Vassar College

Investigating Controls on Hudson River Foraminifera Assemblages:

An Analysis of Sediment Biogeochemistry

Will Riley

Advised by Dr. Laura Haynes

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Abstract

The Hudson River Estuary, despite its deep environmental and humanitarian importance, continues to face anthropogenic threats to its health. This study is one of several new investigations seeking to fill the substantial gap in knowledge on benthic Hudson foraminifera – bioindicators that have the potential to enhance monitoring efforts throughout the estuary. Two shallow push cores were taken off Piermont Pier and assessed for foraminifera genera abundance and sediment biogeochemical characteristics with the aim of describing relationships that exist between the two. *Trochammina*, *Miliammina*, and *Ammoastuta* were the dominant genera observed, forming an assemblage never previously described in the Hudson Estuary. The broadest controls on general assemblage composition appear to be salinity and the local marsh environment. However, *Miliammina* were found to have a statistically significant relationship with organic matter which highlights the importance of controls that exist within the sediment profile. A recent hypoxic event recorded in both cores further demonstrates the immediate relevance of this organic matter control on assemblage composition as climate change is projected to increase the frequency of Hudson deoxygenation events (Howarth et al., 2000). Future work expanding upon the impact of sediment pollution and genera distribution is needed to better understand influences on foraminifera spatially and temporality throughout the estuary.

1. Introduction

Understanding biogeochemical characteristics of the Hudson River Estuary spatially and temporally is necessary for monitoring the health of this crucial waterway. Although humans have long relied on this river for environmental services such as fresh water and transportation, negligence of sewage, industrial waste, and fertilizer has resulted in a legacy of degradation to the waterway and associated ecosystems (Levinton & Waldman, 2006; EPA). The Hudson River is additionally susceptible to future anthropogenic influences, notably climate change, which may have drastic impacts on the current environment (Howarth et al., 2000). Thus, tracking physical changes in the estuary is critical to both the natural and human world.

One effective and widely used method of aquatic health monitoring is through utilization of benthic foraminifera as bio-indicators. Foraminifera are a class of unicellular shelled protist that reflect the chemical and physical parameters of their environment through their assemblage composition and test chemistry. Analysis of assemblage composition – a way to go beyond individual genera trends and examine characteristic groupings – additionally offers a window into the past and serves as a point of comparison for documenting changes into the future. To make interpretations based off assemblage data, however, it is necessary to understand what environmental controls impact foraminifera distribution to begin with. Controls on benthic foraminifera distribution in marine or estuarine environments have been shown to be highly variable by location – dictated by the specific interaction of physical parameters occurring in the geographic region of interest.

Some studies have found that sedimentological parameters such as grain size (Ruiz et al. 2005; Laut et al 2021), heavy metal contamination (Cearreta et al. 2002), or organic matter (Koho et al. 2008; Laut et al. 2021; Martins et al. 2015) have significant relationships with foraminifera

assemblages. Other work cites geochemical porewater parameters such as redox fronts associated with nitrate (Koho et al. 2008; Cardich et al. 2015) or dissolved oxygen (Schönfeld, 2001; Patterson et al. 2000) as having significant correlations with foraminifera distribution. Although some scientific literature name explicitly benthic controls for benthic foraminifera, others implicate that flow within the overlying water column is an important determinant as this relates to sediment deposition and salinity regimes that can have significant relationships with foraminifera communities (Laut et al 2021; Albani et al. 2007; Ruiz et al. 2005). The wide breadth of cited controls is due to the specific conditions of the environment and the foraminifera that inhabit them, for different genera tolerate different microhabitats which is what inherently allows for these shelled protists to be used as bioindicators (Patterson et al. 2000). Even within the study of one general location, there may be multiple controls at play (Laut et al. 2021). Additionally, controls on foraminifera may change naturally over time as climatic and environmental regimes shift. Thus, foraminifera assemblage controls are complex and appear to be both temporally and geographically specific. Local investigation is therefore required to certify what environmental parameters are determining assemblages at that specific site. Only by solidifying an understanding of controls on modern foraminifera can assemblage data be accurately used to monitor environmental health through time.

The southern half of the Hudson River is a tidal estuary where water is saline enough for brackish agglutinated and even calcareous foraminifera to inhabit benthic sediments (Weiss et al., 1977; Pekar et al., 2002; McCrone et al., 1966). Despite the environmental, cultural, and economic importance of the Hudson Estuary, there is a stark absence of research on its foraminifera and their use as bioindicators. The majority of the few published studies focus on documenting Hudson foraminifera assemblages at the macro scale – describing how genera change throughout the entire

estuary through sediment cores taken tens of kilometers apart (Weiss et al., 1977; Pekar et al., 2002; McCrone et al., 1966). As such, these studies are positioned to describe environmental controls enacting upon foraminifera at the broadest scale. Salinity, changing drastically from 32 ppt at the Hudson's mouth to 0 ppt north of the estuary, is subsequently identified as the strongest determinant of assemblages in the Hudson (Weiss et al., 1977; Pekar et al., 2002). The larger foraminifera literature however recognizes the wide breadth of controls that can vary within small areas, suggesting that there may be other controls for Hudson River foraminifera distribution that have not been examined due to the wide net previously cast. Through a collaborative undertaking by Vassar College, Barnard College, and the Lamont Doherty Earth Observatory, a new, ongoing series of studies on Hudson foraminifera are being conducted. These projects are motivated not only by the general need for current Hudson foraminifera work, but by this specific gap in understanding assemblages and their controls at a micro scale.

In this study, we principally seek to document surface biogeochemistry of Hudson River Estuary sediments to provide insight into what processes are currently affecting foraminifera assemblages approximately 50 km up the river in Piermont, NY. Additionally, this study aims to quantify the degree to which sediment geochemical facies correlate with, and thereby control, benthic foraminifera assemblages – results which will ultimately increase the accuracy of extrapolating local environmental health and climatic changes from assemblage data. Five shallow push cores taken within a kilometer of each other were analyzed for foraminifera genera, organic matter, and major porewater ions to meet these aims. Based on the previous foraminifera work in the Hudson, salinity is expected to have a broad influence on assemblage composition. However, controls that vary locally are also likely important, evidenced by the broader foraminifera

literature. Given the benthic parameters examined, we predict that redox fronts in the sediment associated with organic matter and dissolved oxygen influence Hudson foraminifera abundances.

In addition to the driving motivation of documenting and characterizing relationships between foraminifera assemblages and sediment biogeochemistry, this study is interested in the following questions: 1) How do the assemblages identified in this study compare to foraminifera populations outlined by previous studies that also sampled in the Piermont region? 2) How may multiple controls interact to form the assemblages observed at Piermont Pier? 3) Based off our understanding of these relevant controls, how may disturbances in the Hudson River Estuary such as deoxygenation events impact foraminifera abundances?

2. Methodology

2.1 Study Site

The Hudson River is a glacially formed 507 km long river located in east central New York that flows from the Adirondack Mountains in the north to the Upper New York Bay in the south, passing through the Munsee Lenape, Mohican, and Mohawk homelands. The lower half of the river is tidally influenced, resulting in brackish waters as far as 250 km from the estuary's mouth (Levinton & Waldman, 2006). This study focused sampling approximately 50 km up the river along the Piermont Pier, a jetty artificially made of terrestrial debris that juts 1.3 km perpendicularly into the river from the western bank (Figure 1). With a mean tidal range of 0.98 m and an average salinity of 2.9 ppt, this site reflects environmental influences from the Atlantic Ocean (Wong and Peteet, 1999). Piermont Pier sits on a portion of the Hudson River underlaid by soft sediments of the Newark Basin to the west and igneous to metamorphic rocks of the Manhattan Prong to the east. The benthic lithology is largely comprised of muddy sediments with higher proportions of sand and gravel deeper in the main channel (Nitsche et al., 2007). Directly south of the pier is the Piermont Marsh, a 4.11 km^2 complex of shallows and intertidal flats that the Sparkill Creek feeds into (NYS Dept. Environmental Conservation). *Phragmites* and *Spartina alterniflora* dominate the vegetative landscape of the marsh with clumps of these marsh grasses and reeds found along the edges of the pier as well. The climate of this region is subject to both continental and maritime regimes, experiencing an average temperature and precipitation of 28.6 °C and 108 cm respectively (Wong and Peteet, 1999).

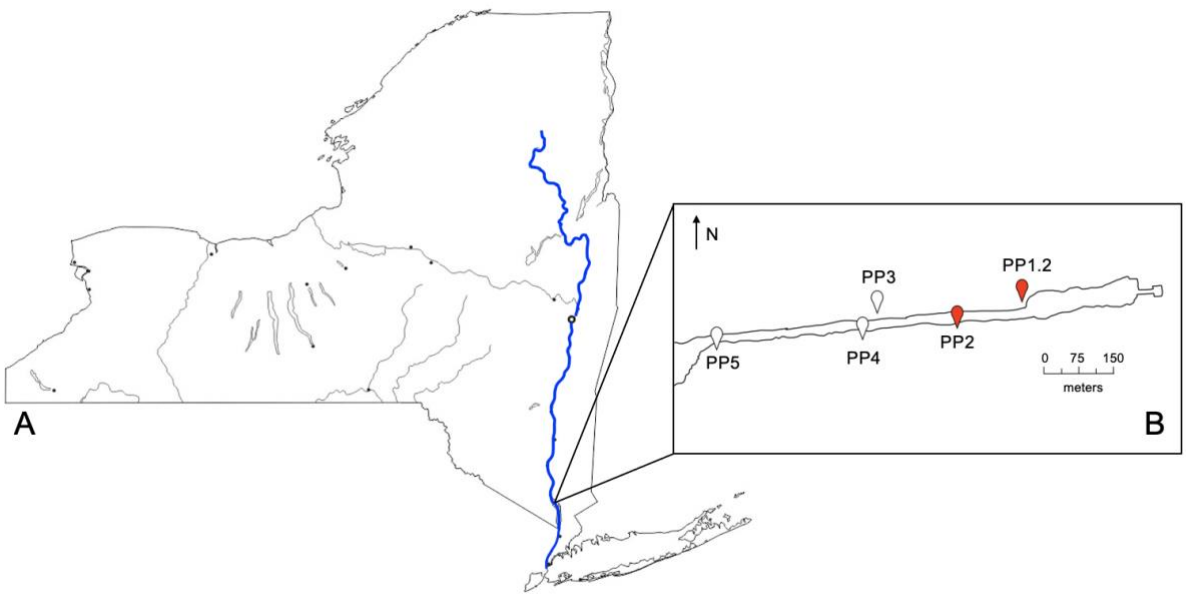

Figure 1 Study site. A. Regional Setting: New York State, Hudson River highlighted. B. Piermont Pier with coring sites marked. Cores used in this study are PP1.2 and PP2, shown here in red.

2.2 Field Work

2.2.1 Core Collection

Five push cores were collected in September 2021 along the pier working from the eastern tip towards the western bank (Figure 1). Three cores were taken on the southern side of the pier (PP2, PP4, PP5) where there was direct exposure to the southern marine influence, and two cores were taken on the northern side (PP1.2, PP3) where marine influence was likely less pronounced. Temperature and conductivity (indicating salinity) were measured at each sampled site using a YSI water quality meter to confirm the tidal influence and establish a baseline of general water characteristics across the gradient. Coring sites were chosen to achieve a representative distribution of the entire pier, although exact coring locations were ultimately determined by the ease of which benthic substrate material could be penetrated by the plastic coring mouth. Push cores were deployed about 10–15m off the pier in 1–1.5 m of water.

2.2.2 Sample Processing

Sample processing occurred immediately after collection on site at the Lamont-Doherty Earth Observatory River Research Center. Cores were sectioned in 1 cm interval, after which each section was split again – half to be used for foraminifera assemblage analysis and half to be used for organic matter and porewater analysis. Subsamples used for foraminifera characterization were stained with Bengal Rose (2g Bengal Rose to 1L 80% ethanol) to identify live individuals, however, due to the agglutinated nature of the tests, little dye was taken up thereby proving this step to be unnecessary. Sectioned cores ranged from 4 to 15 cm with length variable by the suberate they were deployed in and a logistical time constraint of sectioning on site. Porewater was extracted from cores PP1.2 and PP2 for every centimeter subsection using a centrifuge. Samples

were then filtered using a 0.45 µm syringe filter and immediately placed in a cooler before transportation to laboratory to be stored at 4 °C to prevent degassing and organic respiration. Due to the limitation of porewater only being collected for PP1.2 and PP2, only those two cores were utilized for this specific study.

2.3 Laboratory Analyses

2.3.1 Foraminifera

Samples were washed through a tower of 1 mm, 250 µm, and 63 µm sized sieves using a system of hoses and squirt bottles to dislodge clays from the foraminifera shells. The sized-partitioned sediments were dried in an oven at 65 °C for at least 6 hrs. Before picking of the tests from the sediment, samples were split twice using a sediment splitter. Shells were picked from the sediment underneath a dissecting microscope using a fine tipped paint brush and were shorted into welled slides with an aim of picking approximately 300 individual shells per sample. If 300 shells were not found in the first sample split, subsequent splits were examined. Picking stopped after the split containing the 300th shell was picked or the entire sample was picked, whichever occurred first. Collected foraminifera were then identified at the genius level through previously established taxonomy on estuarine foraminifera (Tibert et al., 2012). This study specifically examined the intervals of PP1.2 0–6 cm, 7–8 cm and PP2 0–3 cm, selected due to time limitations and variability of porewater chemistry at those depths. The Shannon Diversity Index was calculated for each centimeter sample to assess for changes in temporal diversity:

$$H' = -\sum_{i=1}^{R} p_i \ln p_i$$

Where H' is the Shannon Diversity Index and p_i is the proportion of i genera in the whole sample.

2.3.2 Porewater

Major cations (Li, Sr, NH_4^+, K, Mn, Ca) and anions (Fl, Cl, NO_3^-, PO_4^{-3} NO_2^-, Br, SO_4^{-2}) of porewater samples was identified using ion chromatography (IC). Micropipettes were used to dilute 500 µl of each sample with 1.2 mL of nanopure water. A series of standards were additionally prepared ranging from 1:10–1:1,000 standard dilutions, and four blanks of nanopure water were dispersed throughout the sampling interval to ensure that there was minimal background contamination. Resultant ion concentrations based on the standard curve were calculated in the Chromeleon software and later corrected for sample dilution. Standard calibration curves had R^2 values > 0.99 for all ions, indicating a high degree of accuracy in measured ion concentration for Piermont samples.

2.3.3 Organic Matter

Organic matter content of each 1 cm subsection was determined through loss on ignition (%LOI). Approximately 5 g of each sample was weighed and then dried at 65 °C for 24 hrs to remove moisture. Samples were again weighed and approximately 2 g of each sample were transferred to porcelain crucibles using tweezers to avoid weighing errors. The crucibles were then put into a muffle furnace at 500 °C for 8 hrs to burn off all organic matter present. After cooling to 70 °C, samples were taken from the furnace and immediately weighed to avoid reabsorption of water back into the sample. Finally, precent organic matter was calculated:

$$Dry\ Weight - Weight\ After\ Combustion = Weight\ Organic\ Matter$$

$$\frac{Weight\ After\ Combustion}{Dry\ Weight} \times 100 = \%\ Organic\ Matter$$

2.4 Statistical Analysis

Q-mode cluster analysis, a form of hierarchical agglomerative cluster analysis, was conducted in RStudio Version 1.4.1103 to establish assemblages based on foraminifera counts. This application was adapted from methods described by Holland (2006). A precent maximum transformation was applied to the data, followed by conversion to a dissimilarity matrix using the Bray metric. This dissimilarity matrix was then fed into a Q-mode cluster analysis using Ward's method (from "cluster" package, using the "agnes" object).

A series of Single Linear Regressions (SLR) and Multiple Linear Regression (MLR) were additionally conducted in RStudio to test for relationships between foraminifera abundance and associated organic matter. Exploratory data analysis (linearity plots) indicated for which foraminifera genera linear regression models would be appropriate. SLR models were fitted with the following equation:

$$Y = \beta_0 + \beta_1 X_1 + \epsilon$$

Where Y was the abundance of the target genera, X_1 was the associated organic matter (%), and ϵ was the error term. The SLR assumptions of linearity, independence, normality, and equal variance were checked to confirm the statistical confidence of these models. The independence assumption is already met as this is a cross-sectional dataset where data was collected only once from each centimeter interval. Other assumptions were checked through assessing for a linear relationship between dependent vs. independent variables (linearity), an even spread of the fitted values vs. the residuals (equal variance), and a normal bell curve of residuals in a histogram (normality). Due to the low number of observations, the normality assumption was not met and thus randomization-based inference (RBI) of 10,000 samples was run to correct for this issue. To determine the best interval for assigning assemblages from the cluster analysis, additional SLRs were run, splitting

samples based on various heights along the dendrograph (0.40 – four assemblage groups, 0.46 – three assemblage groups, and 0.50 – two assemblage groups) and fitting assemblages against organic matter.

3. Results

3.1 Foraminifera Abundance

All foraminifera found belong to benthic, agglutinated genera – no calcareous or planktonic genera were observed. Foraminifera processing and identification found that six genera are present in the studied sediment profiles: *Trochammina*, *Miliammina*, *Ammoastuta*, *Haplophragmoides*, *Ammobaculites*, and *Arcellacea* (Figure 2). Of these six, *Trochammina*, *Miliammina*, and *Ammoastuta* were the dominant genera and accounted for 81–96% of the total foraminifera in each centimeter subsection. In PP1.2, there was a decrease in *Miliammina* mirrored by an increase in *Ammoastuta* from 0 to 6 cm (Figure 3). *Trochammina* abundance typically varied between these two end members and had lower variation in abundance than either of the other two genera (*Trochammina* range = 11% vs. *Miliammina* range = 27% and *Ammoastuta* range = 32%). Similar trends did not occur in PP2 (Figure 4). Minor genera (*Haplophragmoides*, *Ammobaculites*, and *Arcellacea*) were larger components of the total foraminifera population in PP2, occurring at a maximum of four times the amount as in PP1.2. *Miliammina* constituted a proportionally smaller amount of total foraminifera populations in PP2 compared to PP1.2, occurring in lower concentrations than *Arcellacea* between 1–3 cm. PP1.2 had a consistently higher density and abundance of foraminifera compared to PP2, likely at least four times the amount as PP2 based on sample splits. Every >63 µM subsample in PP1.2 was split four times with each picked split yielding at least 300 shells (except for PP1.2 7–8, for which the entire centimeter sample was picked). Conversely, the entirety of the >63 µM subsamples were picked for PP2, and still the 300-shell threshold was not reached. Within PP2, total abundance increased with depth.

Despite the difference in foraminifera abundance between cores, both cores yielded the same Shannon Diversity Index with an averaged value of 1.24 between their samples. The

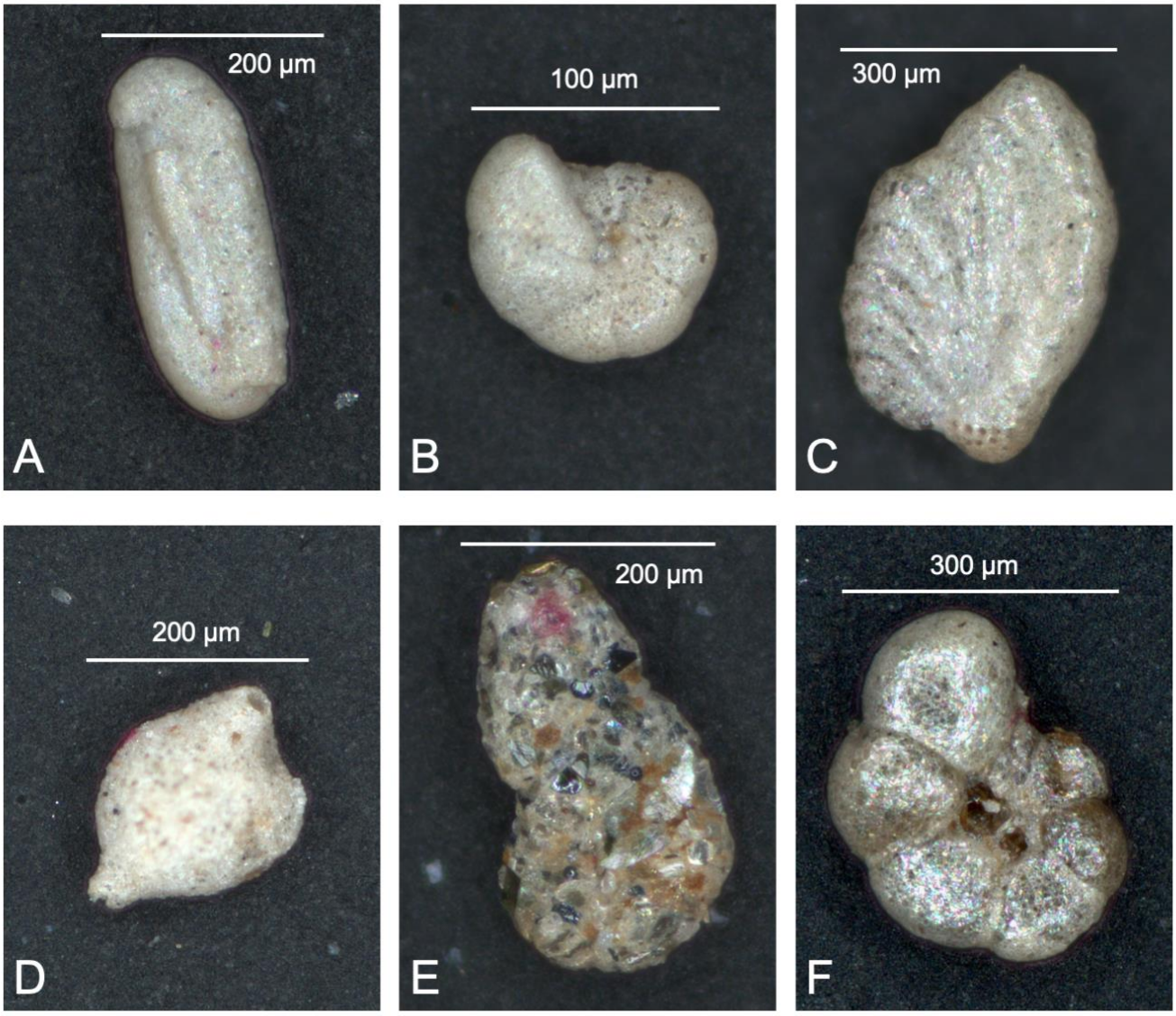

Figure 2 Observed foraminifera genera: A) *Miliammina*, B) *Trochammina*, C) *Ammoastuta*, D) *Arcellacea*, E) *Ammobaculites*, F) *Haplophragmoides*. Dominant genera are A–C, minor genera are D–F. Scales bars are approximate and based off of Tibert et al. (2012).

Shannon Diversity Index for PP1.2 was more consistent between samples (standard deviation = 0.07) than that of PP2 (standard deviation = 0.15), with both the minimum and maximum index values occurring in PP2. This difference highlights the absence of a trend in genera composition seen through the three samples of PP2 compared to the eight samples of PP1.2.

3.2 Foraminifera Assemblages

Q-mode cluster analysis resulted in several possible assemblages that were distinguished by inserting horizontal lines at various heights, thus cutting through stems and separating samples into related assemblages. Due to the small sample size, stems were broken off at the highest possible point – separating samples into two large assemblages. This decision was confirmed by SLR models. No SLR models showed significant relationships between organic matter and proposed assemblage, however, the 0.5 distance had the lowest p-value (0.32) compared to the distance cut offs of 0.46 (p-value = 0.44) and 0.40 (p-value = 0.81). Thus, while the cluster analysis does not indicate statistically significant assemblages, this study will use the dendrogram liberally as a map through which to broadly think about categorizing the assemblage differences that were observed (Figure 5). Using the 0.5 distance cut off, samples were sectioned into two groups: PP1.2 0–3 cm and PP2 1–3 cm in assemblage A and PP1.2 4–6 cm, PP1.2 7–8 cm, and PP2 0–1 cm in assemblage B. Assemblage A's major foraminifera had an average composition of 44% *Ammoastuta*, 33% *Trochammina*, and 14% *Miliammina* while assemblage B had an average composition of 23% *Ammoastuta*, 37% *Trochammina*, and 34% *Miliammina*. Assemblage A is therefore distinguished by a composition rich in *Ammoastuta* but poor in *Miliammina*, while assemblage B is distinguished by a composition poor in *Ammoastuta* but rich in *Miliammina*. Both assemblages have similarly high abundances of *Trochammina*.

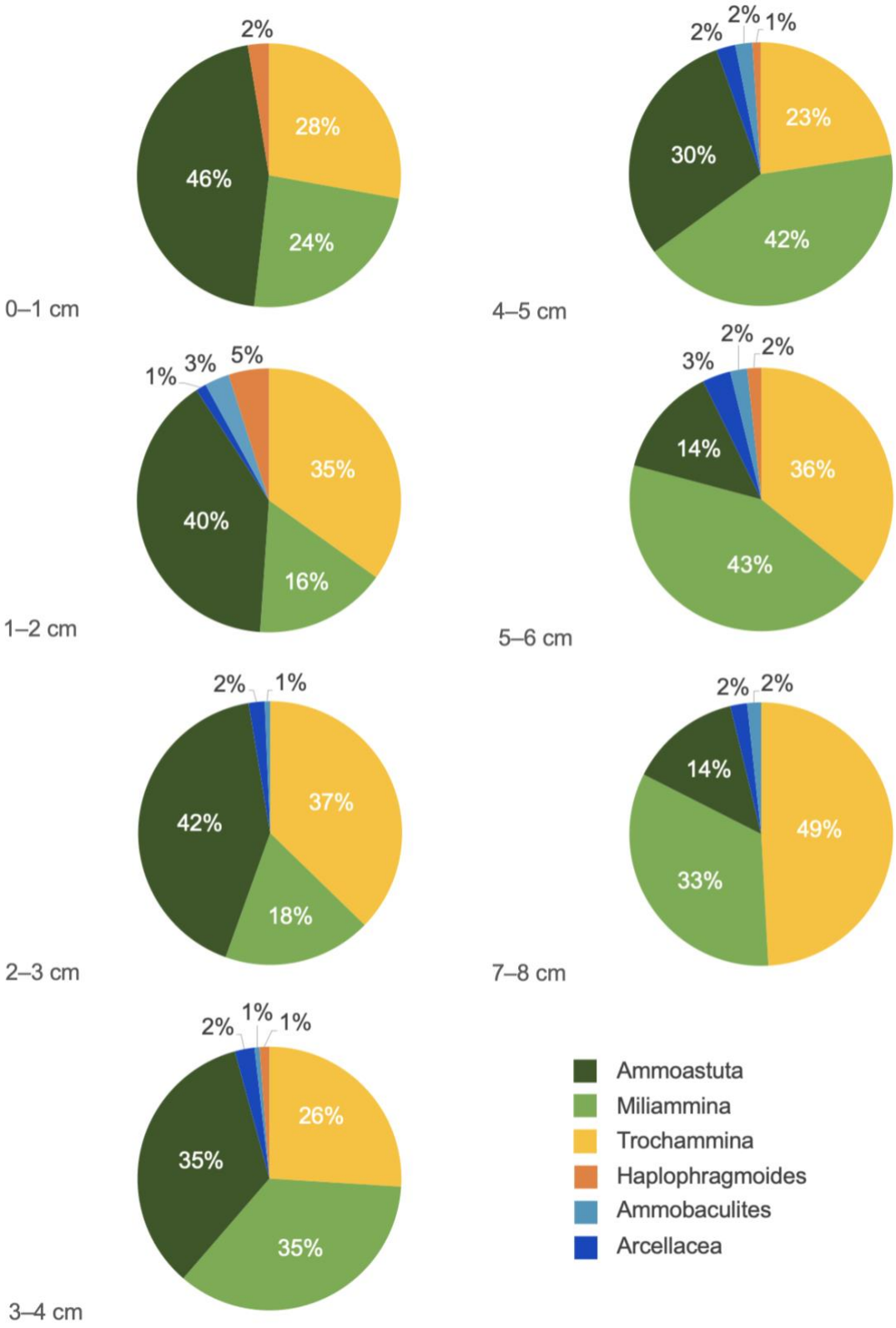

Figure 3 PP1.2 foraminifera genera percent abundance for samples 0–6 cm, 7–8 cm.

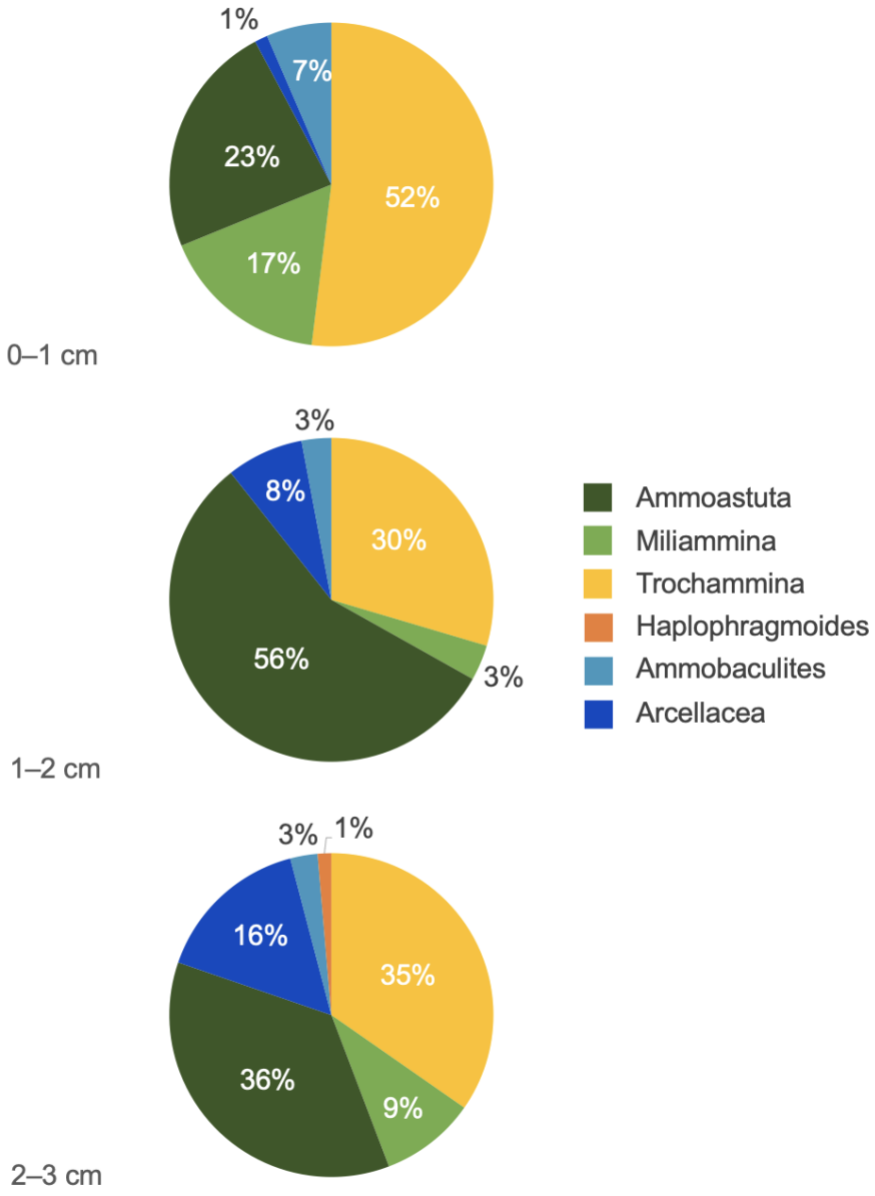

Figure 4 PP2 foraminifera genera percent abundance for samples 0–3 cm.

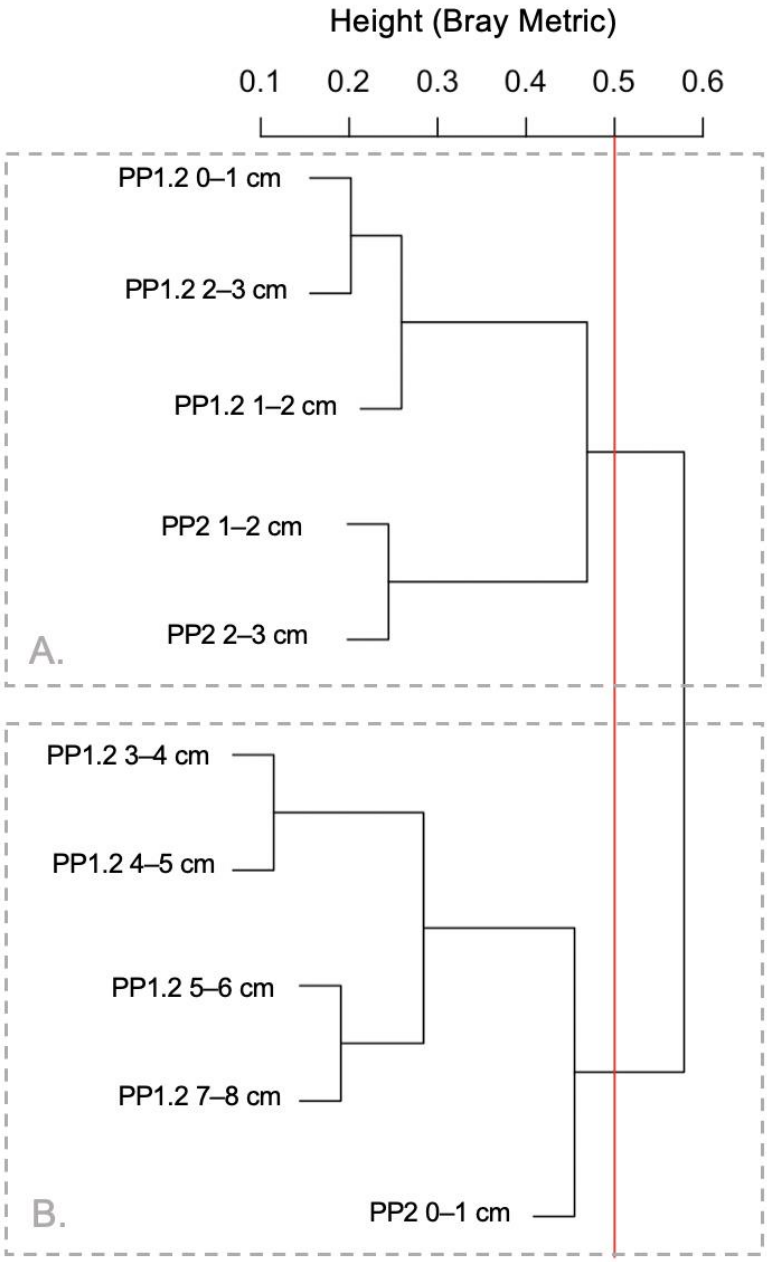

Figure 5 Dendrogram from Q-mode cluster analysis based on dissimilarity matrix generated from precent foraminifera abundance in each picked centimeter subsample. Vertical line is placed at 0.5, intersecting two stems and separating samples at the highest level into two assemblages. Assemblage A is *Ammoastuta* rich *Miliammina* poor while assemblage B is *Ammoastuta* poor and *Miliammina* rich. Both have similarly high abundances of *Trochammina* and low abundances of *Haplophragmoides*, *Ammobaculites*, and *Arcellacea*.

3.3 Geochemical

IC results indicate similar trends in anions and cations for both cores (Figure 6). In PP1.2, a spike in magnesium, calcium, phosphate, nitrate, nitrite, and bromide is observed between 5–6 cm (note: sulfur has a sharp decrease at this same depth interval). Concentrations above and below these peaks are relatively similar and often stable. Similar peaks are observed in PP2, with sodium, potassium, magnesium, nitrite, bromide, chloride, and fluoride reaching maximum values between 5–6 cm (note: nitrate has a peak between 4–5 cm which may be due to natural variation in sediment, and thus this peak will be considered with the rest of the 5–6 cm peaks). A spike in organic matter for PP1.2 and PP2 is observed between 5–6 cm as well (Figure 7). PP3, although not used in this study, additionally had a peak in organic matter at this depth. Overall, ion concentrations tend to be higher in PP2 porewater than PP1.2 porewater. Sodium, potassium, magnesium, nitrite, chloride, and fluoride are continuously higher throughout the porewater profile in PP2 compared to PP1.2. Sodium, potassium, and chloride show a steady decrease in concentration between both cores, while sulfate has a steady increase in concentration in both cores – aside from a notable decrease in PP2 5–6 cm.

3.5 Organic Matter and Foraminifera Correlation

Only *Miliammina* had a linear relationship with organic matter (Figure 8) and therefore this was the only SLR considered. All model assumption were shown to be valid after RBI correction. This model indicates that for every 1% increase of *Miliammina* abundance in a sample, there is, on average, a 2.59% increase in organic matter (95% confidence interval = 0.91 and 4.28, standard error = 0.070). The RBI p-value of 0.0096 is below the α 0.01 significance level, indicating that this is a statistically significant relationship.

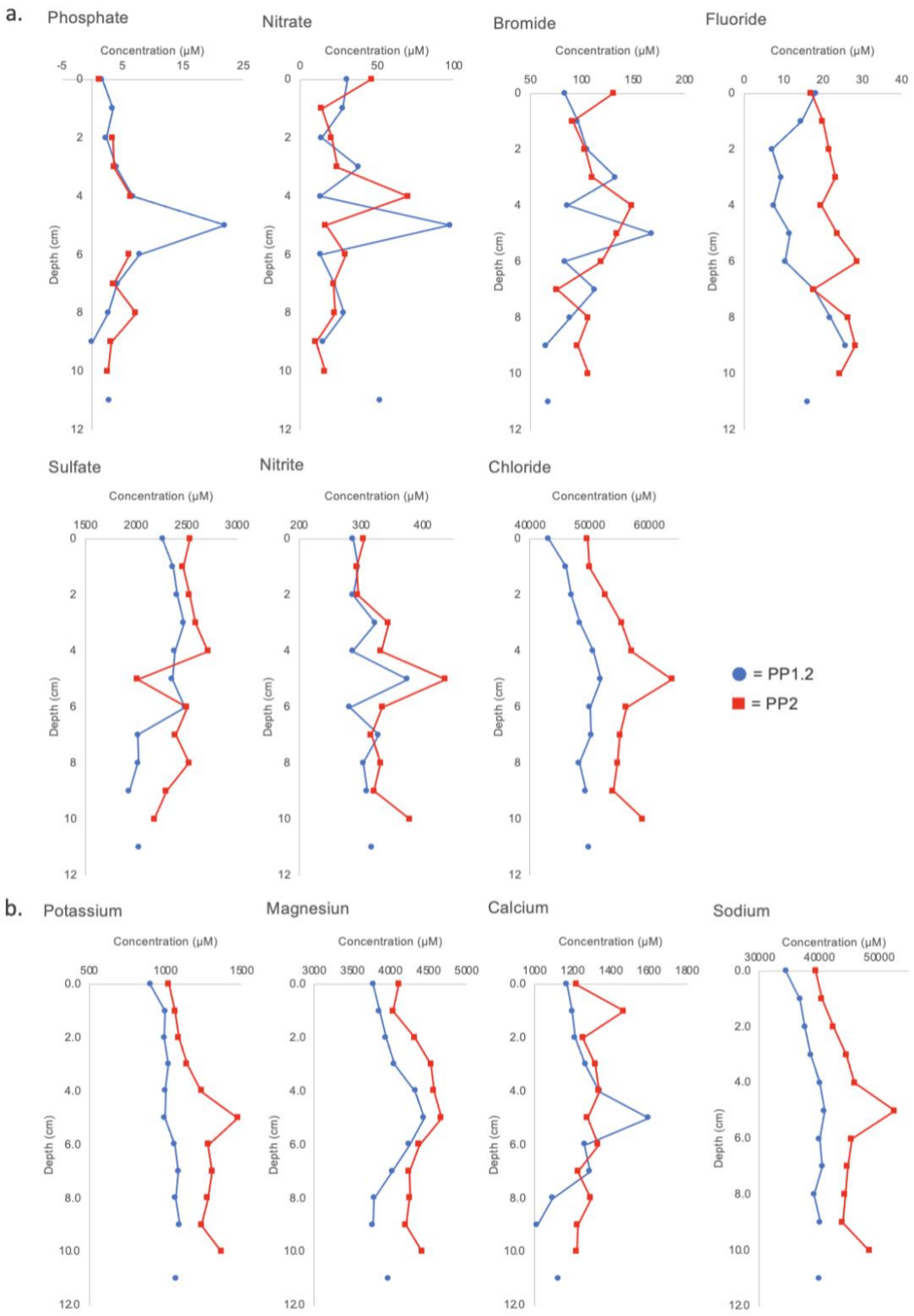

Figure 6 Porewater depth profiles for the first 10–11 cm of PP1.2 and PP2. A) Anions B) Cations

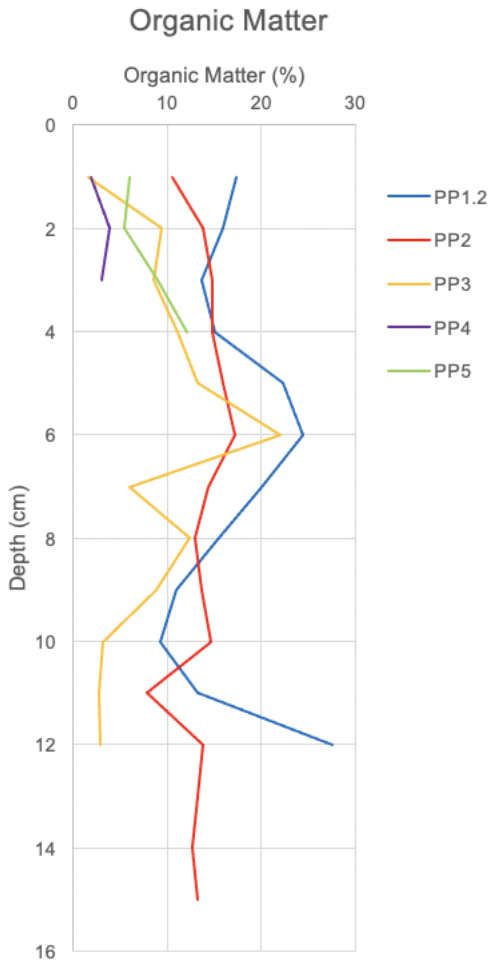

Figure 7 Organic matter (%) depth profile for five all collected cores. The peak in organic matter at between 5–6 cm occurs in all three cores that extend to that depth.

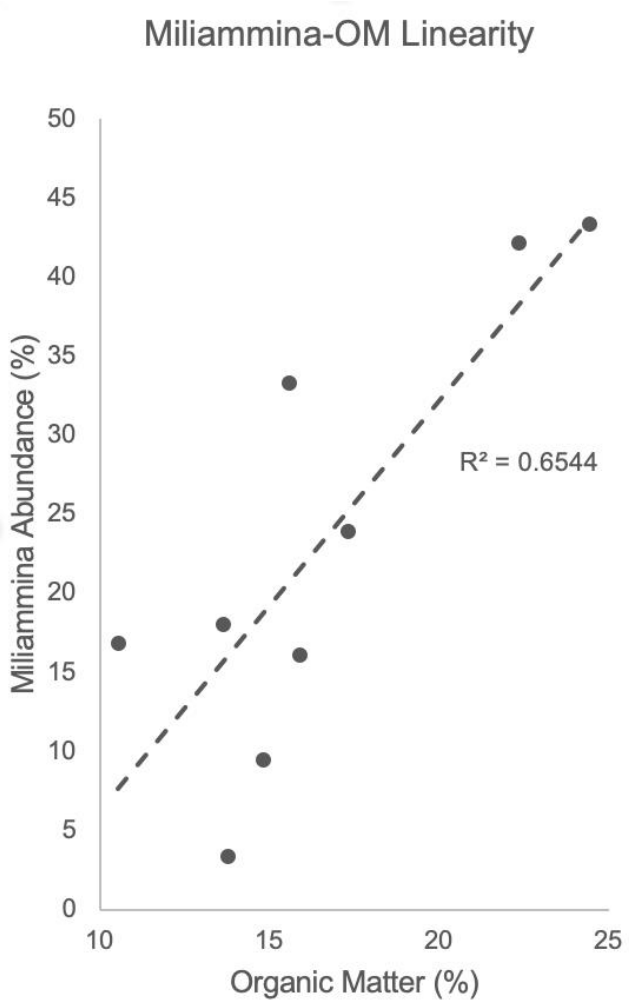

Figure 8 Linearity check for the *Miliammina*~organic matter SLR. The moderately high R^2 value indicates that a linear relationship does exist, and thus they may have a significantly significant relationship – which is proven to be true by the fitted SLR model.

4. Discussion

Through examining how genera abundance, organic matter, and porewater chemistry change with depth in two surface cores, this paper presents data on understudied benthic Hudson foraminifera and their associated sediment biogeochemistry. Two assemblages were identified, and, although they are composed of the same major genera, this separation demonstrates that there is substantial variability of genera abundances within a small spatial and temporal scope. The subsequent sections in this discussion will delve into the interpretations and implications that our data suggest.

4.1 Assemblages of the Greater Piermont Region

Placing the foraminifera genera and abundances found in this study in the context of previous work conducted in the Hudson Estuary reveals the large variability in assemblages observed in this environment. Compared to this study, Weiss et al. (1978) and Pekar et al. (2004) recorded different agglutinated genera in the Piermont region while McCrone et al. (1966) recorded more similar genera but at very different abundances. Weiss et al. (1978) described a clear *Ammobaculities* dominance for this part of the estuary and Pekar et al. (2004), which sampled < 3 km from the Piermont Pier, found *Trochammina* and *Ammoscalaria* to be a dominant. Conversely, this study observed *Ammobaculities* at an abundance of <5% in every sample and *Trochammina* at an average abundance of 35%, not notably larger than the average abundances of 34% and 29% for *Ammoastuta* and *Miliammina* respectively. *Ammoscalaria* was not observed in any samples. Further, neither *Ammoastuta* nor *Miliammina* were mentioned in these two papers despite accounting for approximately 63% of total foraminifera described in this study. McCrone et al. (1966) describes *Miliammina*, *Trochammina*, *Ammoastuta*, and *Ammobaculities* < 5 km from

Piermont Pier, confirming that all the dominant genera observed in this study have been previously documented in the estuary. However, McCrone et al. (1966) notes that *Trochammina* and *Ammoastuta* were in low abundance, with each sampled core section only yielding one or two individuals of each genus. Thus, there is strong disagreement about what foraminifera are dominant or even present in the same relative study area among these four independent studies, indicating that various assemblages exist in the Hudson River Estuary on a small spatial scale.

4.2 Assemblage Controls

Despite differing accounts of the genera and abundance of foraminifera, there is agreement in the literature that modern assemblages in the Piermont region are almost entirely composed of agglutinated genera. This study concurs with this observation as of the >3,000 individual tests picked from Piermont sediment all were agglutinated. Calcareous genera have been documented in high abundance lower in the Hudson Estuary where the salinity of the overlaying water column is higher, leading to the proposed threshold of 15 ppt separating Hudson calcareous and agglutinated dominant assemblages (Weiss et al., 1978; Pekar et al., 2004). This study again concurs with this proposal as both cored locations had a similar surface salinity of 2.8 (PP1.2) and 3.0 (PP2) ppt – well below the 15 ppt threshold. Therefore, salinity is likely a large-scale spatial control that determines the assemblages of foraminifera in the broadest sense. A salinity control on benthic foraminifera is additionally supported in the literature for other estuarine systems (Laut et al 2021; Albani et al. 2007; Ruiz et al. 2005; Lal et al., 2020). However, salinity cannot be the only acting control as the Piermont region likely has similar salinity but notably different assemblages. Influences that vary on a smaller spatial scale must also be at play.

The genera seen throughout both Piermont cores is reflective of assemblages observed in estuary marshes along the eastern US coast. Vance et al. (2002) describes a North Carolinian saltmarsh dominated by *Ammoastuta*, *Trochammina*, and *Miliammina* while Tibert et al. (2012) notes that *Ammoasstuta* and *Miliammina* are the main genera of an estuarine marsh in Virginia. Both of these assemblages are specifically unique from the rest of the entire studied estuary where *Ammobaculities* often dominated. Further, *Trochammina* (Wong and Peteet, 1999) and *Miliammina* (McCrone et al., 1966) have previously been documented in Hudson River Estuary marshes. Piermont Pier sediment therefore appears to reflect a marsh environment. While samples were not collected at a marsh, the Piermont Marsh is several hundred meters down river and clumps of marsh grasses like *Spartina alterniflora* grew directly next to the coring locations of both PP1.2 and PP2. Based off these observations and the previously cited studies, marsh influence through vegetation is likely a strong local control in determining assemblage composition at Piermont Pier.

4.3 Organic Control of Miliammina

The importance of organic matter in controlling certain foraminifera genera has been documented in marine environments (Singh et al., 2021; Smart et al., 1994; Loubere & Fariduddin, 1999). This relationship is due to the scarcity of allochthonous organic matter in the deep sea and thus us a limiting food source (Loubere & Fariduddin, 1999), however, as the Hudson River Estuary is a terrestrial system, organic matter is not limited in the same way and therefore a different relationship is needed to explain the correlation between *Miliammina* and organic matter. Martins et al. (2015) found a significant relationship between *Miliammina* and biopolymer concentrations in organic matter – specifically carbohydrate content. Thus, the same control of

food enrichment on the herbivorous *Miliammina* may explain the covariance seen in this study. Further analysis on the quality of organic matter is needed to cement this specific conclusion. Martins et al. (2015) additionally found a correlation between *Trochammina* and biopolymer concentrations which was not supported in the Piermont sediments but could be another avenue for future investigations.

The relationship between *Miliammina* and organic matter may be one factor in separating the two assemblages described in this study. Assemblage B had higher *Miliammina* abundance than Assemblage A and additionally had 19% more organic matter. Based on the statistically significant correlation and this difference in *Miliammina* and organic matter between the two assemblages, organic matter may be a determinant in how foraminifera can be grouped within a small spatial area.

4.4 Deoxygenation Events

Concurrent changes in porewater chemistry and organic matter point to a period of high organic matter deposition that likely occurred due to an anoxic event during the temporal association of 5–6 cm into the sediment (Figure 6). At this depth, the decrease in sulfur concentrations suggests that specialized bacteria are respiring, using sulfur as an electron acceptor under low oxygen conditions. Additionally, the spike in nutrient concentrations (phosphate and nitrate) at the same depth documents this redox process as bacterial respiration appears to be remineralizing organic matter nutrients to an inorganic state. The spike in organic matter (Figure 7) further supports the hypothesis that low oxygen was pervasive throughout the site during sediment deposition as this build up occurred due to a gross decrease in consumption of the benthic organic debris by bacteria. Combining these interpretations with the organic matter control

suggests that *Miliammina* may additionally be influenced by redox fronts associated with dissolved oxygen – a hypothesis supported by previous studies (Schönfeld, 2001; Patterson et al. 2000).

As no radiometric dating was conducted in this study, it is difficult to determine the exact timing of the deoxygenation event recorded in Piermont surface sediment. Sediment accumulation gives a clue. Sedimentation rates at this site are unknown, however, a rate of 1–3 mm/yr was described in the main river channel near the Tappan Zee (Olsen et al., 1978) while a rate of 0.26 cm/yr was described at Piermont Marsh (Wong and Peteet, 1999). As the Piermont Pier has neither a direct stream inflow to deposit sediment like Piermont Marsh nor direct influence of central river flow, this site likely has a sedimentation rate between these two sites. This estimation puts the organic matter horizon on the scale of accumulating decades to centuries ago in the past. A river wide hypoxic event that occurred in 2020 may be analogous to the one that corresponds with the organic horizon. During this time, eutrophication from sewage and fertilizer resulted in large algal blooms which depleted the river of oxygen and led to a mass fish kill throughout the estuary (Cutler, 2020). Such events are important to track and understand as they effect the river's ecosystems and food webs.

Understanding how foraminifera react to deoxygenation events is particularly important in the modern day as the frequency of eutrophication events in the Hudson River Estuary is expected to increase in the future due to climate change. Fresh water discharge into the lower Hudson is predicted to decrease with climate change, and this change has been shown to increase water residence time and stratification of the water column as well as deepen the photic zone. The combined effect of these factors leads to algal blooms and generally increased primary productivity, ultimately decreasing oxygen levels in the river when those organisms die and are respired (Howarth et al., 2000). As a statistically significant positive relationship was found in the

Piermont cores between *Miliammina* and organic matter, increased eutrophication events may lead to an increase in this genus' abundance in the river as organic matter accumulates during these events. A 10% relative increase in *Miliammina* between PP1.2 5–6 cm and 7–8 cm that corresponds with the dip into the observed hypoxic zone supports this conclusion. Analysis of *Miliammina* abundance may therefore be used to identify past deoxygenation events recorded in longer cores than those analyzed in this study. Additionally, the degree to which *Miliammina* abundances change may be a marker for how severe the impacts of such events are to the benthic community. Although no significant relationship was found between organic matter and *Ammoastuta*, the inverse relationship between *Ammoastuta* and *Miliammina* observed throughout PP1.2 could suggest that increased eutrophication will additionally have a negative impact on *Ammoastuta* abundance in the Hudson River Estuary.

5. Conclusion

This study describes a unique foraminifera assemblage dominated by, *Trochammina*, *Miliammina*, and *Ammoastuta* at Piermont Pier in the Hudson River Estuary. Comparison to previous studies in the Piermont region indicate that multiple and distinctly different assemblages can exist in the same area. While the broadest control on foraminifera distribution across the estuary is salinity, microecosystems in the river such as the Piermont Marsh has is a more significant control on a smaller spatial scale. Moreover, specific genera can have significant relationships with facies in the sediment such as *Miliammina* and organic matter do, demonstrating how multiple variables interact to shape assemblages. As this study found an organic matter spike that signaled a recent deoxygenation event, future increases of eutrophication in the Hudson will likely result in assemblage changes that could favor *Miliammina* abundance. Overall, we have shown that sampling focused in a small area in addition to sampling throughout the estuary is necessary to understand controls on Hudson River Estuary Foraminifera.

Future work on Hudson foraminifera is needed to more fully understand how these protists function in the estuary. Aside from expanding on the amount of work being conducted – especially studying assemblage change at a small scale – examination of lithofacies and heavy metal pollution as controls on foraminifera is needed. Pollution may be a particularly important avenue for research given the Hudson's history with industrial waste dumping. Examination of past foraminifera assemblages through analysis of longer cores is needed to expand upon the gap in temporal knowledge of Hudson foraminifera. In doing so, it will be interesting to note if the *Miliammina* and organic matter relationship remains similarly significant as confirmation of this relationship would support the claim presented in this paper that *Miliammina* can be used as a local

indicator of deoxygenation events through time. Foraminifera work is a critical step in monitoring the health of the Hudson River Estuary and is an area of study worthy of future expansion.

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6. References

Albani, Alberto, Rossana Serandrei Barbero, and Sandra Donnici. 2007. “Foraminifera as Ecological Indicators in the Lagoon of Venice, Italy.” Ecological Indicators 7 (2): 239–53. https://doi.org/10.1016/j.ecolind.2006.01.003.

Cardich, J, D. Gutiérrez, D. Romero, A. Pérez, L. Quipúzcoa, R. Marquina, W. Yupanqui, J. Solís, W. Carhuapoma, A. Sifeddine, A. Rathburn.2015. “Calcareous benthic foraminifera from the upper central Peruvian margin: control of the assemblage by pore water redox and sedimentary organic matter”. Marine Ecology Progress Series 535: 63-87.

Cearreta, A, M.J Irabien, E Leorri, I Yusta, A Quintanilla, and A Zabaleta. 2002. “Environmental Transformation of the Bilbao Estuary, N. Spain: Microfaunal and Geochemical Proxies in the Recent Sedimentary Record.” Marine Pollution Bulletin 44 (6): 487–503. https://doi.org/10.1016/S0025-326X(01)00261-2.

Culter, N. “Thousands of dead fish found floating in the Hudson River suffocated, experts say.” 2020. USA Today

Environmental Protection Agency. “Hudson River PCBs Superfund Site” EPA https://www.epa.gov/hudsonriverpcbs/hudson-river-cleanup

Holland, S. M. “Cluster Analysis”. Jan. 2006. Dep. Geology UGA.

Howarth, R., Swaney, D., Butler, T. *et al.* “Rapid Communication: Climatic Control on Eutrophication of the Hudson River Estuary”. *Ecosystems* **3,** 210–215 (2000). https://doi.org/10.1007/s100210000020

Koho, K. A., R. García, H. C. de Stigter, E. Epping, E. Koning, T. J. Kouwenhoven, and G. J. van der Zwaan. 2008. “Sedimentary Labile Organic Carbon and Pore Water Redox Control on Species Distribution of Benthic Foraminifera: A Case Study from Lisbon–Setúbal Canyon (Southern Portugal).” Progress in Oceanography 79 (1): 55–82. https://doi.org/10.1016/j.pocean.2008.07.004.

Lal K. K., Bonetti C., Woodroffe C. D., Rogers K. “Contemporary distribution of benthic foraminiferal assemblages in coastal wetlands of south-eastern Australia”. 2020. Estuarine Coastal and Shelf Science vol 245. https://doi.org/10.1016/j.ecss.2020.106949

Laut, L., G. da Matta, G. Camara, P. Belart, I. Clemente, J. Ballalai, E. Volino, E. da Conceição

G. Couto. 2021. “Living and dead foraminifera assemblages as environmental indicators in the Almada River Estuary, Ilhéus, northeastern Brazil”. Journal of South American Earth Sciences, Volume 105, ISSN 0895-9811, https://doi.org/10.1016/j.jsames.2020.102883.

Levinton, J., Waldman, J., “The Hudson River Estuary”. 2006. Cambridge University Press.

Loubere, P., Fariduddin, M. “Benthic Foraminifera and the flux of organic carbon to the Seabed”. 1999. Modern Foraminifera. Springer, Dordrecht. https://doi.org/10.1007/0-306-48104-9_11

Martins MVA, Silva F, Laut LLM, Frontalini F, Clemente IMMM, Miranda P, et al. “Response of Benthic Foraminifera to Organic Matter Quantity and Quality and Bioavailable Concentrations of Metals in Aveiro Lagoon (Portugal)”. 2015. https://doi.org/10.1371/journal.pone.0118077

McCrone, Alistair W., and Charles Schafer. “Geochemical and Sedimentary Environments of Foraminifera in the Hudson River Estuary, New York.” 1966. *Micropaleontology*, vol. 12, no. 4, pp. 505–09, https://doi.org/10.2307/1484794. Accessed 17 Apr. 2022.

Nitsche, F. O., W. B. F. Ryan, S. M. Carbotte, R. E. Bell, A. Slagle, C. Bertinado, R. Flood, T. Kenna, and C. McHugh “Regional Patterns and Local Variations of Sediment “Distribution in the Hudson River Estuary.” Estuarine, Coastal and Shelf Science, Sedimentological and ecohydrological processes of Asian deltas: The Yangtze and the Mekong”. 2007. 71 (1): 259–77. https://doi.org/10.1016/j.ecss.2006.07.021.

Olsen, C.R., Simpson, H. J., Bopp, R. F., Williams, S. C., Peng, T. H., Deck, B. L. “A geochemical analysis of the sediments and sedimentation in the Hudson Estuary”. *Journal of Sedimentary Research* 1978; 48 (2): 401–418. doi: https://doi.org/10.1306/212F7496-2B24-11D7-8648000102C1865D

Patterson, T., J-P. Guilbault, Richard E. Thomson. “Oxygen Level Control on Foraminiferal Distribution in Effingham Inlet, Vancouver Island, British Columbia, Canada”. *Journal of Foraminiferal Research* 2000; 30 (4): 321–335. doi: https://doi.org/10.2113/0300321

Pekar S., McHugh C., Christie-Blick N., Jones M., Carbotte S., Bell R., Lynch-Stieglitz J., “Estuarine processes and their stratigraphic record: paleosalinity and sedimentation changes in the Hudson Estuary (North America)”. 2004. Marine Geology, Vol. 209, Iss. 1–4, 113-129. ISSN 0025-3227. https://doi.org/10.1016/j.margeo.2004.05.025.

Ruiz, F., M. L. González-Regalado, J. G. Pendón, M. Abad, M. Olías, and J. M. Muñoz. 2005. "Correlation between Foraminifera and Sedimentary Environments in Recent Estuaries of Southwestern Spain: Applications to Holocene Reconstructions." Quaternary International, Quaternary of the Mediterranean basin and western Asia: marine and terrestrial processes and palaeoenvironments, 140–141 (December): 21–36. https://doi.org/10.1016/j.quaint.2005.05.002.

Schönfeld, Joachim. "Benthic Foraminifera and Pore-water Oxygen Profiles: A Re-assessment of Species Boundary Conditions at the Western Iberian Margin." 2001. Journal of Foraminiferal Research 31 (2): 86–107. https://doi.org/10.2113/0310086.

Singh DP, Saraswat R, Nigam R. "Untangling the effect of organic matter and dissolved oxygen on living benthic foraminifera in the southeastern Arabian Sea. Mar Pollut Bull". 2021 Nov;172:112883. doi: 10.1016/j.marpolbul.2021.112883.

Smart W., King S.C., Gooday A.J., Murray J.W., Thomas E., "A benthic foraminiferal proxy of pulsed organic matter paleofluxes". 1994. Marine Micropaleontology, Volume 23, Issue 2, Pages 89-99. ISSN 0377-8398, https://doi.org/10.1016/0377-8398(94)90002-7.

Tibert, N.E., Hubeny, J., Abbot, M., Kiker, J.M., Walker, L.J. Mckenzie, Shantevia. "Late Holocene sedimentation and paleoenvironmental history for the tidal marshes of the Potomac and Rappahannock Rivers, tributaries to Chesapeake Bay". 2012. Virginia journal of science vol 63

Weiss, Dennis, Kurt Geitzenauer, and Frederick C. Shaw. 1978. "Foraminifera, Diatom and Bivalve Distribution in Recent Sediments of the Hudson Estuary." Estuarine and Coastal Marine Science 7 (4): 393–400. https://doi.org/10.1016/0302-3524(78)90091-9.

Wong, J., Peteet, D., 1999. "Environmental history of Piermont Marsh, Hudson River, NY". Section III: 30. In: Nieder, W.C., Waldman, J.R. (Eds.), Final Reports of the Tibor T. Polgar Fellowship Program, 1998. Hudson River Foundation, NY. (Section III. 30 pp).

Vance, D.J, Corbett, D.R., Culver, S.J. "Foraminiferal Distributions, Sedimentation Rates and Patterns in the Albemarle Estuarine System, North Carolina". 2002. AGU Fall Meeting Dec. 2002. OS22B-0283. https://ui.adsabs.harvard.edu/abs/2002AGUFMOS22B0283V.