BENTHIC FORAMINIFERAL ASSEMBLAGE AND SEDIMENTOLOGICAL CHANGES WITHIN THE PLIOCENE YORKTOWN FORMATION, SOUTHEASTERN VIRGINIA

By

Whittney E. Spivey

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Directors of Thesis: Dr. Stephen J. Culver and Dr. David Mallinson
Major Department: Geological Sciences

Abstract

The Pliocene Yorktown Formation consists of four distinct lithologic units that record three marine transgressive sequences along the U.S. mid-Atlantic margin. The Sunken Meadow Member was deposited during the Zanclean Stage and the Rushmere, Morgarts Beach, and Moore House members are assigned to the Piacenzian Stage. These units were deposited during a time when global atmospheric CO_2 concentrations were similar to present, and average sea-level and mean global temperatures were ~25 meters and ~3°C higher than the pre-industrial, respectively. During the Piacenzian, the largest cool to warm transition took place between Marine Isotope Stages (MIS) M2 (3.3 Ma) and M1 (3.25 Ma) recorded in the Rushmere and Morgarts Beach sediments. The mid-Piacenzian Warm Period (~3.264–3.025 Ma; mPWP) is an interval widely considered to have had climatic conditions similar to projections for the end of the 21st century; the base of the mPWP is defined by the transition between peak MIS M2 and peak MIS M1.

Forty-five samples were collected along the James River near Rushmere, Virginia, and at Pipsico Boy Scout Camp, Spring Grove, Virginia and were analyzed for benthic foraminifer community and sedimentological changes between each member of the formation. These data

are useful for developing boundary conditions for shallow, near-shore environments for paleoclimate modeling.

Discernible differences in grain-size distribution occur between the Sunken Meadow and Rushmere members; generally, the Sunken Meadow Member is composed of generally finer sands, has less mud, and has a higher percentage of sand and phosphatic and glauconitic grains than the Rushmere Member. These sedimentological changes are often subtle in outcrop and occur within decimeters of the contact between the two units, giving the appearance that the two units are conformable in some areas. The most notable change in grain-size occurs at the conformable boundary between the Rushmere and Morgarts Beach members, where the average percentage of sand decreases from ~60% in the Rushmere Member <40% in the Morgarts Beach Member. Foraminiferal analysis distinguishes six biofacies across the entire formation – Formation—two in the Sunken Meadow Member, three within the conformable Rushmere-Morgarts Beach members, and one in the Moore House Member.

The Sunken Meadow Member represents a marine transgression, where changes in benthic foraminiferal assemblages and grain-size distribution indicate up-section deepening of water depth. Deposition of this unit has been interpreted as a mild temperate shallow-shelf setting with normal marine salinity based on the molluscan assemblage. This unit likely records the maximum phase of the transgression (maximum flooding). The Rushmere-Morgarts Beach members record the most extensive transgression in the Pliocene. Grain-size analysis and benthic foraminiferal assemblages indicate a shift in depositional environment from an open, middle shelf environment in the Rushmere Member to a restricted lower energy environment in the Morgarts Beach Member. The molluscan assemblage indicates a subtropical to tropical climate. The least extensive Pliocene transgression is recorded in the Moore House Member. It likely represents a cooler temperate environment and the formation of offshore bars in the Salisbury Embayment.

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By

Whittney E. Spivey

APPROVED BY:

CODIRECTOR OF THESIS: ______________________________

Stephen J. Culver, PhD, DSc

CODIRECTOR OF THESIS: ______________________________

David Mallinson, PhD

COMMITTEE MEMBER: ______________________________

Martin Buzas, PhD

COMMITTEE MEMBER: ______________________________

Harry J. Dowsett, PhD

CHAIR OF THE DEPARTMENT OF
GEOLOGICAL SCIENCES: ______________________________

Stephen J. Culver, PhD, DSc

DEAN OF THE
GRADUATE SCHOOL: ______________________________

Paul J. Gemperline, PhD

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Introduction

The Yorktown Formation records three early to late Pliocene pulses of marine transgression in the Salisbury and Albemarle embayments, from southeastern Virginia to northeastern North Carolina, preserved in Zanclean (5.33–3.6 Ma) to Piacenzian (3.6–2.58 Ma) age sediments of the Sunken Meadow, Rushmere, Morgarts Beach and Moore House members (Figs. 1–3; Ward and Blackwelder, 1980). Regional stratigraphy and molluscan macrofossil biostratigraphy of these units along the James and York rivers has been well documented by previous workers over the past several decades (Johnson, 1969; Ward and Blackwelder, 1980; Blackwelder, 1981a, 1981b; Bailey, 1987; Ward, 1989; Johnson and Ward, 1990; Krantz, 1991; Johnson et al., 1993; Daley, 1999; Ward and Dooley, 2005). Microfossil studies on the Yorktown Formation conducted throughout the 1980s and 1990s focused on benthic and planktic foraminiferal assemblages in Lee Creek Mine, North Carolina (Gibson, 1983; Snyder et al., 1983, 2001) and planktic foraminifera and ostracode assemblages throughout southeastern Virginia (Hazel, 1971; Hazel, 1977; Cronin et al., 1984, 1989; Cronin and Dowsett, 1990; Dowsett and Cronin, 1990; Cronin, 1991; Dowsett and Wiggs, 1992). This study aims to document the benthic foraminiferal assemblage and sedimentological changes in the individual members of the Yorktown Formation at the lectotype locality in Rushmere, Virginia.

The Yorktown Formation was deposited at a time when global atmospheric CO_2 concentrations were similar to present (~400 ppm; Pagani et al., 2010). Continental positioning, land-sea geography, and ocean circulation were also similar to present (Dowsett and Robinson, 2009), but global average temperature and sea-level were ~3°C and ~25 meters higher relative to the pre-industrial, respectively (Dowsett et al., 2016; Haywood et al., 2016). The sediments of the Yorktown Formation have long been recognized for their paleoclimatic significance; Hazel

(1971) was the first to use ostracodes to reconstruct paleotemperatures of the Yorktown Formation, finding that the middle Yorktown faunas indicated a warm temperate climate.

The mid-Piacenzian (3.264–3.025 Ma) Warm Period (mPWP; Dowsett et al., 2016) has been used as an imperfect analogue for near-future climate conditions by the U.S. Geological Survey's Pliocene Research, Interpretation and Synoptic Mapping (PRISM) Project since the late 1980s. The mPWP represents the most recent interval in Earth's history to experience average global warmth comparable to what has been predicted for the second half of the twenty-first century (Cronin and Dowsett, 1993; Dowsett et al., 2009; Dowsett et al., 2016). The transition between Marine Isotope Stage (MIS) M2 and M1 (~3.30–3.24 Ma), which occurs immediately prior to mPWP, is recorded in the conformable Rushmere–Morgarts Beach sediments (Fig. 2). The majority of the studies on the mPWP have been on deep sea cores collected world-wide with few studies focusing on exposed outcrops along the Atlantic Coastal Plain (Cronin, 1991; Cronin et al., 1993; Dowsett et al., 2016; Dowsett et al., 2017).

The first phase of transgression recorded in the Yorktown Formation is preserved in the Zanclean age sediments of the Sunken Meadow Member; this pulse covered the Norfolk Arch, resulting in the deposition of the Sunken Meadow Member in the Albemarle Embayment (Fig. 4, 1st Pulse; Ward and Blackwelder, 1980). The timing of deposition and age of the Sunken Meadow Member is poorly constrained, with estimates placing the unit between 4.8–3.8 Ma (Snyder et al., 1983; Krantz, 1991; Dowsett and Wiggs, 1992; Daley, 1999). The shelly sands of the Rushmere Member and the clayey silts of the Morgarts Beach Member, assigned to the Piacenzian Stage, were deposited during the maximum transgressive phase of the Yorktown Formation that occurred during a period of high eustatic sea level along the Western Atlantic Margin (Fig. 4, 2nd Pulse; Ward and Blackwelder, 1980; Blackwelder, 1981a; Cronin et al., 1989; Krantz, 1991; Ward and Dooley, 2005). The Rushmere–Morgarts Beach transition has been interpreted as a shift from open-marine conditions to a restricted, lower-energy lagoonal environment; however, molluscan fauna in the Morgarts Beach Member indicate normal marine salinities (Ward and Blackwelder, 1980; Krantz, 1991; Ward and Dooley, 2005). The Moore House Member was deposited during the third and final pulse of transgression in the late Pliocene; this pulse is restricted to the area around Rushmere, VA and represents a resumption of higher wave energy conditions (Fig. 4, 3rd Pulse; Ward, 1989; Krantz, 1991; Ward, 2008).

Understanding the ecology of microfossil indicator species is vital to interpreting the fossil assemblage and depositional environments. As the mPWP presents a unique, although imperfect, analogue for near future-warming, documenting and interpreting the environmental changes preserved in the Yorktown Formation sediments aids in creation of boundary conditions for use with paleoclimate modeling focused on improving end of the century projections. The deposition of the Yorktown Formation has broader implications for regional adaptations of near-shore foraminiferal communities to global cool to warm climatic shifts.

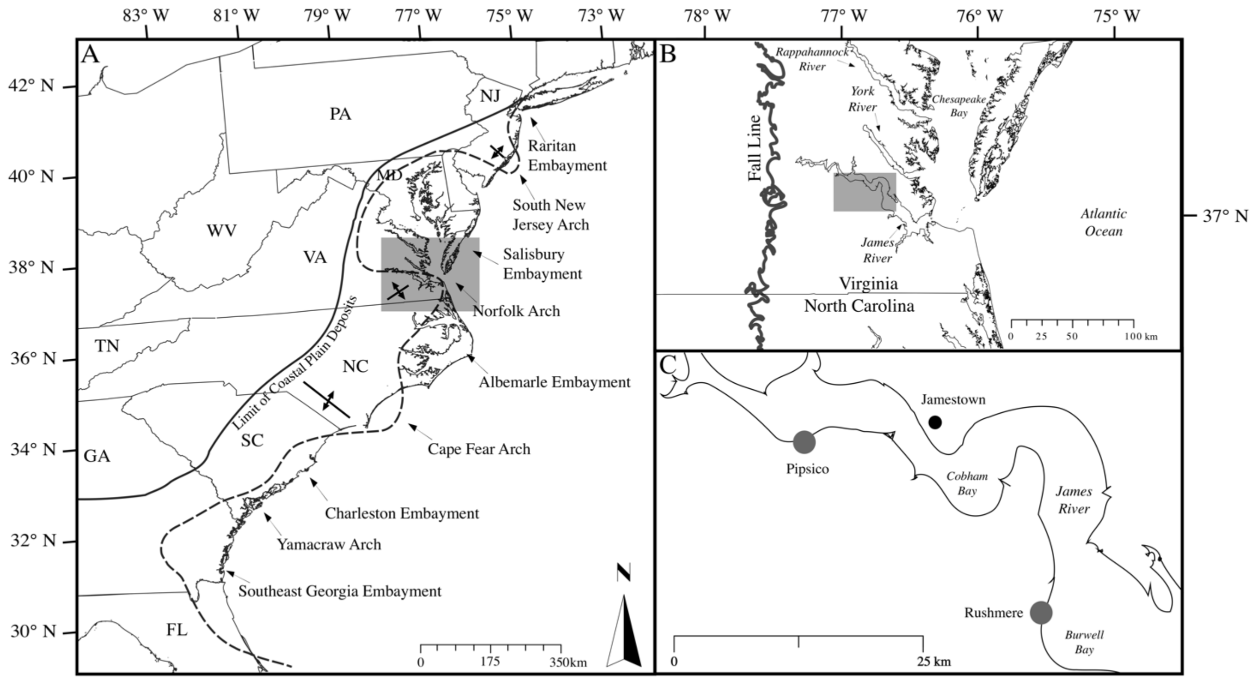

Figure 1: A. Location of the study area (grey rectangle) within the Atlantic Coastal Plain (ACP). Western most line (solid) is the inner limit of coastal plain deposits. Eastern line (dashed) shows the surface (at 500 m depth) of the underlying crystalline bedrock structure of the ACP. Modified from Ward (2008). **B.** Location of study area along the James River (grey rectangle). **C.** Detailed location of field sites (grey circles), with Historic Jamestown (black circle) marked for landmark reference.

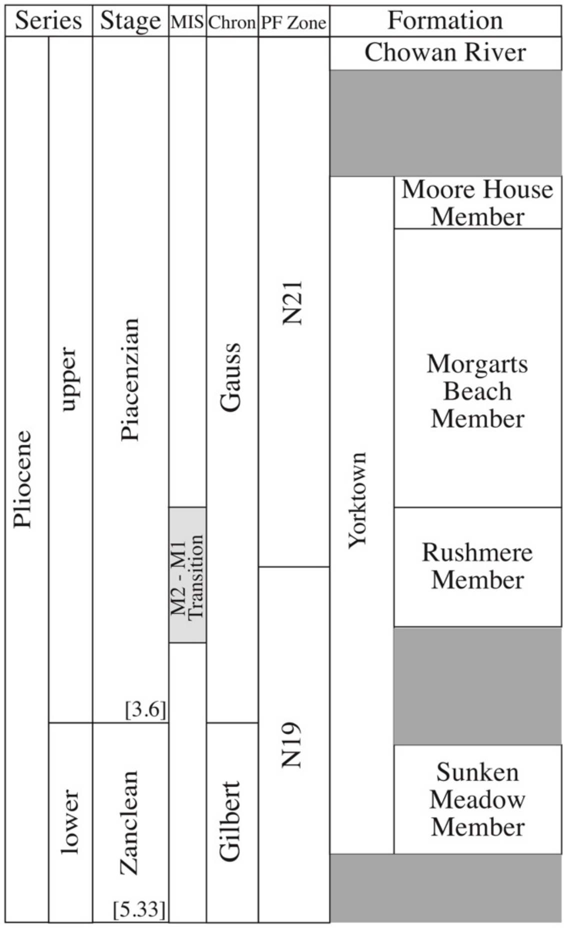

Figure 2: Chronostratigraphic column, showing the approximate location of the Marine Isotope Stage M2 to M1 transition within the Rushmere/Morgarts Beach sediments (Dowsett et al., 2019). Ages for the base of the Zanclean and Piacenzian stages are in brackets. Age control of the Sunken Meadow Member is not well established. Modified from Cronin et al. (1989). Timescale of the MIS M2/M1 transition modified from Dowsett et al. (2016, 2019).

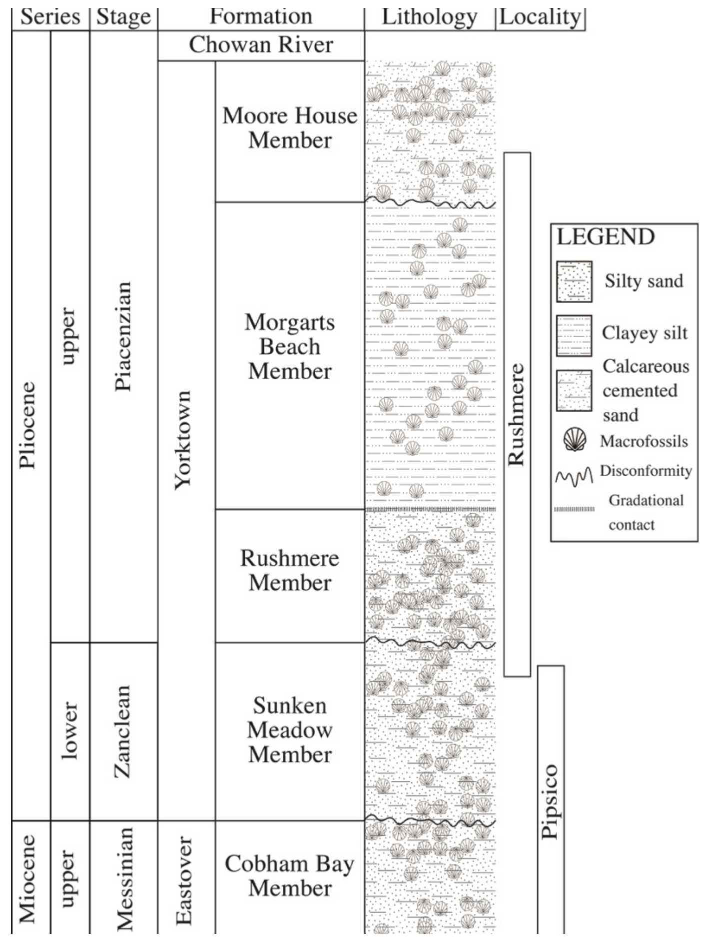

Figure 3: Generalized stratigraphic column and lithostratigraphy of the study area. Exposure of the Sunken Meadow Member is limited at the Rushmere type section but is the only unit in this study seen in outcrop at Pipsico.

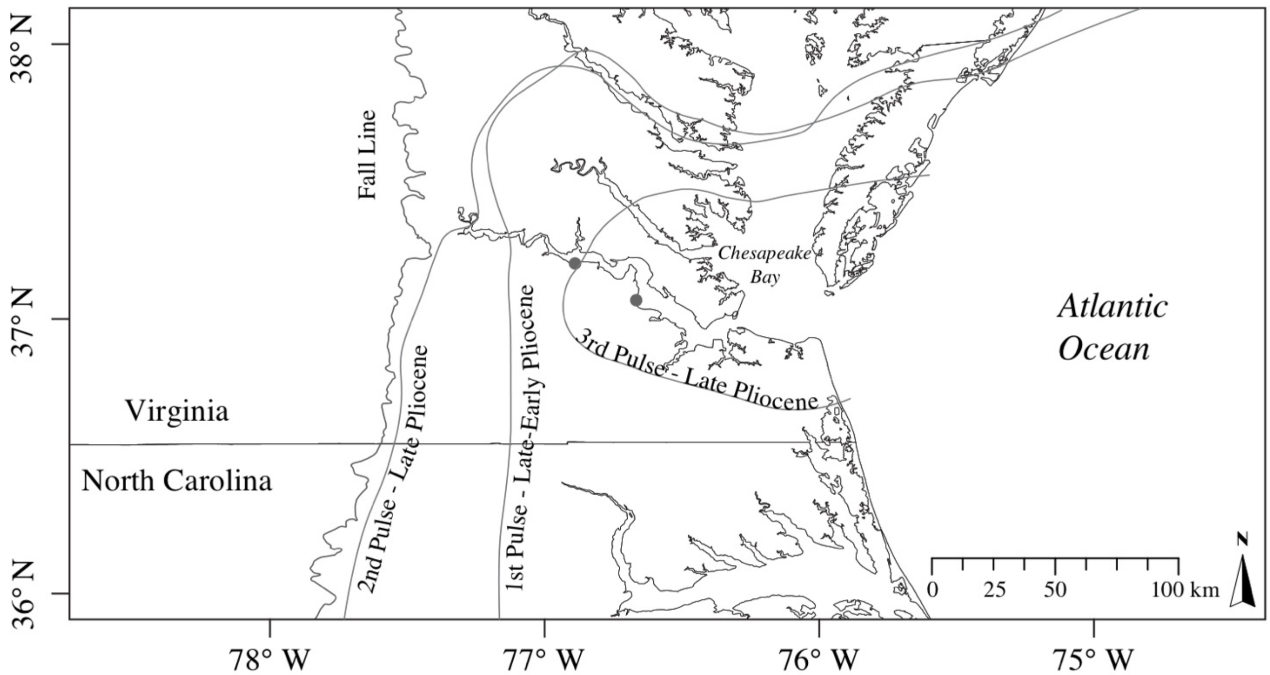

Figure 4: Distribution map showing extent of the preserved deposits of the Pliocene transgressive pulses: Sunken Meadow Member (1st Pulse), Rushmere and Morgarts Beach members (2nd Pulse), and Moore House Member (3rd Pulse). Modified from Ward (2008).

Geologic Setting

The United States Atlantic Coastal Plain (ACP) spans Massachusetts to Florida and is composed of a relatively thick succession of marine and non-marine sediments ranging from Early Cretaceous to Holocene in age (Richards, 1974; Ward and Strickland, 1985; Meng and Harsh, 1988; Olsson et al., 1988; Cronin et al., 1989). These sedimentary packages were deposited atop Precambrian and Paleozoic crystalline basement and filled Mesozoic rift-basins that resulted from the break-up of the supercontinent Pangea and the opening of the Atlantic Ocean basin (Richards, 1974; Cronin et al., 1984; Owens and Gohn, 1985; Ward and Dooley, 2005). The unconsolidated to semi-consolidated sediments along the ACP reach thicknesses up to 2165 m and thin landward reaching nearly zero thickness at the fall line (Fig. 1a, Johnson, 1969; Meng and Harsh, 1988; Olsson et al., 1988; Ward and Dooley, 2005). The irregular bedrock structure underlying the ACP slopes eastward and forms a series of embayments and arches that act as a framework that controls the dip, thickness, and lithology of these deposits (Fig. 1a; Gohn, 1988; Klitgord et al., 1988; Olsson et al., 1988; Ward and Dooley, 2005; Ward, 2008).

Richards (1974) recognized ten "structural provinces", from New Jersey to Florida, that are distinguishable by variations in the slope and configuration of the underlying basement rocks. Those variations result in a complex network of depocenters and regional high areas that are structurally controlled by localized tectonism (Fig. 1a; Gibson, 1970; Ward and Strickland, 1985; Ward and Powars, 2004; Ward, 2008). Sediment loading in the basins and sediment starvation due to erosion and/or bypass along the arches further contribute to the undulous basal geometry of the ACP (Cronin, 1981). Variations in the areal distribution of time-equivalent units is attributable to differential depositional basin mobility (Gibson, 1970).

The post-rifting history of eustatic sea-level variation along the Western Atlantic margin is recorded in the presently emerged sedimentary deposits of the ACP (Cronin et al., 1984). Multiple phases of marine transgressive and regressive cycles, combined with tectonic fluctuations in individual basins, have resulted in the development of a unique stratigraphic profile within each basin (Ward and Strickland, 1985; Olsson et al., 1988). During the highest phases of sea-level high stands, sediments accumulated in the embayments and were then subject to erosion during low stands, forming unconformity bounded sedimentary packages (Ward and Strickland, 1985; Hoffman and Ward, 1989; Daley, 1999; Williams et al., 2009). Each package likely represents a single transgressive event—preserving temporally incomplete marine to marginal marine successions—that generally record warm climate conditions with cooler conditions often reflected by unconformities and erosion of older deposits by younger transgressions (Cronin et al., 1984; Cronin, 1988; Hoffman and Ward, 1989; Dowsett and Cronin, 1990; Daley, 1999; Williams et al., 2009). Correlation of sea-level fluctuation across the Atlantic margin has been complicated by differences in depositional environment, regional tectonic forces and erosion rates, especially in areas where age control of stratigraphic units is limited due to a paucity of biostratigraphic indicator species (Cronin, 1981; Cronin et al., 1984; Cronin, 1991; Daley, 1999).

The Salisbury Embayment, situated within the middle ACP, extends from the southernmost point of New Jersey through Delaware, southeastern Maryland, and Virginia (Fig. 1a; Richards, 1974; Gohn, 1988; Klitgord et al., 1988; Ward and Dooley, 2005). It is a tectonic downwarp bordered by two regional high areas—to the north by the South New Jersey Arch and by the Norfolk Arch to the south (Fig. 1a; Ward and Powars, 2004; Ward and Dooley, 2005; Ward, 2008). The southern flank of the Salisbury Embayment, encompassing the southern area of the Chesapeake Bay and the James River area (this study), has low basement relief of ~30 m or less (Meng, III and Harsh, 1988). Wells drilled throughout Maryland and Virginia show that the basement rocks are deeper in central Maryland than they are to the north or south and rise westward with the upper surface reaching sea level near Washington, D.C. (Richards, 1974).

The embayment has been a depocenter for intermittent marine onlap throughout the Cretaceous period and much of the Cenozoic Era (Gibson, 1970; Ward and Strickland, 1985; Olsson et al., 1988; Ward, 1989; Ward and Powars, 2004; Ward and Dooley, 2005). The wedge-like sedimentary deposits in the Salisbury Embayment range from fluvial to deltaic to open-shelf and are several thousand feet thick to the east, thinning toward the west where units overlap the Piedmont (Gibson, 1970; Ward, 1989; Ward and Dooley, 2005). Subsurface stratigraphic units are truncated or thin near the arches (Ward and Dooley, 2005). Basin shifts throughout the Miocene and Pliocene and localized Mesozoic graben structures acted as structural controls on the dip, thickness and lithology of sediments deposited within the embayment (Richards, 1974; Gibson, 1970; Ward, 1989). From the mid-Miocene through the late Pliocene, the basin shifted southward resulting in the locus of the basin to shift from the Salisbury Embayment into the Albemarle Embayment (Gibson, 1970; Ward, 1989).

Several pulses of rapid sea-level fluctuations during the Cenozoic related to glacial–interglacial climate cycles have resulted in the deposition of packages of shallow marine sediments in the Salisbury Embayment (Fig. 3 and Fig. 4; Berggren, 1972; Ward and Blackwelder, 1980; Cronin, 1981; Krantz, 1991). The Yorktown Formation was deposited within the Salisbury and Albemarle Embayments during the early to late Pliocene (~4.5 Ma to 2.6 Ma), when sea-level was significantly higher than present (Richards, 1974; Ward and Blackwelder, 1980; Blackwelder, 1981b; Gibson, 1970; Ward, 2008; Dowsett et al., 2016). Global sea-levels ranging from +0 m to upwards of +50 m above current have been estimated for the Piacenzian (Dowsett et al., 2010). The high variation in mid-Pliocene eustatic sea-level estimations is attributable to the dynamic topography of Earth's surface due to mantle convection, a lack of direct evidence for polar ice volume, and regional differences in glacial isostasy (Rovere et al., 2014; Dowsett et al., 2016; Miller et al., 2019). Recent estimations of Pliocene global mean sea-level rise based on Mg/Ca ratios and $\delta^{18}O$ from Pacific benthic foraminiferal tests are ~10–20 m but have a high margin of error (upwards of $\pm$15 m; Miller et al., 2019), though the PRISM3 reconstruction (3.264–3.025 Ma) found that a +25 m rise in global mean sea-level relative to present-day is supported by all available, previously published data (Dowsett et al., 2010).

During the Yorktown transgressions, the structural impact of the Norfolk Arch was negligible; the Salisbury and Albemarle Embayments acted as one depocenter, and marine sediments were deposited on top of the Norfolk Arch during the maximum transgressive phase (Gibson, 1970; Cronin et al., 1989; Ward, 1989). Deposits of the Yorktown Formation are widespread throughout southeastern Virginia and northeastern North Carolina. Marine deposits of the Yorktown do not extend northward into Maryland at the surface but have been recovered from wells in Somerset County, MD (McLean, 1950; Mixon, 1985). Time-equivalent deposits south of the Neuse River Basin in North Carolina are attributed to the Duplin Formation (Vaughan, 1924; Richards, 1974; Olsson et al., 1988; Cronin et al., 1989). Richards (1974) suggested that the Cohansey Formation may represent a non-marine equivalent of the Yorktown Formation in New Jersey.

Lithostratigraphic correlation of the Yorktown Formation outside of the York-James Peninsula is difficult to establish due to the highly variable areal distribution and lithology of the members. The upper surface of Yorktown Formation has a general eastward dip, rising from below sea level east of the Chesapeake Bay to ~40 m above sea level at its western limit near Petersburg, Virginia (Oaks et al., 1974; Cronin et al., 1989). It is recognized in Virginia as having a moderate glauconite content (Sunken Meadow and Rushmere members), having a composition of blue clay with yellow-brown saprolites at the top of the unit in eastern outcrops (Morgarts Beach Member), and by the variety, abundance, and types of fossils in the unit (Oaks et al., 1974). In areas that lack fossils, the Yorktown Formation is often indistinguishable from the underlying Eastover Formation in outcrop (Hobbs, 2009). The absence of the Yorktown Formation on the Delmarva Peninsula (across the Chesapeake Bay to the northeast) is attributed to erosion, rather than nondeposition (Mixon, 1985). In northern North Carolina, deposits of the Yorktown Formation separated into two units suggesting that only two phases of transgression are recorded for the Pliocene in the Albemarle Embayment (Daley, 1999).

Previous Work

Initial investigations of Miocene and post-Miocene stratigraphy in the ACP began in the 1800s and were mainly generalizations with few regional correlations (Oaks and Dubar, 1974). These early studies were scattered, with few workers mapping more than one state. One exception to this was Finch's (1823) correlation of strata "in the banks of the James River, Va" (now called the Yorktown Formation) with the London Clay in England, based chiefly on the presence of fossil shark teeth in both units. In the 1830s, workers such as Lea (1833) and Rogers (1836) proposed that some of the exposed Tertiary strata were Miocene to Pliocene in age—findings that were later supported by numerous workers. Throughout the later 1800s, the fossil-rich strata around Yorktown, Virginia, were popular with biostratigraphers attempting to make stratigraphic correlations. Many initial biostratigraphic correlations of the sediments exposed in Maryland and Virginia were largely incorrect due to the collection of specimens without field notes (Daley, 1999).

Investigations over the first half of the 20th Century (1900–1950) used Shattuck's (1901, 1902, 1906) "terrace-formation" hypothesis as the basis for correlation methodologies; these studies used morphologic analysis in preference to stratigraphic analysis wherein "terraces" were inferred from early geologic and topographic maps and separated by eastward-dipping scarps. Previous sea-level positions were assumed to be at the toe of each scarp and lateral correlation between New Jersey and Florida was based on the altitude range of the surface of "morphostratigraphic units" defined in these studies (Oaks and DuBar, 1974). Few studies detailed stratigraphic relations of post-Miocene units as this was widely considered to be unnecessary during this time. The earliest official descriptions of the Yorktown Formation were made by Clark and Miller (1906) along the York and James Rivers near Yorktown, Virginia;

however, those studies did not clearly designate a type locality for the unit and attributed it to the Miocene but did distinguish it from the underlying St. Mary's Formation (Johnson, 1969).

Around this time, the earliest foraminiferal assemblage work on the Yorktown Formation sediments was being conducted near Suffolk and Yorktown, Virginia (Cushman, 1918). Cushman (1918) noted that the faunas attributed to the Duplin Formation—a time-equivalent unit of the Yorktown Formation—in South Carolina distinctly differed from those of the Yorktown Formation of Virginia. This was also observed in macrofossil assemblages, leading workers to conclude that there was a climatic variation between the northern and southern basins (Daley, 1999).

Throughout the 1930s, 1940s, and 1950s, workers such as Cushman and Cahill (1933), Dorsey (1948), Anderson (1952), and McLean (1956) continued to refine the benthic foraminiferal taxonomy of Miocene units—including the Yorktown Formation—throughout Maryland and Virginia. Early stratigraphic distinction between beds within the unit made by Mansfield (1931, 1943) was based on invertebrate paleontologic observations, lacked lithostratigraphic descriptions, and separated the Yorktown Formation into faunal zones instead of lithologic units. Post-1950 geologic investigations of the ACP shifted toward stratigraphic analysis beginning with Darton (1951), Hack (1955), and Potter (1955) in Maryland. Surficial extension of the Yorktown Formation into Maryland was proposed by Stephenson and MacNeil (1964); however, the evidence presented was widely considered insubstantial and this extension of the Yorktown was rejected. McLean (1950) proposed that the Yorktown could be present in the subsurface based on observation of sediments recovered from a well drilled at Crisfield, MD but he felt that the absence of foraminifera in this unit was not enough to separate it from the underlying St. Mary's Formation. Johnson (1969) subdivided the Yorktown Formation into eight facies designated by lithologic features but did not use a formal designation for the individual units.

By the 1970s, microfossil workers reassigned the Yorktown Formation to the Pliocene; Hazel (1971) based the reassignment on ostracods, and Akers (1972) correlated the Jackson Bluff Formation (Florida) with the Yorktown Formation, assigned to planktic foraminiferal zones N18–N19 (Hazel, 1977). The development of ostracode biozonation of the Yorktown Formation by Hazel (1971, 1977) provided a framework to correlate the Yorktown Formation with a global time scale (Cronin et al., 1984; Cronin et al., 1989). The planktic foraminiferal assemblage of the Yorktown Formation from Virginia to North Carolina has been well documented in several studies (e.g., Gibson, 1983; Snyder et al., 1983; Cronin et al., 1984; Dowsett and Wiggs, 1992). These studies refined the age range of the Yorktown, collectively placing the unit in planktic zones N19–N21 (~4.8–2.8 Ma; Cronin et al., 1984).

Ward and Blackwelder (1980) contributed the first formal definition and designation of lithostratigraphic units within the Yorktown Formation. They recognized that the deposition of the sediments comprising the Yorktown Formation is largely controlled by similar geomorphological conditions as the Miocene sediment packages but noted that the Yorktown is Pliocene in age, not Miocene as previously thought. Ward and Blackwelder (1980) named and described four members within the Yorktown Formation using lithostratigraphic principles and assigned a lectostratotype locality near Rushmere, Isle of Wight County, Virginia (Rushmere Locality of this study). The basal Sunken Meadow Member corresponds to Mansfield’s Zone 1, while the overlying Rushmere, Morgarts Beach, and Moore House members correspond to Mansfield’s Zone 2 (Ward and Blackwelder, 1980).

Methods and Materials

Sample Collection

A total of 45 samples were collected for this project. Thirty-six samples were collected from the lectotype locality of the Yorktown Formation at Rushmere, near Smithfield, Virginia, on Oct. 19th, 2018 (Rushmere, Fig. 1; Appendix A); this location is also designated as the type locality for the Rushmere Member by Ward and Blackwelder (1980). Three sections of exposed cliffs, roughly 20 m apart, on the right bank of the James River, were scraped clean to reveal fresh, unweathered surfaces for sampling. At the base of the cliff, roughly 1 m of the Rushmere Member was exposed, with ~ 6 m of the Morgarts Beach Member conformably overlying the Rushmere. At each section, three samples were collected from the Rushmere Member, spaced 30 cm apart vertically, and six samples were taken from the Morgarts Beach Member, spaced 50 cm apart vertically. The Moore House Member, overlying the Morgarts Beach Member, was exposed but inaccessible near the top of the cliff. Several samples were taken from slump blocks of this indurated unit on the beach. The Sunken Meadow Member, the basal member of the Yorktown Formation and underlying the Rushmere Member, was accessed by digging below beach level at the base of the cliffs. Three holes, one for each cliff section, were dug to ~70 to 90 cm deep. Two samples per hole were taken between 35 and 80 cm beneath the Sunken Meadow/Rushmere contact. Distinction between the Sunken Meadow and Rushmere members in the field was based on the presence of *Chesapecten jeffersonius* and the absence of *Chesapecten madisonius* in the Sunken Meadow Member. *Chesapecten jeffersonius* is common throughout the Sunken Meadow Member and absent in the overlying sediments of the Rushmere Member, where *C. madisonius* dominates (Ward, 2008). Outcrop sections from the Rushmere locality were graphically logged using the methodology of Farrell et al. (2012, 2013).

Three additional samples of the Morgarts Beach Member and one additional sample of the Moore House Member were collected from the Rushmere Member type locality, on March 16th, 2019. These samples were collected in a single transect and are stratigraphically higher than the samples collected from the Morgarts Beach Member in October, 2018. A second field site (Pipsico) with access to the Sunken Meadow Member, near the Pipsico Boy Scout Camp, Spring Grove, Virginia, was sampled by USGS geologists (H. Dowsett and K. Foley) in March of 2019 (Figs. 1–2). Five additional samples of the Sunken Meadow Member were collected from this location, stratigraphically below the samples collected at Rushmere in October, 2018. Due to the poor condition of the outcrops at the field sites, attributed to a wetter than average winter, only one transect was sampled at Pipsico, and the section was not logged using the methodology in Farrell et al. (2012, 2013). Access to the outcrop was limited by several large slumps, preventing a regular sampling interval; roughly 1 m of the exposed Sunken Meadow Member was sampled.

Microfossil Sample Preparation

Bulk sediment samples collected in the field were dried in an oven overnight at 40°C. Fifty grams of each dried sample were weighed to be used for foraminiferal analysis. Each 50 g aliquot was processed as follows: samples were soaked for roughly 24 hours in a dilute solution of distilled water with 0.15 grams of caustic soda (NaOH) and 0.15 grams of sodium hexametaphosphate ($Na(PO_3)_6$) to disaggregate silts and clays. After soaking, samples were wet-sieved over stacked 8-inch #25 and #230 U.S. Standard Sieve (710 μm and 63 μm openings, respectively) to remove mud and larger mollusk shell fragments. Both size fractions (>710 μm and 63–710 μm) were then dried overnight in the oven. This process was repeated two to three times as needed until all mud was removed from samples. For the indurated shell hash of the

Moore House Member, large bulk samples taken from slump blocks were rinsed to remove loose sand and particles to minimize potential contamination from the modern beach sand. Bulk samples were then broken (not crushed) into roughly sand-sized particles using a mortar and pestle and soaked following the procedure outlined above.

Sieves were rinsed and sprayed with a dilute solution of Methylene blue after each sample was wet-sieved to avoid cross-contamination between samples. Sieved samples were split and picked at random to obtain 300 specimens of benthic foraminifera from the 63–710 μm size fraction (Appendix B); all planktic foraminifera were picked from the same split fraction to enable calculation of planktic/benthic ratios (%planktics) and for later identification by USGS personnel.

Benthic foraminifera species were identified by comparing specimens with SEMs and illustrations in the published literature (e.g., Cushman, 1918; Cushman and Cahill, 1933; Dorsey, 1948; Anderson, 1952; McLean, 1956; Todd and Low, 1981, Gibson, 1983; Snyder et al., 1988; Culver and Goshorn, 1996). Identification of the most abundant species was confirmed by comparison with type specimens in the Cushman Collection, Smithsonian Institution, Washington, D.C.

Grain-size Analysis

Thirty-gram aliquots of sediment per sample were processed using the wet-sieving technique outlined above. The >63 μm size fraction was dry-sieved at half-phi intervals using a RO-TAP sieve shaker with a sieve stack ranging from -2 phi to 4 phi (ϕ; 4 mm to 63 μm, respectively; Appendix C). Weight percent of the >63 μm size fraction was calculated for each sample and entered into the GRADISTAT worksheet, following the protocol documents in Blott and Pye (2001). Modal grain-size was visually estimated for each sample using histograms (Appendix D). Weight percentages of grain-sizes smaller than 4 ϕ (mud) are estimated using the difference between bulk and washed sample weights. Grain-size analysis was not calculated for the three indurated samples of the Moore House Member; mechanical fragmentation of the samples prior to wet-sieving would introduce bias in grain-size distribution.

Foraminiferal Abundance Data Analysis

Relative abundances of species were calculated from foraminiferal census data for 33 samples; species richness and percent Textulariina, Miliolina, and Rotaliina were calculated for each sample. Q-mode cluster analysis (Mello and Buzas, 1968) was used to distinguish groups within relative abundance data. Species represented by 3% or more of the assemblage in one or more samples were included in the cluster analysis dataset. Twelve samples (11 Morgarts Beach Member and one Moore House Member) were barren. Prior to analysis, relative abundance data were transformed using the equation $2\,arc\sin\sqrt{p_i}$ (Buzas, 1979), where p_i is equal to the fraction of the ith species. All samples were analyzed together using Ward's linkage and Euclidean distances in PAST4 (Paleontological Statistics, Version 4.03 Software, Hammer, Ø, Natural history Museum, University of Oslo, 2020).

Results

Sedimentological Data

The Yorktown Formation is largely composed of bioclastic (molluscan shells), silty sands and sandy muds (Fig. 5 and Fig. 6). In outcrop, the sediments vary in color from greenish grey to blue grey to yellowish brown. Few sedimentary structures are visible at the outcrop level in the Yorktown Formation across its entire areal distribution, though scour and fill structures, burrowing, and cross-bedding are observable along the York River (Johnson, 1972). No sedimentary structures are visible in outcrop at the sites accessed for this study. Large molluscan fossils dominate throughout the entire unit, with the exception of the Morgarts Beach Member, which has significantly lower abundances of macrofossils than the other three members. The thickness of the formation varies from >12 m in eastward exposures to a few cm towards the fall line to the west (Ward and Blackwelder, 1980).

Overall, mean grain-size for the >63 μm size-fraction of the members of the Yorktown Formation plot into two distinct groups: the Sunken Meadow, Rushmere and Moore House members range between ~1 to 2 phi (ϕ) and the Morgarts Beach Member ranges between ~2.5 to 3.5ϕ (Fig. 6). Mean grain-size for the Morgarts Beach Member is >4ϕ when the mud-sized fraction is included in the analysis (Appendix E). Values for sorting (σ_I; Fig. 6) generally plot between ~1 to 2σ, with the highest values occurring in the Rushmere Member; values <1σ occur in the lower section of the Morgarts Beach Member. Average percent sand values also plot into two distinct groups, with the Sunken Meadow, Rushmere and Moore House members containing ~70% of sand-sized grains and the Morgarts Beach Member containing <40% of sand-sized grains (Fig. 6).

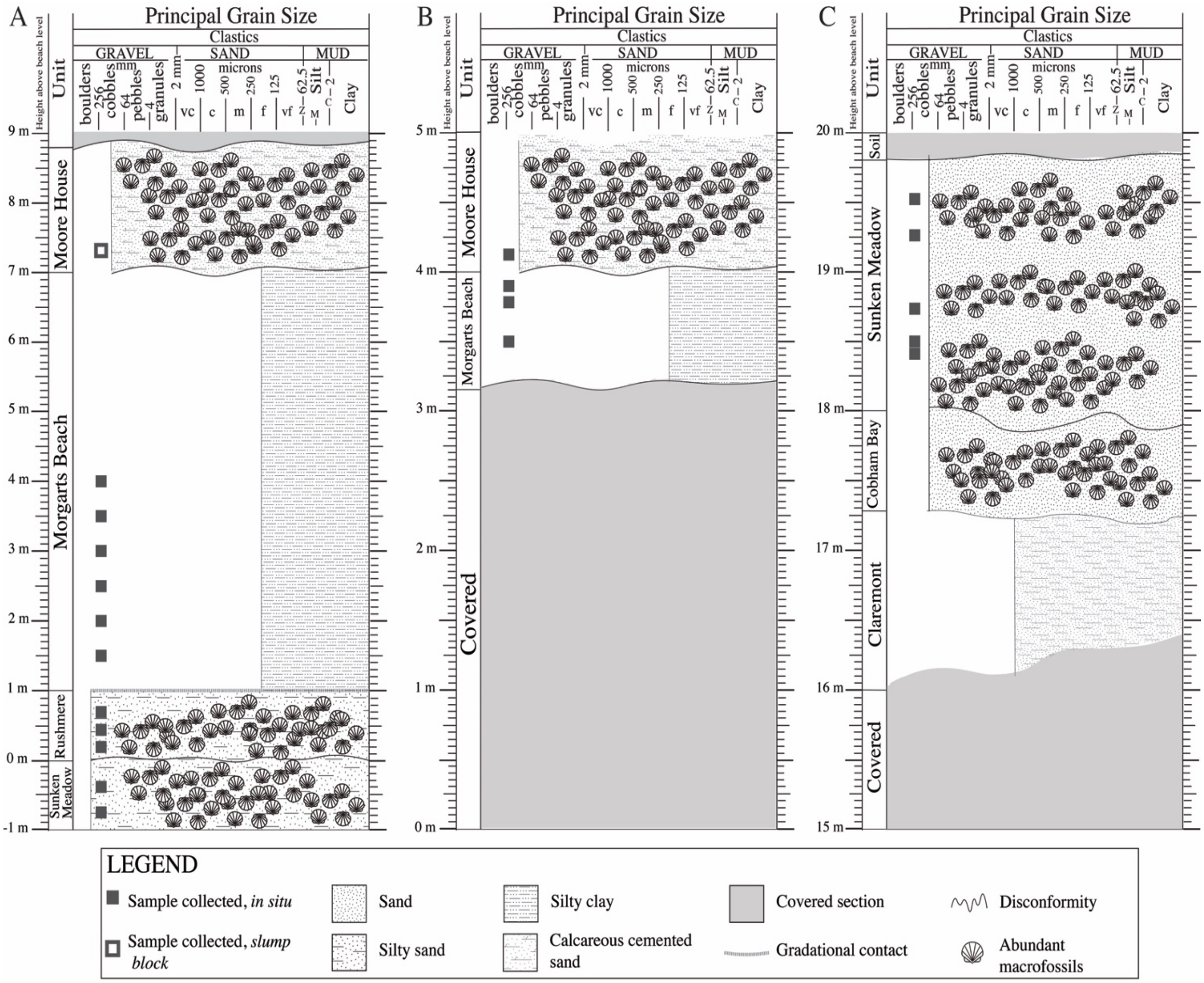

Figure 5: Stratigraphic logs of the sampled outcrops. Graphic log modified from Farrell et al., 2013. **A.** Composite log of the three transects sampled at Rushmere, VA in October 2018. **B.** Log based on field notes taken during March 2019 sampling at Rushmere, VA. **C.** Log based on field notes taken during March 2019 sampling at Pipsico, VA. Note that portions of the sections accessed during the March 2019 sampling were obscured by slumps due to poor weather prior to sampling.

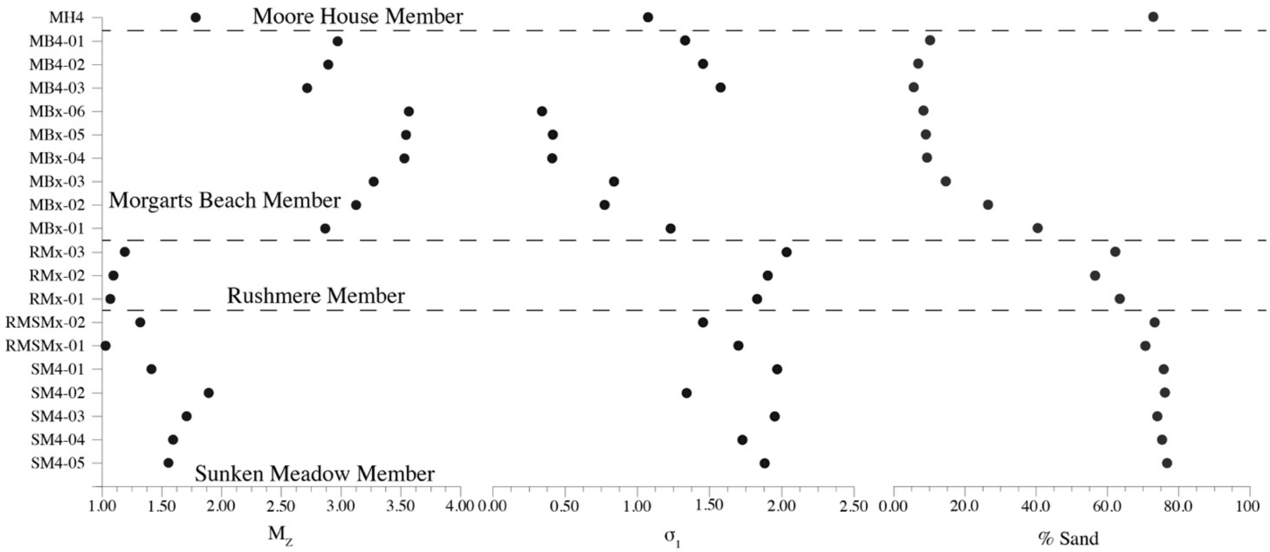

Figure 6: Sediment characteristics arranged stratigraphically. Left: Mean grain-size of the >63 μm size fraction in phi (ϕ, M_z) for all samples. Center: Average sorting value calculated from grain-size distribution of the >63 μm size fraction in phi (σ_I). Right: Average percent sand for all samples. Where replicates are averaged, the sample name is designated with a lower-case x (e.g., RMx-01).

Sunken Meadow Member

The Sunken Meadow Member is the basal unit of the Yorktown Formation; it is bounded by unconformities, between the underlying Cobham Bay Member of the Eastover Formation and the overlying Rushmere Member. This unit is a greenish-grey, shelly, muddy sand in outcrop and averages ~3 m in thickness (Ward and Blackwelder, 1980). Large mollusks (>10 cm) are common throughout the unit.

At Pipsico, the Sunken Meadow Member is composed of poorly sorted, medium sand (Table 1; Appendix C; Appendix D). The sands are largely sub-rounded quartz, with minor glauconite, phosphates, and shell fragments. Mean grain-size of the >63 μm size-fraction ranges from ~1.5 to 2 phi (ϕ; ~260–375 μm; Table 1; Fig. 6). The distribution of grains is very coarse skewed and leptokurtic to very leptokurtic (Table 1). At Rushmere, the upper Sunken Meadow is composed of poorly sorted, coarse to medium sand (Table 1) dominated by sub-rounded to rounded quartz with minor glauconite, phosphate, and micas. Shell fragments are also abundant. The mean grain-size ranges from ~ 0.7 to 2 ϕ (~280–600 μm; Table 1, Fig. 6). The distribution of grains is very coarse skewed and platykurtic to very leptokurtic (Table 1). The mode for all Sunken Meadow samples ranges from 2 to 3.5 ϕ (88–250 μm; Table 1, Appendix D). One sample (SM4-02) is bi-modal, with most grains equally distributed between 2–2.5 ϕ and 2.5–3 ϕ (Appendix D). The average percent sand for the Sunken Meadow Member ranges from ~70% to 76% (Fig. 6; Appendix C).

Table 1: Summary table of grain-size characteristics (>63 μm size-fraction) for the Sunken Meadow Member calculated using the Folk and Ward method. M_z, mean phi size; σ_I, sorting (based on phi size); Mode ϕ, mode phi size; M_G, mean micron size; σ_G, sorting (based on micron size); Mode, mode micron size. Modes are visually determined from the histograms in Appendix D.

Sample Name	*φ*			*μm*			*Description*			
	M_z	σ_I	Mode	M_G	σ_G	Mode	Mean	Sorting	Skewness	Kurtosis
RMSM1-02	1.820	1.004	2–2.5	283.3	2.005	177–250	Medium sand	Poorly sorted	Very coarse skewed	Very leptokurtic
RMSM2-02	1.247	1.521	2–2.5	421.2	2.871	177–250	Medium sand	Poorly sorted	Very coarse skewed	Very leptokurtic
RMSM3-02	0.892	1.830	2–2.5	538.9	3.55	177–250	Coarse sand	Poorly sorted	Very coarse skewed	Leptokurtic
RMSM1-01	1.688	1.280	2–2.5	310.5	2.428	177–250	Medium sand	Poorly sorted	Very coarse skewed	Very leptokurtic
RMSM2-01	0.696	1.914	2–2.5	617.3	3.770	177–250	Coarse sand	Poorly sorted	Very coarse skewed	Platykurtic
RMSM3-01	0.695	1.897	2–2.5	617.7	3.724	177–250	Coarse Sand	Poorly sorted	Very coarse skewed	Platykurtic
SM4-01	1.412	1.964	2–2.5	375.5	3.900	177–250	Medium sand	Poorly sorted	Very Coarse Skewed	Leptokurtic
SM4-02	1.895	1.338	2–2.5 2.5–3	268.9	2.528	177–250 125–177	Medium sand	Poorly sorted	Very coarse skewed	Very leptokurtic
SM4-03	1.709	1.947	3–3.5	305.9	3.855	88–125	Medium sand	Poorly sorted	Very coarse skewed	Very leptokurtic
SM4-04	1.595	1.724	2.5–3	330.9	3.303	125–177	Medium sand	Poorly sorted	Very coarse skewed	Very leptokurtic
SM4-05	1.557	1.878	3–3.5	339.8	3.677	88– 125	Medium sand	Poorly sorted	Very coarse skewed	Very leptokurtic

Rushmere Member

The Rushmere Member is almost indistinguishable from the underlying Sunken Meadow Member in some areas. It is a greenish-grey to blue-grey shelly, muddy fine sand in outcrop. At

Rushmere, the average thickness of this unit is ~2 m, with the contact between the Sunken Meadow Member occurring roughly 1 m below beach level; the upper contact with the overlying Morgarts Beach Member is gradational. Macrofossils are abundant and consist of mollusks, dominated by *Chesapecten madisonius,* and scleractinian corals. This unit is composed of very poorly to poorly sorted, medium to coarse sand, dominated by sub-rounded to rounded quartz, with abundant phosphates, glauconite, shell fragments, and echinoderm spines. Micas are also present. Mean grain-size of the >63 μm size-fraction ranges from ~ 0.8 to 1.2 ϕ (~435–570 μm; Table 2, Fig. 6). The distribution of grains is very coarse skewed throughout the unit and varies from mesokurtic to very leptokurtic. The modal grain-size for all Rushmere Member samples is 2 to 2.5 ϕ (Table 2; Appendix D). Average percent sand ranges from ~56–63% (Fig. 6; Appendix C).

Table 2: Summary table of grain-size characteristics (> 63 μm size fraction) for the Rushmere Member calculated using the Folk and Ward method. M_z, mean phi size; σ_I, sorting (based on phi size); Mode ϕ, mode phi size; M_G, mean micron size; σ_G, sorting (based on micron size); Mode, mode micron size. Modes are visually determined from the histograms in Appendix D.

Sample Name	*φ*			*μm*			*Description*			
	M_z	σ_I	Mode	M_G	σ_G	Mode	Mean	Sorting	Skewness	Kurtosis
RM1-03	1.566	1.784	2–2.5	337.7	3.443	177-250	Medium sand	Poorly sorted	Very coarse skewed	Very leptokurtic
RM2-03	1.188	2.133	2–2.5	439.0	4.385	177–250	Medium sand	Very poorly sorted	Very coarse skewed	Leptokurtic
RM3-03	0.813	2.170	2–2.5	569.2	4.500	177–250	Coarse sand	Very poorly sorted	Very coarse skewed	Very platykurtic
RM1-02	1.201	1.738	2–2.5	435.0	3.336	177–250	Medium sand	Poorly sorted	Very coarse skewed	Leptokurtic
RM2-02	0.900	2.162	2–2.5	535.9	4.475	177–250	Coarse sand	Very poorly sorted	Very coarse skewed	Very platykurtic
RM3-02	1.181	1.795	2–2.5	441.2	3.470	177–250	Medium sand	Poorly sorted	Very coarse skewed	Mesokurtic
RM1-01	1.185	1.500	2–2.5	439.7	2.828	177–250	Medium Sand	Poorly sorted	Very coarse skewed	Leptokurtic
RM2-01	0.811	1.905	2–2.5	570.1	3.746	177–250	Coarse sand	Poorly sorted	Very coarse skewed	Mesokurtic
RM3-01	1.204	2.072	2–2.5	434.0	4.204	177–250	Medium sand	Very poorly sorted	Very coarse skewed	Mesokurtic

Morgarts Beach Member

The Morgarts Beach Member conformably overlies the Rushmere Member and is a grey to blue-grey, slightly sandy clay that is yellowish-brown when weathered. Small bivalves (*Mulinia* spp.) and gastropods (*Turritella* spp.) are common throughout the unit. The sands are composed of sub-round to round fine quartz grains, with some glauconite, micas and abundant foraminifera, ostracodes, and echinoderm spines and plates. Where weathered, brownish grains are abundant, and fossil material is absent in washed residues.

Grain-size analysis (Table 3) of samples shows that the >63 μm size-fraction of the Morgarts Beach Member is generally a poorly sorted to very well sorted fine to very fine sand with mean grain-size ranging from ~ 2.7 ϕ to 3.6 ϕ (~82–151μm; Fig. 6; Table 3). Distribution of grains is coarse to very coarse skewed and generally ranges from mesokurtic to leptokurtic and very leptokurtic throughout the unit with the exception of one sample, MB2-02, which is platykurtic. All Morgarts Beach Member samples have a modal grain-size of 3.5 to 4 ϕ for the >63 μm size-fraction (Table 3; Appendix D); when the <63 μm size-fraction is included in grain-size distribution, modal grain size is >4 ϕ (<63 μm; Appendix E). Mean percent sand ranges from ~40% at the base of the unit to ~7% at the top (Fig. 6; Appendix C).

Table 3: Summary table of grain-size statistics (>63 μm size-fraction) for the Morgarts Beach Member calculated using the Folk and Ward method. M_z, mean phi size; σ_I, sorting (based on phi size); Modeϕ, mode phi size; M_G, mean micron size; σ_G, sorting (based on micron size); Mode, mode micron size. Modes are visually determined from the histograms in Appendix D.

Sample Name	*φ*			*μm*			*Description*			
	M_z	σ_I	Mode	M_G	σ_G	Mode	Mean	Sorting	Skewness	Kurtosis
MB4-01	2.976	1.328	3.5–4	127.1	2.511	63–88	Fine sand	Poorly sorted	Very coarse skewed	Very leptokurtic
MB4-02	2.900	1.452	3.5–4	133.9	2.736	63–88	Fine sand	Poorly sorted	Very coarse skewed	Very leptokurtic
MB4-03	2.722	1.573	3.5–4	151.6	2.975	63–88	Fine sand	Poorly sorted	Very coarse skewed	Leptokurtic
MB1-06	3.556	0.341	3.5–4	84.01	1.267	63–88	Very fine sand	Very well sorted	Very coarse skewed	Mesokurtic
MB2-06	3.553	0.395	3.5–4	85.18	1.315	63–88	Very fine sand	Well sorted	Very coarse skewed	Leptokurtic
MB3-06	3.606	0.285	3.5–4	82.14	1.218	63–88	Very fine sand	Very well sorted	Coarse skewed	Mesokurtic
MB1-05	3.579	0.305	3.5–4	83.73	1.235	63–88	Very fine sand	Very well sorted	Coarse skewed	Mesokurtic
MB2-05	3.550	0.399	3.5–4	85.39	1.319	63–88	Very fine sand	Well sorted	Very coarse skewed	Leptokurtic
MB3-05	3.531	0.537	3.5–4	86.50	1.451	63–88	Very fine sand	Moderately well sorted	Very coarse skewed	Very leptokurtic
MB1-04	3.568	0.309	3.5–4	84.29	1.239	63–88	Very fine sand	Very well sorted	Coarse skewed	Mesokurtic
MB2-04	3.510	0.476	3.5–4	57.77	1.391	63–88	Very fine sand	Well sorted	Very coarse skewed	Leptokurtic
MB3-04	3.544	0.445	3.5–4	85.74	1.361	63–88	Very fine sand	Well sorted	Very coarse skewed	Very leptokurtic
MB1-03	3.506	0.474	3.5–4	88.00	1.389	63–88	Very fine sand	Well sorted	Very coarse skewed	Leptokurtic
MB2-03	3.263	0.690	3.5–4	104.2	1.613	63–88	Very fine sand	Moderately well sorted	Very coarse skewed	Leptokurtic
MB3-03	3.074	1.346	3.5–4	118.7	2.542	63–88	Very fine sand	Poorly sorted	Very coarse skewed	Very leptokurtic
MB1-02	3.146	0.759	3.5–4	113.0	1.692	63–88	Very fine sand	Moderately sorted	Very coarse skewed	Mesokurtic
MB2-02	3.050	0.834	3.5–4	120.8	1.783	63–88	Very fine sand	Moderately sorted	Very coarse skewed	Platykurtic
MB3-02	3.206	0.721	3.5–4	108.4	1.648	63–88	Very fine sand	Moderately sorted	Very coarse skewed	Leptokurtic
MB1-01	2.88	1.114	3.5–4	135.1	2.164	63–88	Fine sand	Poorly Sorted	Very coarse skewed	Mesokurtic
MB2-01	2.809	1.332	3.5–4	142.7	2.517	63–88	Fine sand	Poorly sorted	Very coarse skewed	Leptokurtic
MB3-01	2.927	1.242	3.5–4	131.5	2.365	63–88	Fine sand	Poorly Sorted	Very coarse skewed	Leptokurtic

Moore House Member

The Moore House Member is the uppermost unit of the Yorktown Formation. It unconformably overlies the Morgarts Beach Member in the area around Yorktown, Va. This unit is largely inaccessible in outcrop, due to vegetation cover and a lack of ability to access the top of exposed cliffs but can be present in slump blocks at ground level; one *in situ* and three slump block samples were collected for this study from Rushmere, Va. The Moore House Member is often semi- to completely indurated and, as such, grain-size analysis was not possible on three of the four samples collected. Mechanical separation of indurated grains by crushing larger pieces would skew results toward smaller size fractions.

In outcrop, the Moore House Member is an orangish-brown shell hash that is dominated by large bivalve and barnacle fossils but with some sub-rounded quartz sand. Fragments of mollusks, bryozoa, and other marine organisms are abundant. The >63 μm size-fraction of the unlithified sample is composed of poorly sorted, medium sands (Table 4, Fig. 6); large fossils were not present in this sample. Distribution of grains is fine skewed and leptokurtic for this sample (Table 4). This sample is bimodal, with modal grain-size for the >63 μm size-fraction evenly distributed between 1–2 ϕ (Table 4; Appendix D) Percent sand for this sample is ~73% (Fig. 6; Appendix C).

Table 4: Summary table of grain-size statistics (>63 μm size-fraction) for the Moore House Member calculated using the Folk and Ward method. M_z, mean phi size; σ_I, sorting (based on phi size); Mode ϕ, mode phi size; M_G, mean micron size; σ_G, sorting (based on micron size); Mode, mode micron size. Modes are visually determined from the histogram in Appendix D.

Sample Name	*φ*			*μm*			*Description*			
	M_z	σ_I	Mode	M_G	σ_G	Mode	Mean	Sorting	Skewness	Kurtosis
MH4	1.784	1.072	1–1.5 1.5–2	290.4	2.103	250-500	Medium sand	Poorly sorted	Fine skewed	Leptokurtic

Foraminifera: General Characteristics

The highest average percentage of planktic foraminifera in foraminiferal assemblages (%P; Fig. 7) occurs in the Rushmere Member (4.49%, Table 5); and the lowest values occur in the Moore House Member (~0–1%; Table 5). Planktic and benthic foraminifera are most abundant in the Morgarts Beach Member (Fig. 7; left). Calculated numbers of benthic foraminifers per 1g of sediment range from ~13 (in the Moore House Member) to upwards of 24,000 in the Morgarts Beach Member (Table 5). Calculated numbers of planktic foraminifers per 1g of sediment range from ~0 to 76 (Table 5).

Relative proportions of test type are plotted in Figure 7 (right); Rotaliids dominate the benthic foraminiferal assemblage for all samples, ranging from ~80% to 100% (Table 5; Fig. 7). Agglutinated foraminifera are most abundant in the Moore House Member (Fig. 7; Table 5), but also occur in relatively high proportions in the upper Sunken Meadow Member (Fig. 7; Table 5). Textulariids do not exceed 15% of the assemblage in any sample. Miliolids are the least abundant test type in all samples (Table 5, Fig. 7); the highest percentage occurs in the Moore House Member (6% in MH2; Table 5), with an overall average of ~2.5% for the unit. Miliolids are absent in the Morgarts Beach Member, and do not exceed 2% of the foraminiferal assemblage in either the Rushmere or Sunken Meadow members, averaging ~1% in these two units (Table 5; Fig. 7).

The average of both Fisher's alpha (α) and Shannon's diversity index (H) for benthic foraminiferal data follow the same general pattern when plotted (Fig. 8) and range from ~3.00 to 8.00 (α) and ~2.00 to 2.60 (H), respectively. Average values for species diversity are lowest in the muddy Morgarts Beach Member and relatively high by comparison in the sandy Sunken Meadow and Moore House members (Fig. 8). Average values for evenness (E) range from ~0.30

to 0.50 (Fig. 8) with the lowest values occurring in the Sunken Meadow Member and the highest values occurring in the Morgarts Beach Member (Table 5).

Preservation of foraminifera is highly variable in the Morgarts Beach Member at Rushmere. Eleven out of 21 samples collected from this unit were barren of foraminifera and lacked fossil material (ostracodes, echinoderm spines, macrofossil fragments, etc.) that was present in non-barren samples. The Morgarts Beach Member is visibly weathered in outcrop at Rushmere; the grey muds sharply transition to yellowish-brown saprolites in the upper ~4 m of the unit. This phenomenon was studied in detail by Herman (1987) and attributed to groundwater leaching.

Table 5: Values for foraminiferal assemblage characteristics by sample. Samples are in stratigraphic order, with replicates grouped together. Grey bars separate Yorktown Formation members. CG, cluster group; n, number of specimens picked, S, number of species; Bf/g, calculated number of benthic foraminifera per 1g of sediment; Pf/g, calculated number of planktic foraminifera per 1g of sediment, %P, percent of planktic foraminifera; t, number of agglutinated species; m, number of miliolid species; r, number of rotaliid species; %t, percent of textulariids; %m, percent of miliolids; %r, percent of rotaliids; α, Fisher's alpha; H, Shannon's diversity index; *E*, evenness (Buzas and Gibson, 1969).

Sample Name	**CG**	**n**	**S**	**Bf/g**	**Pf/g**	**%P**	**t**	**m**	**r**	**%t**	**%m**	**%r**	**α**	**H**	***E***
MH1	5	299	24	13.43	0	0	2	1	21	11.71	0.33	87.96	6.217	2.462	0.4889
MH2	5	287	24	15.22	0.11	0.69	2	2	20	15.33	6.27	78.40	6.441	2.446	0.4811
MH3	5	288	29	27.40	0.29	1.03	2	0	27	11.11	0.00	88.89	8.251	2.767	0.5485
MB2-06		288	14	918.84	3.19	0.35	0	0	14	0	0	100.00	2.886	1.624	0.4223
MB2-05	3	320	16	4576.88	14.30	0.31	0	0	16	0.31	0	99.69	3.657	1.956	0.442
MB2-04	3	296	18	4253.04	14.37	0.34	1	0	17	0.68	0	99.32	4.398	2.12	0.4626
MB2-03	3	292	21	5572.96	9.54	0.34	1	0	20	0.68	0	99.32	5.368	2.2	0.4298
MB1-02	4	310	21	5007.57	0	0	1	0	20	2.26	0	97.74	5.271	2.176	0.4195
MB2-02	3	312	19	7912.82	76.08	1.89	0	0	19	0	0	100.00	4.578	2.143	0.4485
MB3-02	3	311	20	24633.75	14.33	0.32	1	0	19	0.64	0	99.36	4.886	2.087	0.403
MB1-01	4	297	22	4276.80	72.00	1.66	0	0	22	0	0	100.00	5.648	2.066	0.3588
MB2-01	4	314	21	1062.42	67.67	1.57	1	0	20	0.32	0	99.68	5.205	2.251	0.4523
MB3-01	4	271	19	2524.50	75.47	1.81	1	0	18	0.74	0	99.26	4.823	2.206	0.4777
RM1-03	6	305	19	346.47	7.95	2.24	1	0	18	1.64	0	98.36	4.568	2.285	0.5172
RM2-03	4	333	22	512.86	9.24	1.77	1	0	21	0.30	0	99.70	5.487	2.389	0.4957
RM3-03	6	322	25	651.16	6.95	2.13	1	0	24	0.62	0	99.38	6.583	2.394	0.4384
RM1-02	6	283	21	161.00	6.83	4.07	1	1	19	4.24	0.35	95.41	5.29	2.348	0.4981
RM2-02	6	329	26	416.87	15.20	3.52	2	0	24	1.52	0	98.48	6.891	2.35	0.4033
RM3-02	6	298	23	346.40	8.95	4.49	1	1	21	1.01	0.34	98.66	6.381	2.482	0.4987
RM1-01	1	241	28	38.56	1.28	3.21	2	1	25	11.20	2.07	86.72	8.243	2.728	0.5465
RM2-01	6	275	26	154.71	3.94	2.48	1	1	24	1.82	0.36	97.82	7.309	2.599	0.5172
RM3-01	4	301	26	1412.61	11.24	2.27	1	1	24	1.99	0.33	97.67	7.02	2.457	0.4487
RMSM1-02	1	323	25	103.36	1.60	1.52	2	2	21	6.19	1.24	92.57	6.405	2.2	0.3609
RMSM2-02	1	348	25	217.46	4.37	1.97	2	1	22	8.91	1.44	89.66	6.281	2.538	0.506
RMSM3-02	1	295	23	431.41	3.41	1.34	2	2	19	14.92	1.69	83.39	6.002	2.533	0.5475
RMSM1-01	1	302	21	171.80	1.14	0.66	2	0	19	2.65	0	97.35	5.176	1.972	0.3422
RMSM2-01	1	276	23	84.70	1.84	2.13	2	1	20	4.35	1.09	94.57	6.089	2.061	0.3416
RMSM3-01	1	286	23	248.56	2.03	1.38	2	1	20	15.03	0.35	84.62	5.987	2.504	0.5317
SM4-01	2	282	22	261.89	5.57	2.08	0	0	22	0	0	100.00	5.6	2.269	0.4397
SM4-02	2	295	28	249.29	2.54	1.01	2	0	26	3.73	0	96.27	7.656	2.425	0.4036
SM4-03	2	321	23	407.94	3.81	0.93	2	0	21	0.93	0	99.07	5.698	2.028	0.3303
SM4-04	2	295	25	335.64	7.96	2.32	2	0	23	2.37	0	97.63	6.924	2.131	0.3239
SM4-05	2	331	28	24.92	0.60	2.36	2	0	26	3.93	0	96.07	7.384	2.383	0.2869

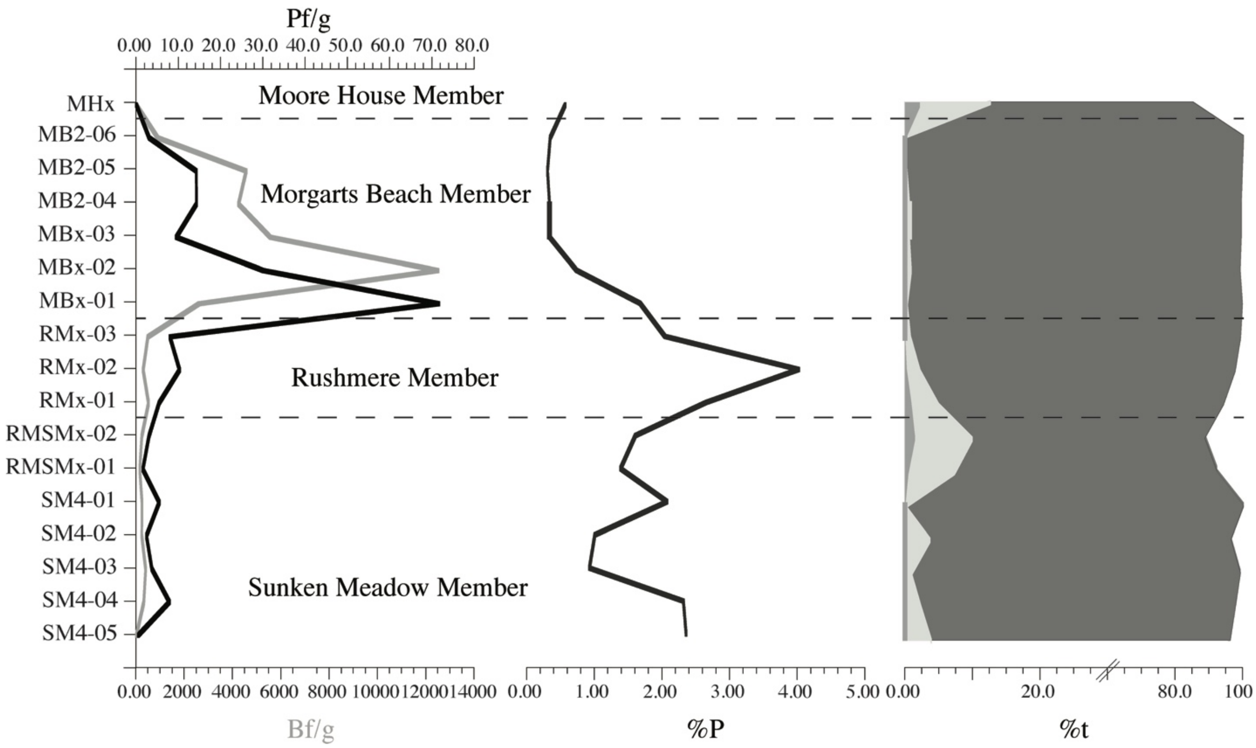

Figure 7: Left: Plots of the average number of benthic foraminifera (grey; Bf/g) and planktic foraminifera (black; Pf/g) per 1 g of sediment. Samples arranged stratigraphically. Center: Plot of the average percent of planktic foraminifera in the foraminiferal assemblage (%P). Right: Plot of the average percentage of Rotaliid (dark grey), Textulariid (light grey), and Miliolid (medium grey) benthic foraminifera (%t). Where replicates are averaged, the sample name is designated with a lower-case x (e.g., RMx-01).

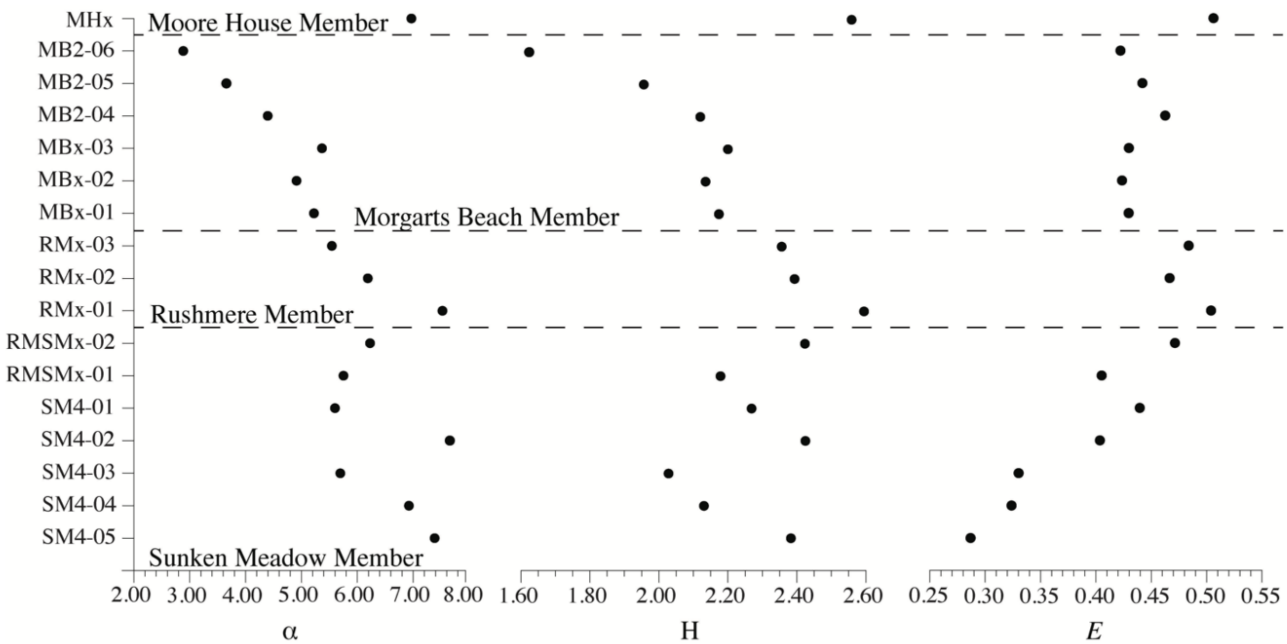

Figure 8: Species diversity data arranged stratigraphically. Plots of the average values for Fisher's alpha (left, α), Shannon's diversity index (center, H), and evenness (right, *E*). Where only one sample contained foraminifera or replicate samples were not collected, the sample name is listed. Where replicates are averaged, the sample name is designated with a lower-case x (e.g., RMx-01).

Cluster Analysis of Foraminiferal Relative Abundance Data

The dendrogram resulting from Q-mode cluster analysis of benthic foraminiferal relative abundance data is shown in Figure 9. The 33 samples clustered into six groups (1–6, Fig. 9) at a Euclidean distance of ~1.50. Group 1 is composed of seven samples and 46 taxa (Table 6), dominated by *Epistominella danvillensis* (32.24%) with *Elphidium* cf. *E. excavatum* (11.32%), *Trochulina bassleri* (8.98%), and *Buccella depressa* (5.73%) in relatively high abundance. Group 2 contains five samples and 44 taxa, with *Globocassidulina crassa* (23.10%), *Trochulina bassleri* (20.85%), and *Epistominella danvillensis* (20.32%) comprising ~65% of the total assemblage (Table 6). Group 3 is composed of five samples and 31 taxa, with *Buliminella elegantissima* (29.16%), *Elphidium* cf. *E. excavatum* (21.29%), *Epistominella danvillensis* (13.09%), and *Buccella frigida* (6.45%) as the most abundant taxa (Table 6). Group 4 is composed of six samples and 42 taxa, with *Buliminella elegantissima* (24.24%) dominating and *Elphidium* cf. *E. excavatum* (18.74%), *Epistominella danvillensis* (15.32%), and *Bolivina paula* (6.72%) also abundant (Table 6). Groups 3 and 4 differ slightly in the relative percentages of the three most abundant species in both groups (*Buliminella elegantissima, Elphidium* cf. *E. excavatum*, and *Epistominella danvillensis*) and the ~2% change in abundance of *Buccella frigida* (decreasing from Group 3 to Group 4) and *Bolivina paula* (increasing from Group 3 to Group 4). One sample (MB2-06) did not cluster in a particular group, and instead clustered with Groups 3 and 4 combined (grey triangle, Fig. 9). This sample has the lowest number of taxa (14) of all samples included in the analysis and is dominated by *Elphidium* cf. *E. excavatum* (37.69%), with *Buliminella elegantissima* (23.46%), *Epistominella danvillensis* (18.08%), and *Bolivina paula* (6.54%) in abundance (Table 7). Group 5 is composed of three samples and 39 taxa, with *Elphidium* cf. *E. excavatum* (25.42%) dominating and *Trochulina bassleri* (12.93%), *Cibicides lobatulus* (7.74%), and *Cibicides americanus* (6.57%) abundant (Table 6). Group 6 is composed of six samples and 42 taxa, with *Elphidium* cf. *E. excavatum* (21.79%), *Epistominella danvillensis* (17.34%), *Trochulina bassleri* (10.98%), and *Buccella depressa* (9.24%) as the most abundant taxa (Table 6).

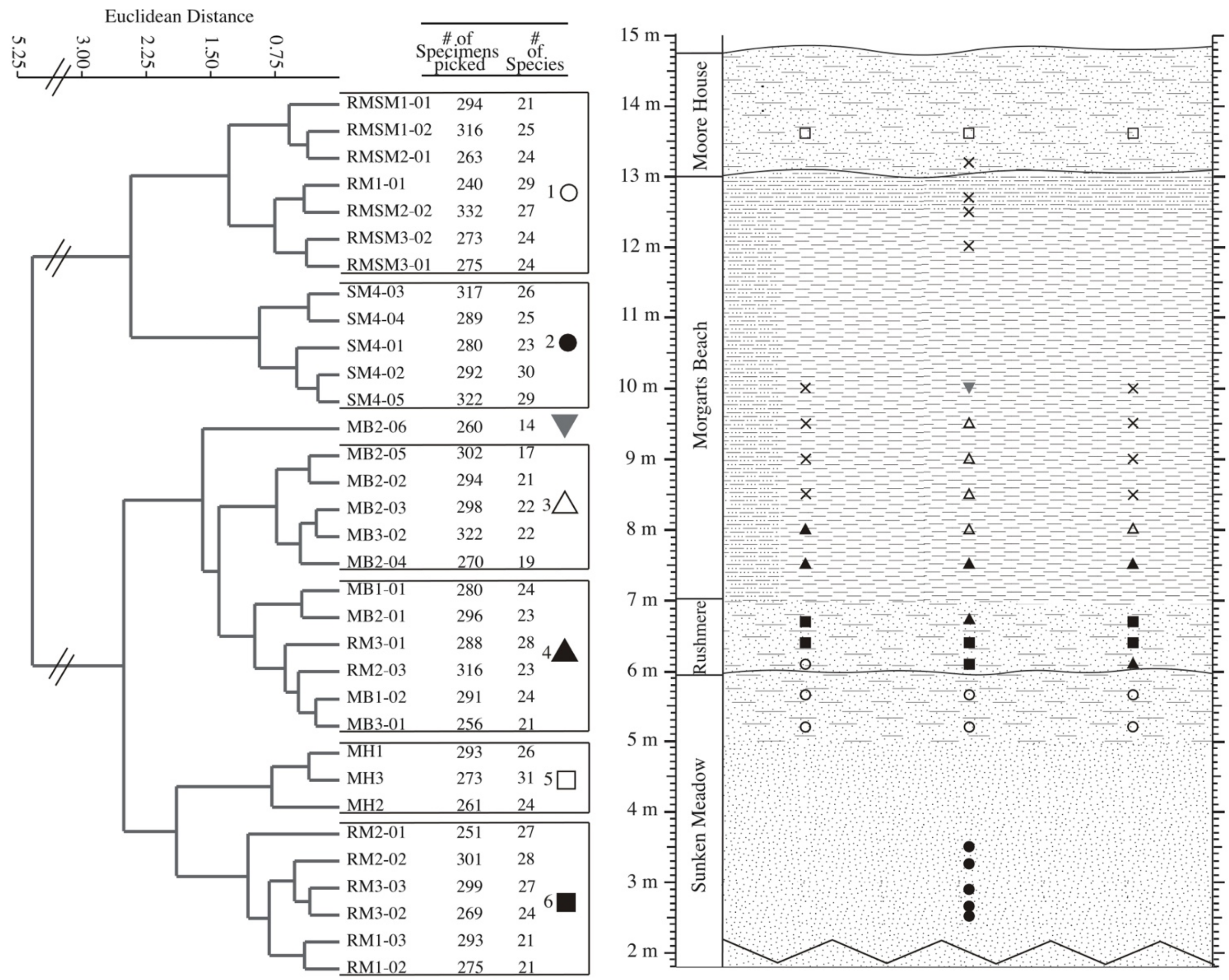

Figure 9: Left: Dendrogram from cluster analysis of benthic foraminiferal relative abundance data with six biofacies bracketed. Right: Composite stratigraphic column with all samples plotted in stratigraphic position. Barren samples not included in the cluster analysis are marked with X. The Sunken Meadow Member is truncated, as denoted by the jagged line. Unit thickness and stratigraphic position of samples is based on outcrops in the study area at the time of sampling.

Table 6: Mean percent abundance and range for taxa in biofacies defined by cluster analysis of benthic foraminiferal relative abundance data.

Biofacies 1 7 Samples, 46 Taxa	Mean %	Range	Biofacies 2 5 Samples, 44 Taxa	Mean %	Range	Biofacies 3 5 Samples, 31 Taxa	Mean %	Range
Epistominella danvillensis	32.24	15.42–28.30	*Globocassidulina crassa*	23.10	17.47–32.81	*Buliminella elegantissima*	29.16	26.49–33.33
Elphidium cf. *E. excavatum*	11.32	4.76–15.21	*Trochulina bassleri*	20.85	20.07–21.74	*Elphidium* cf. *E. excavatum*	21.29	14.07–27.15
Trochulina bassleri	8.98	4.76–12.92	*Epistominella danvillensis*	20.32	14.29–26.64	*Epistominella danvillensis*	13.09	11.72–15.19
Buccella depressa	6.34	4.17–9.64	*Cibicides fletcheri*	7.95	1.04–12.33	*Buccella frigida*	6.45	2.38–10.99
Cibicides lobatulus	5.73	2.38–8.79	*Cibicides lobatulus*	5.27	2.21–7.14	*Trochulina bassleri*	5.59	4.08–6.30
Textularia gramen	5.13	2.38–9.89	*Rosalina floridana*	3.80	1.79–5.68	*Bolivina paula*	4.76	2.32–5.78
Textularia deltoidea	4.29	0.34–10.55	*Cibicides americanus*	1.83	0–3.08	*Buccella depressa*	4.09	2.01–5.78
Cibicides fletcheri	4.07	3.06–5.42	*Bolivina paula*	1.69	1.04–2.86	*Pseudononion* spp.	3.35	2.04–4.07
Buliminella elegantissima	3.54	1.58–6.63	*Buliminella elegantissima*	1.54	0–3.08	*Nonionella miocenica*	2.14	1.32–3.40
Bolivina paula	3.13	0–5.49	*Buccella depressa*	1.41	0.95–2.14	*Pseudononion pizarrense*	1.85	0.66–3.70
Globocassidulina crassa	2.90	1.51–5.44	*Buccella inusitata*	1.13	0.34–1.89	*Buccella inusitata*	1.51	0.73–3.74
Rosalina floridana	2.78	0.38–4.36	*Textularia gramen*	1.13	0–2.05	*Bolivina imporcata*	1.18	0.37–2.04
Buccella inusitata	1.18	0.38–1.90	*Textularia deltoidea*	1.10	0–2.48	*Cibicides fletcheri*	0.78	0–1.11
Buliminella bassendorfensis	0.15	0–0.44	*Elphidium* cf. *E. excavatum*	1.05	0.35–1.89	*Valvulineria floridana*	0.73	0–2.96
Quinqueloculina seminula	1.02	0–2.08	*Cassidulinoides bradyi*	0.99	0–2.21	*Globocassidulina crassa*	0.70	0.34–0.99
Buccella frigida	0.80	0–2.50	*Trifarina illingi*	0.90	0.31–1.79	*Buliminella bassendorfensis*	0.42	0–1.10
Bolivina imporcata	0.68	0–1.81	*Bolivina imporcata*	0.87	0.63–1.43	*Fissurina* spp.	0.40	0–0.99
Buliminella curta	0.66	0–1.52	*Bulimina gracilis*	0.81	0.31–1.38	*Textularia deltoidea*	0.36	0–0.74
Fissurina spp.	0.53	0–1.14	*Pseudononion pizarrense*	0.45	0–0.95	*Guttulina austriaca*	0.29	0–0.74
Cibicides americanus	0.48	0–1.36	*Bolivina subdilatata*	0.27	0–1.04	*Buccella anderseni*	0.28	0–0.67
Cassidulina laevigata	0.42	0–2.55	*Buccella anderseni*	0.26	0–0.62	*Cibicides americanus*	0.28	0–0.67
Lagena pseudosulcata	0.36	0–0.73	*Buliminella bassendorfensis*	0.26	0–0.63	*Buliminella curta*	0.22	0–0.74
Pseudononion spp.	0.27	0–1.58	*Cassidulina laevigata*	0.26	0–0.69	*Bolivina robusta*	0.21	0–0.68
Pseudononion pizarrense	0.23	0–0.90	*Fissurina* spp.	0.26	0–0.62	*Cibicides lobatulus*	0.20	0–1.01
Nonionella miocenica	0.22	0–0.83	*Nonionella miocenica*	0.26	0–0.62	*Fursenkoina fusiformis*	0.20	0–0.67
Buccella anderseni	0.21	0–0.83	*Bulimina elongata*	0.21	0–0.71	*Bolivina subdilatata*	0.13	0–0.66
Lagena cf. *L. marginata-perforata*	0.21	0–0.73	*Buliminella brevior*	0.21	0–1.03	*Discorbis orbicularis*	0.07	0–0.34
Valvulineria floridana	0.21	0–1.47	*Buliminella curta*	0.19	0–0.62	*Reussoolina laevis*	0.07	0–0.33
Bulimina gracilis	0.20	0–0.63	*Bolivina robusta*	0.14	0–0.68	*Lenticulina americana*	0.07	0–0.34
Patellina advena	0.20	0–0.73	*Buccella frigida*	0.14	0–0.36	*Parafissurina bidens*	0.07	0–0.37
Guttulina austriaca	0.18	0–1.25	*Pseudononion* spp.	0.14	0–0.68	*Rosalina floridana*	0.07	0–0.34
Guttulina sp. A	0.16	0–0.42	*Valvulineria floridana*	0.14	0–0.71			
Quinqueloculina lamarckiana	0.15	0–0.73	*Discorbis orbicularis*	0.13	0–0.35			
Bolivina subdilatata	0.13	0–0.90	*Lagena* sp. C	0.13	0–0.36			
Bolivina robusta	0.11	0–0.42	*Lagena* sp. D	0.13	0–0.34			
Fursenkoina fusiformis	0.10	0–0.38	*Reussoolina laevis*	0.12	0–0.62			
Reussoolina laevis	0.10	0–0.38	*Cancris sagra*	0.07	0–0.35			
Sigmomorphina sp. A	0.10	0–0.37	*Cibicides* sp. D	0.07	0–0.36			
Uvigerina calvertensis	0.10	0–0.42	*Globulina gibba*	0.07	0–0.34			
Bolivina brevior	0.06	0–0.42	*Guttulina* sp. D	0.07	0–0.34			
Bolivina marginata multicostata	0.06	0–0.42	*Lenticulina americana*	0.07	0–0.35			
Globulina gibba	0.06	0–0.42	*Lagena pseudosulcata*	0.06	0–0.31			
Trifarina occidentalis	0.05	0–0.34	*Sigmoidella kagaensis*	0.06	0–0.31			
Valvulineria danvillensis	0.05	0–0.38	*Uvigerina calvertensis*	0.06	0–0.31			
Lagena sp. C	0.05	0–0.37						
Bulimina inflata	0.04	0–0.30						

Table 6, cont'd: Mean percent abundance and range for taxa in biofacies defined by cluster analysis of benthic foraminiferal relative abundance data.

Biofacies 4 6 Samples, 42 Taxa	Mean %	Range	Biofacies 5 3 Samples, 39 Taxa	Mean %	Range	Biofacies 6 6 Samples, 42 Taxa	Mean %	Range
Buliminella elegantissima	24.24	16.77–28.52	*Elphidium* cf. *E. excavatum*	25.42	18.32–30.65	*Elphidium* cf. *E. excavatum*	21.79	16.33–27.27
Elphidium cf. *E. excavatum*	18.74	16.02–22.30	*Trochulina bassleri*	12.93	8.81–15.70	*Epistominella danvillensis*	17.34	14.18–19.06
Epistominella danvillensis	15.32	11.11–20.36	*Cibicides lobatulus*	7.74	4.78–11.11	*Trochulina bassleri*	10.98	8.87–14.29
Bolivina paula	6.72	5.36–9.18	*Cibicides americanus*	6.57	5.46–7.28	*Buccella depressa*	9.24	6.32–15.70
Trochulina bassleri	6.38	3.78–8.23	*Textularia deltoidei*	5.57	4.40–6.51	*Buliminella elegantissima*	7.39	1.59–10.58
Buccella depressa	5.48	3.82–8.93	*Textularia gramen*	5.29	4.21–5.86	*Bolivina paula*	7.35	4.10–11.30
Buccella frigida	3.52	0–10.13	*Bolivina paula*	4.90	2.68–6.14	*Cibicides lobatulus*	3.78	1.00–6.77
Pseudononion spp.	3.33	1.01–6.01	*Epistominella danvillensis*	4.90	0.38–9.89	*Cibicides fletcheri*	3.08	0.33–8.37
Nonionella miocenica	3.16	1.07–5.56	*Rosalina floridana*	3.70	2.56–5.46	*Buccella inusitata*	2.82	0.80–6.32
Buccella inusitata	1.92	0.71–3.13	*Buccella inusitata*	3.15	1.83–4.21	*Buccella frigida*	2.27	0.66–5.95
Valvulineria floridana	1.50	1.01–2.41	*Buliminella elegantissima*	3.08	1.92–5.12	*Rosalina floridana*	2.02	0.67–4.38
Cibicides fletcheri	1.32	0–4.05	*Buccella depressa*	2.29	1.83–2.73	*Textularia deltoidea*	1.81	0.67–4.36
Cibicides lobatulus	1.21	0.34–2.08	*Quinqueloculina seminula*	2.28	0–6.51	*Globocassidulina crassa*	1.54	0.33–3.98
Textularia deltoidei	0.93	0–2.08	*Ammonia beccarii*	1.90	0.34–4.98	*Pseudononion* spp.	1.21	0–3.34
Rosalina floridana	0.85	0–2.78	*Cibicides fletcheri*	1.57	0.38–3.30	*Bolivina imporcata*	1.19	0–1.99
Fissurina spp.	0.71	0–1.35	*Bolivina imporcata*	1.20	1.10–1.37	*Valvulineria floridana*	0.76	0–3.19
Pseudononion pizarrense	0.58	0–2.03	*Buccella frigida*	0.74	0.34–1.10	*Nonionella miocenica*	0.75	0.36–1.37
Bolivina imporcata	0.57	0–1.27	*Uvigerina calvertensis*	0.72	0–1.83	*Buccella anderseni*	0.70	0.33–1.37
Globocassidulina crassa	0.57	0–1.39	*Elphidium advena*	0.61	0–1.83	*Buliminella curta*	0.55	0–1.12
Buliminella curta	0.40	0–0.68	*Nonionella miocenica*	0.61	0.34–1.10	*Fissurina* spp.	0.45	0–1.33
Cibicides americanus	0.40	0–1.35	*Pseudononion* spp.	0.59	0–1.10	*Cibicides americanus*	0.39	0–1.67
Buliminella bassendorfensis	0.34	0–1.35	*Valvulineria floridana*	0.59	0–1.10	*Bolivina brevior*	0.30	0–1.82
Buccella anderseni	0.29	0–0.71	*Buccella anderseni*	0.48	0–0.77	*Ammonia beccarii*	0.27	0–1.59
Guttulina austriaca	0.18	0–0.78	*Amphistegina lessonii*	0.37	0–1.10	*Quinqueloculina seminula*	0.19	0–0.40
Lagena cf. *L. marginata-perforata*	0.18	0–0.39	*Discorbis orbicularis*	0.37	0–0.73	*Bolivina robusta*	0.18	0–0.37
Bulimina gracilis	0.11	0–0.35	*Trifarina illingi*	0.37	0–1.10	*Bulimina elongate*	0.18	0–0.40
Reussoolina laevis	0.11	0–0.35	*Globocassidulina crassa*	0.36	0–0.73	*Lenticulina americana*	0.18	0–0.40
Uvigerina calvertensis	0.11	0–0.36	*Fissurina* spp.	0.35	0–0.68	*Uvigerina calvertensis*	0.18	0–0.40
Bolivina marginata multicostata	0.06	0–0.34	*Sagrina primitiva*	0.13	0–0.38	*Cassidulina laevigata*	0.12	0–0.40
Bolivina robusta	0.06	0–0.34	*Guttulina* sp. C	0.13	0–0.38	*Discorbis orbicularis*	0.12	0–0.74
Bolivina subdilatata	0.06	0–0.34	*Lenticulina americana*	0.13	0–0.38	*Trifarina occidentalis*	0.11	0–0.66
Bulimina inflata	0.06	0–0.36	*Quinqueloculina lamarckiana*	0.13	0–0.38	*Guttulina austriaca*	0.11	0–0.33
Cassidulina laevigata	0.06	0–0.34	*Cancris sagra*	0.12	0–0.37	*Textularia gramen*	0.11	0–0.66
Discorbis orbicularis	0.06	0–0.36	*Guttulina* sp. D	0.12	0–0.37	*Marginulina* sp. A	0.07	0–0.40
Fursenkoina fusiformis	0.06	0–0.34	*Pseudononion pizarrense*	0.12	0–0.37	*Pyrulina albatrossi*	0.07	0–0.40
Globulina gibba	0.06	0–0.35	*Sigmomorphina* sp. A	0.12	0–0.37	*Bolivina subdilatata*	0.06	0–0.33
Guttulina sp. B	0.06	0–0.35	*Valvulineria* sp. B	0.12	0–0.37	*Bulimina gracilis*	0.06	0–0.33
Valvulineria danvillensis	0.06	0–0.34	*Guttulina* sp. A	0.11	0–0.34	*Fursenkoina fusiformis*	0.06	0–0.33
Lagena pseudosulcata	0.06	0–0.35	*Parafissurina bidens*	0.11	0–0.34	*Lagena* cf. *L. marginata-perforata*	0.06	0–0.33
Lagena sp. D	0.06	0–0.36				*Reussoolina laevis*	0.06	0–0.33
Quinqueloculina seminula	0.06	0–0.35				*Lagena* sp. D	0.06	0–0.37
Lenticulina americana	0.05	0–0.32				*Pseudononion pizarrense*	0.06	0–0.36

Table 7: Mean percent abundance of taxa in sample MB2-06.

Biofacies - MB2-06 1 Sample, 14 Taxa	Mean %
Elphidium cf. *E. excavatum*	37.69
Buliminella elegantissima	23.46
Epistominella danvillensis	18.08
Bolivina paula	6.54
Buccella depressa	5.39
Buccella frigida	2.69
Bolivina imporcata	2.31
Bolivina robusta	0.77
Trochulina bassleri	0.77
Buccella anderseni	0.39
Fissurina spp.	0.39
Lagena sp. D	0.39
Pseudononion spp.	0.39
Valvulineria floridana	0.39

Discussion

The Yorktown Formation as a whole has been interpreted as being deposited in an open neritic environment over several transgressive and regressive cycles (Ward and Blackwelder, 1980; Cronin et al., 1984; Ward and Strickland, 1985; Edwards et al., 2009). The units of the Yorktown Formation are generally massive, often bioturbated and lack visible sedimentary structures in outcrop. Articulated bivalve fossils can often be found in life position at the Rushmere type locality. As such, grain-size analysis in combination with foraminiferal paleoecology is vital to determine the specific environments in which each member of the formation was deposited.

Age models for the deposition of the Yorktown Formation are based on ostracode and calcareous nannofossil assemblages (Hazel, 1971; Akers, 1972; Cronin et al., 1984). Planktic foraminifera occur in too few numbers (<20 in any sample in this study) with various states of preservation in the Yorktown Formation, making biostratigraphic refinement difficult; the timing and duration of deposition of the individual members in this unit is presently largely unestablished (Ward and Blackwelder, 1980; Cronin et al., 1984). The age of the Yorktown Formation is early to late Pliocene (~4.8–3.0 Ma, ~4.0–3.0 Ma, and ~4.8–3.1 Ma according to Krantz, 1991, Dowsett and Wiggs, 1992, and Snyder et al., 1983, respectively).

Global changes in climate during the Pliocene are recognized as widespread marine deposits across the Atlantic Coastal Plain. Three phases of sea-level rise are recorded in the Salisbury embayment as the Yorktown Formation sediments. Paleotemperature reconstructions based on ostracodes, planktic foraminifera, and palynomorph assemblages and $\delta^{18}O$ data from mollusks show a general warming trend from temperate to subtropical conditions in southeastern Virginia prior to the onset of Pleistocene glaciation (Cronin, 1988; Cronin and Dowsett, 1990;

Krantz, 1990; Groot, 1991). Benthic foraminiferal assemblages recorded in this study support water depths of at least 40 m and warm temperate waters for much of the Pliocene in this region.

Transgression 1: Sunken Meadow Member

The lower portion of the Sunken Meadow Member (SM4 samples in Fig. 6), exposed at Pipsico, is composed of coarse to medium quartz sands (Table 1). This section generally fines upward, with a slight decrease in percentage of sand (Fig. 6). Mean grain-size also supports an overall upwards fining (Fig. 6). The upper portion of the Sunken Meadow Member (RMSM samples in Fig. 6), accessed at Rushmere, is characterized by an increase in phosphorite and glauconite grains, a larger mean grain-size and a slight overall increase in muds compared to the lower section (Fig. 6; Appendix C). There is also an increase of gravel-sized bioclastic material at the Rushmere locality (Fig. 5). The sands are generally poorly sorted medium and coarse quartz with shell fragments common throughout the unit (Table 1). The high concentration of fossils, and the occurrence of phosphorite and glauconite are characteristics of condensed sections, which form during periods of low sedimentation during transgressions and are commonly associated with maximum flooding surfaces (Baum and Vail, 1988). No sedimentary structures were visible during sampling of either section.

Cluster analysis of the benthic foraminiferal assemblages indicates two biofacies in the Sunken Meadow Member; biofacies 1 (Fig. 9, 1; Table 6) contains all Sunken Meadow Member samples and one Rushmere Member sample collected at Rushmere, and biofacies 2 (Fig. 9, 2, Table 6) contains all Sunken Meadow Member samples collected at Pipsico. Biofacies 2 is the basal portion of the Sunken Meadow Member and is characterized by three predominant taxa: *Globocassidulina crassa*, *Trochulina bassleri*, and *Epistominella danvillensis*. Biofacies 1 is dominated by *Epistominella danvillensis* (>30%, Table 6), but *Elphidium* cf. *E. excavatum* also occurs in relatively high abundance.

A high abundance of *Globocassidulina crassa* may represent higher oxygen concentrations, and lower influxes of organic matter (de Almeida et al., 2015). This species is ubiquitous in shelf to slope settings and has been observed in water depths ranging from 30 m to upwards of 1000 m (Murray, 1991). *Epistominella danvillensis* is characteristic of water depths <500 m (Keller, 1980) and this species occurs in higher percentages in these samples than those reported by Gibson (1983), who noted that higher abundances (>9%) occur in areas of greater water depth.

The genus *Elphidium* has been traditionally considered diagnostic of shallow shelf environments (Katrosh and Snyder, 1982), and the species *Elphidium excavatum* is ubiquitous across much of the North American continental shelf (Culver and Buzas, 1980). Gibson (1983) stated that *Elphidium excavatum* is characteristic of lagoon, sound and shallow neritic environments. The relative abundance of individual species is an important consideration in determination of water depth—*Elphidium clavatum* Cushman (= *E. excavatum*) is found off the coast of New Hampshire in water depths of 40–60 m at maximum percentages of 13% of the total assemblage but will comprise from 15 to 40 percent of the assemblage in waters less than 30 m deep (Gibson, 1963). Katrosh and Snyder (1982) posited that *E. excavatum* is opportunistic, increasing in abundance in environments where conditions are not ideal for most species. The absence of *Globocassidulina crassa* and the occurrence of *Elphidium* cf. *E. excavatum* in biofacies 2 is suggestive of an increase in organic matter up-section but not definitive of a change in water depth.

The low percent planktics (%P; < 2.5%; Table 5; Fig. 7) and low density of planktic foraminifera (~1–8 PF/g; Table 5; Fig. 7) is indicative of water depths of less than 100 m for the unit as a whole (Murray, 1976; Gibson, 1989). The number of species (S) ranges from 21–28 (Table 5). Values for species diversity (Shannon Information Function; *H)* and evenness (E) are low to moderate (~2.0–2.5 and ~0.29–0.44, respectively; Table 5; Fig. 8) in biofacies 2. Based upon Gibson and Buzas (1973), this supports an interpretation of <100 m of water depth. In biofacies 1, values for H are moderate (~2.0–2.5; Table 5) and values for E are moderate to high (~0.34–0.54; Table 5). The value ranges for S, H, and E in both biofacies occur in water depths <100 m in the areas between Florida and Cape Hatteras and between Maryland and Cape Cod (Gibson and Buzas, 1973). The dominant species in both biofacies 2 and biofacies 1 are suggestive of an open inner to outer shelf environment.

Snyder et al. (2001) interpreted the depositional environment for the Sunken Meadow Member at Lee Creek Mine, Aurora, NC (in the Albemarle Embayment) to be middle to outer neritic. They noted that the benthic foraminifera of the Sunken Meadow Member at Lee Creek Mine have geographically widespread distributions but that these biotas are indicative of cool temperatures in modern deposits, supported by the planktic foraminiferal assemblages from Lee Creek Mine documented by Snyder et al. (1983). The benthic foraminiferal assemblages at Lee Creek Mine differ significantly from the assemblages recorded in this study; Snyder et al. (2001) recorded the Sunken Meadow Member as being dominated by *Nonionella miocenica*, composing ~30–60% of the benthic assemblage at Lee Creek Mine. In contrast, *Nonionella miocenica* occurs as only ~0.2% of the assemblage in this study. Their assemblage also contains one species that is restricted to the unit—*Caucasina gracilis*—which is not observed at either Pipsico or Rushmere in the Salisbury Embayment. These species have modern representatives that are known to tolerate oxygen depletion and an increase in organic material (Snyder et al., 1983; Snyder, 1990).

Bailey (1987) interpreted the Sunken Meadow Member in the Albemarle Embayment as representing a middle shelf environment based upon bedding characteristics, grain-size distribution and molluscan fossil assemblages. He interpreted the foraminiferal and molluscan assemblages recorded by Gibson (1967, 1983) as suggestive of 40 m maximum water depths and suggested that the sands of the Sunken Meadow Member represent a "winnowed sand sheet" produced by reworking—under moderate energy conditions—the underlying Eastover Formation sediments.

Hazel (1971, 1977) reconstructed paleotemperatures for the lower Yorktown Formation using ostracode fauna and estimated deposition of the Sunken Meadow Member in a warm temperate climate, with annual bottom water temperatures ranging from ~12.5°C (winter) to ~20°C (summer). This is consistent with the observations made by Ward and Blackwelder (1980) that the molluscan fauna of the Sunken Meadow Member are indicative of a temperate, shallow, normally saline shelf. Cronin and Dowsett (1990) determined that Sunken Meadow bottom water temperatures for February and August were 10.1°C and 12.1°C, respectively, whereas modern bottom water temperatures for the same approximate latitude (37°N) are ~5.5°C and 14.5°C for winter and summer (Cronin et al., 1989). Dowsett and Wiggs (1992) collected one sample from the Sunken Meadow Member and based upon the dominance of the planktic species *Globigerina bulloides* which occurs in high numbers in water temperatures ~5–15ºC, posited that the Sunken Meadow could have been deposited in environmental conditions warmer than today in the Salisbury Embayment. Snyder et al. (1983) suggest cooler water temperatures for the Sunken Meadow based on the planktic foraminiferal assemblage at Lee Creek Mine, NC.

Snyder et al. (2001) interpreted a benthic foraminiferal assemblage from the Sunken Member at Lee Creek Mine—where *Nonionella miocenica* is dominant with high relative abundances of *Caucasina gracilis and Pseudononion pizarrensis*—as suggestive of cooler temperate environmental conditions. They proposed that these species could tolerate oxygen depletion and nutrient enrichment as a result of upwelling, and hence cooler water temperatures could be a localized factor in the Albemarle Embayment (Snyder et al., 2001). The benthic foraminiferal assemblage recorded in this study does not directly favor either temperature interpretation over the other.

Overall, the Sunken Meadow represents a relatively extensive marine transgression, deposited in a middle shelf environment with water depths less than 100 m. The upper section of the unit (at Rushmere) likely represents a slight increase in water depth and increase in organic matter, consistent with the increase of glauconite and phosphorite in this portion of the Sunken Meadow Member. Grain-size analysis of samples and a lack of sedimentary structures at both Pipsico and Rushmere do not support the interpretation of storm winnowing – the Sunken Meadow sands are poorly sorted (Table 1, Appendix C; Appendix D) in contrast to observations by Bailey (1987).

Krantz (1991) noted that embayments often record only the highest sea levels of a transgression. This is supported by the increase in glauconite and phosphate, grain-size data and the concentration of fossil material near the unconformity between the Sunken Meadow and Rushmere members. Reworking of sediments and deposition as a transgressive lag would have occurred during sea-level fall and subsequent rise as the seafloor was exposed to wave scouring processes (Catuneanu, 2006).

Transgression 2: Rushmere–Morgarts Beach members

At its type locality, approximately 1 m of the Rushmere Member is exposed. It is composed of fine to medium sand, characterized by a high abundance of quartz and large macrofossils (bivalves, gastropods, coral, etc.), with some glauconite and phosphorite grains throughout the unit. Large bivalve and gastropod fossils (> 10 cm) are noticeably abundant in outcrop, with no sedimentary structures visible. The concentration of large macrofossils in the Rushmere Member is likely the result of high molluscan productivity combined with minor post-depositional winnowing. Several genera of gastropods and large pieces of scleractinian coral are present suggesting reworking or movement of sediments. However, articulated *Chesapecten* fossils are visible in the outcrop indicating limited transport of fossils and minimal current activity (Bailey, 1987). Very little evidence of dissolution is observable and as such is not considered to be a factor in diagenetic alteration of the Rushmere Member sediments. Sorting of the sand in which the fossils occur does not support winnowing; generally, the Rushmere Member sediments are poorly sorted (Table 2; Appendix C; Appendix D). Mean grain-size (of the >63 μm size-fraction) fines upward and average percent sand values are relatively consistent throughout the Rushmere sediments (Fig. 6).

The Morgarts Beach Member is composed of muds and the sand-sized fraction is poorly to very well sorted (Table 3). Quartz and mica predominate, but smaller fossil grains (echinoderm spines, shell fragments, etc.) are also common. Overall, this member fines upwards, as shown by the decreasing mean grain-size and percentage of sand (Fig. 6). The contact between the Rushmere and Morgarts Beach members is gradational in outcrop at some localities (Ward and Blackwelder, 1980; Snyder et al., 2001), although this was not observed in this study; the contact between the Rushmere and Morgarts Beach members is sharp with a rapid decrease in macrofossil abundance and size, and an increase in finer sediments (Fig. 6). However, grain-size analysis shows that the contact is gradational over ~ 1 dm (Figs. 5–6). The transition from fine sands to silts suggests either a deepening of the water or a transition from an open marine environment to a protected lagoonal environment (Ward and Blackwelder, 1980; Bailey, 1987). In the upper section of the Morgarts Beach Member, mean grain-size of the >63 μm size-fraction increases and the sorting values decrease, while the overall percentage of sand does not change significantly (Fig. 6; Table 3; MB4 samples). These sedimentologic changes have not been correlated to other features seen in outcrops or cores collected across southeastern Virginia. The change in grain-size distribution could be attributable to minor changes in the offshore, such as migration of an offshore bar, or record a minor storm bed. Higher resolution sampling across the region combined with subsurface data is needed to characterize minor sedimentological changes in the Morgarts Beach Member.

The cluster analysis dendrogram (Fig. 9) shows three distinct biofacies in the transgression (2nd pulse, Fig. 4) during which the Rushmere and Morgarts Beach members were deposited. Biofacies 6 contains six Rushmere samples, biofacies 4 contains two Rushmere samples and four of the lowermost Morgarts Beach samples, and biofacies 3 contains five of the six remaining (non-barren) Morgarts Beach samples. Sample MB2-06 clusters with both biofacies 3 and biofacies 4 (Fig. 9).

Biofacies 6 has the same three most abundant species as biofacies 1, but in different rank order. Biofacies 1 is dominated by *Epistominella danvillensis*, whereas biofacies 6 is dominated by *Elphidium* cf. *E. excavatum* followed by *Epistominella danvillensis* and *Trochulina bassleri*, (Table 6). *Buliminella elegantissima* is present in relatively high abundance (~7%; Table 6) in biofacies 6 samples; this species is relatively abundant in Sunken Meadow Member samples in the Albemarle Embayment (~10%; Snyder et al., 2001) but occurs in much lower mean percentages in the Rushmere and Morgarts Beach member samples (<10%; Snyder et al., 2001) than samples in this study (~7– 0%; Table 6). Values for species diversity (S = <30, H = 2.29–2.6) and evenness (E = 0.40–0.52) are only slightly higher than those of biofacies 1 and 2. Percent planktics are highest in this biofacies (max. ~4.5%, Fig. 7), though are indicative of water depths of less than 100 m (Murray, 1976; Gibson, 1989).

Bailey (1987) postulated that the Rushmere Member accumulated in an inner to middle shelf environment, citing shell transportation and storm winnowing as evidence of water depths ranging 10–40 m. Paleotemperature estimates by Hazel (1988) and Krantz (1990) for the Rushmere Member indicate a warm temperate climate, consistent with higher sea-levels and higher temperatures than those of the Sunken Meadow Member. According to Cronin et al. (1989) summer bottom water temperatures for the Rushmere-Morgarts Beach range from ~14.5°C to ~18°C and winter bottom water temperatures range from ~11.5°C to ~16°C.

The interpretations of benthic foraminifera in the Albemarle Embayment at Lee Creek Mine are similar to those in the Salisbury Embayment of southern Virginia (Snyder et al., 2001). Based on distributions of *Buccella frigida*, *Elphidium excavatum*, *Globocassidulina crassa*, and *Cibicidoides floridanus*, or related modern taxa (for extinct species), Snyder et al. (2001) stated that the Rushmere Member at Lee Creek Mine was deposited in a middle- to outer-neritic environment. However, the benthic foraminifera found in Lee Creek Mine, Aurora, NC, differ from those found in Rushmere samples of this study. Snyder et al. (2001) recorded relatively high abundance of *Cibicides lobatulus*, *Parafissurina bidens*, *Globocassidulina crassa*, and *Nonionella miocenica*. The most abundant species found in biofacies 6 of this study (*Elphidium* cf. *E. excavatum*, *Epistominella danvillensis*, *Trochulina bassleri,* and *Buccella depressa*) are similar to those documented in Snyder et al. (2001) in that they have wide geographic distributions, persist in both overlying and underlying sediments, and combined with other data support the interpretation that the Rushmere Member was deposited in a warmer, more offshore (deeper shelf) environment than the underlying Sunken Meadow Member (Culver and Buzas, 1980; Culver and Buzas, 1981; Katrosh and Snyder, 1982; Gibson, 1983).

All Morgarts Beach Member samples (biofacies 3 and 4) are dominated by *Buliminella elegantissima*, with the exception of sample MB2-06, where *Elphidium* cf. *E. excavatum* is the dominant species. This sample also has the lowest values for species diversity (S = 14, H = 1.624), richness (α = 2.886), and concentration of benthic and planktic foraminifera in this unit (Table 5; Fig. 8). Biofacies 3 and 4 are both dominated by *Buliminella elegantissima*, *Elphidium* cf. *E. excavatum*, and *Epistominella danvillensis*. *Bolivina paula* occurs in higher percentages in biofacies 4 than it does in biofacies 3 while *Buccella frigida* occurs in higher abundance in biofacies 3 than in biofacies 4 (Table 6).

Buliminella elegantissima is restricted to depths of less than 200 m but most commonly occurs in modern inner shelf environments on the North American Atlantic shelf and in the northern Gulf of Mexico (Gibson, 1967; Culver and Buzas, 1980, 1981; Poag, 2015). It is generally considered to be indicative of nutrient-rich, reduced oxygen waters, and sediments with high organic content (Katrosh and Snyder, 1982; Sen Gupta and Machain-Castillo, 1993; Culver et al., 2008; Culver et al., 2011). *Elphidium excavatum* is also common and often dominant in shallow shelf environments (Schnitker, 1971; Culver and Buzas, 1980, 1981). *Epistominella danvillensis* does not constrain water depth as it commonly occurs at water depths of <500 m (Keller, 1980). *Bolivina paula* is limited to depths of less than 200 m but is characteristic of shallow shelf settings (Gibson, 1967; Culver and Buzas, 1980; Katrosh and Snyder, 1982). In biofacies 4, the co-occurrence of *Buliminella elegantissima* and *Bolivina paula* indicates that water depths were no deeper than 200 m during deposition. *Buccella frigida* is ubiquitous across the eastern North American continental shelf; modern distribution is generally restricted to latitudes above 37 ºN although it has been recorded off the Florida coast (Culver and Buzas, 1980). Gibson (1967) considered *B. frigida* to be indicative of very shallow water, and modern assemblages with abundant *Elphidium* cf. *E. excavatum* and *B. frigida* occur in Long Island Sound, where *B. frigida* is limited to water depths of 15–33 m (Buzas, 1965; Culver and Buzas, 1980). In summary, low species diversity, few planktics and the general dominance of *Buliminella elegantissima* and *Elphidium* cf. *E. excavatum* indicate that the Morgarts Beach Member was likely deposited in an inner shelf setting open to influence from deeper shelf waters, as indicated by the presence of *Epistominella danvillensis*.

The Morgarts Beach Member, like the Rushmere Member, represents a warm temperate marine environment based on paleotemperature estimates by Hazel (1988) and Krantz (1990), where summer bottom water temperatures were ~3°C higher than present (Cronin, 1991). Ward and Blackwelder (1980) postulated that this unit was deposited in a lower energy restricted setting than the Rushmere Member due to the finer grain size and lack of large molluscan fossils. This finding was supported by Bailey (1987) who interpreted the Morgarts Beach to be a shallower shelf environment than the Rushmere. Snyder et al. (2001) found that the Morgarts Beach Member has less mud than the Rushmere Member at Lee Creek Mine—a finding that is not shared with this study. The Morgarts Beach Member has a significantly higher concentration of mud than any other member in the Yorktown Formation in southeastern Virginia (~60 to 90%; Fig. 6, Table 3; Appendix C). The sharp faunal turnover at the Rushmere-Morgarts Beach contact, where *Buliminella elegantissima* increases from 7% to greater than 20% in abundance, and the decrease in percent planktics indicates a shallower water setting than that represented by the Rushmere Member. The increase in muds in the Morgarts Beach Member could be attributed to a shallow, low energy, protected, inner shelf (lagoonal?) environment (Ward and Blackwelder, 1980; Ward and Strickland, 1985).

Transgressive pulse 2 (Fig. 4) in the Salisbury Embayment is interpreted to be the largest in the Neogene due to the large areal distribution of the Rushmere and Morgarts Beach members along the Atlantic Coastal Plain (Ward and Blackwelder, 1980; Krantz, 1990). The Rushmere Member was likely deposited in an open, middle neritic setting and records the maximum transgressive phase in the Pliocene (Ward and Blackwelder. 1980). The high abundance of *Elphidium* cf. *E. excavatum* could indicate higher levels of nutrients than were present during the deposition of the Sunken Meadow Member. A low energy, high nutrient, restricted shallow inner shelf environment (lagoon?) is recorded in the deposition of the Morgarts Beach Member, as indicated by the fine-grained sediment and the abundance of *Buliminella elegantissima*. Ward and Blackwelder (1980) hypothesized localized tectonic reactivation and the formation of offshore bars to account for the change to a restricted depositional setting.

Transgression 3: Moore House Member

Grain-size data are limited for the Moore House Member as the samples collected for this study are an indurated shell hash; Ward and Blackwelder (1980) described the exposed Moore House Member at its type locality near Yorktown, VA as “sandy shell beds and cross-bedded shell hash and locally is cemented to form a very indurated rock.”

This unit is also commonly a bioclastic calcareous sandstone that has large-scale cross-bedding (>1 m) at some localities (not accessed in this study; Johnson, 1972; Ward and

Blackwelder, 1980). Bivalve fossils are commonly abraded, with few articulated specimens observable in outcrop. Sedimentary structures were not visible in outcrop at Rushmere, VA. The concentration of large bivalve fossils is likely the result of winnowing of finer grained sediments and diagenetic alteration is present in the form of induration, though calcareous material is relatively well preserved. Large barnacle overgrowths are common on bivalve fossils, which generally indicates intertidal to shallow subtidal conditions.

Biofacies 5 characterizes the Moore House Member. It is dominated by *Elphidium* cf. *E. excavatum* and other shallow shelf species such as *Trochulina bassleri*, *Cibicides lobatulus*, and *Cibicides americanus*. Species richness and evenness (S = ~25, H = 2.4–2.7, *E* = 0.48–0.55) are higher than the values of all other biofacies in this study (Table 5). Percentage of miliolid and textulariid foraminifera are higher in the Moore House Member, ~6% and ~15%, respectively, compared to other Yorktown Formation members (Fig. 7, Table 5). Numbers of benthic (~13–27) and planktic foraminifera (~1) per gram are lowest in this unit compared to other members. Percent planktics are comparable to those of biofacies 4 (≤1%; Fig. 5; Table 5). The primary and secondary species in biofacies 5 occur in all other biofacies at varying proportions. Water depths of <100 m are likely based on the low numbers of planktic foraminifera (Murray, 1976; Gibson, 1989) and the high abundance of benthic species typical of shallow marine settings.

This transgression is the least extensive in the Pliocene (Fig. 4) and is absent in the Albemarle Embayment. Snyder et. al (2001) noted that the hiatus represented by the absence of the Moore House Member at Lee Creek Mine, Aurora, NC, roughly corresponds to a cooling event and subsequent marine regression in the Albemarle Embayment. However, Cronin et al. (1989) record the warmest temperatures in the Yorktown Formation from a sample in the Moore

House Member (~20°C). The Moore House Member has been interpreted to have been deposited as an offshore bar in very shallow (5–25 m) waters (Johnson, 1972).

Conclusions

Further refinement of the foraminiferal assemblage and interpretations of the Sunken Meadow Member would be possible with additional sampling at the Pipsico location. Likewise, development of a more precise age model for the deposition of the Yorktown Formation is necessary to understand the timing and magnitude of the marine transgressions recorded. Paleotemperature reconstructions have demonstrated that the western Atlantic Ocean was significantly warmer during the middle Pliocene than present.

The results of this study support the findings of previous studies on the Yorktown Formation, specifically that the units of the Yorktown Formation record three distinct pulses of marine transgression (Ward, 2005) and represent relatively rapid climatic shifts in the mid to late Pliocene. The individual transgressions were of varying magnitude and duration. The members of the Yorktown Formation at the lectotype section are lithologically distinguishable units, with characteristic benthic foraminiferal assemblages in the Salisbury Embayment. The Yorktown deposits of the Albemarle Embayment differ in lithology and benthic foraminiferal assemblages to those of the Salisbury Embayment, suggesting different regional controls on deposition and paleoenvironment.

The results of this study support the following:

1. The Sunken Meadow and Moore House members were deposited under cooler climate conditions than the Rushmere and Morgarts Beach members.
2. The benthic foraminiferal assemblages recorded at the Rushmere type locality show significant shifts in the proportions of taxa with each transgression, suggesting that water depth, temperature, and other environmental factors such as an increase in organic matter impacted the benthic foraminiferal assemblages.

3. The Rushmere and Morgarts Beach sediments record the greatest water depths in the mid-Pliocene, where the Rushmere Member represents the maximum transgressive phase, and the transition between the units represents a shift from open, inner shelf conditions to a more restricted lagoonal environment.

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Appendix A.

Sample location, latitude/longitude, and approximate elevation.

Sample Name	*Locality*	*Latitude*	*Longitude*	*Elevation (m)*
SM4-05	Pipsico			
SM4-04	Pipsico			Approximate elevation is
SM4-03	Pipsico	37° 12' 07.35" N	76° 52' 55.25" W	unknown due to condition of
SM4-02	Pipsico			outcrop during sampling
SM4-01	Pipsico			
RMSM1-01	Rushmere	37° 03' 59.54" N	76° 40' 09.41" W	-0.10
RMSM2-01	Rushmere	37° 03' 58.83" N	76° 40' 09.38" W	-0.05
RMSM3-01	Rushmere	37° 04' 00.22" N	76° 40' 09.30" W	-0.14
RMSM1-02	Rushmere	37° 03' 59.54" N	76° 40' 09.41" W	0.20
RMSM2-02	Rushmere	37° 03' 58.82" N	76° 40' 09.36" W	0.25
RMSM3-02	Rushmere	37° 04' 00.22" N	76° 40' 09.30" W	0.14
RM1-01	Rushmere	37° 03' 59.54" N	76° 40' 09.41" W	0.70
RM2-01	Rushmere	37° 03' 58.82" N	76° 40' 09.36" W	0.82
RM3-01	Rushmere	37° 04' 00.22" N	76° 40' 09.30" W	1.67
RM1-02	Rushmere	37° 03' 59.54" N	76° 40' 09.41" W	1.06
RM2-02	Rushmere	37° 03' 58.82" N	76° 40' 09.36" W	1.12
RM3-02	Rushmere	37° 04' 00.22" N	76° 40' 09.30" W	1.67
RM1-03	Rushmere	37° 03' 59.54" N	76° 40' 09.41" W	1.35
RM2-03	Rushmere	37° 03' 58.82" N	76° 40' 09.36" W	1.42
RM3-03	Rushmere	37° 04' 00.22" N	76° 40' 09.30" W	1.67
MB1-01	Rushmere	37° 03' 59.54" N	76° 40' 09.41" W	2.12
MB2-01	Rushmere	37° 03' 58.82" N	76° 40' 09.36" W	2.22
MB3-01	Rushmere	37° 04' 00.22" N	76° 40' 09.30" W	2.17
MB1-02	Rushmere	37° 03' 59.54" N	76° 40' 09.41" W	2.62
MB2-02	Rushmere	37° 03' 58.82" N	76° 40' 09.36" W	2.72
MB3-02	Rushmere	37° 04' 00.22" N	76° 40' 09.30" W	2.67
MB1-03	Rushmere	37° 03' 59.54" N	76° 40' 09.41" W	3.12
MB2-03	Rushmere	37° 03' 58.82" N	76° 40' 09.36" W	3.22
MB3-03	Rushmere	37° 04' 00.22" N	76° 40' 09.30" W	3.17
MB1-04	Rushmere	37° 03' 59.54"N	76° 40' 09.41" W	3.62
MB2-04	Rushmere	37° 03' 58.82" N	76° 40' 09.36" W	3.72
MB3-04	Rushmere	37° 04' 00.22" N	76° 40' 09.30" W	3.67
MB1-05	Rushmere	37° 03' 59.54" N	76° 40' 09.41" W	4.12
MB2-05	Rushmere	37° 03' 58.82" N	76° 40' 09.36" W	4.22
MB3-05	Rushmere	37° 04' 00.22" N	76° 40' 09.30" W	4.17
MB1-06	Rushmere	37° 03' 59.54" N	76° 40' 09.41" W	4.62
MB2-06	Rushmere	37° 03' 58.82" N	76° 40' 09.36" W	4.72
MB3-06	Rushmere	37° 04' 00.22" N	76° 40' 09.30" W	4.67
MB4-03	Rushmere			3.80
MB4-02	Rushmere	37° 04' 01.34" N	76° 40' 09.99" W	4.40
MB4-01	Rushmere			4.55
MH1	Rushmere	Collected from slump	Collected from slump	
MH2	Rushmere	block; original	block; original longitude	Collected from slump block; original elevation unknown
MH3	Rushmere	latitude unknown	unknown	
MH4	Rushmere	37° 04' 01.34" N	76° 40' 09.99" W	4.85

Appendix B.

Foraminiferal census data.

Species	*MH1*	*MB1-02*	*MB1-01*	*RM1-03*	*RM1-02*	*RM1-01*	*RMSM1-02*	*RMSM1-01*	*SM4-01*	*SM4-02*	*SM4-03*	*SM4-04*	*SM4-05*	*MH2*	*MB2-06*	*MB2-05*	*MB2-04*
Ammonia cf. *A. beccarii*	1													13			
Amphistegina lessonii																	
Bolivina brevior					5	1											
Bolivina imporcata	4		2	4		3	2		4	2	2	2	3	3	6	3	1
Bolivina marginata multicostata		1				1											
Bolivina paula	18	18	15	12	25	6	7	3	8	6	4	3	4	7	17	7	14
Bolivina robusta					1	1		1		2					2		
Bolivina subdilatata		1									1	3				2	
Buccella anderseni	2		2	4	3	2	1		1	1			2	2	1		1
Buccella depressa	8	15	25	46	29	10	21	28	6	3	3	4	5	6	14	16	7
Buccella frigida	1	15	2	2	6	6	1		1	1				2	7	18	15
Buccella inusitata	10	5	2	5	3	1	6	5	4	1	6	3	3	11		3	2
Buliminella bassendorfensis			1			1	1	1		1	2	1				3	
Buliminella brevior										3							
Buliminella curta		1	1	2	1		1	2				1	2				2
Buliminella elegantissima	15	83	77	31	17	13	5	10	5	9	3		6	5	61	80	90
Bulimina elongata					1				2	1							
Bulimina inflata			1														
Bulimina gracilis							2		1	4	2	4	1				
Cancris sagra												1					
Cassidulina laevigata		1				1						2	2				
Cassidulinoides bradyi										2	7	5	1				
Cibicides americanus	16	1	2	1			3	4	8	9		3	7	19			
Cibicides fletcheri	3	3		11	5	12	10	9	32	36	9	3	39	1			3
Cibicides lobatulus	14	1	3	6	16	19	17	7	20	16	7	18	17	29			
Cibicides sp. D									1								
Discorbis orbicularis			1									1	1	1			
Epistominella danvillensis	13	41	57	55	39	37	129	142	60	52	68	77	46	1	47	45	41
Elphidium advena																	
Elphidium cf. *E. excavatum*	80	56	53	65	75	35	43	31	3	3	6	1	3	80	98	82	38
Fissurina spp.	2	1	2	2		2			1	1			2		1	3	
Fursenkoina fusiformis		1						1									
Globocassidulina crassa	1		2	3	2	8	13	16	50	51	104	74	70			3	2
Globulina gibba						1				1							
Guttulina austriaca						3										1	2
Guttulina sp. A	1					1		1									
Guttulina sp. B																	
Guttulina sp. C														1			
Guttulina sp. D										1							
Lagena pseudosulcata						1	1						1				
Lagena cf. *L. marginata-perforata*		1															
Lagena sp. C									1		1						
Lagena sp. D			1							1	1				1		
Lenticulina americana												1		1			
Marginulina sp. A																	
Nonionella miocenica	1	9	3	4	1	2		2	1		1		2	1		4	4
Parafissurina bidens	1																
Patellina advena																	
Pseudononion pizarrense					1					1	3	1	2		1	2	10
Pseudononion spp.	2	12	6	3			5			2					1	12	11
Pyrulina albatrossi																	
Quinqueloculina lamarckiana							1							1			
Quinqueloculina seminula	1				1	5	3							17			
Reussoolina laevis							1						2			1	
Rosalina floridana	16	1	1	5	5	9	6	8	5	8	18	12	15	8			
Sagrina primitiva														1			
Sigmoidella kagaensis													1				
Sigmomorphina sp. A																	
Textularia deltoidea	17	6		5	12	17	7	1		5	2	2	8	17			2
Textularia gramen	17					10	13	7		6	1	5	5	11			
Trifarina illingi									5	2	1	4	1				
Trifarina occidentalis								1									
Trochulina bassleri	46	11	17	26	27	31	16	14	59	61	65	58	70	23	2	17	17
Uvigerina calvertensis	1		1			1	1						1				
Valvulineria danvillensis																	
Valvulineria floridana	2	7	3	1					2						1		8
Valvulineria sp. B																	
Indeterminate agglutinated	1	1												16		1	
Indeterminate hyaline	5	18	17	12	8	1	7	8	2	3	4	6	9	10	28	17	26
Planktic foraminifera			5	7	12	8	5	2	6	3	3	7	8	2	1	1	1
Total	*299*	*310*	*297*	*305*	*283*	*241*	*323*	*302*	*282*	*295*	*321*	*295*	*331*	*287*	*288*	*320*	*296*

Species	*MB2-03*	*MB2-02*	*MB2-01*	*RM2-03*	*RM2-02*	*RM2-01*	*RMSM2-02*	*RMSM2-01*	*MH3*	*MB3-02*	*MB3-01*	*RM3-03*	*RM3-02*	*RM3-01*	*RMSM3-02*	*RMSM3-01*
Ammonia cf. *A. beccarii*						4			1							
Amphistegina lessonii									3							
Bolivina brevior																
Bolivina imporcata	5	6		4	5	5	6		3	2	1	3	3	3	2	1
Bolivina marginata multicostata																
Bolivina paula	15	17	22	29	34	14	12	11	16	15	17	23	17	16	15	8
Bolivina robusta	1	2	1		1								1			
Bolivina subdilatata							3					1				
Buccella anderseni	1			1	2	1	1			2	1	1	1	1		
Buccella depressa	13	17	16	13	21	24	32	12	5	6	14	19	17	11	14	13
Buccella frigida	30	7		32	2	2	2	2	3	22	6	10	16	8		4
Buccella inusitata	2	11	5	7	9	2	2	1	5	4	8	12	17	6	4	5
Buliminella bassendorfensis	3		4											1		
Buliminella brevior																
Buliminella curta			2	2		2	2	4		1	1	1	3		4	
Buliminella elegantissima	78	78	72	53	24	4	22	5	6	92	65	26	25	66	9	7
Bulimina elongata						1						1				
Bulimina inflata							1									
Bulimina gracilis			1					1				1		1	1	
Cancris sagra									1							
Cassidulina laevigata					1	1										7
Cassidulinoides bradyi																
Cibicides americanus	1	1	4		1		1		19	2		5				2
Cibicides fletcheri	3	3	12	3	1	21	18	10	9	2	3	6	6	2	9	13
Cibicides lobatulus			2	6	10	17	20	8	20	3	3	3	10	6	24	18
Cibicides sp. D																
Discorbis orbicularis		1							2				2			
Epistominella danvillensis	32	35	44	44	49	45	78	111	27	35	45	57	48	32	72	80
Elphidium advena									5							
Elphidium cf. *E. excavatum*	47	75	66	51	69	41	44	40	50	67	41	60	59	57	13	20
Fissurina spp.		2	4		4		1	3	1	1	3	2		2	2	2
Fursenkoina fusiformis		1			1			1		2						
Globocassidulina crassa	2	2	3	1	1	10	5	4	2	1		4	5	4	6	6
Globulina gibba														1		
Guttulina austriaca	1			1	1						2	1				
Guttulina sp. A																1
Guttulina sp. B														1		
Guttulina sp. C																
Guttulina sp. D									1							
Lagena pseudosulcata							1	1						1	1	2
Lagena cf. *L. marginata-perforata*					1			1			1			1	2	1
Lagena sp. C															1	
Lagena sp. D													1			
Lenticulina americana				1	1	1				1		1				
Marginulina sp. A						1										
Nonionella miocenica	4	10	6	13	3	1			3	9	8	3	1	16		
Parafissurina bidens	1															
Patellina advena							1	1								2
Pseudononion pizarrense	5	6	6				3		1	3	1			3		2
Pseudononion spp.	10	6	3	19	4	2	1		3	9	10	10	2	8		
Pyrulina albatrossi						1										
Quinqueloculina lamarckiana															2	
Quinqueloculina seminula						1	5	3					1	1	3	1
Reussoolina laevis				1				1				1		1		
Rosalina floridana		1	3	2	5	11	9	1	7			2	5	8	10	12
Sagrina primitiva																
Sigmoidella kagaensis																
Sigmomorphina sp. A							1		1						1	
Textularia deltoidea	1		1	1	3	5	7	4	12	2	2	2	3	6	17	29
Textularia gramen					2		24	8	16						27	14
Trifarina illingi									3							
Trifarina occidentalis					2											
Trochulina bassleri	17	12	15	26	43	25	30	29	39	17	20	42	24	21	30	25
Uvigerina calvertensis				1	1	1			5				1			
Valvulineria danvillensis			1					1								
Valvulineria floridana	1	1	3	5		8			3		4	2	1	4	4	
Valvulineria sp. B									1							
Indeterminate agglutinated	1								4							
Indeterminate hyaline	18	18	18	17	28	24	16	13	11	13	15	23	29	13	22	11
Planktic foraminifera	1	6	5	6	12	7	7	9	3	1	5	7	14	7	4	4
Total	*292*	*312*	*314*	*333*	*329*	*275*	*348*	*276*	*288*	*311*	*271*	*322*	*298*	*301*	*295*	*286*

Appendix C.

Grain-size distribution data.

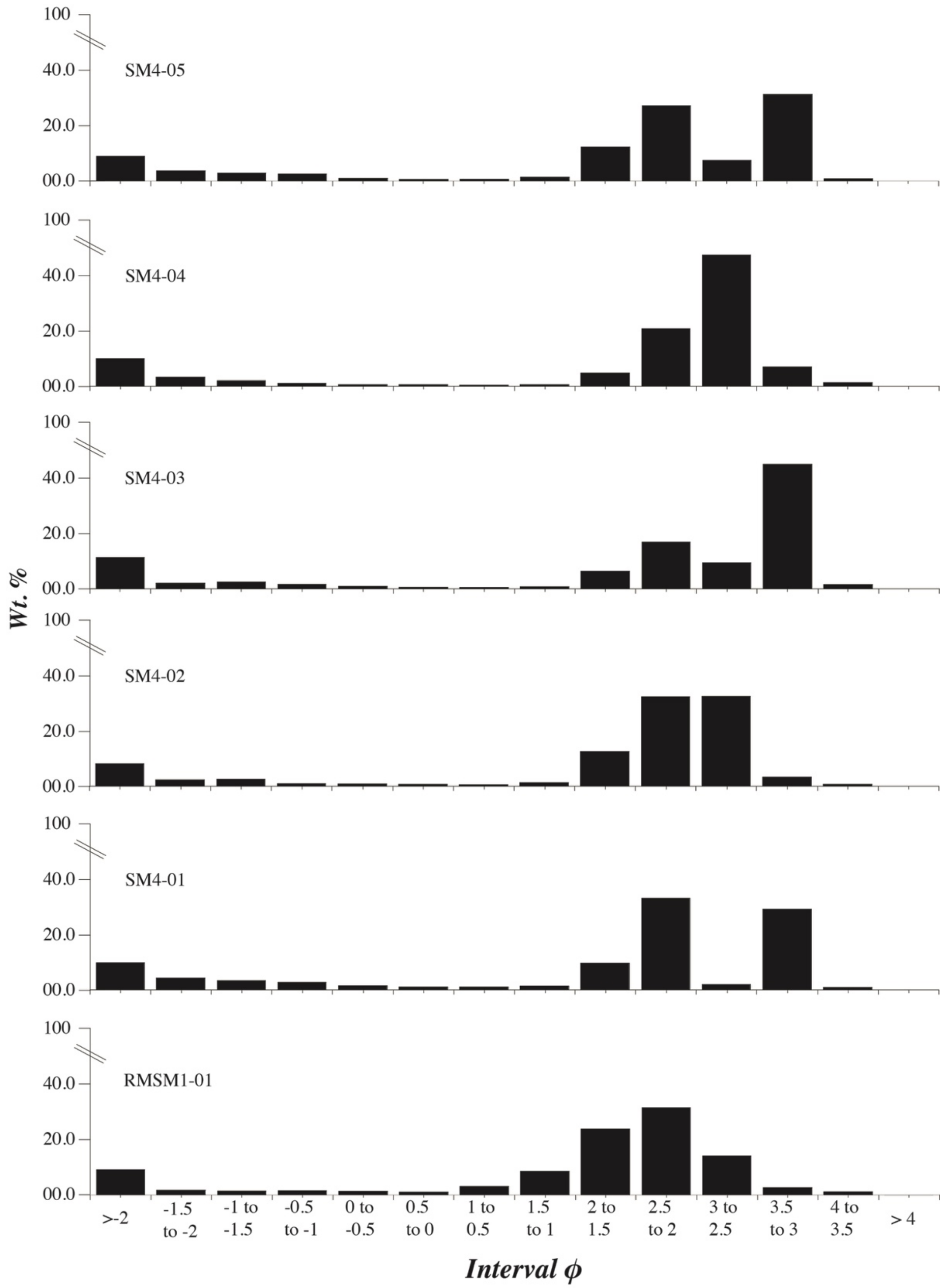
		Sample Name																				
		SM4-05	*SM4-04*	*SM4-03*	*SM4-02*	*SM4-01*	*RMSM1-01*	*RMSM2-01*	*RMSM3-01*	*RMSM1-02*	*RMSM2-02*	*RMSM3-02*	*RM1-01*	*RM2-01*	*RM3-01*	*RM1-02*	*RM2-02*	*RM3-02*	*RM1-03*	*RM2-03*	*RM3-03*	*MB1-01*
Bulk Sample Wt.		30.47	30.05	30.14	29.48	30.66	29.99	31.52	30.31	29.77	29.97	34.93	29.93	30.16	31.46	29.93	31.2	30.29	37.3	29.93	31.46	30.02
Gravel Wt.		4.23	4.09	4.24	3.41	4.89	3.11	6.41	6.32	1.53	3.09	5.78	3.27	4.36	4.14	3.35	6.45	3.3	3.02	4.28	7.85	0.3
Sand Wt.		23.39	22.65	22.3	22.44	23.25	22.86	20.88	21.11	24.32	21.77	22.86	22.01	17.93	18.08	18.37	16.24	17	26.84	18.43	16.72	11.88
Mud Wt.		2.85	3.31	3.6	3.63	2.52	4.02	4.23	2.88	3.92	5.11	6.29	4.65	7.87	9.24	8.21	8.51	9.99	7.44	7.22	6.89	17.84
% Gravel		13.88	13.61	14.07	11.57	15.95	10.37	20.34	20.85	5.14	10.31	16.55	10.93	14.46	13.16	11.19	20.67	10.89	8.10	14.30	24.95	1.00
% Sand		76.76	75.37	73.99	76.12	75.83	76.23	66.24	69.65	81.69	72.64	65.45	73.54	59.45	57.47	61.38	52.05	56.12	71.96	61.58	53.15	39.57
% Mud		9.35	11.01	11.94	12.31	8.22	13.40	13.42	9.50	13.17	17.05	18.01	15.54	26.09	29.37	27.43	27.28	32.98	19.95	24.12	21.90	59.43
Sieve Phi	*Phi (φ) Interval*	*Grain Size Distribution (Wt., g)*																				
-2	>-2	2.45	2.67	3	2.13	2.75	2.34	4.75	4.57	0.55	1.85	3.98	1.82	3.47	2.37	1.75	4.31	1.33	1.77	3.3	5.8	0
-1.5	-1.5 to -2	1.01	0.89	0.56	0.61	1.2	0.42	1.05	1.18	0.47	0.55	0.93	0.74	0.35	1.17	0.93	1.31	1.04	0.81	0.48	1.18	0.12
-1	-1 to -1.5	0.77	0.53	0.68	0.67	0.94	0.35	0.61	0.57	0.51	0.69	0.87	0.71	0.54	0.6	0.67	0.83	0.93	0.44	0.5	0.87	0.18
-0.5	-0.5 to -1	0.68	0.28	0.45	0.26	0.77	0.39	0.7	0.79	0.65	0.95	0.39	0.92	0.57	0.66	0.78	0.52	0.85	0.55	0.57	0.68	0.22
0	0 to -0.5	0.25	0.16	0.26	0.23	0.42	0.33	0.57	0.69	0.31	0.52	0.33	1.05	0.56	0.64	0.47	0.24	0.52	0.43	0.43	0.52	0.06
0.5	0.5 to 0	0.14	0.17	0.17	0.2	0.3	0.24	0.55	0.46	0.52	0.78	0.24	0.74	0.45	0.41	0.61	0.28	0.63	0.32	0.28	0.31	0.18
1	1 to 0.5	0.17	0.12	0.14	0.16	0.3	0.78	1.11	1.08	1.14	1.08	0.78	1.13	0.78	0.5	0.72	0.36	0.71	0.36	0.34	0.36	0.18
1.5	1.5 to 1	0.37	0.17	0.22	0.34	0.4	2.2	2.14	2.14	2.65	2.29	2.2	2.59	1.84	1.28	1.56	0.48	1.46	0.95	1	0.82	0.42
2	2 to 1.5	3.36	1.28	1.7	3.28	2.72	6.16	5.4	5.5	6.52	5.88	6.16	6.17	4.55	3.95	4.51	3.95	3.83	4.46	4.25	3.72	1.35
2.5	2.5 to 2	7.48	5.56	4.47	8.43	9.31	8.15	6.62	7.02	8.21	6.56	8.15	6.47	5.37	4.66	5.34	4.87	4.46	6.1	5.26	4.91	1.45
3	3 to 2.5	2.05	12.65	2.48	8.46	0.54	3.64	2.89	2.65	3.61	2.56	3.64	2.22	2.65	1.76	2.58	2.13	2.52	2.2	1.75	1.8	0.88
3.5	3.5 to 3	8.62	1.86	11.9	0.86	8.18	0.66	0.6	0.49	0.43	0.58	0.66	0.44	0.59	1.75	0.83	1.38	0.84	1.96	2.05	1.7	2.07
4	4 to 3.5	0.22	0.36	0.43	0.19	0.24	0.28	0.28	0.25	0.26	0.53	0.28	0.25	0.54	2.39	0.94	1.86	1.11	2	2.44	1.78	4.66
>4	>4	0.05	0.04	0.08	0.03	0.07	0.03	0.02	0.04	0.02	0.04	0.03	0.03	0.03	0.08	0.03	0.17	0.07	7.51	0.06	0.12	0.41

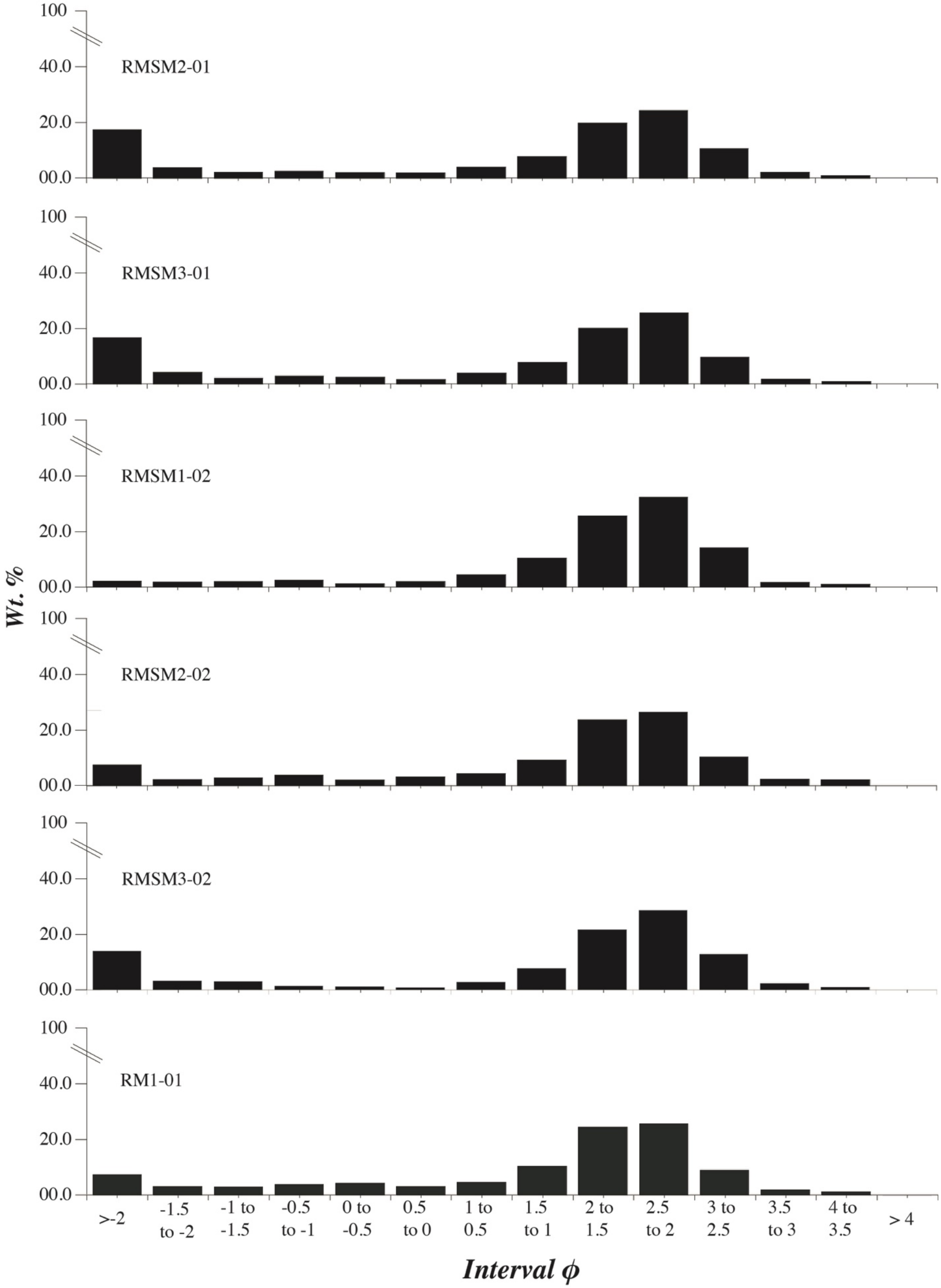
		Sample Name																				
		MB2-01	*MB3-01*	*MB1-02*	*MB2-02*	*MB3-02*	*MB1-03*	*MB2-03*	*MB3-03*	*MB1-04*	*MB2-04*	*MB3-04*	*MB1-05*	*MB2-05*	*MB3-05*	*MB1-06*	*MB2-06*	*MB3-06*	*MB4-03*	*MB4-02*	*MB4-01*	*MH4*
Bulk Sample Wt.		30.12	29.93	30.38	30.38	30.43	31.11	30.32	30.65	30.61	30.38	30.13	30.32	30.19	30.26	30.31	30.44	30.54	35.68	31.51	31.03	30.06
Gravel Wt.		0.72	0.53	0.01	0.06	0.01	0	0	0.52	0	0	0.01	0	0	0	0	0	0	1.13	0.17	0.24	0.44
Sand Wt.		12.86	11.64	10.07	8.45	5.54	3.43	4.07	5.93	2.05	3.62	2.83	2.99	3.05	2.14	1.95	3.14	2.56	2.01	2.16	3.16	21.91
Mud Wt.		16.54	17.76	20.3	21.87	24.88	27.68	26.25	24.2	28.56	26.76	27.29	27.33	27.14	28.12	28.36	27.3	27.98	32.54	29.18	27.63	7.71
% Gravel		2.39	1.77	0.03	0.20	0.03	0.00	0.00	1.70	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	3.17	0.54	0.77	1.46
% Sand		42.70	38.89	33.15	27.81	18.21	11.03	13.42	19.35	6.70	11.92	9.39	9.86	10.10	7.07	6.43	10.32	8.38	5.63	6.85	10.18	72.89
% Mud		54.91	59.34	66.82	71.99	81.76	88.97	86.58	78.96	93.30	88.08	90.57	90.14	89.90	92.93	93.57	89.68	91.62	91.20	92.61	89.04	25.65
Sieve Phi	*Phi (φ) Interval*	*Grain Size Distribution (Wt., g)*																				
-2	>-2	0.35	0.27	0	0	0	0	0	0.29	0	0	0	0	0	0	0	0	0	0.02	0	0	0.14
-1.5	-1.5 to -2	0.19	0.14	0	0.04	0	0	0	0.18	0	0	0	0	0	0	0	0	0	0.11	0.08	0.12	0.12
-1	-1 to -1.5	0.18	0.12	0.01	0.02	0.01	0	0	0.05	0	0	0.01	0	0	0	0	0	0	0.1	0.09	0.12	0.18
-0.5	-0.5 to -1	0.28	0.22	0.01	0.05	0.01	0	0.01	0.03	0	0	0	0	0	0.01	0.01	0	0	0.09	0.04	0.05	0.22
0	0 to -0.5	0.22	0.09	0.01	0.06	0.01	0	0.01	0.01	0	0.01	0	0	0.01	0	0.01	0.01	0	0.1	0.05	0.06	0.41
0.5	0.5 to 0	0.23	0.13	0.01	0.05	0.01	0.01	0.01	0.02	0.01	0.02	0	0.01	0.01	0.02	0.01	0.01	0.01	0.05	0.03	0.06	1.04
1	1 to 0.5	0.18	0.14	0.03	0.08	0.01	0.01	0.04	0.01	0.01	0.03	0.02	0.01	0.01	0.03	0.01	0.02	0.01	0.06	0.05	0.05	2.98
1.5	1.5 to 1	0.38	0.27	0.2	0.18	0.08	0.01	0.05	0.05	0.01	0.02	0.03	0.01	0.01	0.03	0.01	0.03	0.01	0.12	0.07	0.06	4.98
2	2 to 1.5	1.43	1.1	0.87	0.77	0.39	0.1	0.22	0.37	0.01	0.07	0.05	0.01	0.04	0.04	0.01	0.03	0.01	0.14	0.06	0.07	4.96
2.5	2.5 to 2	1.59	1.35	1.06	1.06	0.54	0.16	0.31	0.59	0.02	0.12	0.07	0.04	0.06	0.05	0.01	0.05	0.01	0.15	0.1	0.14	3.12
3	3 to 2.5	0.94	0.86	0.61	0.64	0.31	0.13	0.32	0.48	0.04	0.15	0.06	0.06	0.11	0.06	0.04	0.08	0.02	0.12	0.12	0.14	0.61
3.5	3.5 to 3	2.23	2.17	2.24	1.84	1.32	0.8	0.88	1.19	0.5	0.82	0.64	0.68	0.62	0.4	0.5	0.71	0.54	0.24	0.08	0.89	3.14
4	4 to 3.5	4.95	4.93	4.68	3.56	2.77	2.17	2.11	2.99	1.42	2.25	1.9	2.11	2	1.43	1.32	2.12	1.89	1.84	1.56	1.64	0.45
>4	>4	0.43	0.38	0.35	0.16	0.09	0.04	0.11	0.19	0.03	0.13	0.06	0.06	0.18	0.07	0.02	0.08	0.06	0	0	0	0

Appendix D.

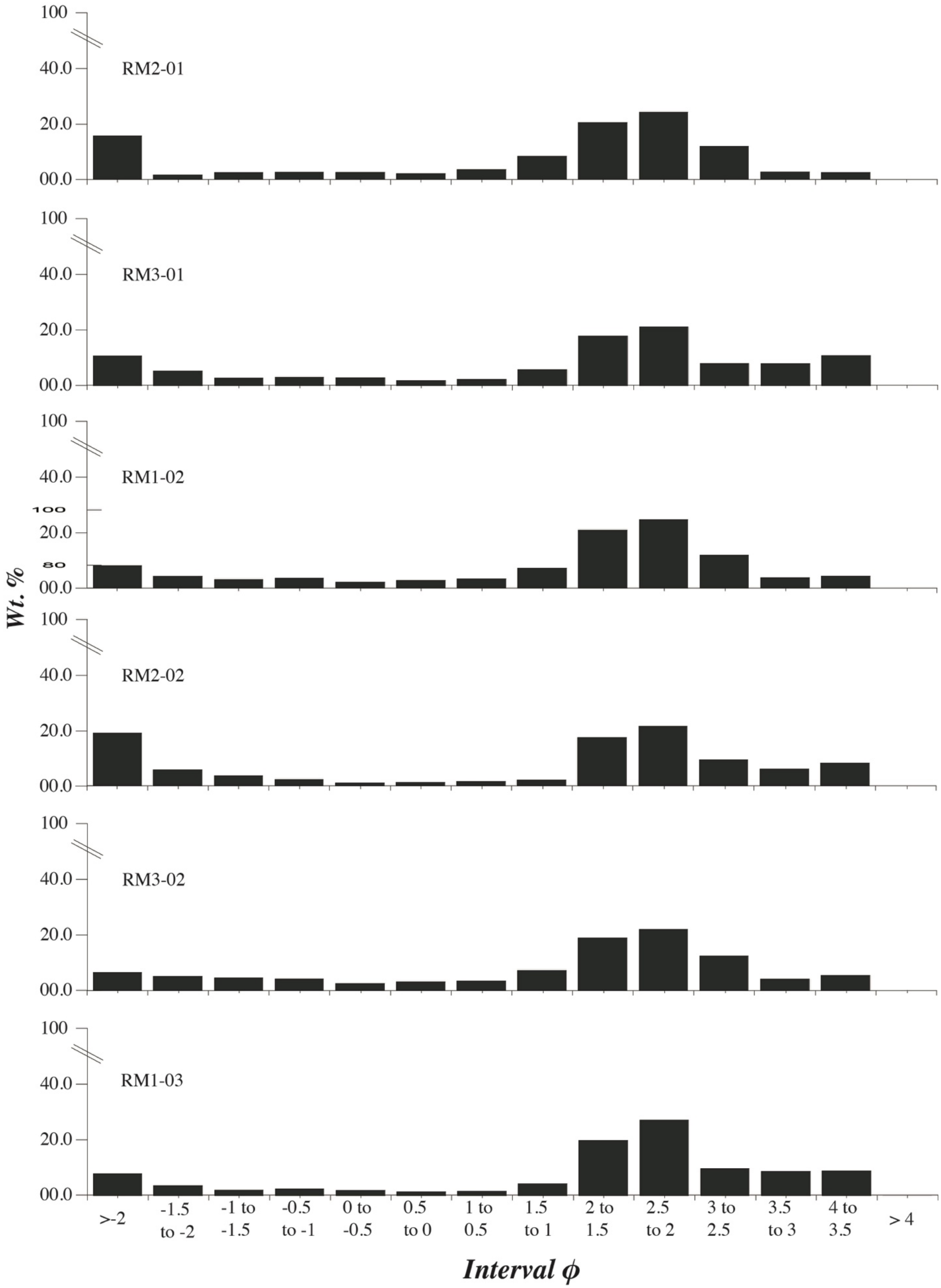
Histograms of grain-size distribution (>63 µm size-fraction only) in stratigraphic order.

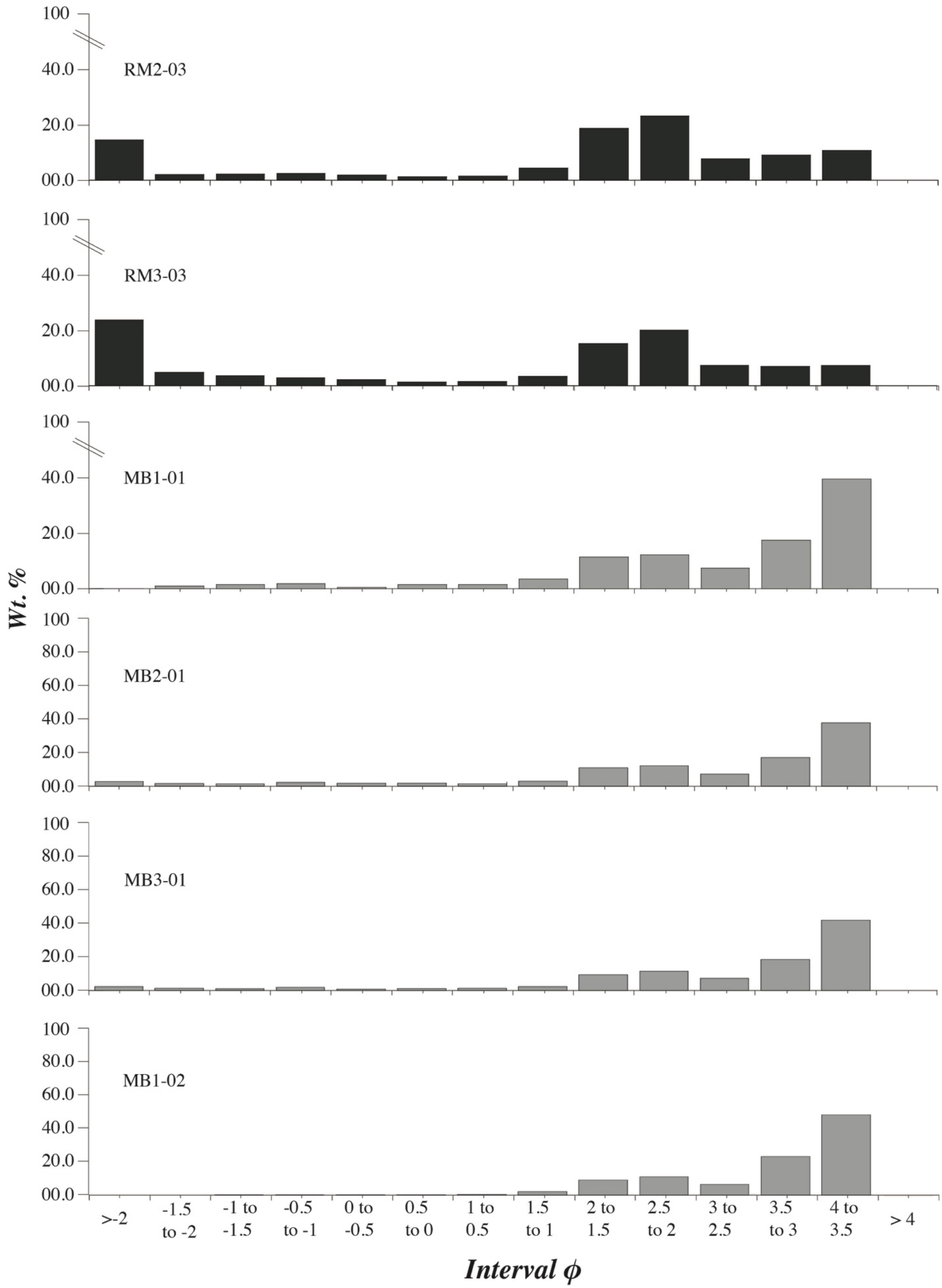
Members are color-coded for visual distinction: Sunken Meadow Member – Black, Rushmere Member – dark gray, Morgarts Beach Member – medium gray, and Moore House Member – light gray.

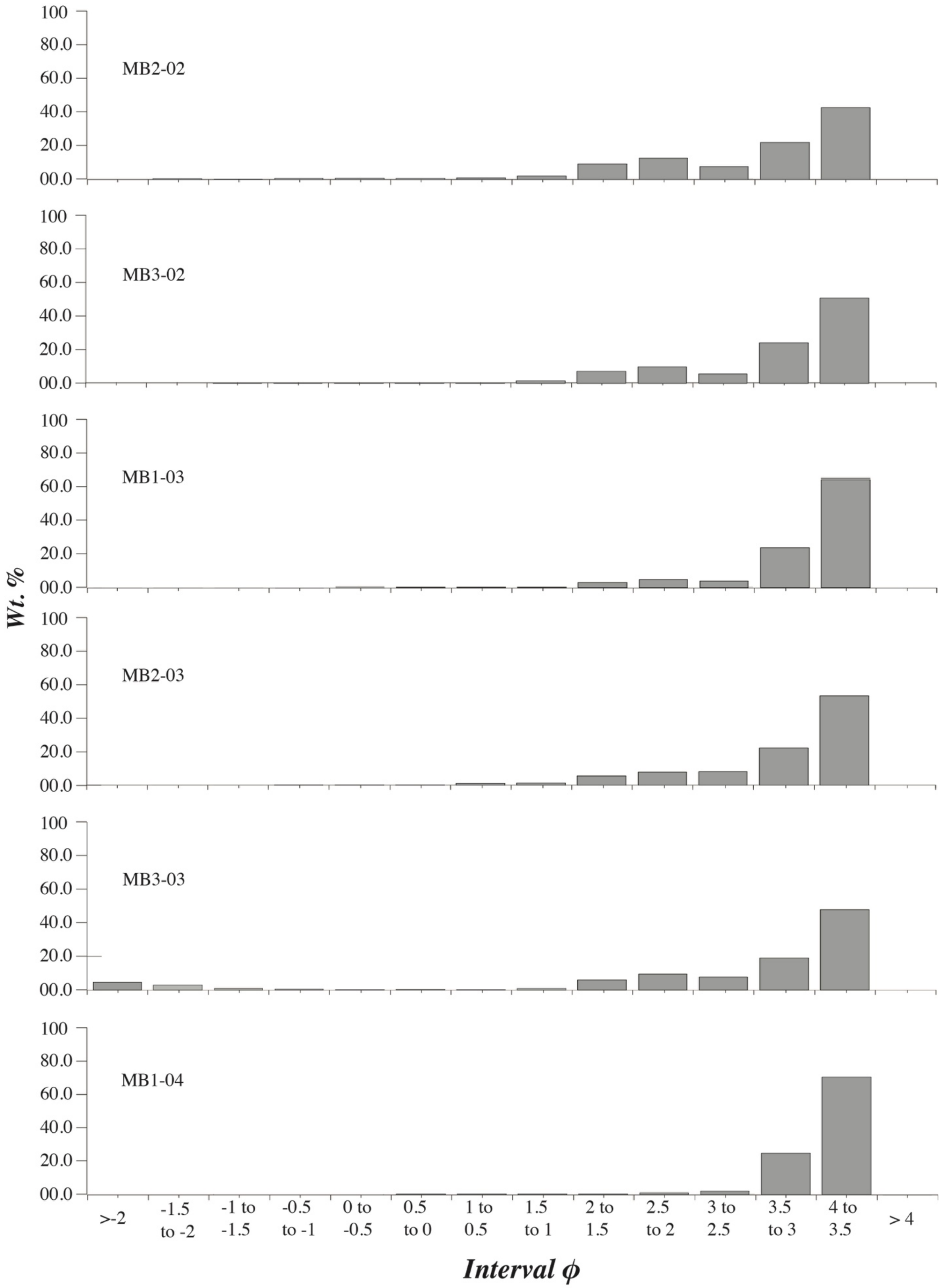


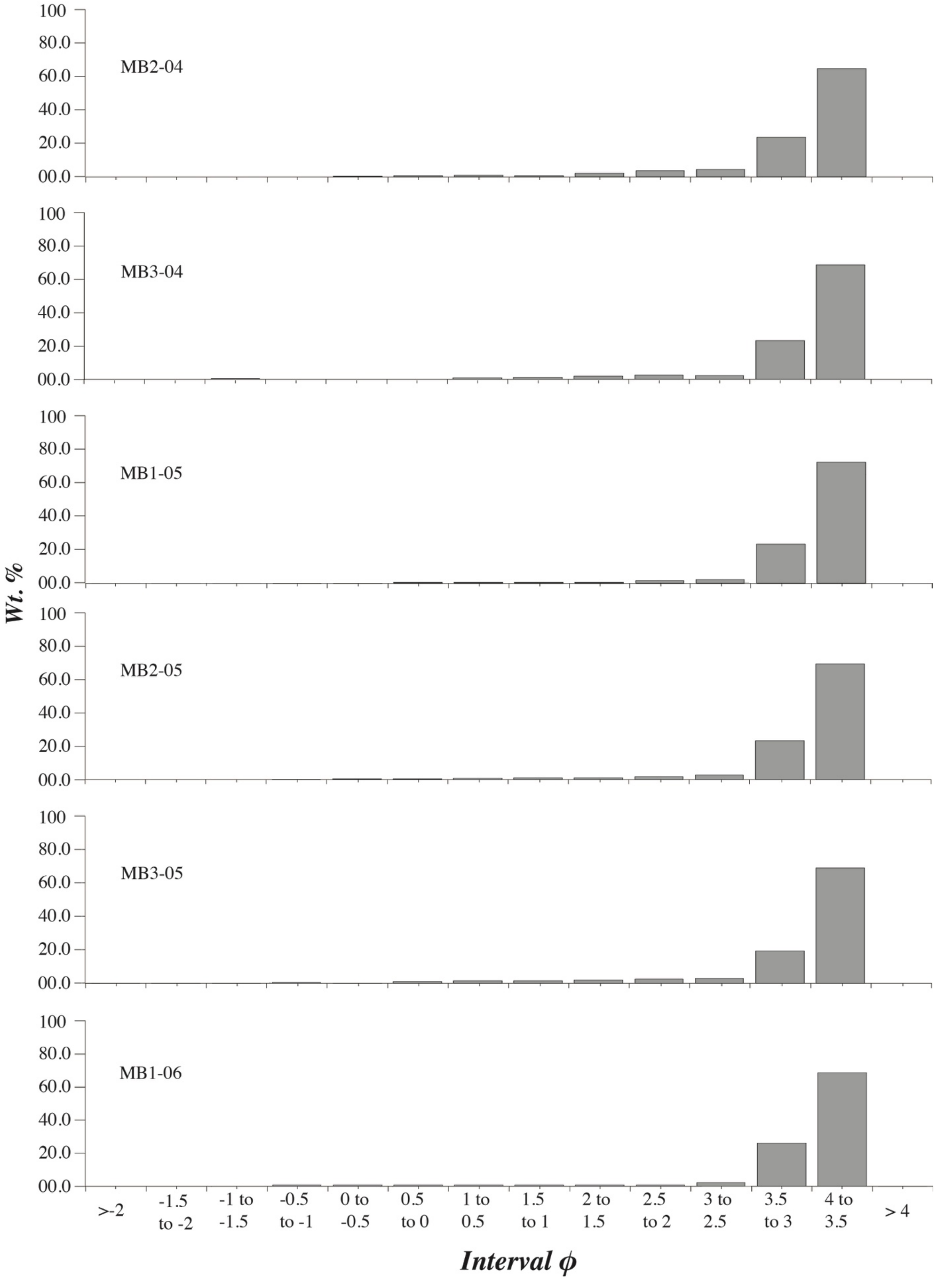


Wt. %
RMSM2-01
RMSM3-01
RMSM1-02
RMSM2-02
RMSM3-02
RM1-01
100
40.0
20.0
00.0
>-2
-1.5 to -2
-1 to -1.5
-0.5 to -1
0 to -0.5
0.5 to 0
1 to 0.5
1.5 to 1
2 to 1.5
2.5 to 2
3 to 2.5
3.5 to 3
4 to 3.5
> 4
Interval ϕ

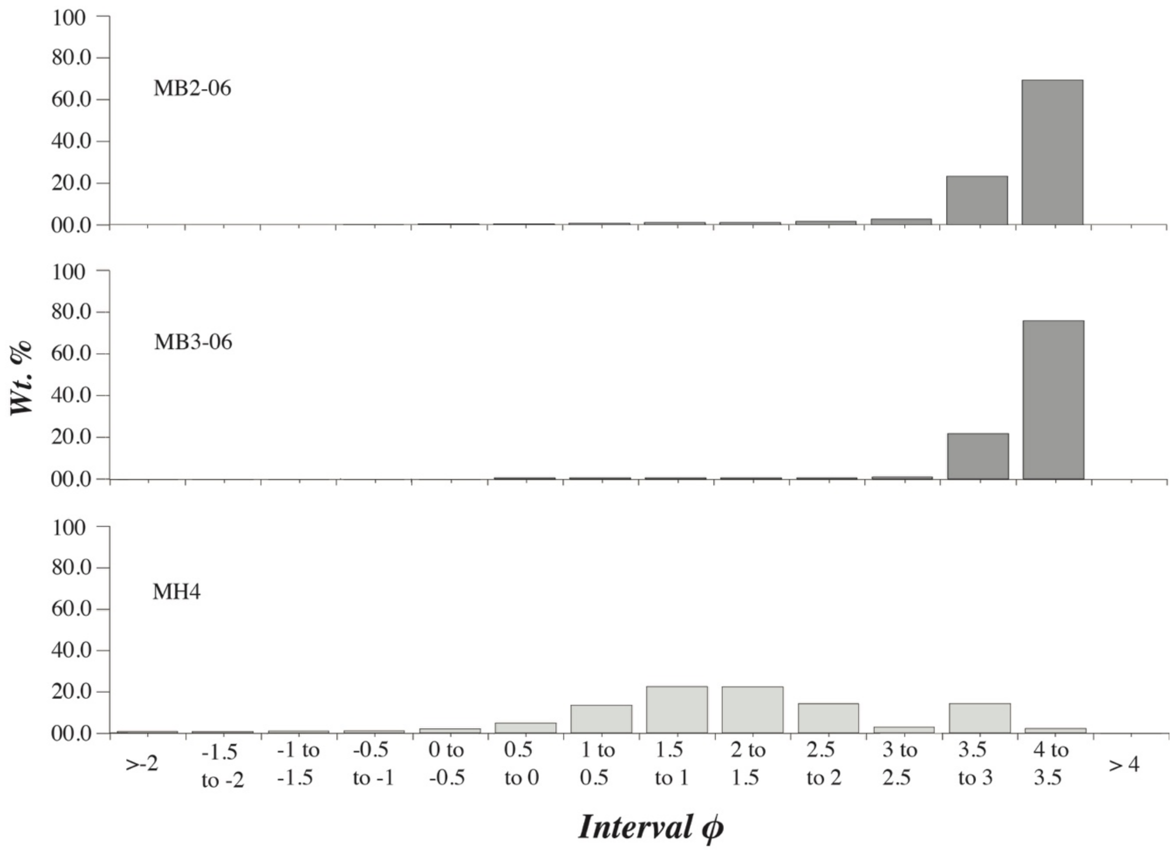

Wt. %
100
40.0
20.0
00.0
RM2-01
RM3-01
RM1-02
RM2-02
RM3-02
RM1-03
>-2
-1.5 to -2
-1 to -1.5
-0.5 to -1
0 to -0.5
0.5 to 0
1 to 0.5
1.5 to 1
2 to 1.5
2.5 to 2
3 to 2.5
3.5 to 3
4 to 3.5
> 4
Interval ϕ


RM2-03
RM3-03
MB1-01
MB2-01
MB3-01
MB1-02
Wt. %
100
80.0
60.0
40.0
20.0
00.0
>-2
-1.5 to -2
-1 to -1.5
-0.5 to -1
0 to -0.5
0.5 to 0
1 to 0.5
1.5 to 1
2 to 1.5
2.5 to 2
3 to 2.5
3.5 to 3
4 to 3.5
> 4
Interval φ


MB2-02
MB3-02
MB1-03
MB2-03
MB3-03
MB1-04
Wt. %
100
80.0
60.0
40.0
20.0
00.0
>-2
-1.5 to -2
-1 to -1.5
-0.5 to -1
0 to -0.5
0.5 to 0
1 to 0.5
1.5 to 1
2 to 1.5
2.5 to 2
3 to 2.5
3.5 to 3
4 to 3.5
> 4
Interval ϕ



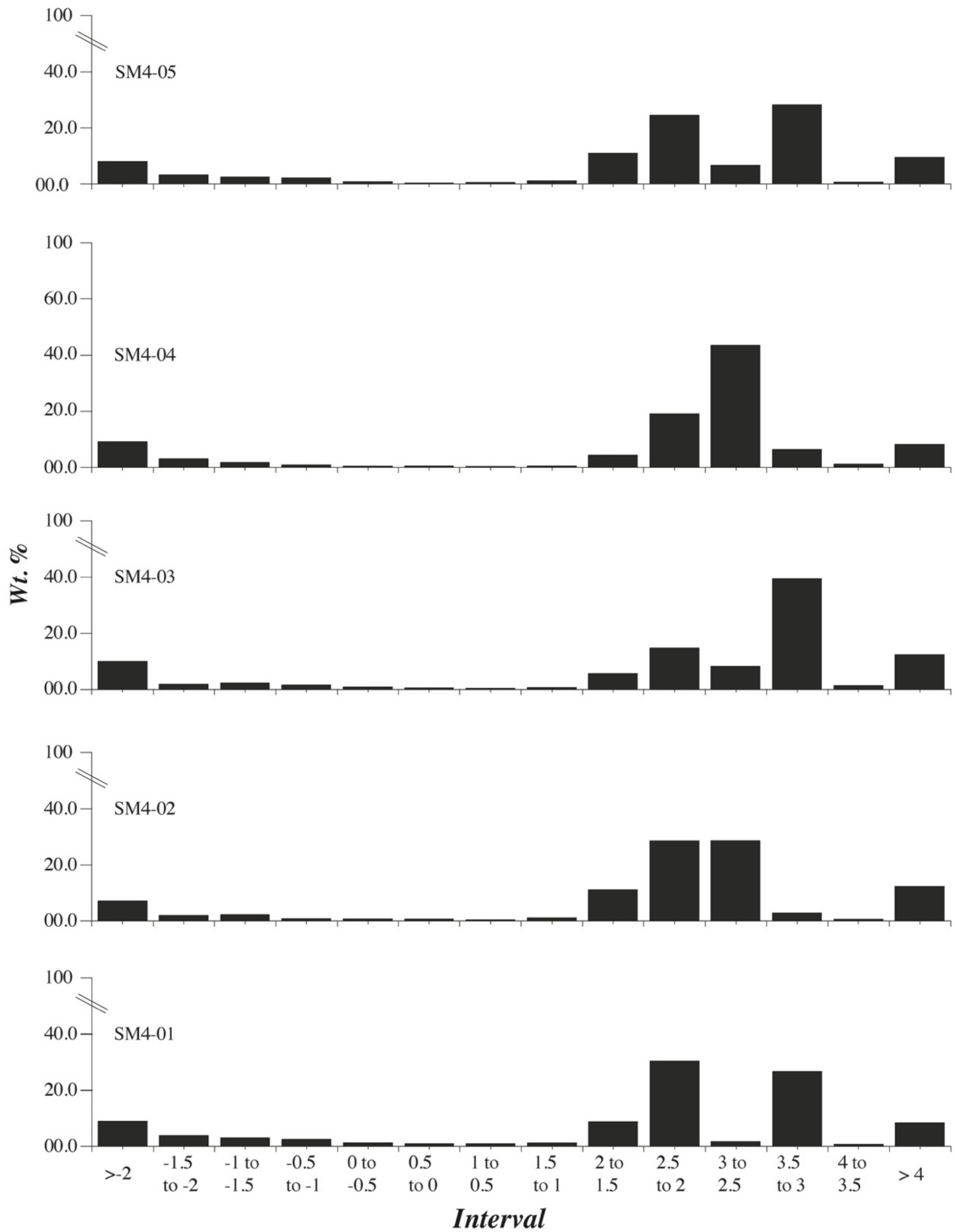
MB2-04
MB3-04
MB1-05
MB2-05
MB3-05
MB1-06
Wt. %
100
80.0
60.0
40.0
20.0
00.0
>-2
-1.5 to -2
-1 to -1.5
-0.5 to -1
0 to -0.5
0.5 to 0
1 to 0.5
1.5 to 1
2 to 1.5
2.5 to 2
3 to 2.5
3.5 to 3
4 to 3.5
> 4
Interval ϕ

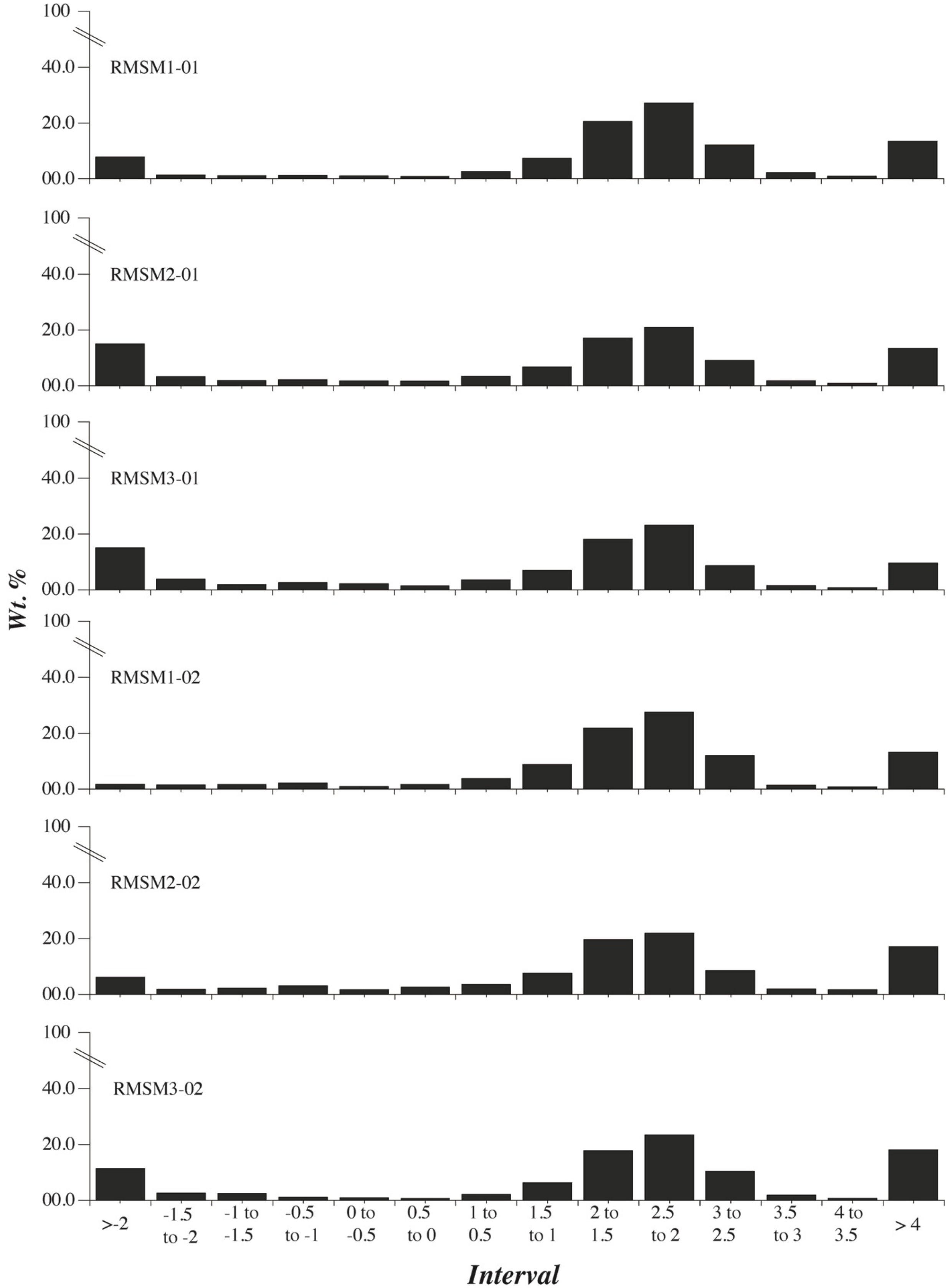

Wt. %
MB2-06
MB3-06
MH4
100
80.0
60.0
40.0
20.0
00.0
>-2
-1.5 to -2
-1 to -1.5
-0.5 to -1
0 to -0.5
0.5 to 0
1 to 0.5
1.5 to 1
2 to 1.5
2.5 to 2
3 to 2.5
3.5 to 3
4 to 3.5
> 4
Interval φ

Appendix E.

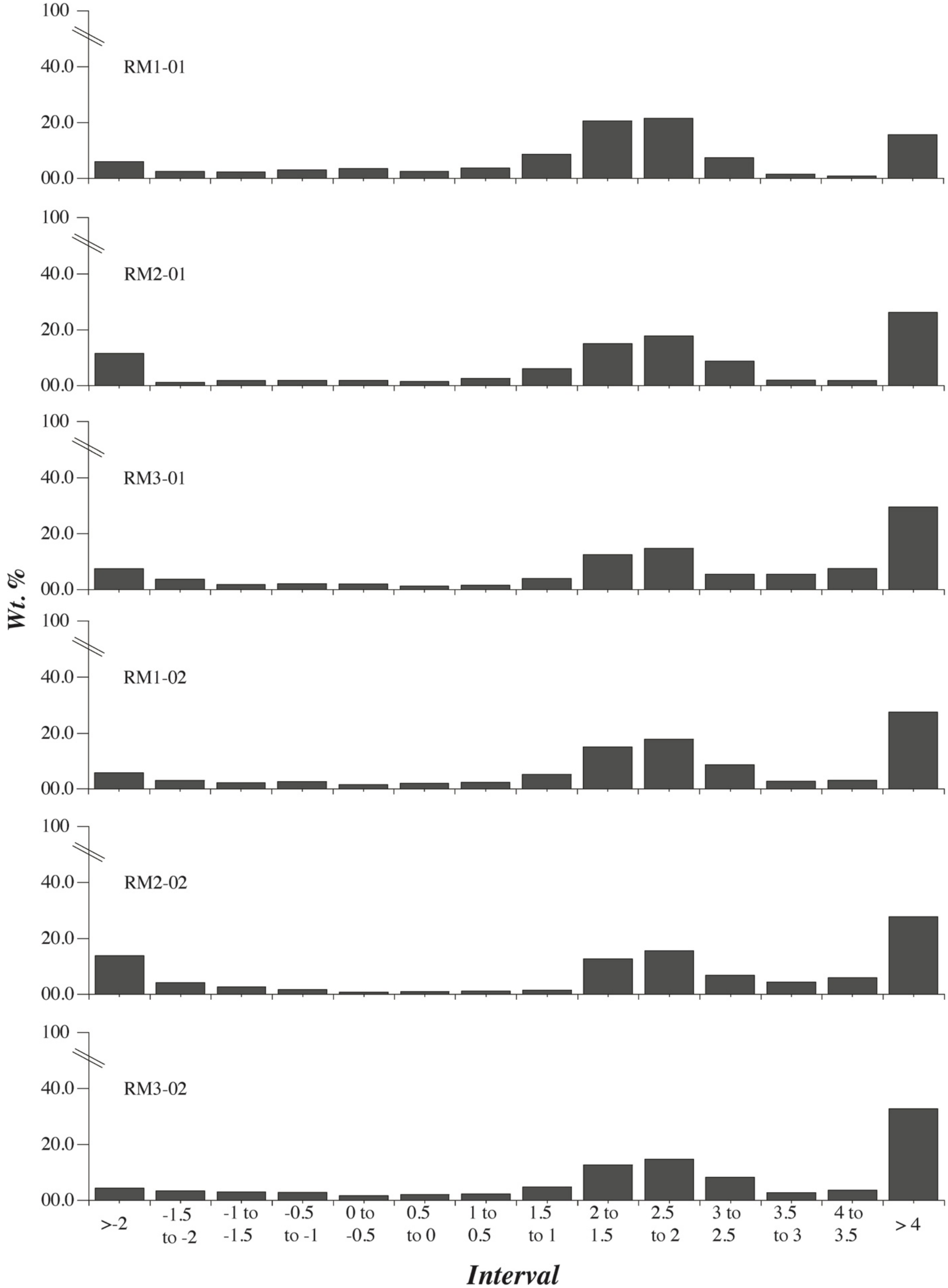
Histograms of grain-size distribution (all grain-size fractions) in stratigraphic order.

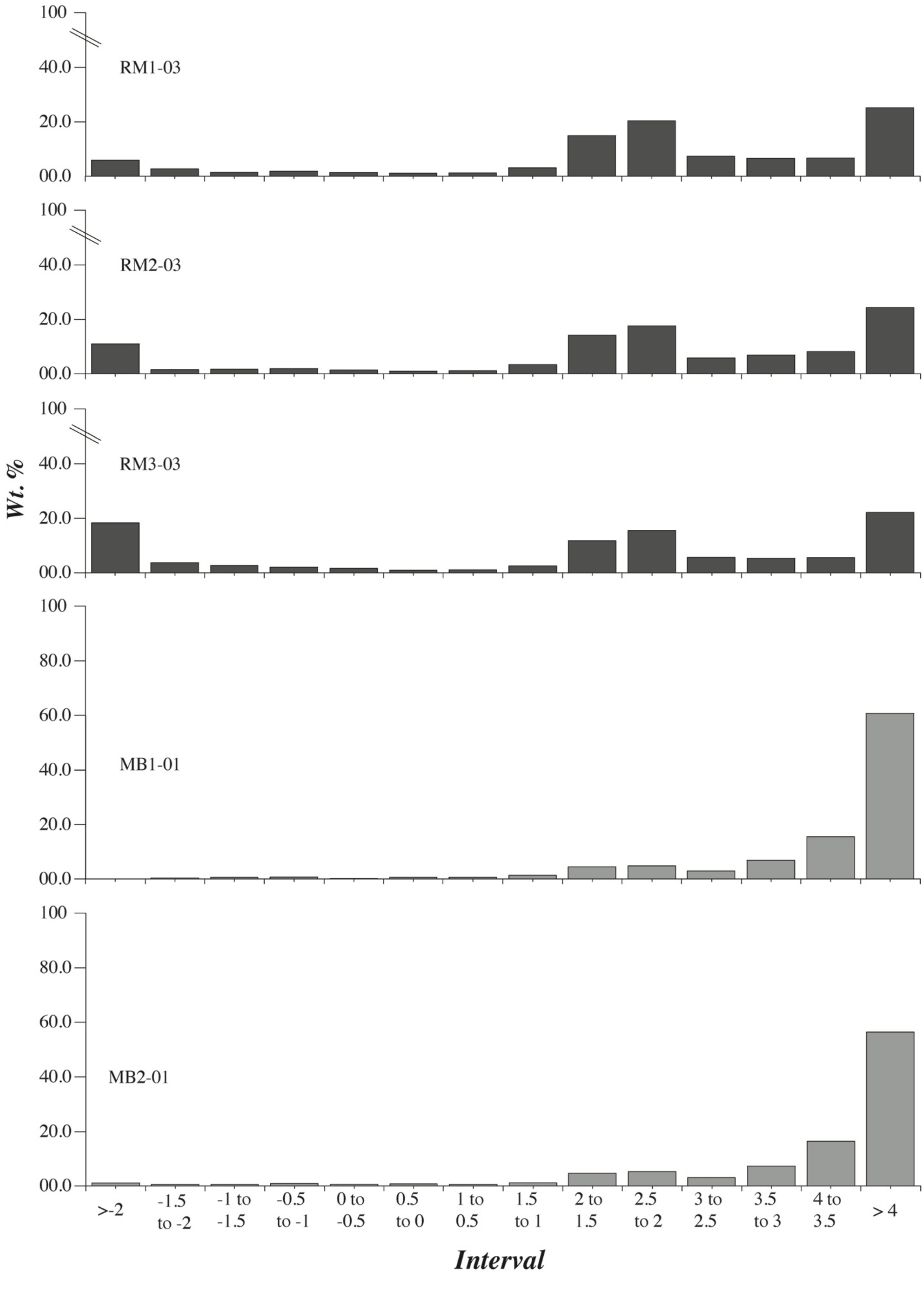
Members are color-coded for visual distinction: Sunken Meadow Member – Black, Rushmere Member – dark gray, Morgarts Beach Member – medium gray, and Moore House Member – light gray.

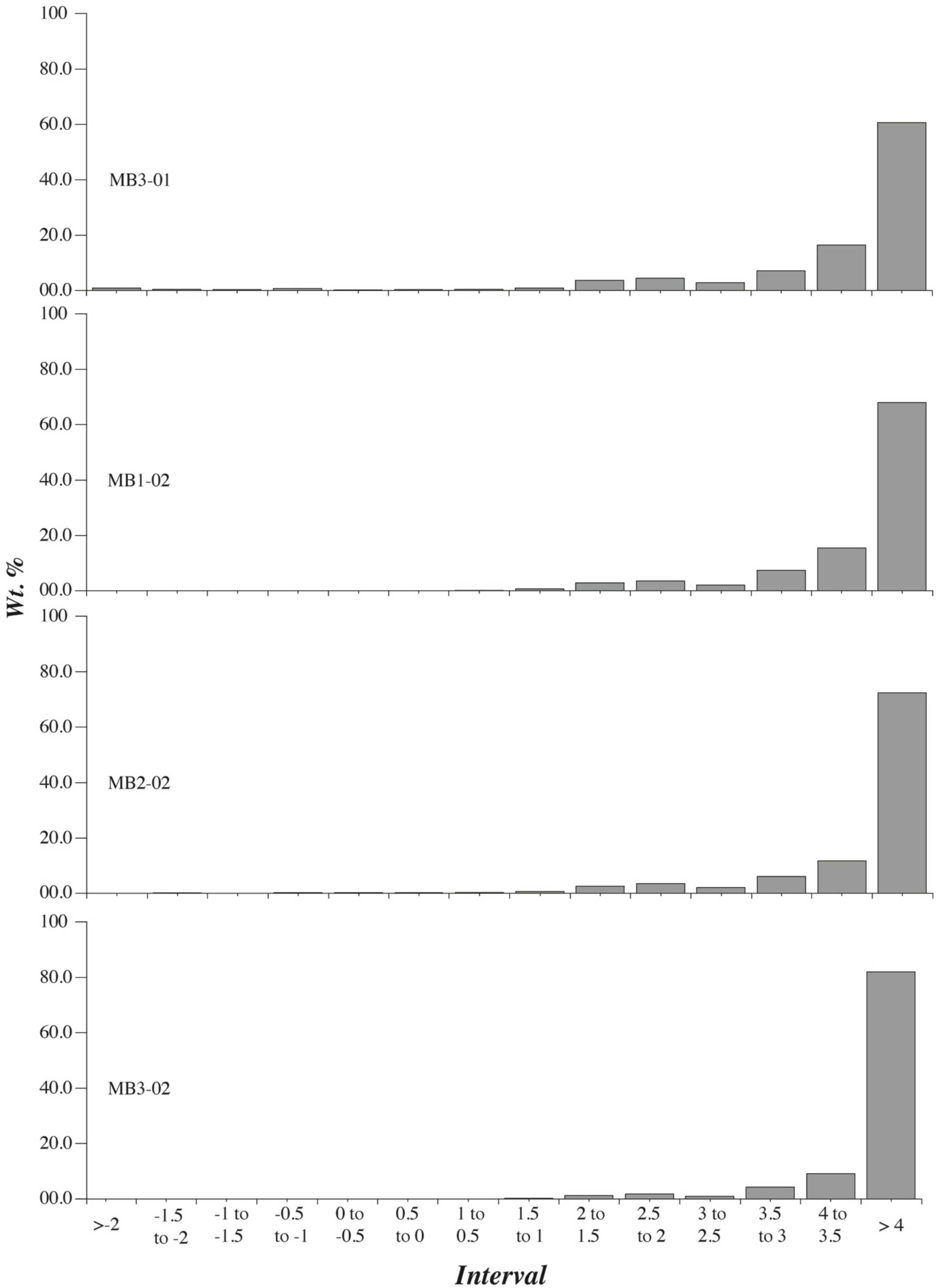




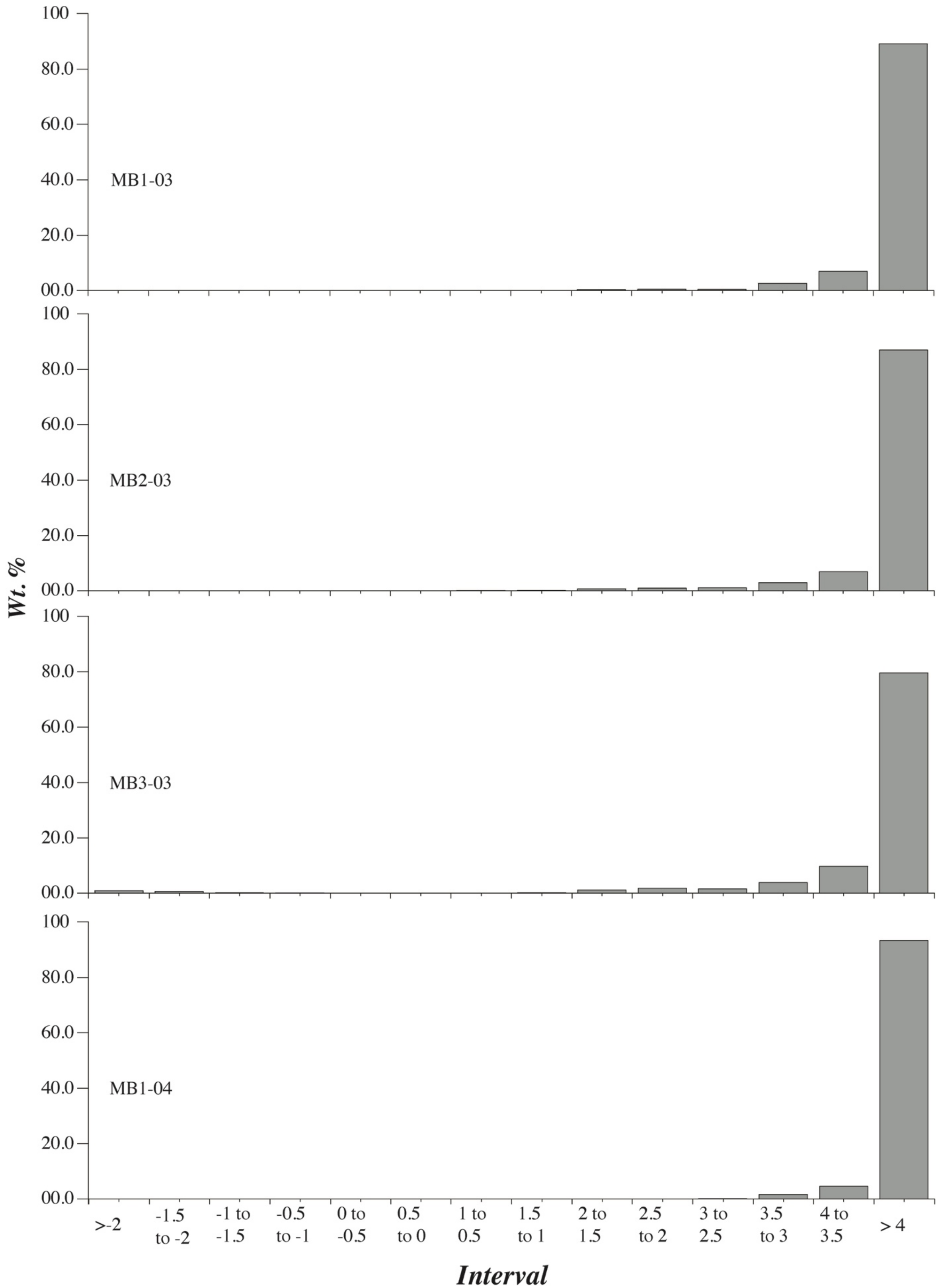
Wt. %
100
40.0
20.0
00.0
RMSM1-01
RMSM2-01
RMSM3-01
RMSM1-02
RMSM2-02
RMSM3-02
>-2
-1.5 to -2
-1 to -1.5
-0.5 to -1
0 to -0.5
0.5 to 0
1 to 0.5
1.5 to 1
2 to 1.5
2.5 to 2
3 to 2.5
3.5 to 3
4 to 3.5
> 4
Interval


RM1-01
RM2-01
RM3-01
RM1-02
RM2-02
RM3-02
Wt. %
100
40.0
20.0
00.0
>-2
-1.5 to -2
-1 to -1.5
-0.5 to -1
0 to -0.5
0.5 to 0
1 to 0.5
1.5 to 1
2 to 1.5
2.5 to 2
3 to 2.5
3.5 to 3
4 to 3.5
> 4
Interval

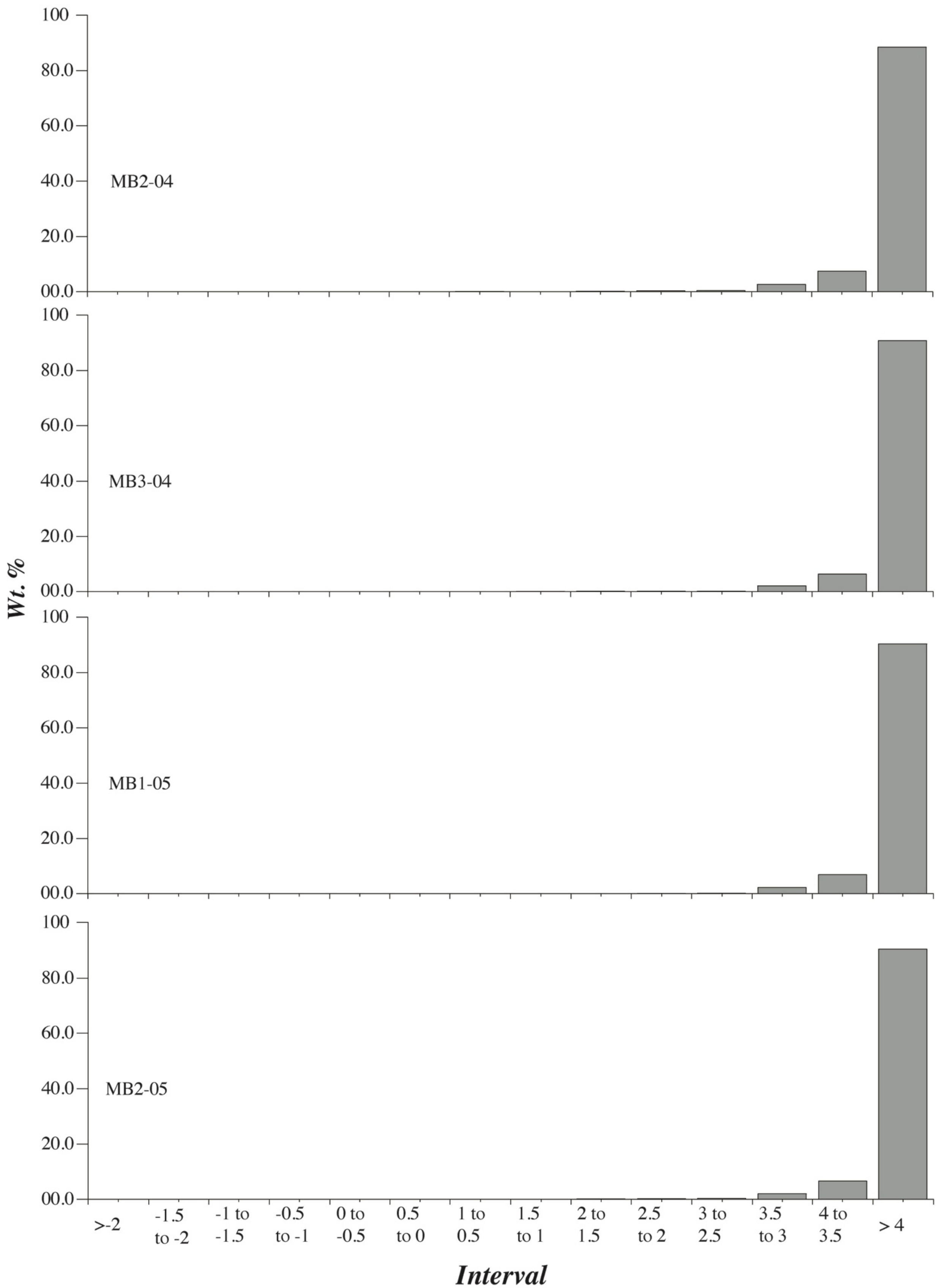

100
40.0
20.0
00.0
RM1-03
RM2-03
RM3-03
Wt. %
80.0
60.0
MB1-01
MB2-01
>-2
-1.5 to -2
-1 to -1.5
-0.5 to -1
0 to -0.5
0.5 to 0
1 to 0.5
1.5 to 1
2 to 1.5
2.5 to 2
3 to 2.5
3.5 to 3
4 to 3.5
> 4
Interval

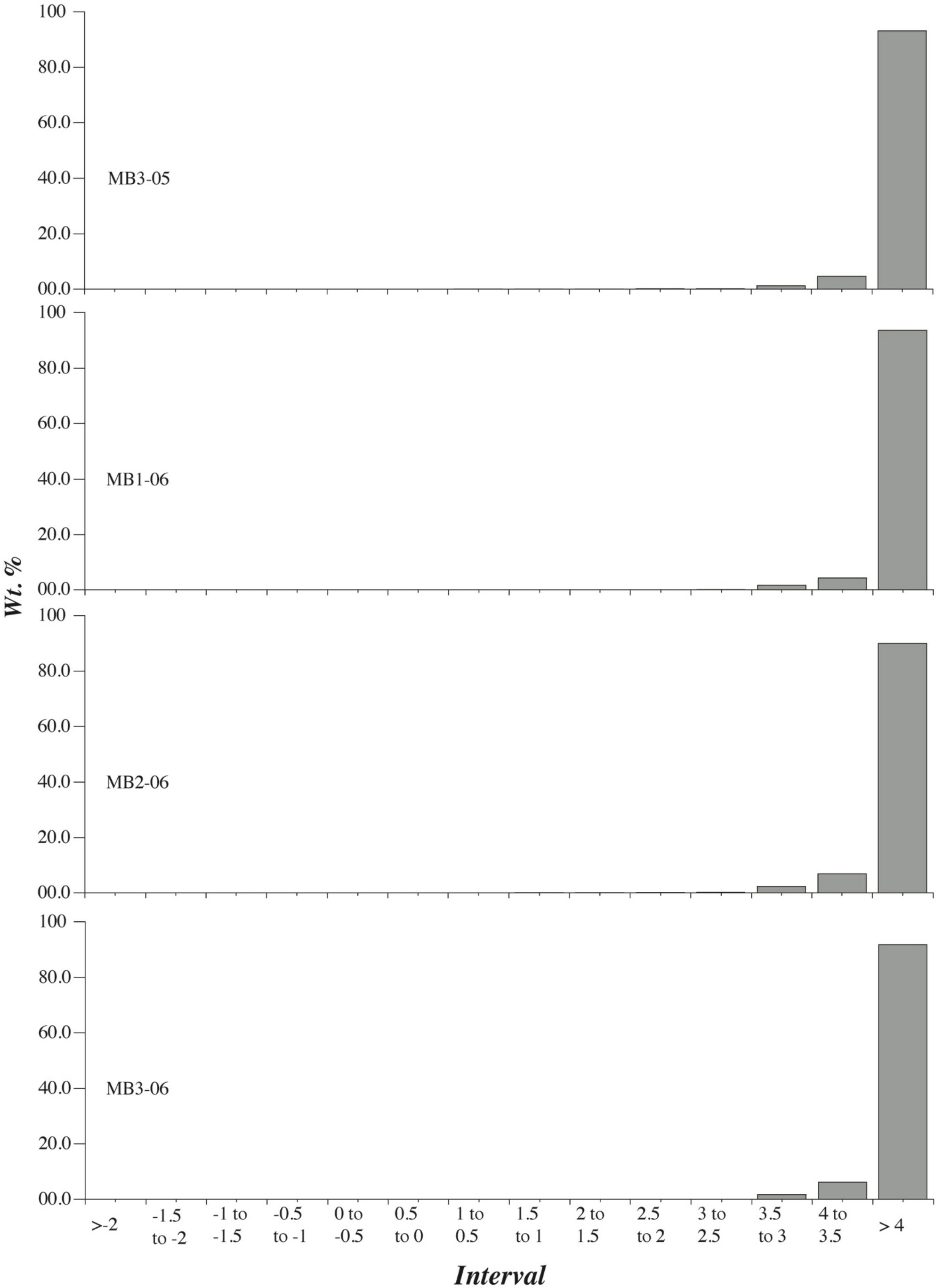


Wt. %
MB3-01
MB1-02
MB2-02
MB3-02
100
80.0
60.0
40.0
20.0
00.0
>-2
-1.5 to -2
-1 to -1.5
-0.5 to -1
0 to -0.5
0.5 to 0
1 to 0.5
1.5 to 1
2 to 1.5
2.5 to 2
3 to 2.5
3.5 to 3
4 to 3.5
> 4
Interval

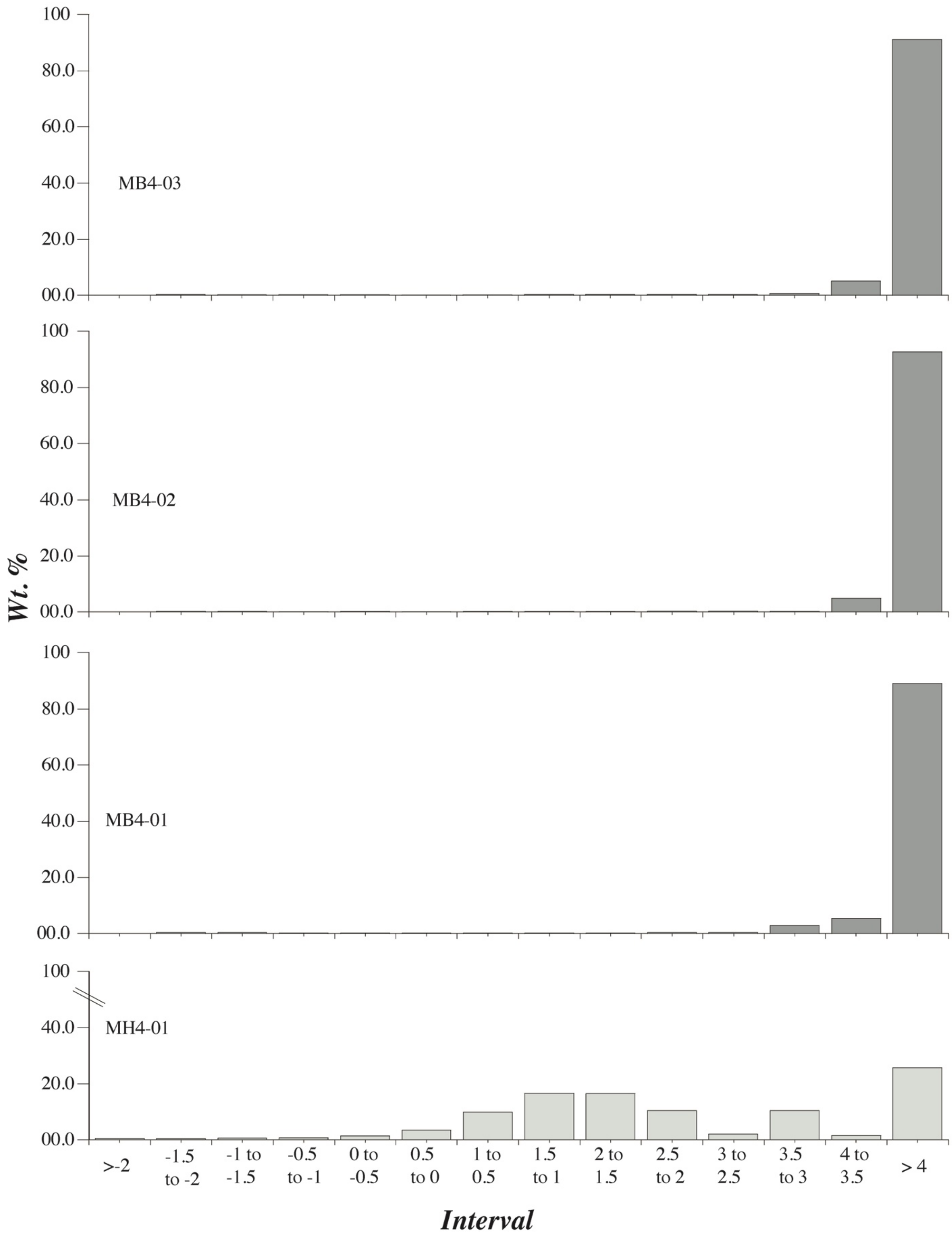


100
80.0
60.0
40.0
20.0
00.0
MB1-03
MB2-03
MB3-03
MB1-04
Wt. %
>-2
-1.5 to -2
-1 to -1.5
-0.5 to -1
0 to -0.5
0.5 to 0
1 to 0.5
1.5 to 1
2 to 1.5
2.5 to 2
3 to 2.5
3.5 to 3
4 to 3.5
> 4
Interval


Wt. %
MB2-04
MB3-04
MB1-05
MB2-05
100
80.0
60.0
40.0
20.0
00.0
>-2
-1.5 to -2
-1 to -1.5
-0.5 to -1
0 to -0.5
0.5 to 0
1 to 0.5
1.5 to 1
2 to 1.5
2.5 to 2
3 to 2.5
3.5 to 3
4 to 3.5
> 4
Interval



MB3-05
MB1-06
MB2-06
MB3-06
Wt. %
100
80.0
60.0
40.0
20.0
00.0
>-2
-1.5 to -2
-1 to -1.5
-0.5 to -1
0 to -0.5
0.5 to 0
1 to 0.5
1.5 to 1
2 to 1.5
2.5 to 2
3 to 2.5
3.5 to 3
4 to 3.5
> 4
Interval



Wt. %
MB4-03
MB4-02
MB4-01
MH4-01
100
80.0
60.0
40.0
20.0
00.0
>-2
-1.5 to -2
-1 to -1.5
-0.5 to -1
0 to -0.5
0.5 to 0
1 to 0.5
1.5 to 1
2 to 1.5
2.5 to 2
3 to 2.5
3.5 to 3
4 to 3.5
> 4
Interval