight mass (suspended material) from the initial sample mass will yield the mass of the phi class that has settled out.

Methods

The MAP was drilled by The United States Geological Survey (USGS) Eastern Geology and Paleoclimate Center drillers (Jeffrey Grey and Keith Moody). Plastic liners placed at the bottom of the drill string just above the auger drill bit, allowed for recovery of 5 ft (1.5 m) cores. Upon surfacing, these plastic core casings were sealed, labeled according to the site, hole, and core number (MAP S# C#), and described. Field descriptions were recorded within 5 minutes of retrieval before condensation build up concealed any notable features. From August 22 through August 26, 2016, the MAP drilled 359 ft (109.42 m) of section. Of that 328.65 ft (100.17 m) was successfully recovered, resulting in 91.5% recovery. We recovered a total 72.6 ft (22.13 m) of Marlboro Formation at 10 holes across 6 sites. I focused on cores recovered from site 3 due to the excellent preservation of sedimentary structures.

The cores from these six MAP drill sites are curated in the Rutgers core repository at 4 °C. In early September 2016, a router placed on a set path running horizontally across the plastic cases was used to cut the core liner, the router bit was set at a height which would result in weakening the hard plastic case without breaking through or damaging the core trapped inside. A metal wire was placed on the core top and the core was split through the middle by pushing it through the stationary wire. The core was then separated into working and archive halves, pictures were taken in sunlight, core descriptions were recorded, and samples were retrieved. All samples reported here were retrieved from cores recovered in the MAP unless otherwise noted.

Clay Mineral Analysis by X-ray Diffraction

All clay samples analyzed by X-ray Diffraction (XRD) were run at Rutgers University on a Philips Xpert Diffractometer under the instruction and guidance of Dr. Thomas Emge. Samples were selected from MAP Hole 3A Core 11, due to its excellent preservation of laminated sedimentary structures (Fig. 7). The Marlboro Formation at MAP Hole 3A spans the interval 50.5-55.7 ft (15.392- 16.977 m). The primary focus for XRD analyses is to detect changes in mineralogy between laminae and interspersing bulk sediments, as well has between "couplets". I define a "couplet" here: from the bottom, a couplet consists of a raised lamina and the subsequent bulk sediments (Fig. 7a); each couplet is terminated upon reaching the next overlying lamination in the core. I counted 84 couplets throughout MAP Hole 3A Core #11 over 1.07 m of section (1.27 cm / couplet).

For clay mineral analysis, two couplets were selected for sampling from the top 51.4-51.5 ft (15.67- 15.70 m), middle 53.2-53.3 ft (16.22-16.25 m), and bottom 54.5-54.55 ft (16.61-16.63 m) of MAP Hole 3A Core #11; between two and four samples were collected from the bulk portion of each couplet for a total of 14 bulk samples and one sample was collected from the laminae of each couplet for a total of 6 laminae samples. These samples were cut out of the working half core using a razor blade and measured out to 1.5 cm³ for the bulk samples, and much smaller volume for the laminae samples given their smaller size. Samples were then dried overnight in a 60°C oven.

Samples were moved directly from the oven to be crushed into a homogenous fine powder using a mortar and pestle. Samples were then immediately placed inside a titanium sample dish and scraped flat using a glass slide and analyzed using a Philips Xpert diffractometer. Each sample was run for 1 hour and 50 minutes; this slow scanning speed allowed for greater resolution of data and improved signal to noise ratio. Data was analyzed and interpreted using the Highscore+ program to qualitatively diagnose the resulting diffractograms and identify what phases were present in each sample. Following qualitative analysis semi quantitative analyses were made using the program Jade7 in order to analyze relative percentages of the most common minerals identified. This was done by comparing RIR values, which are representative of scattering strength; this is the standard method for clay mineral concentration comparison referred to as 'semi quantitative'.

XRF & X-Radiography

Using the ITRAX core scanner at Lamont Doherty Core Repository (LDEO), Clara Chang ran 1.6 m from MAP Hole 3A Core #11 and 1.6 m for MAP Hole 3B Core #12. XRF analyses were conducted for 23 major element concentrations and were selected for their common occurrence in marine sediments. The core scanner was fitted with a Molybdenum tube at 30kV, 55mA. These XRF analyses were performed in 0.2 cm intervals at 15 seconds per interval and the output units were in counts/second/mA. Additionally, x-radiography analysis on MAP Hole 3A Core #11 were run on the same machine in 0.1 cm intervals at 10 seconds per interval. Distance between emitter and sample were kept extremely small and a prolene film was wrapped over the face of the core to improve signal to noise ratio. Spectra were processed using the proprietary Cox Analytical software Q-Spec, which fit the model to the data. Extra lines to account for a wide Fe peak were added, and extra lines for W were added to account for degradation of the XRF detector.

The XRF data are compiled here as counts per unit time per unit area and plotted against core photographs to evaluate possible correlations between elemental variance and visible features. Variation in single element percentages and element-element ratios may be indicative of changing sediment provenance, redox conditions, biologic activity, etc. as previously described in other marine cores (Croudace et al., 2006; Rothwell et al., 2006; Thomson et al., 2006).

Carbonate Carbon Isotopes

Bulk δ^{13} C and δ^{18} O isotopes were analyzed at the Rutgers stable isotope lab. I also used published bulk isotope data from several other NJCP cores (Kent et al., 2003; Zachos et al., 2006; Wright and Schaller 2013; Makarova et al., 2017) (Fig. 3).

I collected samples from the group of cores recovered during the MAP. The values I report here were collected at irregular intervals from 64.2 to 50.3 acd (19.6 – 15.3 m) in the cores from MAP Hole 3A and from 59.5 to 47.8 acd (18.1 – 14.6 m) in the cores from Hole 3B. Roughly 1 cm³ samples were collected after splitting the cores at the Rutgers–IODP Core Repository and dried in an oven at 50°C at Rutgers University. Once dried, samples were homogenized using an agate mortar and pestle. Each bulk carbonate sample was then weighed using a microscale and analyzed at the Rutgers stable isotope lab using a Micromass Optima mass spectrometer with an attached multiprep device. Bulk carbonate samples were reacted in 100% phosphoric acid (H₃PO₄) at 90°C for 15

min, and the evolved CO₂ gas was collected in a liquid nitrogen cold finger. Isotopic compositions are reported here as ratios in standard delta notation in parts per thousand (per mil, ‰) $\delta = [(R_{sample}/R_{standard}) - 1] \times 1000$, where R=¹³C/¹²C or ¹⁸O/¹⁶O, relative to Vienna Pee Dee belemnite (δ^{13} CVPDB and δ^{18} OVPDB). One-sigma analytical errors are based on analyses of an internal laboratory reference material (~8 standards for every 24 samples) and are ±0.05‰ and ±0.08‰ for δ^{13} C and δ^{18} O, respectively. The %CaCO₃ values were determined by converting the transducer reading for each sample analysis to a mass of CaCO₃ using an empirically derived calibration based on individual transducer readings and sample weight.

The bulk carbonate samples for MAP Hole 3A were collected immediately after splitting the cores however the samples for MAP Hole 3B were not collected until ~ ten months later.

Grain Size Analysis

Generation of grain size distributions were initially done using a Malvern Mastersizer 3000 at Rutgers University in B. Horton's lab in the Department of Marine and Coastal Sciences at Rutgers University. Subsequent grain size distribution data was generated using traditional pipette methods in G. Ashley's sedimentology lab in the Department of Earth and Planetary Sciences at Rutgers University.

I selected samples from MAP Hole 3A Core 11 (Fig. 7b). At this location the Marlboro Formation spans the interval 49.8 - 54.8 acd (15.2 - 16.7 m). I chose two adjacent couplets from the top, middle, and bottom of the core for sampling. I collected four to five samples from each selected couplet and placed each sample in a 50 mL vial

which was filled with 40mL of 1N Acetic acid to ensure dissolution of carbonate material. The acid remained in the vials for a period of 24 hours. The vials were shaken every two hours for the first six hours of this period, after shaking the caps were loosened to allow evolving gases to escape.

After the initial 24 hour soaking period the acetic acid was decanted using a pipette and plastic tubing. Each sample was filled with 40mL of de-ionized water and run through a centrifuge and then decanted, this rinsing process was repeated twice to ensure thorough removal of acetic acid. I then filled the sample vials with 40mL of Calgon[™] solution (5.5g metasodium phosphate/1 liter deionized water). The samples were mechanically stirred in the solution using a battery powered stirrer and left for 24 hours. The samples were then run once more in the centrifuge before being decanted; this process was also performed twice. The sample-Calgon solution was left overnight in a sonicade bath in the Stable Isotope Lab (SIL) in the Department of Earth and Planetary Sciences before being transported to the Malvern for grain size analysis.

In the Malvern lab, I performed one final stir of the sediments by running each sample through a small sonicade for thirty minutes to ensure a homogenous solution. Using a pipette, I transferred the sample solution from its 50mL vial to the Malvern Mastersizer 3000 until reaching the 2% obscurity threshold.

Throughout this first run-series of twenty-five samples erratic, anomalous, secondary peaks were recorded in roughly half of the samples near the 1mm mark. Visually inspecting the sample solution, it was clear there is not 1mm-sized material; to test if this peak was artificial, I sieved samples through a 63 µm screen and repeated the

deflocculation process; the 1mm peak persisted upon running these fine fraction samples through the Malvern.

This distorting effect that clay mineral morphology has on grain size distributions prompted me to implement the traditional pipette method of grain size analysis. I collected 8 samples from MAP Hole 3A Core #11 and removed all material coarser than 4 phi ($62 \mu m$). Each sample had a dry weight of between 25 and 33 grams and each sample was prepared using the same carbonate dissolution and deflocculation process implemented in the Malvern experiment, outlined above.

Results

The Paleocene-Eocene boundary is defined by at a level that separates two δ^{13} C analyses that mark the beginning of the δ^{13} C decrease known as the CIE (Aubry et al., 2007) that occurs at 57.1 acd at MAP Hole 3A (Fig. 8). The beginning of the decrease at MAP Hole 3B is less clear, but appears to be best placed at 57.05 acd (Figs. 8 and 9), suggesting little offset between holes A and B. I correlate the lithostratigraphic and clay mineralogic records to the carbon isotope record and CIE (Fig. 8). Pre-CIE values recorded in the Vincentown Formation at MAP Hole 3A range from approximately - 0.4‰ to -2.8‰. The CIE onset marking the P-E boundary is recognized at MAP Hole 3A by a 3.75‰ drop at 57.0° (57.0 acd) in δ^{13} C and its coincident 2.7% drop in %CaCO₃ (Fig. 9) to near zero levels (< 0.5%). The lowest δ^{13} C_{bulk} values recorded at MAP (-5.3‰ at 55.4 acd) are not as low as seen at Wilson Lake (-6‰; Fig. 3); this, coupled with the overall shape of the CIE at MAP (i.e. the Medford and Wilson Lake cores show similar post-initiation patterns; Fig. 3) implies a truncated initiation of the CIE at MAP (Fig. 3).

 δ^{13} C values obtained from the cores recovered from MAP holes 3A and 3B remain below -3‰ throughout the rest of the Marlboro Formation. The Marlboro Formation at MAP is capped by an unconformity overlain by the Lower Eocene Manasquan Formation. This unconformity is placed at MAP 3B and 47.8 acd and in a core break in MAP Hole 3A between cores 10 and 11 (50 and 48 ft acd).

Lithostratigraphy

As at other locations on the NJCP, the Paleocene/Eocene boundary is marked by a radical change in sedimentation pattern as the kaolinite rich Eocene Marlboro clays (Fig. 10a) sits above the Paleocene sands and silts of the Vincentown Formation (Fig. 10b) (Fig. 6) (Gibson et al., 2000; Kent et al., 2003). At MAP, the Vincentown Formation is similar in lithology to other updip NJCP cores; it is a dark green silty glauconite (to occasionally glauconitic) quartz sand, deposited in a marine environment; the similar abundances and covariance of quartz and glauconite sand has been interpreted as reworked glauconite in other reworked NJ cores (e.g. Sugarman, et al. 2005). The Vincentown Formation at MAP has slightly laminated texture, very different (thinner laminae, much more numerous) from the Marlboro laminations described below. The Vincentown laminations range in size from mm to multiple cm in length and are recorded here as slightly depressed fissures with a "frowning" upsection, parabolic geometry due to minor distortion in the coring process.

However, as seen previously at Wilson Lake (Miller et al., 2017), the MAP cores preserve a distinct transitional unit between the Vincentown sands and Marlboro clays, spanning the P/E boundary from 58.0 acd to 55.0 acd (17.7 - 16.8 m) in MAP Hole 3B

(Fig. 8). This unit is distinguished from the underlying Vincentown Formation and overlying Marlboro Formation based on lithology and cumulative coarse fraction %. The clay content within this unit varies and peaks as the coarse fraction decreases to ~55% (Fig. 8). These values are markedly different from the ~80% coarse fraction found in the Vincentown Formation, while remaining distinct from the very low values (<2.5%) that are characteristic of the overlying Marlboro Formation, I place the base of the Marlboro Formation at 55 acd in MAP Hole 3A and 3B, which is the inflection point for the rapid increase of % fine-fraction toward Marlboro values (2.5%). Both %CaCO₃ and δ^{13} C follow the lithological changes within this unit described as alternating clay-rich to sand-rich, with increased clay content being coincident with increases in %CaCO₃ and δ^{13} C. It is within this transitional unit that the onset of the CIE is placed: at 57.1 acd in MAP Hole 3A and 57.05 acd in MAP Hole 3B (Fig 8).

The Marlboro Formation in the MAP cores is a very fine-grained gray-green clay that was deposited in a marine, prodelta environment (see Discussion). This coloration is contrary to reports made by Self-Trail et al. (2017), who described the formation at Medford as part of the "red weathered belt" citing the ODP 174AX Medford corehole (Sugarman et al., 2010). The ODP Leg 150X Medford cores were obtained close to land's surface (6 - 10.5 ft) (1.8 - 3.2 m) and contained very little Marlboro Formation, being relatively shallow these cores were subject to surficial weathering as also noted at the nearby MAP Site 1. However, the downdip Marlboro Formation recovered at MAP Sites 3-5 show no evidence of such weathering and the colors are gray-green, not red.

There is some noticeable bioturbation near the bottom of the Marlboro Formation at MAP 3 that becomes extremely rare upsection. Two textures are described in the Marlboro in MAP Site 3: the laminated couplets described below are associated with extremely fine scaled (>1mm) "frowning" lens texture and a massive, shiny texture bereft of the previously mentioned lenses. The second is as slightly raised "chicken wire" structures. There is some relationship between the presence of large cracks or breaks in the core and the presence of this second massive texture.

The most distinct sedimentary structures found in the cores recovered during the MAP are the semi-regular, rhythmic, mm scale raised laminations most clearly visible at Hole 3A and 3B. 84 laminae occur in a 3.5 ft (1.07m) span in MAP Hole 3A Core #11 (Fig. 6a). Laminae are not evenly spaced throughout the core, there are regions of greater and lesser laminae frequency that are by nature inversely related to the thickness of the couplets (Fig. 11). The average distance between successive laminae is used to calculate couplet thickness. The mean couplet thickness at MAP Hole 3A Core #11 is ~1.28 cm, which is greater than the 1.0 cm mode value. The Marlboro couplets previously described at other locations on the NJCP, notably Wilson Lake B (Lombardi, 2014; Wright and Schaller, 2013; Fig. 12) were slightly thicker (1.8 cm).

As with other NJCP sites, the Marlboro Formation is truncated by an unconformity that separates it from the base of the Manasquan Formation in most sites; at Ancora and Millville the Marlboro Formation is overlain by a sandy silt similar in lithology to the Vincentown Formation (Sugarman, 2010: Makarova, 2017). The Marlboro Formation at MAP is relatively thin (6.2 ft, 1.89 m at MAP Hole 3B; ~3.5 ft, 1.07 m at MAP Hole 3A) compared to other NJCP sites (e.g., ~15 m at Wilson Lake). I attribute the relative thinness not only to erosional removal of much of the CIE section, but also nondeposition as seen on topsets elsewhere (see Discussion). Differential erosion is indicated even in the closely spaced Hole A and B records. Despite only being 8 ft (2.44 m) apart, MAP Hole 3B recovered a more expanded Marlboro section (2.7 ft (0.82 m) more than the S3A sister hole), highlighting the extremely irregular surface of the top of the Marlboro Formation.

MAP 3A-3B Correlation

My correlations (Fig. 3) show that MAP Holes 3A and 3B provide the thickest section of the lowermost part of the Marlboro Formation, and thus one of the most expanded view of the initiation of the CIE recorded in the marine realm. The two holes were drilled 8 ft (2.44 m) from one another with a 3 ft (0.91 m) offset to minimize core breaks. This offset was performed to maximize the possibility that missing sedimentary sections from a given hole are recovered from the adjacent sister hole. Missing sections are primarily due to coring gaps; however, as noted above, the discrepancy in thickness between sister holes may also be due to the irregular contact between the Marlboro and the overlying Manasquan. Despite only being ~8 ft (2.44 m) apart, MAP Hole 3B recovered 2.7 ft (0.82 m), or ~70%, more Marlboro Formation than the adjacent hole at MAP Hole 3A.

Depths of these two sister holes were correlated by adjusting the drilling depths to account for core expansion; this correlation provides adjusted core depth (acd) units and adequately aligns the major characteristics of the core: %CaCO₃, δ^{13} C, and coarse fraction % which was measured by Makarova (2017). Preliminary correlations between the A and B holes were made visually, as the color and sheen of the different formations and transitional units are apparent; the Vincentown Formation (Fig. 10b) is darker, and

coarser grained in comparison to the lighter, gray to tan Marlboro Formation (Fig 10a); the interspersing transitional layers alternate between being dominated by one of these two characteristics (Fig. 8). After a rough visual correlation was made, I fine-tuned my correlation by comparing lithostratigraphic data: the changes in coarse grain fraction the appearance and disappearance of primary depositional features such as raised laminae, alternating texture, and the appearance and disappearance of secondary sedimentary structures such as bioturbation and sulfidic mineralization.

These acd units are arbitrary outside the correlation of the associated holes. However, they allow for a common unit of measurement when comparing the two sister holes and adjust the drilling core depths when accounting for core expansion. Carbon isotopic data can be used to recognize the onset of the CIE at MAP and to justify our hole-to-hole correlation. The CIE initiation at MAP is defined by a precipitous 3.75‰ decrease in δ^{13} C and its coincident 2.7% drop in %CaCO₃ to near zero values (< 0.5%) at 57.1 acd in MAP Hole 3A Core #11. In Hole MAP Hole 3B, the 3.00‰ decrease in δ^{13} C and its coincident 2.6% decrease in %CaCO₃ occurs in Core 12 at 57.05 acd in the (Fig. 9). Using these bulk isotope records I divide the data collected from MAP into two sections: pre-CIE and CIE "onset".

XRD, Grain Size, and XRF

XRD clay sample analysis using the Phillips Xpert Diffractometer produces a series of diffraction peaks related to the planes of atoms in a sample. The position and intensity of these peaks, recorded as a diffractogram, are determined by the crystal structure of the sample. The samples from MAP Hole 3A Core #11 produce

diffractograms with notable peaks for quartz, kaolinite, illite, smectite, and muscovite (Fig. 13). By magnifying the 2θ range most important for clay minerals (7.5 to 30.5) and using the Jade7 data analysis program and semi-quantitative methodology outlined above, I compare the weighted percentages of the most common materials (Supplementary Material 1). I find that kaolinite typically is the dominant clay mineral representing a total weight percent between 30-40%, similar, if slightly lower than that recorded at Clayton (up to 50% kaolinite) by Gibson (2000) at Bass River (up to 40% kaolinite) by Cramer et al. (1999) and at Wilson Lake B (up to 44% kaolinite) by Lombardi (2014). I compare the weight percentages of kaolinite and the second most dominant clay mineral montmorillonite, a swelling smectite clay mineral. It must be noted that the weight percentage of montmorillonite does occasionally surpass that of kaolinite; however, these samples also experience a severe drop in muscovite % due to a background reading error in the Jade7 program (Supplemental Material 1). The kaolinitemontmorillonite data comparison is displayed against core photos showing the laminations (Fig. 14). These data may suggest a possible relationship between the deposition of subsequent laminae couplets and changes in mineral composition of the sediment source, with higher kaolinite (>35%) recorded in 4 of 6 clay laminations examined (Fig. 14). However, only 6 couplets have been analyzed, and these do not record consistent changes in mineralogy. Thus, further study is required before confident interpretations can be made.

The Malvern grain size experiments resulted in a mean recorded grain size of 7.34 μ m (Fig. 15), although in calculating this average grain size I discarded three data points which reported results of ~1 mm Dx(50). These three data points were derived from

samples which had 4 unique runs, the other three runs for each of these samples resulted in data similar to the overall average derived from the Malvern. They were discarded as they are statistical outliers from the triplicates. They are shown in Figure 15 at 51.25, 51.265, and 51.8 acd for comparison. The average grain size of 7.34 μ m is consistent with previous particle size measurements of the Marlboro Clay e.g., Lombardi (2014) reported a mode of 5.9 – 7.1 microns, preferring the mode over the mean grain size due to similar bimodal results using a Coulter LS 13 320 Laser Diffraction Particle Size Analyzer. I also note that many samples also displayed Dx (90) peaks of ~1 mm, which must be artificial, given the 63 μ m sieving.

I hypothesize that this ~1 mm peak is an artifact caused by the platy morphology of clay minerals. Because micas are irregular and non-spherical, they fall through the Malvern in an unpredictable, irregular fashion, being struck by a laser multiple times triggering "phantom" peaks in the grain size trend.

To test my hypothesis, I collected "clean" beach sand; that is sand lacking micas as ensured by visual inspection under a binocular microscope. I sieved this sand into through a 250 μ m sieve. I also collected mica from the Rutgers mineral collection and sieved the mica particles through a 128 μ m sieve. Returning to the Malvern, I ran the clean silt to sand fractions which generated a predictable histogram. After several runs of clean silt and sand, I spiked my samples with their equivalent size fraction of mica samples. The first run generated a predictable histogram; however subsequent runs began to display the "phantom" mica peaks of >1mm size (Fig. 16).

Subsequent grain size analysis employing the classical sieve and pipette method of eight samples taken from the same core (MAP Hole 3A Core #11) resulted in a mean

grain size below 2 μ m (Fig. 17). Weighted cumulative percentage graphs for these samples indicate a range between 51% and 68% of total sediments (by weight) having less than 2 μ m diameter (Fig. 17). These results are comparable to previous work contrasting pipette and laser diffraction methods for clay fraction materials (McCave et al., 1986, Loizeau et al., 1994).

Previous studies implementing laser diffraction techniques to determine the mean grain size of the Marlboro Formation have indicated variable mean diameters with modes ranging from ~5 to 7 μ m (Lombardi, 2014). However, the results from this study suggests that the sand sized fraction has previously gone over-represented due to the effects of the platy morphology of clay minerals on laser diffraction analysis. Such phenomenon has been previously reported when comparing pipette and laser diffraction methods for fine (<2 μ m) fraction particles (Konert and Vandenberghe, 1997; Beuselinck et al., 1998). Several other authors (McCave et al., 1986, Loizeau et al., 1994) argue that laser diffraction underestimates the amount of clay particles by 20-70% with respect to the clay content determined from pipette analysis.

Despite the various disadvantages to the pipette method, it may be the best method available when analyzing extremely fine sediments below silt size fraction. Disadvantages include that it requires large individual sample sizes, is time consuming, and is heavily dependent on laboratory technique and operator error (Syvitski et al., 2007). Konert and Vandenberghe (1997) suggested using a higher grain size threshold for the clay size fraction when laser diffraction analysis is applied, citing the platy form of clay minerals resulting a coarsening effect on the results (<2 µm in pipette method corresponds to an ~8 µm grain size as defined by laser diffraction). Particle size analyzers including the Malvern are best suited for measuring "sortable silt" (10-63 µm size range; McCave et al., 1986). Previous studies that have indicated that the Marlboro Formation is a fine silt were incorrect and it is proper to term the Marlboro as the "Marlboro Clay" as used in some previous studies (e.g., Darton, 1948, Kopp et all., 2009; Self-Trail et al., 2017), though I use the more general term 'Marlboro Formation' to be consistent with previous usage in New Jersey (e.g., Miller et al., 2017).

Data obtained via XRF analysis of Hole 3A C11 indicates a decrease in calcium (from 80 to 10 counts/seconds/mA) beginning at 57.0 – 56.0 acd, which is interpreted as representing the characteristic drop in CaCO₃ into the low carbonate zone (Fig. 9). This XRF data also indicates a spike in sulfur (1.5 to 12 counts/seconds/mA) and iron (from ~900 to 1350 counts/seconds/mA) at ~56.4 acd which is explained by the proximity of a ~2cm sulfidic nodule which can be seen in that portion of the core. Despite analyzing 23 major element abundances, the data collected via XRF does not appear to illuminate changes in the paleoenvironment of the NJCP during the PETM and is thus not incorporated in my interpretations or the model I invoke (see Discussion).

Discussion

In order to explain the various datasets and chronostratigraphic relationships among sites on the NJCP, I implement a subaqueous delta clinoform model associated with deposition of fluid muds on a continental shelf. I draw evidence for this model from our various observations of the sedimentologic, mineralogic, and geochemical characteristics of the Marlboro Formation at MAP and compare my data and interpretations with the observations recorded on modern muddy shelves, particularly the Amazon (AMASED studies including; (Kineke & Sternberg, 1995; Kineke, Sternberg et al., 1996; C. Nittrouer, Kuehl, et al., 1986; C. A. Nittrouer & DeMaster, 1996; Walsh et al., 2004) Kopp et al., (2009) similarly used an Amazon depositional model for the Mid-Atlantic Coastal Plain. In this discussion, I discuss thickness variations within the CIE along the paleoshelf (Fig. 3), the source of the muds, a fluid mud transport mechanism, ultimate depositional environment of the Marlboro Formation, and draw connections to modern day analogs.

Correlating MAP and Medford 174AX (Wright and Schaller)

Wright and Schaller (2013) presented δ^{13} C bulk data from Medford Leg 174AX cores where they place the CIE within the Vincentown Formation, as reported by Sugarman et al. (2010). The Vincentown Fm. in this core is a dark green, glauconite, quartz, silty, sand, deposited in a lower shoreface environment (Sugarman et al., 2010). I interpret the interval from 11.7 acd (3.6 m) to 10.5 acd (3.2 m) at Medford 174AX (Fig. 18) as equivalent to the Transition Zone at MAP, Site 3A Core 12, and Site 3B Cores 12 and 13 (Fig. 8). Unfortunately, the contact between the Transition Zone and the Marlboro Fm. at Medford Leg 174AX is not preserved due to a coring gap . I correlate the MAP Sites 3A and 3B to the Medford 174AX coreholes (Fig. 18) in an attempt to reconcile the CIE records at these sites. Medford 174AX records extremely low %CaCO₃ (< 0.3%) interpreted here as the result post depositional dissolution that also altered the bulk carbon isotopic signature. This post depositional effect is the likely explanation for the persistently lower δ^{13} C values at Medford 174AX compared to those preserved at MAP (JD. Wright, unpublished data, personal communication, 2018).

Lithological Support: this correlation aligns both the Medford 174 AX and MAP Sites 3A and 3B such that the CIE initiation is preserved within the Transition Zone: 1.5 - 2.0 feet (0.46 – 0.61 m) before the base of the Marlboro Fm at Medford, NJ.

MAP: CIE initiation 2.0' (0.61 m) below base of Marlboro

Medford 174AX: CIE initiation 1.55' (0.47 m) below core break.

Isotopic Support: This correlation also compares the shape and magnitude of the δ^{13} C trends at these geographically proximal locations.

MAP: CIE initiation at 57.0 acd with δ^{13} C of -1.8‰ decreasing to -5.3‰ at 55.4 acd.

Total change in δ^{13} C: -3.5‰

Total core length: 1.6'

Medford 174AX: CIE initiation at 11.5 acd, with δ^{13} C of -3.5‰ decreasing to -5.9‰ just prior to core break 10.5 acd.

Total change in δ^{13} C: 2.4‰.

Total core length: 1.0' (0.3 m)

At MAP the δ^{13} C values continue to sharply decrease until the contact between the transition zone and overlying Marlboro Fm. is reached. This contact is not preserved in the Medford 174AX corehole indicating truncation of the δ^{13} C record relative to MAP Sites 3A and 3B. This may explain the difference in magnitude of δ^{13} C excursion between Medford 174AX (2.4‰) MAP Site 3A (3.5‰) and Site 3B (3.0‰). A thin 1.2 ft (0.37 m) partly disturbed and visibly weathered Marlboro Fm. was recovered above the coring gap at Medford 174AX. The especially low δ^{13} C values at the top of this record (as low as 7.7‰ at 5.0' acd) in the Marlboro Fm. of the Medford 174AX core and outcrop are much lower than elsewhere on the NJCP, including at MAP. These low δ^{13} C values were obtained from samples collected near hemititic-red weathered surfaces characterized by extremely low %CaCO₃ values. Thus, I do not interpret these δ^{13} C values as representative of the depositional environment and suggest that they instead reflect alteration by diagenetic effects (e.g. the formation of siderite).

Thickness Variations along the Paleoshelf

The shape of the CIE has commonly been used to correlate the PETM among deep sea, shallow marine, and terrestrial sites (Bains, et al., 2003; Röhl et al., 2007). The CIE has been separated in the pre-CIE, and CIE (onset, "core", and recovery) (Fig. 1; summarized by Makarova et al. (2017). Here, I use the shape of the CIE to correlate among several sites along a transect on the NJCP (Fig. 3).

The CIE onset occurs as a sharp decrease at MAP Hole 3A (3.5‰ at 57.10 acd), MAP Hole 3B (3.0‰ at 57.05 acd) (Fig. 8), Wilson Lake B (WLB) (3.2‰ at 111.47 m) (Fig. 3), Millville (MV) (2.4‰ at 273.76 m) (Fig. 3), and Bass River (BR) (3.6‰ at 357.29 m) (Fig. 3). As with other sites, the onset of the CIE on the NJCP is coeval with the initiation of the low carbonate zone.

Unlike many sites, the Marlboro Formation at MAP does not record a second decrease in δ^{13} C values after the initial rapid decrease at the initiation of the CIE onset. The second decrease in δ^{13} C values ends in an interval of blocky, relatively stable, low δ^{13} C values at WLB, MV, and BR (Fig. 3). Previous studies (e.g., Stassen (2012),
Makarova (2017)) have equated this interval of low δ^{13} C values with the "core", though this assumption needs testing. This second decrease in δ^{13} C values is recorded at: WLB (2.1‰ at 110.19 m, culminating in a δ^{13} C minimum of -6‰ at 107.99 m), MV (1.7‰ at 272.76 m, culminating in a δ^{13} C minimum of -4.5‰ at 271.85 m), and BR (1.2‰ at 357.13 m, culminating in a δ^{13} C minimum of -3.1‰ at 356.92 m) (Fig. 3). Lacking a second δ^{13} C decrease at MAP the δ^{13} C minimum value at Hole 3A is -5.3‰ and at MAP Hole 3B it is -4.5‰. Thus, the total decrease in δ^{13} C values from the initiation of onset to the δ^{13} C minimum for the sites listed are:



This indicates that at MAP the second δ^{13} C decrease is of the CIE initiation is truncated, even though the initial decrease is expanded (Fig. 19) "onset" (precipitous decrease in δ^{13} C), and either truncated or completely bypassed "core" (sustained section of low δ^{13} C values), and "recovery" (section in which δ^{13} C values return to pre-CIE values). In this study I define truncation as an incomplete record due to post depositional erosion, and bypass as incomplete record of the CIE due to nondeposition. The "recovery" sections recorded at other sites on the NJCP is defined as the portion of the CIE that records δ^{13} C values returning towards pre-CIE values. This is recorded at Bass River (352.96 m), and partially at Millville (265.65 m) (Makarova et al, 2017). While the δ^{13} C_{bulk} record at Wilson Lake B also begins returning towards pre-CIE values near 101.03 m the benthic foraminifera assemblage at Wilson Lake A suggests no recovery (Stassen et al., 2012), though Makarova et al. (2017) suggested the recovery was partly represented at Wilson Lake B. Given the irregularity of the thickness of the Marlboro Formation a direct correlation between Wilson Lake A and Wilson Lake B may not be exact. Even so, I hesitate to confidently interpret this section as correlative with the "recovery" sections at Millville and Bass River.

Thus, I interpret that both the CIE "core" and recovery as absent at MAP, even if it is present at downdip WLB, MV, and BR sites as interpreted by previous studies (Fig. 3) (i.e. Stassen (2012), Makarova (2017). However, the early CIE onset is preserved and is expanded (Fig. 3, 9). I suggest that this expanded MAP record provides one of the marine realm's most expanded views of the initiation of the onset of the CIE (Fig. 3, Fig. 9).

Correlating the sites across the NJCP, using the bulk isotope records and the shape of the CIE recorded in the Marlboro Formation, a distinct pattern becomes apparent: the furthest updip site at MAP records an expanded CIE-onset with bypassed "core" and recovery sections (Fig. 3). Downdip at the mid-basin site, Wilson Lake B, the isotope record preserves a less expanded onset (Fig. 19) and truncated CIE "core" with partially bypassed recovery section. It is only at the furthest downdip sites of Millville and Bass River that the full CIE, including the recovery sections, are possibly recorded, at least as interpreted by Stassen (2012) and Makarova (2017). Although at Millville the possible recovery is diced by at least one unconformity (Makarova et al., 2017). However, the preservation of the recovery section especially at Bass River is accompanied by a very condensed record of the onset (see also Stassen et al., 2012).

This is made clear when overlapping the MAP 3A-B δ^{13} C record on top of the record Wilson Lake B which is downdip by 9 km (Fig. 19). The Marlboro at MAP does not record the full CIE shift of the onset, nor does it record the core or recovery portion of the CIE. However, the MAP Hole 3B does record an expanded CIE onset of 1.8 m compared to an equivalent 1.2 m at Wilson Lake B. This suggests that Early Eocene sedimentation rates were ~50% higher at MAP than at Wilson Lake B.

Additionally, a large (>2‰), sharp, CIE onset is clear at all four sites in this correlation: MAP, Wilson Lake B (see Miller et al., 2017), Millville, and Bass River. However, the three landward sites (MAP, Wilson Lake B, and Millville) show a section where δ^{13} C values decrease by over 1‰ below the CIE (Fig. 3). At MAP Hole 3A, pre-CIE δ^{13} C values at 60.77 acd are -0.65‰; these values decrease to -2.80‰ at 59.20 acd near the top of the Vincentown Formation before increasing in δ^{13} C values to -1.58‰ at 57.40 acd in the transitional unit, just below the CIE initiation at 57.1 acd.

A similar record is reported at Wilson Lake B where δ^{13} C values begin to decrease in the transitional lithology tentatively assigned to the Vincentown Formation between 368.0 – 369.0 ft (112.17 – 112.47 m) with a total change of ~2‰ by 365.7 ft (111.47 m; see discussion in Miller et al., 2017). A similar record occurred at Millville, NJ, where another pre-CIE δ^{13} C decrease occurred (Fig. 3; Wright and Schaller, 2013). Most deep-sea records lack a large pre-CIE δ^{13} C, decrease including the thickest open ocean Site 690 on the Maud Rise (Bains et al., 1999). Preservation of this pre-CIE decrease may be attributed to the higher resolution record in NJ, for the CIE sections at Wilson Lake and Millville are ~15 m thick (Fig. 3) versus < 4 m at Site 690, and to the preservation of the transition zone (0.61 m at MAP, 0.53 m at WLB, and indeterminate thickness at MV).

This pre-CIE δ^{13} C distinct decrease below the CIE onset has been referred to as the precursor (Miller et al., 2017) and Pre-Onset Excursion (POE) (Bowen et al., 2015). While it is not immediately certain that this pre-CIE δ^{13} C fluctuation is global or even regional, there does appear to be a distinct pattern in which the thickness of the section between the "precursor" and CIE increases with proximity to land (Fig. 3).

These pre-CIE δ^{13} C values recorded at Medford (below the CIE initiation: -2‰ in the "precursor/POE", -1‰ below that) are much lower than at Wilson Lake B (1‰), Millville (2‰), and Bass River (2‰). I speculate that this along shelf variation results from changes in the contributions to bulk carbonate as changes occur to the % plankton, nannofossil species assemblage, and other carbonate phases, which vary as a result of water depth and/or proximity to shore. Riverine input also affects the δ^{13} C of DIC. This has been observed in the modern study region from the Potomac river (-11‰) to the surface waters of the Atlantic (~1‰) off the edge of the continental shelf (Sackett and Moore, 1966). Thus, variations in the quantity of riverine input, movement of the bottom salinity front, and distance from shore and source of carbonate (nannofossil content, riverine input) might also be responsible for variability in the δ^{13} C record of the NJCP sites. Regardless, the shape of the changes in the CIE across these sites remains robust and can be used to correlate among them (Fig. 3).

Origin: Cretaceous Muds

Early mineralogic studies of the Marlboro Formation report an abundance of kaolinite that is characteristic of the unit. These data were previously interpreted as evidence for increased precipitation and chemical weathering along the coastal region near the Salisbury Embayment during the PETM (Gibson et al., 1993). However, kaolinitic clays in nearshore and deep-sea deposits are far too abundant and appear to have been deposited far too rapidly to have been formed via chemical weathering near the time of deposition (e.g., John et al., 2012). Thus, I accept the hypothesis that these minerals formed prior to their deposition in the Marlboro Formation during the PETM (John et al., 2012). Several sections of the Potomac Formation and Group, proximal to the Salisbury Embayment, experienced large-scale deposition of kaolinite during the mid-Cretaceous (Force and Moncure, 1978; Spoljaric, 1988). As such, either the Potomac or Raritan Formations stand as the likeliest source of kaolinite for the Marlboro Formation (Kopp et al., 2009). However, kaolinite is also found in abundance throughout Piedmont soils from Florida to Pennsylvania (Johnson, 1970) and the northern extent of these regions should be included from the list of possible sediment source regions for the Marlboro Formation.

These clay minerals, sourced from reworked Cretaceous sediments, make up the bulk of the Marlboro Formation clay mineralogy. The hypothesized high temperatures and increased precipitation characteristic of the PETM (summarized in Kopp et al., 2009), would have enhanced rates of physical erosion of these Cretaceous clay sources and expedited riverine transport of such sediments to the Salisbury Embayment. Thus, I propose that the Marlboro Formation was fed its constituent sediments by mud laden tropical-subtropical river systems, most likely via the paleo-Susquehanna, paleo-Potomac, and paleo-Delaware (Kopp et al., 2009).

The rapid increase in sediment supply to the nearshore environment of the Salisbury Embayment resulted in the thick accumulation of muds (Fig. 20). These muds, amassing seasonally offshore of their paleo riverine sources, could have been transported as fluid mud, and acted as an episodic transport mechanism for a great quantity of sediments to the paleoshelf. As the paleodepth of the embayment increased, due to a sealevel increase (Harris et al., 2010; Sluijs et al., 2008), rapid sediment influx and deposition began, rapidly building seaward dipping clinoform delta structures.

Transport Mechanism: Fluid Muds

Fluid muds are near-bed, high-concentration suspensions of sediment that play an integral role in sediment deposition along fine-sediment laden continental shelves today. Defined as having suspended sediment concentrations (SSC) >10g/l (Kineke and Sternberg., 1995) these distinct bodies of suspended sediment behave in a non-Newtonian fashion, forming when the settling velocity of clay particles begin to be impeded by inter particle interactions (Mehta, 2002), which becomes increasingly more important at higher SSC of fine-grained sediments (Dyer, 1989; Dade and Nowell, 1991). This characteristic non-Newtonian motion may serve as the basis for a more accurate definition of fluid muds rather than a somewhat arbitrary SSC. Fluid muds accumulate as the rate of particle settling is reduced in localized volumes of water. This phenomenon is triggered by the flow of the upward escaping water and the "onset of a suspended particle supported framework" (Faas, 1991). While particle resuspension and erosion of the seabed likely

play some role in fluid mud formation studies have shown these dense packages of suspended sediments to primarily be a result of density-driven estuarine circulation, flocculation, and salt induced stratification (Kineke and Sternberg, 1995).

Today, fluid muds are typically found in riverine influenced shelf and estuarine environments characterized by high SSC's. They accumulate during slack currents in areas where the rates of sediment deposition are typically too fast to allow the sediments to agglomerate and form mud beds (Allen et al., 1980). These fluid muds can exist in a mobile phase or remain stationary above the stable seabed. Regardless, they are considered distinct from the seabed due to their "relative lack of mechanical strength" (Kineke and Sternberg et al., 1995). These muds modify transport flow and have been observed transferring sediments far from their source as they bypass over shallow zones. This culminates in the deposition of great volumes of continental-derived sediment in shelf environment in deeper waters of the paleo-prodelta near the clinoform break (Fig. 21).

Modern studies indicate that the presence of a bottom salinity front is a requisite for fluid mud formation (Kineke and Sternberg, 1995). When broad regions are dominated by fluid muds, bottom friction can decrease by as much as 50%; this allows tidal energy to propagate across-shelf over further distances, much more efficiently (Beardsley et al., 1995). If fluid muds could be formed by resuspension alone, we would expect to see them being built on muddy continental shelves during both ebb and flow; however, they are only observed to be formed during flooding periods in nearshore environments at the salinity front (Kineke and Sternberg, 1995). Temperature and salinity anomalies recorded within fluid muds provide additional support for nearshore production and subsequent transport of fluid muds to the shelf, rather than *insitu* formation on the shelf itself. Temperature and salinity values are often much lower than those recorded in the overlying water masses (Kineke and Sternberg, 1995). If these muds were formed locally, then they would be expected to have the same temperature and salinity as the overlying waters. Observations of this anomaly persevering across shelf also suggests that fluid muds do not readily mix with overlying water, and serve as a buffer, inhibiting mixing between the seabed and the overlying water mass (Kineke and Sternberg, 1995).

While ambient currents and waves are certainly vital for sediment movement seaward on gently sloping continental shelves (Wright et al., 2001), the formation of fluid muds make transport of such sediments across shelves spanning 100's of kilometers possible. Upon reaching sufficiently deep waters, fine-grained fluvial sediments, turned fluid muds, rapidly fall out of suspension, building subaqueous delta mud clinoforms that downlap onto a basal unit (Fig. 21: Walsh, Nittrouer et al., 2004).

While such a fluid mud transport system cannot be indisputably demonstrated for the Marlboro Formation paleoshelf, a fluid mud transport mechanism explains several sedimentary characteristics of the Marlboro Formation on the NJCP, including: the dominance of very fine particles (>2 μ m), clay mineralogy, preservation of an upright lignite fragment at Wilson Lake (Wright and Schaller, 2013; Miller et al., 2017), the lack of bioturbation, and the rhythmic laminae couplets. Modern fluid mud driven environments have been observed to experience episodic gravity flows, in which rapid (on the scale of minutes to hours) sedimentation events could preserve laminations in the sedimentary record (with 0.5 to 3 year frequency on the modern Amazon shelf), which is the favored mechanism for the Marlboro laminations in this model.

The "laminae couplets", discussed above, that were recovered during the MAP have been previously reported on at other sites on the NJCP, notably by C. Lombardi (2014) at Wilson Lake B and Wright and Schaller (2013) at Millville. These previous descriptions were largely dismissed as drilling artifacts produced by drilling mud, termed "drilling biscuits" or "discs" (Pearson and Thomas, 2015) (Fig. 22). However, because the MAP used a USGS operated auger, sans drilling fluid, as the means of core retrieval, I assert that these laminations found in the Marlboro Formation at MAP are, in fact, primary sedimentary structures. Preservation of physical laminations in fine-grained marine sedimentary deposits is generally the result of two distinct environmental conditions that work to inhibit colonization by benthic organisms: suboxic bottom water conditions or extremely rapid sediment influx. Benthic foraminifera along the NJCP PETM transect document low, but not anoxic, conditions (Harris et al., 2010; Stassen et al., 2015). Thus, I propose the later of these two possible scenarios; that these laminations are preserved by high sediment accumulation rates, accentuated by episodic fluid mud driven gravity flows.

Shallow-marine sediment distribution is highly variable during the PETM, the following mechanisms should be considered as possibly playing a role in the environmental forcing responsible for providing sedimentation rates high enough to preserve these laminations:

- Increased tropical cyclone activity caused by warmer atmospheric and sea surface temperatures during PETM (Korty et al., 2008; Sluijs 2006).
- 2. Cold front wave resuspension events (Allison et al., 2000).
- 3. Monsoonal precipitation patterns (Zachos et al., 2006).
- Frontal mixing variability with seasonal changes in fluvial discharge (This study)

Differentiating the laminae material from the bulk sediments in the Marlboro Formation has been a primary focus of this study. However, results from grain size, mineralogic, and elemental composition analysis comparisons indicate that the two materials appear to be nearly identical, although XRD analyses suggest a slight increase in kaolinite in the laminations relative to the bulk samples (from 25-30% to >35%). I suggest that the uniformity in very fine sediment size implies that the sediments of both the bulk and the laminae are largely derived from the same fluid mud reservoir and that laminae represent episodic rapid gravity flow driven deposition events, possibly associated with boundary shear stresses generated by waves and currents (e.g., Sternberg, et al., 1995), and large flooding events. Occasional slight changes in clay mineralogy between laminae may represent slight changes to composition of the fluid mud reservoir between gravity flow events.

The position of such a fluid mud reservoir would vary seasonally and be controlled by migration of the bottom salinity front. In periods of relatively heavy freshwater discharge, the bottom salinity front would be forced seaward. When the fluid mud reservoir reaches the rollover point (Figs. 21, 23), it has the potential to trigger a gravity flow, dumping great deals of sediment seaward of the rollover point in a short period of time (hours); these events are the interpreted mechanism responsible for the laminations noted here at MAP and elsewhere on the NJCP.

Quantifying any compositional differences between the laminae and bulk material of the Marlboro Formation was a major focus of this study. However, several major sources of uncertainty were involved with the experiments conducted with that aim. The complications with grain size analysis of the clay to fine silt grain size of the Marlboro clay via the Malvern are outlined above, and data obtained in this laminae-to-bulk grain size comparison are provided in the supplemental material (S2). Compounding this, any grain size analysis comparing bulk to laminae sediment size distributions via the pipette method is prohibited due to the minimum required mass of sediment when using that method (\sim 30g/sample). Visual inspection of the laminae indicates that these structures must contain a higher percentage of swelling clays compared to the bulk of the core. XRD analysis however, does not produce a consistent measurable difference between the two (Fig. 14). One caveat to this dataset, as outlined by Moore and Reynolds (1989) suggests that small differences in swelling clay percentages on the order of $\sim 2\%$ may be unrecognizable due to the small physical size and broad diffraction peaks of these of these minerals.

If the laminae couplets recovered in the MAP are the product of fluid mud driven gravity flows, then they provide evidence supporting rapid deposition and a short timescale for the CIE (Wright and Schaller, 2013). However, it is difficult to quantify the average rate of sedimentation using these laminae couplets; their deposition, while rhythmic, is irregular, implying an irregular rate and/or volume of fluid mud "dumps". Any attempts of using lamination count as a chronostratigraphic tool is further complicated by the irregular thickness of the Marlboro Formation, even between cores recovered at MAP, which implies non-steady rates of deposition and/or preservation between sites, and thus through time. Finally, while there is only one major unconformity capping the Marlboro Formation at MAP, other undetected hiatuses may have occurred at short or long intervals, as expected in an autocyclical process such as clinoform progradation, regardless of whatever time scale is used for sedimentation rate at Medford.

Deposition: Clinoform Model

Kopp et al. (2009) compare the depositional setting of the Marlboro Formation to a tropical-subtropical river dominated shelf, primarily based on the preservation of magnetofossils and the geographic of extent fine-grained sediments (for an alternative interpretation, see Wong et al., 2013). During the PETM, the shallow ~400 km wide Salisbury Embayment area experienced increased temperatures and precipitation (Kopp et al., 2009) that was accompanied by high rates of sediment discharge composed primarily of clay sized particles. Such environmental conditions would have been conducive for the formation of large-scale sedimentary structures referred to as clinoforms. Clinoforms are the "dominant building blocks of continental-margin stratigraphic sequences" (Coe, 2003); these morphological features are characterized as having a sigmoidal shape, with inclined deposits that are associated with their successive progradational depositional pattern (Christie-Blick and Driscoll, 1995). As seen in modern muddy continental shelf environments around the world, deltas build seaward into a basin as proximal accommodation space is filled and sediments suspended in fluid muds are deposited in the shape of a subaqueous clinoform. These structures have been observed offshore of several major river mouths today; including the Amazon, Ganges-Brahmaputra, Fly, and Huanghe (Walsh, Nittrouer et al., 2004). Clinoform structures are characterized by their inclined surfaces with low dip angles at the top and base that "terminate upon running tangential with the horizontal" (Coe, 2003). Clinoform structures have a large range in scale from bedform features on the order of centimeters in size to continental margin accumulations which can grow to become several hundred meters thick and several hundreds of kilometers wide (Pirmez et al., 1998).

Clinoforms are composed of three distinct units: the topset, foreset, and bottomset beds (Fig. 21). The upper portion of the clinoform is comprised of the topset beds which are thin and often reworked by tides, frontal zone currents, and waves (Nittrouer and Demaster 1996); these topset beds gradually thicken as they gently slope seaward toward the rollover point which marks the topset-foreset transition point. The foreset beds, which mark the prodelta facies, are marked by the highest sediment accumulation rates in the clinoform and have very steep dips compared to the thin bottomset beds (Walsh, Nittrouer et al., 2004).

Events of rapid sediment influx appear to be instrumental to the formation of the relatively thick foreset beds. The high rates of sediment accumulation in this region commonly preserve physically laminated sediments which can be composed of faintly laminated muds or mud interlaminated by thin layers of sand or silt (Nittrouer, Kuehl et al., 1986). The deep and distal bottomset region culminates in the termination of the clinoform structure, and experiences greatly reduced rates of sediment supply which

limits accumulation and allows for bioturbation to take place (Walsh, Nittrouer et al., 2004).

In addition to the Amazon, two additional major river systems which build subaqueous clinoform are the Ganges-Brahmaputra and Huange He. Across all three of these study sites the foreset section bears the highest inclination, which is typically \sim 1:200 (i.e. <1°) (Kuehl et al., 1989; Alexander et al., 1991).

The preservation of muddy clinoform structures is controlled by relative sea-level fluctuations. The shallow topset and upper foreset portion of a clinoform is especially susceptible to erosion via shear stress, induced by wave or tidal action; or in extreme cases, by subaerial exposure (Nittrouer et al., 1996). This leads to preferential preservation of the lowermost portion of the stratigraphic section, the thin bottomset and lowermost foreset. Margins with increased rates of subsidence, and thus greater accommodation space, are expected to experience greater preservation of the topset and upper foreset sections of the clinoform. Deeper sites would also experience greater preservation of these sections.

This pattern of preservation potential across a sub aqueous clinoform (Fig. 23) explains the variability of the CIE-records observed along the NJCP in a downdip direction, discussed above (Fig. 3). It also explains the irregular top of the Marlboro Formation across the NJCP, which was deposited during a time of regionally rising sea levels, and experienced subsequent erosion as the relative sea-level lowered. Thus, it seems likely that it was shear stress driven erosional forces, associated with wave energy, that are the most likely explanation for the irregular top of the Marlboro Formation; the rapid sedimentation grossly exceeded the accommodation space available and when the top of the Marlboro Formation reached wave base, erosional forces began sweeping sediments away. This style of clinoform deposition is consistent with the sedimentary characteristics observed in NJCP cores and with the environmental records of the region during the PETM, which is based off of the benthic biofacies and the distribution of magnetofossils (Stassen et al., 2015).

Modern Analog: the "Appalachian Amazon"

Fluid mud processes are considered an integral component for subaqueous clinoform delta formation in the modern Amazon (Kineke et al., 1996). These mobile fluid muds are also pivotal for the preservation of sedimentary depositional features along the Amazon shelf, such as thin laminations, as the shear stresses produced by tidal currents in the topset and foreset regions would otherwise be sufficient to exceed the critical stress for erosion on such strata (Kineke and Sternberg, 1995).

The sedimentary features outlined for the MAP (this study), the clay mineralogy analyzed at Wilson Lake B (Lombardi et al., 2014) and the environmental indicators based off of biofacies assemblages (Stassen et al., 2015) and a possible decrease in sea surface salinity (Zachos et al., 2006) further support the hypothesis that conditions on the NJCP during the PETM were similar to those on the modern Amazon shelf region. This would suggest that the two environments could have possessed similar depositional environments and sedimentation rates, although Kopp et al., (2009) suggests that a volume scaling comparison indicates that the Salisbury Embayment during the PETM would require only one quarter of the riverine input that the modern Amazon receives in order to maintain similar environmental conditions.

Support from sedimentological observations made in this study includes: 1) the great quantities of kaolinite observed in the Marlboro Formation (up to >40% by weight), which is associated with extremely high rates of detrital and freshwater input (Gibson et al., 2000); 2) the extremely fine grain size (>2 μ m) that travelled far from the hypothesized paleo-Potomac, paleo-Susquehana, and/or paleo-Delaware river sources (Kopp et al., 2009); 3) the lack of bioturbation; and 4) the preservation of thin laminae. Shallow cores collected northwest of the river mouth during the AMASEDS project, are described as primarily homogenous muds possessing laminations described as thin $(\sim 1 \text{ mm})$, silts found at 1-20 cm intervals (Kuehl et al., 1986b). The laminations in the modern Amazon are thicker than those observed at MAP (Fig. 11) (Jaeger et al, 1995), and the areas in which laminations occur have greater percentages of smectite minerals (>40%) and lower percentage of kaolinite (as low as 16%) (Patchineelam and Figueiredo, 2000), than recorded at MAP (Fig. 14). This lack of kaolinite is attributed to the Cabo Norte Shoal which effectively traps the kaolinite near the river mouth. It is possible that the Salisbury Embayment topography facilitated the transport of kaolinite further into the basin, there is also evidence of a sharp peak in charcoal at Medford, WLB, and MV which has been ascribed to wildfires in the region (Fung et al., 2016). Effects of large wildfires on erosion and runoff may have also affected the transport of clay minerals across the continental shelf.

Fluid mud processes are considered an integral component for subaqueous clinoform delta formation in the modern Amazon (Kineke et al., 1996). These mobile fluid muds are also pivotal for the preservation of sedimentary depositional features along the Amazon shelf, such as thin laminations, as the shear stresses produced by tidal currents in the topset and foreset regions would otherwise be sufficient to exceed the critical stress for erosion on such strata (Kineke and Sternberg, 1995). Tidal forces themselves are unlikely to be the primary mechanism of couplet deposition due to different temporal scales. Transport of fluid muds in the Amazon occurs on timescales longer than tidal, ranging from 0.5 - 3.0 years (Ducat and Kuehl, 1995; Kuehl et al., 1996).

The warm PETM climate instigated enhanced rates of weathering in the Salisbury Embayment region leading to great quantities of sediment being transported to the shallow marine environments via tropical to sub-tropical river systems, most likely the paleo-Susquehanna, paleo-Potomac, and/or paleo-Delaware. At the river mouth, riverborne sediments would have met the salinity front, sands would drop out (Jaeger et al., 1995), and the salts in the estuarine waters would have neutralized the clays' negative charge, thus causing the previously free-flowing clay minerals to begin flocculating together and allowing for the formation of fluid muds. These fluid muds were then transported cross-shelf by tidal forces enhanced by the reduction of bottom friction, where they were ultimately deposited on the continental shelf, a sediment-starved region of transgressive Upper Paleocene sediments (Fig. 10b). Using the modern Amazon as an analog for PETM subaqueous delta clinoforms, this facies model occupies space between two end member water depths:

- Nearshore (<15 30 m water depth), shallower than this and the topset would be eroded away by high shear stresses;
- Outer shelf (~80 m water depth), deeper than this and the bottomset is terminated due to low sediment supply.

Sediment accumulation is dependent on both the rate of sediment supply and the combined rate of all sediment removal mechanisms; and is thus not directly correlated to suspended sediment concentrations (SSC). This is why depositional rates are expected to be much higher in a subaqueous clinoform delta, especially in the outer topset/foreset sections (Fig. 21), than in the nearshore environment fed by the same sediment source. Despite the nearshore environment's proximity to the sediment source, this region experiences the greatest rate of resuspension via tidal and wave energy, which works to curtail sediment accumulation. I apply the modern Amazon as a model for subaqueous clinoform delta deposition where sediment accumulation rates range from <0.1 cm/yr to >10 cm/yr with accompanying SSC's between >500 mg/l and 10 mg/l, these trends are responsible for the characteristic progradation of subaqueous delta clinoforms towards shelf-break and the increase in sedimentation rate upsection within these structures (Kuehl et al., 1985).

The highest accumulation rates occurring at ~60 m water depths in the modern Amazon, roughly equivalent to the paleodepth estimates at MAP during the PETM. Fluid mud driven sediment deposition is recognized as occurring in separate discrete events (Cacchione et al., 1995; Kuehl et al., 1996) with a semi regular reoccurrence of every 0.5 to 3 years in the modern Amazon (Ducat and Kuehl, 1995; Kuehl et al., 1996). These events seem to be driven by seasonal variability in both fresh water and sediment supply and their effect on the location of the bottom salinity front (Kineke, Sternberg, 1995). As discussed above, I propose a similar mechanism for the laminations found in the Marlboro Formation along the NJCP, high background sedimentation rates punctuated by gravity flows occurring when a fluid mud reservoir passes over the threshold of the clinoform rollover point. These events result in rapid progradation of the foreset region seaward, the preservation of the observed laminations, and prevent colonization of benthic communities.

In addition to variability in seasonal riverine discharge as well as wave and tidal forces, the deposition of fluid muds on the modern Amazon is also affected by the migration of mud banks. These mud banks, which may number up to 15 or more at a time, are estimated to contain the equivalent mass of the annual mud supply of the Amazon river system. Their formation produces a system of ephemeral depositional 'bank' and erosional 'inter-bank' phases. The bank phase zones are protected from wave energy which plays a role in the dynamic depositional environment along the NW South American coast.

Thus, long term sedimentation patterns in the Salisbury Embayment during this time period would have been controlled by complex interactions between sedimentary, hydrologic, and hydraulic processes operating at many different timescales, further muddying attempts of using the Marlboro laminae couplets as quantitative chronostratigraphic tools.

Reconciling CIE Distributions with a Clinoform Model

The fluid mud driven clinoform model outlined above explains the differential preservation of the Vincentown Formation, transitional units, Marlboro Formation, and the CIE onset, and subsequent low, along the NJCP. Initial rapid lobe building events, triggered by the environmental conditions of the PETM (summarized by Kopp et al., 2009), record the onset of the PETM and is thus expanded at locations closer to land (i.e, MAP, Wilson Lake B), due to the geometry of the prograding clinoform (Fig. 23). Subsequent lobes record the "core" and later the recovery of the CIE which are preserved at distal sites (i.e, Millville and Bass River). The sigmoidal, seaward dipping shape of the clinoform lobes explain the condensed onset at distal sites as well as truncation of the onset at MAP due to the unconformity capping the Marlboro Formation (Fig. 23). Resuspension of sediments due to reworking of the topset explains the bypassed "core" and recovery at MAP, as well as the possibility of either a bypassed or dissected recovery section at the nearby Wilson Lake B site (Figs. 3, 23). Thus, either Wilson Lake B never recorded (bypassed) the recovery, if sediment accommodation was filled fast enough for that section of the CIE to be deposited within wave base depths; alternatively, it may have been deposited, but subsequently eroded away by an unconformity (truncated) analogous to the onset at MAP. The nature of nondeposition makes differentiating between these two scenarios difficult, if not impossible. This study correlates PETM sites on the NJCP based on the stable isotopic signatures recorded in and just below the Marlboro Formation, and suggests a fluid mud driven clinoform depositional environment similar to the modern Amazon, citing the differential preservation of the CIE, and the sedimentology of the Marlboro Formation as supporting evidence. Thus far, this clinoform model only depicts the paleoenvironment in two dimensions along the downdip transect (Fig. 2). However, a three-dimensional study could be conducted by drilling adjacent holes along strikeline at the various sites included in this study. Such a project would test my depositional model and extend our understanding of the paleoenvironment of the NJCP during the PETM.

Speculations/Thoughts on Sedimentation Rates

If I apply the same rhythmicity of the laminae couplets on the Amazon shelf (0.5-3 yrs) to those recorded at MAP (84 couplets) and assume constant sedimentation, I calculate deposition of the laminated section of the Marlboro Formation at MAP Hole 3A as taking place over a possible 42 – 252 year timeframe (2.55 cm/yr – 0.42 cm/yr). However, our unknown variables: possible periods of nondeposition, paleo-riverine input, flood frequency, fluid mud reservoir volume, mudbank geography, etc. would greatly affect any quantitative chronostratigraphic constraint. Thus, I stress that any proposed CIE-onset timeframe based on laminae couplet count should only be used to establish relative sedimentation rates between sites along the NJCP (Fig. 23) and to suggest that there is some sedimentologic indication that the initiation of the onset may have been faster than previously proposed by Zeebe et al., (2016). Likewise, using the Amazon model to explain the presence of these laminae couplets would indicate a rate of onset slower than the near instantaneous rates established by Wright and Schaller (2013).

Conclusions

Differential preservation of the CIE along a downdip transect on the NJCP, alongside the sedimentary characteristics of the Marlboro Formation at MAP support a fluid mud driven clinoform depositional model for the NJCP during the PETM (Fig. 23). This model is analogous to the modern Amazon shelf environment.

Using this model to correlate between sites on the NJCP allows for several observations: 1) The CIE record preserves an expanded early onset at MAP and a progressively more condensed onset moving downdip. The later portion of the onset is

truncated at MAP while the "core" and the recovery are completely bypassed (Figs. 3, 19) Moving downdip, sites preserve a progressively more condensed record of the onset and "core", and also preserve the recovery; 3) comparing the records at MAP and Wilson Lake suggests Eocene sedimentation rates were 50% higher at MAP (Fig. 19).

The "Appalachian Amazon" was the result of a much warmer world during the PETM. The greater temperatures strengthened the hydrological cycle which intensified physical weathering on terrestrial sediments (Kopp et al., 2009). This physical erosion attacked the thick Cretaceous-age laterites in the nearby Potomac Formation, which is interpreted to be the source of the great quantities of kaolinite which are characteristic of the Marlboro Formation (Gibson, et al., 2000). Upon reaching the saline shallow marine Salisbury Embayment the clay minerals formed fluid muds. Modern fluid muds are reported to reduce bottom friction by upwards of ~50% (Beardsley et al., 1995), allowing tidal and wave energy to propagate the fine-grained sediments far across the broad embayment. Bypassing shallow zones these sediments would have experienced swift deposition upon reaching sufficient depth, building quickly prograding foresets in a prodelta environment (Fig. 21). This structure, a sub aqueous clinoform characterized by a thin re-worked topset, thick, rapidly deposited foresets, and a distal, progressively thinning bottomset (Figs. 21, 23), has several modern analogs.

On modern muddy continental shelves analogous to the paleoenvironment of the "Appalachian Amazon" (Kopp et al, 2009) it has been emphasized that rapid sedimentation events, gravity driven flows of muddy sediments crossing the clinoform rollover point, occur semi-regularly. Such 'dumps' have been directly observed in the Amazon (Cacchione et al., 1995; Kuehl et al., 1996), and may also be responsible for the preservation of muddy laminations that have been described in the Marlboro Formation on the NJCP.

Laminations observed in the Amazon, have been reported to reflect 0.5 - 3 year rhythmic cycles (Ducat and Kuehl, 1995; Kuehl et al., 1996). While the laminae couplets at MAP differ in grain size and clay mineralogy, they may be the result of similar processes. However, while the MAP laminae couplets appear rhythmic they are also irregular (Fig. 7a). The inconsistent frequency of laminae occurrence and highly irregular overall thickness of the Marlboro Formation, (~ 70% difference in thickness between offset holes 3A and 3B, drilled 8 ft apart) indicates non uniform rates of sedimentation and prevents lamination count from quantitatively constraining the rate of the onset of the PETM. Amazon sedimentation rates are useful for predicting relative rates of sedimentation among sites on the NJCP; however, these rates cannot be applied directly to MAP. Observations made at MAP compared with modern muddy analogs does indicate sedimentation rates around 10's of cm per kyr; and possibly orders of magnitude higher during episodic gravity-driven flows.

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Figure 1: Carbon Isotope Excursion (CIE) at ODP 690 outlining the onset, core (yellow), and recovery (blue) of the CIE. Modified from Makarova et al., (2017)



Figure 2: Map of coreholes on New Jersey Coastal Plain (NJCP) where the Marlboro Formation has been recovered, including the subject of this study (MAP) in blue.



among sites. The toothed line at the top of each record represents the unconformity separating the Marlboro Formation from the overlying Manasquan uniform to demonstrate the difference in resolution between the 'onset' (red), 'core' (yellow), 'recovery' (blue), and 'pre-CIE activity' (green) intervals Formation. (Modified after Makarova et al., 2017) 2018), BR (Cramer et al., 1999; John et al., 2008) and MAP S3A (Blue) and 3B (Magenta). Records are aligned on the CIE 'onset' and vertical scale is Figure 3: Correlation of bulk carbonate d13C records between NJCP ODP sites: Wilson Lake B (Wright, Schaller 2013), Millville (Makarova et al.,



Figure 4: Medford Auger Project (MAP) sites (1 - 6) and cross section. Depicting the ground surface (blue line), top of Marlboro Fm. (red line) and bottom of Marlboro Fm. (green line).



Figure 5: Isopach Map of Marlboro Fm. in the Salisbury Embayment. Contour lines are drawn based on the basement structures (labeled) and coreholes (x marks). Note that the maximum thickness of Marlboro Formation sediments would have been located offshore. Light gray shading is used where Marlboro Formation is not preserved (thickness = 0 ft). Fall line (thick red) separates pre-Cretaceous from Cenozoic strata. Possible locations of Potomac and Susquehanna river sources are shown. Modified after Kopp et al. (2009)


Figure 6: Clay Mineral % and Lithology P-E Boundary Salisbury Embayment, red circles represent sites that underwent X-ray diffraction analysis. (Gibson et al. 2000)



Figure 7(a): Raised laminae (mm scale) and bulk material (couplets) in Marlboro Formation MAP S3A Core #11





Figure 7(b): MAP Hole 3A Core 11 laminae continue to rise 20 minutes post-split



al., 2017), % CaCO₃, and δ^{13} C of bulk carbonates. The % CaCO₃ and δ^{13} C are depicted in magenta for MAP Hole S3A and in cyan for MAP Hole S3B. Toothed red line represents unconformity between the Marlboro Formation and the overlying Manasquan Formation. The bold red line represents the initiation of the CIE. Depths are modified and adjusted for core expansion. The low Carbonate Zone is shaded in light orange. Figure 8: Compilation of data for MAP HoleSite 3A and MAP HoleSite 3B, from Medford, NJ: Lithology, cumulative grain size (Makarova et



Figure 9: Magnified view of d13C and %CaCO3 records for MAP Hole 3A and Hole 3B near the initiation of the CIE. MAP Hole 3A is depicted in cyan, MAP Hole 3B is depicted in magenta. The red line marks the initiation event. Light orange shaded region demarks low carbonate zone (>1%). Depths are modified and adjusted for core expansion.



Figure 10(a) (Top): Kaolinite rich Marlboro Clay MAP Hole 3B Core #11Figure 10(b) (Bottom): Glauconitic quartz silty sand Vicentown Formation MAP Hole 3B Core #13



Figure 11: Laminae couplet frequency graph MAP Hole 3A Core #11 depicting thickness of bulk sediment between successive laminations (cm). 84 total laminations at MAP Hole 3A Core #11 over 3.5 ft (1.07 m). Average thickness of a laminae couplet (lamination + bulk material) ~1.28 cm



Figure 12: Marlboro laminae couplet series from Wilson Lake B described by C. Lombardi (2014)



Figure 13: MAP 3A XRD analysis bulk (top) vs laminae (bottom); (S) Smectite, (I) Illite, (K) Kaolinite, (I/S) Illite/Smectite, (Q) Quartz, (C) Chlorite



class clay (blue) within and between couplets. White fill data points represent lamina samples and hollow points represent bulk samples. Occasional marked changes in distribution occur at couplet boundary laminae (53.73 acd, 54.73 acd) which may suggest a change in composition of the fluid mud reservoir in between gravity driven flow events. Although this is not recorded at 51.28 acd, indicating the need for further investigation. Figure 14: X-ray Diffraction (XRD) analysis of MAP Hole 3A Core #11 comparing weight % of Kaolinite (red) to Montmorillonite, a smectite



content determined by pipette analysis. Vandenberghe, 1997; Beauseluick et al., 1998). Laser diffraction underestimates the amount of clay particles by 20-70% with respect to clay mean grain size between 6-8 µm. Such discrepancy has been recorded elsewhere and is attributed to the platy form of clay minerals (Konert and rates for the fine fraction. Data from the pipette method indicates mean grain size <2 µm while the Malvern results depicted here indicate a coarser monochromatic light (McCave, 1986). This is opposed to the classic sieve and pipette grain size analysis method based on Stoke's sedimentation Figure 15: Grain size analysis via laser diffraction on the Malvern Mastersizer 3000, which operates using the forward scattering of











Figure 16: Mica test histograms:

- (a) Clean sand and silt histogram
- (b) First run post mica spike
- (c) Second run post mica spike
- (d) Third run post mica spike
- (e) Fourth run post mica spike



Grain Size (phi)





Grain Size (phi)

(b) 51.0 acd



Grain Size (phi)





Grain Size (phi)

(d) 52.025 acd



Grain Size (phi)





Grain Size (phi)

(f) 53.75 acd



Grain Size (phi)





(h) 54.4 acd

Figure 17(a-h): Cumulative weight graphs of grain size analysis results via pipette method from MAP Hole 3A Core #11. Y-axis denotes weight represented, X-axis denotes phi-class. Dry weight of samples 25-31 g. Weighted cumulative percentage graphs for these samples indicate a range between 51% and 68% of total sediments (by weight) having less than 2 μ m diameter. (a) 50.9 acd (b) 51.0 acd (c) 51.95 acd (d) 52.025 acd (e) 53.65 acd (f) 53.75 acd (g) 54.325 acd (h) 54.4 acd



Figure 18: Reconciling and correlating datasets from Medford, NJ collected at MAP Sites 3A and 3B (this study) and at Medford 174AX (Wright and Schaller, 2013). This correlation places the initiation of the onset of the CIE within the transitional unit at all 3 sites. I hypothesize that the especially low values at Medford 174AX are due to diagenetic effects and that the full onset of the CIE is not recorded at Medford due to its updip location.



Figure 19: Medford MAP Hole 3B records an expanded CIE onset ~6' compared to 4' at downdip Wilson Lake B. Suggests that Eocene sedimentation rates were 50% higher at Medford.



Figure 20: Depiction of mud-laden rivers emptying onto wave/tide dominated deltas and distributing sediments down drift of source, building mud clinoforms that progressively downlap onto thew sediment starved shelf. (Plint 2012)



Figure 21: Cartoon illustrating clinoform growth. Topset, foreset and bottomset portions of the clinoform are indicated, as well as relative rates of sediment accumulation and the rollover point (topset–foreset transition). No scale is provided as clinoforms are scale independent. Upward accretion is limited by physical processes (e.g., wave base, tidal currents), and sediment supply regulates seaward expansion. (Walsh and Nittrouer, 2004)



Figure 22: Laminae proposed as artifacts of drilling fluid (Pearson, Nicholas 2014)



distally. Truncation of CIE record occurs updip due to resuspension of topsets and erosion inherent to the overlying unconformity. NJCP well sites in a downdip direction supports variation in CIE preservation between sites. Initiation of the CIE has thicker record updip and thins depicting a fluid mud reservoir source bypassing shallow zones and rapidly building foresets in a prodelta environment at the rollover point. Overlaying Figure 23: (Top) NJCP drill sites drawn to scale in terms of distance between wells and CIE recovery thickness. (Bottom) Idealized Clinoform model