The Stratigraphic Record of the mid-Piacenzian Warm Period within the Atlantic Coastal Plain

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ABSTRACT: Anthropogenic climate change is an existential threat to our planet, impacting everything from the delicate balance of ecosystems to the availability of vital resources. Coastal regions, particularly vulnerable to the impacts of climate change due to rising sea levels and changing weather patterns, are experiencing increased erosion, flooding, and habitat loss. Understanding how coastal regions responded to past warming is crucial for developing effective adaptation and mitigation strategies. One past interval commonly used to examine and compare with climate model projections of near future conditions is the mid-Piacenzian Warm Period (MPWP) which occurred between ∼3.3 and 3.0 Ma. Here we review the stratigraphy of Atlantic Coastal Plain (ACP) sediments to determine the stratigraphic position of the MPWP by evaluating ages based upon existing and new planktic foraminifer occurrence data calibrated to the current geologic time scale (GTS2020). We identify geologic formations representing pre-, syn-, and post-MPWP environments. The Sunken Meadow Member of the Yorktown Formation in Virginia and North Carolina and the Wabasso beds in the subsurface of Georgia and Florida both fall within Planktic Foraminiferal Zone PL1 and represent pre-MPWP Pliocene deposits. Parts of the Yorktown Formation in southeastern Virginia and northern North Carolina, the Duplin Formation in North Carolina and South Carolina, and the Raysor Formation in South Carolina and Georgia, fall within Planktic Foraminiferal Zone PL3 and were deposited following a major regression associated with a global drop in sea level during Marine Isotope Stage (MIS) M2 and represent syn-MPWP deposits. Representing the immediately post-MPWP climate conditions (Planktic Foraminiferal Zone PL5) are the Chowan River, Bear Bluff, and Cypresshead Formations. This work provides a record of the MPWP from Georgia to Virginia and provides a stratigraphic framework within which the impacts of a profound global warming on the east coast of the United States can be assessed.

1. INTRODUCTION

The changing climate is a threat to our environment, infrastructure, and public health. Climate models project conditions for the end of this century that are generally outside of our experience (IPCC 2013; Hayhoe et al. 2017). Instrumental data and historical records illuminate climate conditions from at most several thousand years ago. Deep-time (e.g. Pliocene) paleoclimate records sample conditions similar to those projected by Earth System Models for our future. The Pliocene, long a focus of U.S. Geological Survey paleoclimate research, remains one of the best deep-time process analogs for near future climate conditions (Zubakov and Borzenkova 1983; Dowsett and Poore 1991; Burke et al. 2018). Paleoenvironmental syntheses of Late Pliocene (3.264–3.025 Ma) marine and terrestrial conditions have established global scale shifts in land cover types, patterns of wet and dry, sea-ice distribution, elevated sea levels, elevated sea surface temperatures (SST), and reduced pole-to-equator temperature gradients (Dowsett et al. 2016; Haywood et al. 2020).

The existential hazards associated with climate change call for increased understanding of impacts on marine biodiversity and economy at regional scales. The coastal and shallow marine ocean economy includes fishing, shipping, transportation, energy, and recreation, as well as crucial ecosystem services (OECD 2016; Mehvar et al. 2018). Today, US southeastern marine ecosystems (Virginia to Florida coastal regions) support high biodiversity including many protected marine species. For example, the region provides calving grounds for *Eubalaena glacialis,* the endangered North Atlantic Right Whale, and supports a diverse array of marine life (Fautin et al. 2010; Gulland et al. 2022). The Atlantic Coastal Plain (ACP) preserves evidence of the effects of Late Pliocene global warming on shelf to marginal marine regions. In this paper we summarize Pliocene stratigraphy of the ACP (from Virginia to Georgia) to establish a workable stratigraphic framework within which we can identify the mid-Piacenzian Warm Period (MPWP; Dowsett et al. 2010) and research the effects that Late Pliocene climate change has had on shelf and shallow marine settings.

2. MATERIALS AND METHODS

2.1. Atlantic Coastal Plain Stratigraphy

Atlantic Coastal Plain sediments have been described and their paleontology interpreted for centuries. The first written accounts of the geology and paleontology of the lower James River in the vicinity of Jamestown, Virginia, followed shortly after the John Smith expedition in 1607 (Ward and Allmon 2019). German physician and naturalist Johan Schoepf's (1787) "Contributions to the mineralogical knowledge of the eastern part of North America and its mountains," published in 1787, contains astute observations and comparisons of coastal plain units, particularly in New Jersey (Clark 1894; Smith 1914; White 1953). The published travels of naturalists like William Bartram, who journeyed through Virginia, the Carolinas, Georgia, and Florida, contain anecdotal accounts of coastal plain geology and paleontology (Bartram 1791). Finch (1823, 1833) described extensive cliff exposures containing shells along the York River in Virginia that would later be known as the Yorktown Formation. While travelling in North America during 1841-1842, Charles Lyell described richly fossiliferous

Neogene sediments of the ACP recognizing the paleoclimatic signals they contain (Lyell 1845a; Lyell 1845b). Many other geologists also proceeded to observe and document the geology and paleontology of the coastal plain (Hodgson 1846; Tuomey 1848; Emmons 1858; Dall and Harris 1892; Clark 1906; Veach and Stephenson 1911; Mansfield 1929; Cooke 1936; Cooke et al. 1943), laying the groundwork for our current understanding of the Neogene stratigraphy of the ACP.

Despite an ever expanding and impressive body of work through the present day, correlations between some units are still problematic and, in those cases, a stratigraphic framework remains tentative. Correlation of coastal plain units between basins separated by subaerially exposed ridges and shallow marine features is challenging due to lack of lateral continuity. In addition, there are few absolute dates available for coastal plain sediments, so biostratigraphy and biochronology take on prominent roles for correlating and dating marine sediments. Planktic foraminifera in the ACP are generally rare and occurrences are discontinuous, often impacted by poor preservation and/or reworking. Still, as an aid for correlation they have been used along with mollusks and other microfossil groups (primarily calcareous nannofossils and ostracodes) to place sediments in biozones. Zonation schemes referred to in this review are listed in Table 1.

Within our stratigraphic summary we synthesize available planktic foraminiferal occurrence data used to bracket ages of various Pliocene coastal plain units in light of the latest zonal schemes. Dowsett (2024) combined planktic foraminifer occurrence data from previous workers with analysis of samples containing assemblages not previously published. These data are used here to assess the correlations made by previous workers and where possible to update age estimates based upon calibrated biochronologic events using the current geologic time scale, GTS2020 (Gradstein et al. 2020). To simplify comparison to the large body of 20th Century ACP microfossil research, we have for the most part not updated planktic foraminifer taxonomy (e.g. we do not distinguish *Globoconella* from other globorotaliids). We use the convention of referring to "left bank" or "right bank" of rivers (when facing downstream) when identifying locations as it is more descriptive than using cardinal directions.

2.2. Correlation of Late Neogene Atlantic Coastal Plain Units

Atlantic Coastal Plain stratigraphy is most easily discussed by regions (e.g. southeastern Virginia and North Carolina north of the Neuse River, southern North Carolina and northeastern South Carolina, etc.) generally bounded by structural arches (text-figure 1).

TABLE 1
Fossil zonation schemes.

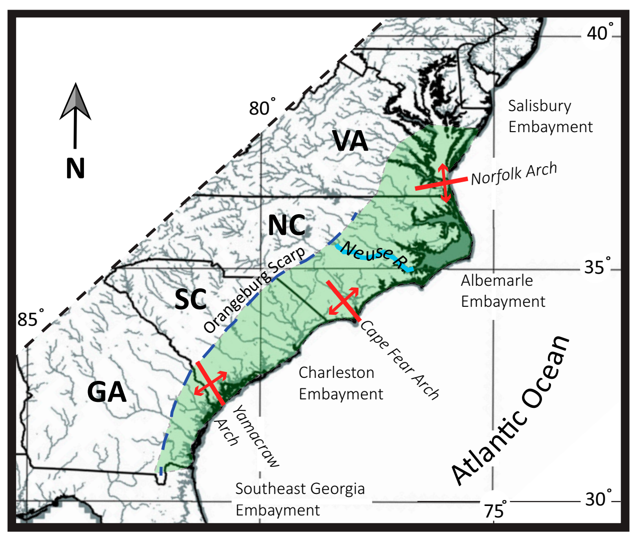
Fossil Group	Zones	Reference
Planktic foraminifera	N Zones	Blow (1969), Blow (1979)
Planktic foraminifera	PL Zones	Berggren et al. (1995), Wade et al. (2011)
Nannofossil	NN Zones	Martini (1971)
Nannofossil	CN Zones	Okada and Bukry (1980)
Mollusks	M Zones	Blackwelder (1981a)
Ostracodes	*P. inexpectata, O.vaughani*	Hazel (1971)
Ostracodes	A-C	Cronin (1980)

In many cases, detailed discussions of the relative stratigraphic position of beds of the same formation from different localities exist (Ward and Gilinsky 1993; Campbell and Campbell 1995; Campbell et al. 1995), but analysis at this scale is beyond the scope of this work. Instead, we take a broad view of the Pliocene-Pleistocene coastal plain units. Our focus is an overview understanding of Pliocene stratigraphy resulting from large scale paleoclimate changes prior to, during, and after the Late Pliocene MPWP.

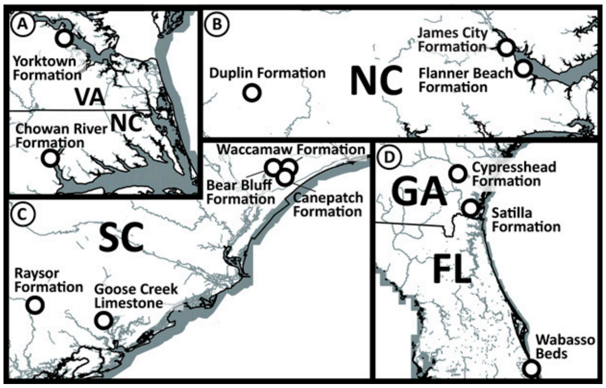
3. RESULTS

3.1. Southeastern Virginia and North Carolina (north of Neuse River)

In southeastern Virginia, the Pliocene Yorktown Formation rests unconformably on the Upper Miocene Eastover Formation. The Pleistocene Chowan River Formation rests unconformably on the Yorktown and is unconformably overlain by the James City and Bacons Castle Formations (Ward and Blackwelder 1980). In North Carolina, north of the Neuse River, the Yorktown rests unconformably on the Middle Miocene Pungo River Formation (Weems et al. 2019). The Chowan River and James City Formations sit above the Yorktown, and the Late Pleistocene Flanner Beach Formation rests unconformably on the James City Formation. There are other younger Pleistocene units (e.g. Windsor, Norfolk, Tabb, etc.),



TEXT-FIGURE 1
Major structural features of the Atlantic Coastal Plain. From north to south: Salisbury, Albemarle, Charleston, and Southeast Georgia Embayments. While the Albemarle Embayment may not be a structural basin (Gohn 1988), it is retained here due to its widespread usage in the literature. Structural arches: Norfolk Arch, Cape Fear Arch, and Yamacraw Arch. Approximate spatial distribution of Pliocene units in the southeastern U.S. shown by green shading. Orangeburg Scarp (dashed blue line) represents mid-Piacenzian shoreline. The Neuse River in North Carolina divides the Yorktown Formation to the north from the age-equivalent Duplin Formation to the south.



TEXT-FIGURE 2
Location of type sections for formations discussed in the text. A) Type sections of the Yorktown Formation on the right bank of the James River at Rushmere, Isle of Wight County, Virginia, and the Chowan River Formation on the Chowan River at Colerain Beach, Bertie County, North Carolina. B) Type sections of the Duplin Formation at Natural Well, in Duplin County, North Carolina, the James City Formation on the Neuse River below Fort Point, Craven County, North Carolina, and the Flanner Beach Formation on the Neuse River at Flanner Beach, Craven County, North Carolina. C) The neotype section of the Raysor Formation on the left bank of the Edisto River, upstream from Givhans Ferry State park, Dorchester County, South Carolina, type section of the Bear Bluff Formation on the left bank of the Waccamaw River at Bear Bluff, Horry County, South Carolina, the type section of the Waccamaw Formation below Tully Lake on the Waccamaw River, Horry County, South Carolina, and type section of the Canepatch Formation on the right bank of the Intracoastal Waterway near Canepatch Swamp, Horry County, South Carolina, and the Goose Creek Limestone on Goose Creek, Berkeley County, South Carolina. D) Type sections of the Cypresshead Formation on Goose Creek, Wayne County, Georgia, the Satilla Formation on the right bank of the Satilla River at Satilla Bluff, Camden County, Georgia, and the Wabasso beds in the Phred 1 core hole south of Wabasso, Indian River County, Florida.

but they are generally less fossiliferous and outside the scope of this work.

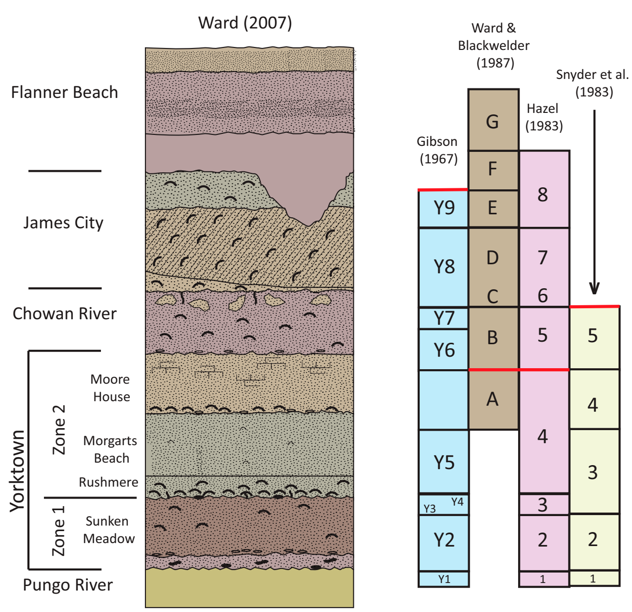
The Yorktown Formation is discussed below in more detail than other Pliocene units because of its extensive spatial coverage, well known occurrences of multiple fossil groups, and excellent nearly continuous exposures along the York and James Rivers. Thus, it forms a stratigraphic reference for discussion of units that are located farther south along the ACP.

3.1.1. Yorktown Formation

From the first use of the term "Yorktown" by Dana (1862), through the revision of Miocene and Pliocene units of the York-James Peninsula and adjacent areas in southeastern Virginia by Ward and Blackwelder (1980), to most recently the reevaluation by Dowsett et al. (2021), the Yorktown Formation has played a pivotal role in our understanding of the Pliocene history of the ACP (Cronin et al. 1984; Ward et al. 1991; Ward 2008).

The type section of the Yorktown Formation is on the right bank of the James River at Rushmere (=Fergusson's Wharf in older literature), Isle of Wight County, Virginia (Ward and Blackwelder 1980) (text-figure 2A). The Yorktown, more so than correlatives to the south, has the benefit of relatively continuous exposures, particularly along the James and York Rivers, as well as notable quarry exposures in the literature (e.g. Rice's Pit in Hampton, Virginia; Yadkin Pit/Deep Creek in Chesapeake, Virginia; Lee Creek Mine near Aurora, North Carolina). A nearly continuous sequence of Neogene outcrops can be investigated along the James River from near Hopewell in the northwest, to Hampton Roads near the mouth of the Chesapeake Bay in the southeast (Ward and Blackwelder 1980; Cronin et al. 1989; Ward 2008; Dowsett et al. 2021). This allows direct observation of physical stratigraphic relationships, in contrast to Pliocene units in the Carolinas and Georgia where outcrops are less frequent and often have discontinuous spatial distributions (Huddlestun 1988; Ward and Huddlestun 1988). The name Yorktown Formation is used as far south as the Neuse River in North Carolina (text-figure 1). South of the Neuse River, age-equivalent sediments are mapped as the Duplin Formation (Miller 1912; Owens 1989; Ward et al. 1991).

The Pliocene age of the Yorktown Formation was first established by Hazel (1971) based upon ostracod biostratigraphy. Hazel quantitatively analyzed occurrences of ostracodes from Yorktown Formation samples and divided the formation into a lower *Pterygocythereis inexpectata* Zone, roughly equivalent to Mansfield's Zone 1 (Mansfield 1929), and an *Orionina vaughani* Zone, which represented the middle and upper parts of the Yorktown Formation, equivalent to Mansfield's Zone 2 (text-figure 3). Hazel indicated the base of Zone 1 was equivalent to part of Planktic Foraminiferal Zone N18 of Blow (1969) or ~5 Ma, as reported in Ward and Blackwelder (1980). Cronin et al. (1984) summarized available biostratigraphic and



TEXT-FIGURE 3
General lithology at Lee Creek Mine (left) after Ward (2007) showing Yorktown Formation members and Mansfield's (1929) zones. Lithologic units at Lee Creek Mine according to previous author's (Gibson 1967; Hazel 1983; Snyder et al. 1983; Ward and Blackwelder 1987), right. Horizontal red lines indicate different authors placement of the top of the Yorktown Formation.

paleomagnetic data and suggested a maximum age of 4.8 Ma for the base of the Sunken Meadow Member, and 3.0 Ma for the top of the Moore House Member. Krantz (1991) tied Neogene units on the ACP to then available marine oxygen isotope records, bracketing the Yorktown Formation between 4 and 3 Ma. Dowsett and Wiggs (1992) suggested a Yorktown age between 4 and 2.9 Ma (3.1 Ma when calibrated to GPTS2020; Gradstein et al. 2020) based upon planktic foraminifer biochronology. Dowsett et al. (2021) dated Zone 2 Yorktown as ∼3.3 to 3.0 Ma based upon correlation of biomarker records to offshore sequences. The age of the top of Zone 2 (top of the Moore House Member) at the lectostratotype at Rushmere, Virginia, remains unconstrained.

A synthesis of paleontological work at Lee Creek Mine, covering multiple fossil groups, was published in three volumes of the Smithsonian Contributions to Paleobiology series between 1983 and 2001 (volume 4 was later published as Virginia Museum of Natural History Special Publication 14, in 2008). While many of the individual contributions support similar stratigraphic conclusions, some data are anomalous. Due to the importance of the Yorktown Formation in Virginia and North Carolina to the stratigraphic framework of the ACP further south, additional discussion is warranted.

Gibson (1967) documented the occurrence of the mollusk *Placopecten clintonius*, a marker for Zone 1 Yorktown, in his Lee Creek units 1 and 2 (text-figure 3). This firmly established a biochronologic correlation with Zone 1 in the southeastern Virginia type region, named Sunken Meadow Member by Ward and Blackwelder (1980). Gibson (1967) considered the top of the Yorktown to be at the top of his unit 9 (currently considered the top of the James City Formation).

Graphic correlation of the Lee Creek Mine section shown in Hazel (1983) indicated the base of the Yorktown was equivalent to 110.00 composite units (cu), and the top 78.17 cu, in the graphic correlation model of Dowsett (1989a) (J. E. Hazel, USGS, written communication, 1989). Calibration of those horizons using GTS2020 yields an age of ∼4.4 Ma for the base of the Sunken Meadow Member (unconformable contact with the Miocene Pungo River Formation) and ∼3.0 Ma for the top of the Yorktown exposed at Lee Creek Mine (top of Hazel's Unit 4, text-figure 3).

Snyder et al. (1983) documented the occurrences of planktic foraminifera from a section within Lee Creek Mine using the same unit nomenclature as Gibson (1967) and Hazel (1983). Both Gibson and Hazel show an unconformity at the top of Unit 2 (text-figure 3). Above the unconformity, Hazel placed his Units 3 and 4 in his *Orionina vaughani* Zone, equivalent to Yorktown Zone 2 in the type region. This is corroborated by the molluscan stratigraphy developed by Gibson (1987).

Snyder et al. (1983) recorded few to common *Globorotalia praescitans* (= *Globorotalia puncticulata*) in samples throughout the lower part of Zone 1 Yorktown (Sunken Meadow Member) at Lee Creek Mine. *Globorotalia puncticulata* first appeared in the southwest Pacific Ocean approximately 5.2 to 4.8 Ma, with a delayed migration to the northern mid-latitudes ∼4.2 Ma (Dowsett 1989a, Dowsett 1989b). The presence of *Globorotalia puncticulata* in the samples from Unit 1 and the lower part of Unit 2 at Lee Creek Mine (text-figure 3) generally supports the graphic correlation-based age of ∼4.4 Ma for the base of the Yorktown at that locality. The last occurrences of *Dentoglobigerina altispira* (3.13 Ma) and *Sphaeroidinellopsis subdehiscens* (3.16 Ma), suggest the upper part of the Yorktown at Lee Creek (Moore House Member) may be close to 3.0 Ma.

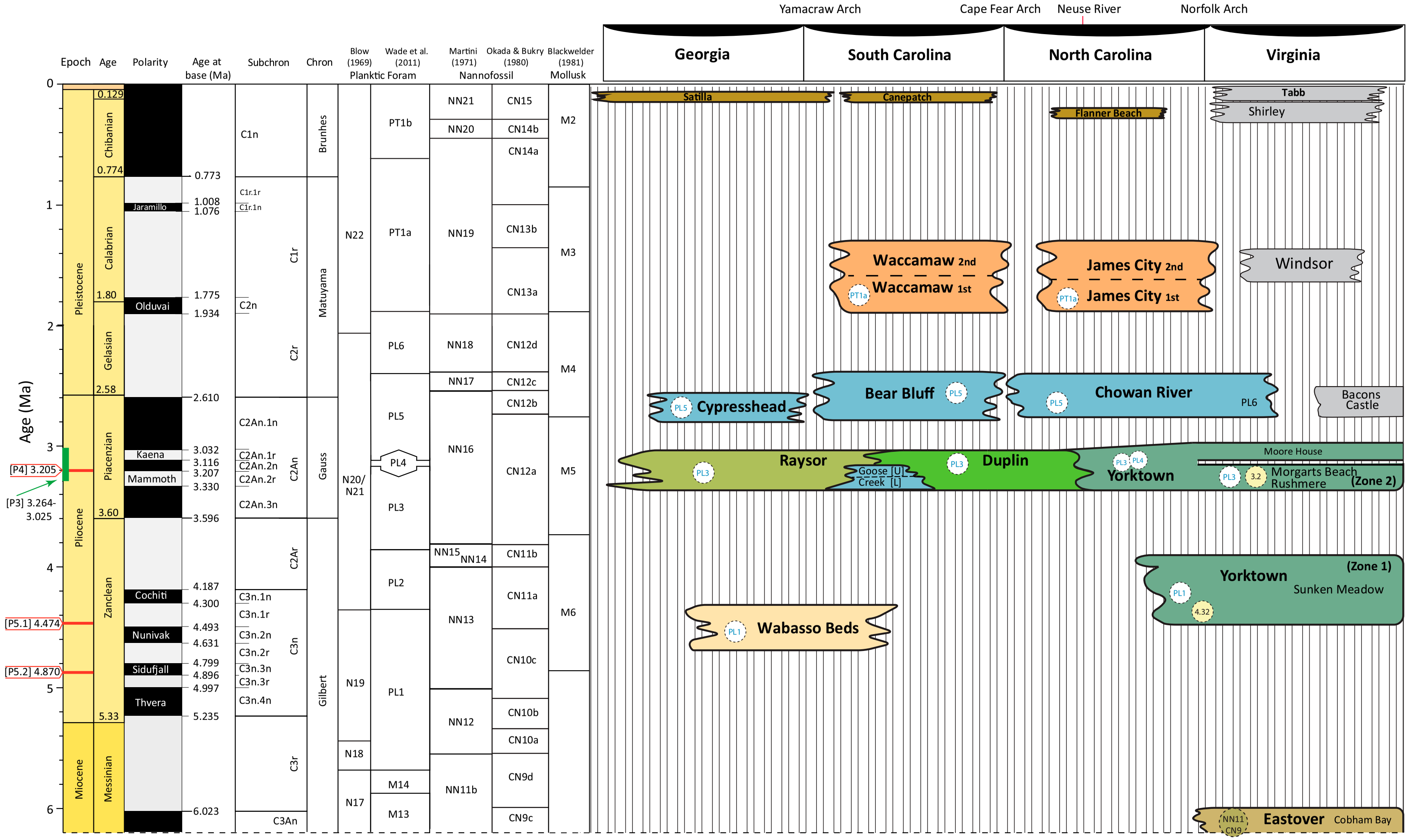
Snyder et al. (1983) did not show an unconformity between their Lee Creek Units 2 and 3 (text-figure 3). In addition, they documented rare occurrences of *Globorotalia margaritae* within samples bridging their Units 3 and 4. *Globorotalia margaritae* evolved at ∼6 Ma and last appeared ∼3.85 Ma in the open ocean (Raffi et al. 2020). The LAD (last appearance datum) of *Globorotalia margaritae* defines the top of Planktic Foraminiferal Zone PL2. The seemingly anomalous occurrences at Lee Creek are not easily explained by contamination or reworking. Snyder et al. (1983) obtained samples from only fresh material and each sample was confined to a stratigraphic interval of 5 cm. While not an explanation for the occurrences of *Globorotalia margaritae* so high in the section, it is clear that different investigators recorded sampling schemes from the north, west, and southwestern walls of the mine (Gibson 1983a, Gibson 1983b, Hazel 1983; Snyder et al. 1983; Gibson 1987; Snyder et al. 2001) as well as several composite sections (Curran and Parker 1983; Ward and Blackwelder 1987) as mining operations expanded, yielding slightly different litho- and biostratigraphic interpretations. Issues also arise with correlating sections at Lee Creek Mine due to several studies occurring over a number of years (Ward 2007).

Yorktown planktic foraminifer assemblages have also been reported by Akers (1972) who published a list of species from Rice's Pit on the lower York-James Peninsula. Dowsett and Wiggs (1992) reported occurrences from Rice's Pit, Yadkin Pit, and outcrops at Yorktown, Sunken Meadow, Rushmere, and Morgarts Beach. Dowsett and Spivey (2021) documented abundances from Rushmere, and Robinson and Dowsett (2023) from the Sunken Meadow Member at Pipsico Scout Reservation. The co-occurrence of *Globorotalia puncticulata* and *Globigerina nepenthes* (LAD 4.37 Ma) in the Sunken Meadow Member near its type locality on the James River suggests placement near the top of Zone PL1. This agrees with the graphic correlation-based age of ∼4.32 Ma at Lee Creek Mine (see above). Based upon available data, we place the Sunken Meadow Member (Zone 1 Yorktown) near the PL1/PL2 boundary (∼4.4 Ma). The Sunken Meadow Member correlates with mollusk Zone M6 of Blackwelder (1981a).

Zone 2 Yorktown (Rushmere, Morgarts Beach and Moore House members) unconformably overlies the Sunken Meadow Member and can be confidently placed in Planktic Foraminiferal Zones PL3 and PL4, and the occurrence of *Chesapecten septenarius* places Zone 2 Yorktown in Mollusk Zone M5 of Blackwelder (1981a). In southeastern Virginia this unconformity has been associated with marine isotope stage (MIS) M2 (Dowsett et al. 2019; Dowsett et al. 2021), which occurred at 3.33 Ma (Lisiecki and Raymo 2005) (See discussion below).

3.1.2. Chowan River Formation

The Chowan River Formation was named by Blackwelder (1981b) for an unconformity-bounded package of sometimes shelly sands, silts and clays along the Chowan River from



TEXT-FIGURE 4
Correlation chart showing stratigraphic relationships of units on the Atlantic Coastal Plain from Virginia to Georgia. Geologic time scale and paleomagnetic stratigraphy from GTS2020 (Gradstein et al. 2020). Biostratigraphic zonations for planktic foraminifers after Blow (1969) and Wade et al. (2011). Calcareous nannofossil zonations after Martini (1971) and Okada and Bukry (1980). Mollusk zonation after Blackwelder (1981a). Where units can be placed in biostratigraphic zones, those zones are indicated within white circles. Vertical thickness of units is not intended to represent duration. Rather, ages of units lie within those intervals. Position of the MPWP (3.264 to 3.025Ma) shown by green bar on age axis (Dowsett et al. 2010). Positions and ages of Pliocene paleoenvironmental reconstructions are shown in red on age axis: [P4] 3.205 Ma (Dowsett et al. 2016), [P5.1] 4.474 Ma and [P5.2] 4.870 Ma (Dowsett et al. 2023). See text for additional information.

Colerain Landing to Edenhouse Landing, North Carolina. Prior to Blackwelder (1981b) many workers used the "Croatan Beds" proposed by Dall (1892) to indicate these units (Hazel 1971; Hazel 1983; Gibson 1983a). Beds of shelly and silty sand previously placed in the lower Croatan were assigned to the Chowan River Formation. The upper Croatan sands, silts and clays became the James City Formation (see below).

The Chowan River Formation is present in southeastern Virginia and northeastern North Carolina and is divided into a lower Edenhouse Member and upper Colerain Beach Member (Blackwelder 1981b). The Chowan River Formation unconformably overlies the Pliocene Yorktown Formation and is unconformably overlain by the Pleistocene James City Formation. Molluscan assemblages from the type locality of the Chowan River Formation at Colerain Beach, Bertie County, North Carolina (text-figure 2A) are similar to those of the Bear Bluff Formation in North and South Carolina (Ward and Gilinsky 1993) suggesting a probable correlation. The age of the Chowan River Formation is not well constrained, but calcareous nannofossils and planktic foraminifera indicate placement within Zones NN16-NN18 and N21, respectively (Cronin et al. 1984). The uppermost 9 samples from Snyder and others (1983) at Lee Creek Mine (their Unit 5 in text-figure 3) are actually from the Chowan River Formation (Ward 2007). The presence of *Globigerina apertura* suggests the unit is probably no younger than the lowest part of Zone PT1a (1.64 Ma). Blackwelder (1981a) placed the Chowan River Formation in Mollusk Zone M4. He/U dating of corals from the Chowan River Formation at Mount Gould, North Carolina, and Lee Creek Mine gave ages of 1.91 Ma and 2.4 Ma respectively (Bender, 1973; Blackwelder, 1981a). These data are consistent with an Early Pleistocene age. The Chowan River Formation is placed in Planktic Foraminiferal Zone PL5, within the Gelasian Age of the Early Pleistocene (text-figure 4).

3.1.3. James City Formation

DuBar and Solliday (1963) designated deposits exposed on the right bank of the Neuse River, about 4.8 km below the mouth of the Trent River, as the James City Formation. The type section, now obscured by rip-rap, is 1 km downstream from Fort Point, Craven County, North Carolina (text-figure 2B). The James City Formation is a fine to medium, silty, calcareous sand with abundant fossils. It unconformably overlies the Chowan River Formation and is unconformably overlain by the Flanner Beach Formation. The James City Formation has two lithologically similar beds with distinct molluscan assemblages (Ward et al. 1991). Both an upper and lower bed are evident at Lee Creek Mine.

Globorotalia truncatulinoides is present at Lee Creek Mine (Gibson 1983a) in sediments previously assigned to the Yorktown Formation (Gibson 1967) or Croatan Beds (Hazel 1971; Hazel 1983) but now understood to be the James City Formation (text-figure 3). This indicates placement in Zone PT1, confirming a Pleistocene age younger than ~1.9 Ma. This is in agreement with Cronin et al. (1984) who placed the James City Formation in an interval of reversed polarity within Planktic Foraminiferal Zone N22, Nannofossil Zone NN19, and Mollusk Zone M3 of Blackwelder (1981a). This suggests placement in Zone PT1a (~1.1 Ma), Calabrian Age of the Early Pleistocene (text-figure 4).

3.1.4. Flanner Beach Formation

The Flanner Beach Formation was named by DuBar and Solliday (1963) for Late Pleistocene unconsolidated clays, sandy clays, argillaceous sands, and peaty sands and clays of the lower Neuse Estuary, which unconformably overlie the James City Formation. The type section of the Flanner Beach Formation is on the right bank of Neuse River at Flanner Beach, Craven County, North Carolina (text-figure 2). The Flanner Beach Formation contains mollusks, rare benthic foraminifers, diatoms, wood, leaves, seeds, and pollen. It is exposed at Lee Creek Mine (text-figure 3) with an extensive marine biota (Ward 2007). No planktic foraminifers were recovered, but the Flanner Beach Formation correlates to Ostracod Zone "C" of Cronin (1980) and Mollusk Zone M1 of Blackwelder (1981a). Based on uranium-series and amino acid dating of fossils, Miller (1985) indicated the Flanner Beach Formation to be about 200,000 years old and correlated it to MIS 7 (0.24 Ma to 0.19 Ma). However, Parham et al. (2013) obtained an OSL date of 0.084 Ma which would suggest correlation to MIS 5.

3.2. Southern North Carolina and South Carolina

In North Carolina, south of the Neuse River, the Pliocene Duplin Formation rests unconformably on the Eocene Castle Hayne Formation. The Goose Creek Limestone is restricted to the Charleston, South Carolina, area but appears to correlate to, and for the purposes of this work is considered equivalent to, parts of the Duplin and Raysor Formations. The Duplin is unconformably overlain by the Bear Bluff Formation, which in turn is unconformably overlain by the Waccamaw Formation. The Late Pleistocene Canepatch Formation rests unconformably on the Waccamaw.

3.2.1. Duplin Formation

The Duplin Formation was originally described (but not named) by Conrad (1841) for exposures in Duplin County, North Carolina, including the now recognized type section at Natural Well, 2.9 kilometers southwest of Magnolia, Duplin County, North Carolina (text-figure 2C) (DuBar et al. 1974; Ward et al. 1991; Campbell 1992). While the Natural Well section was discussed by others (Dall and Harris 1892), Dall (1896) was the first to refer to the "Duplin beds at the Natural Well." Miller (1912) confined the Duplin Formation to sands, clays, and shelly marls in the area south of the Neuse River resting unconformably on Cretaceous and Eocene (Castle Hayne Formation) deposits. The Duplin Formation is unconformably overlain by the Bear Bluff Formation and interfingers with the Raysor Formation in South Carolina (Huddlestun 1988; Owens 1989; Ward et al. 1991). The Duplin, like most of the units of the ACP, undoubtedly represents multiple minor cycles of deposition. With few outcrops showing stratigraphic sequence, we consider the Duplin Formation *sensu lato*, to be correlative with Zone 2 Yorktown (Rushmere and Morgarts Beach members) in Virginia and North Carolina north of the Neuse River.

Cronin (1991) indicated the Duplin Formation in North Carolina to be between 3.5 and 3.0 Ma using planktic foraminifera and calcareous nannofossils. Planktic foraminifer assemblages recovered from the Duplin Formation in cores located in Florence and Darlington Counties, South Carolina, contain among other taxa *Sphaeroidinellopsis* spp., *Globigerina decoraperta*, and *Globorotalia inflata* (Dowsett 2024). The planktic foraminifer assemblages recovered from the Duplin Formation suggest placement near the top of Zone PL3. This would indicate an age of ∼ 3.3 Ma to 3.0 Ma and fits well with the estimated age assigned to the base of the Rushmere Member of the Yorktown Formation (Zone 2) at its type locality on the James River at Rushmere, Virginia (Dowsett et al. 2021). The presence of the mollusk *Chesapecten septenarius* at the type section of the Duplin Formation at Hidden Well, at the base of the Robeson Farm site (=Lower Goose Creek equivalent, Britt et al., 1992), and at other localities (Blackwelder and Ward 1979), supports correlation with the Rushmere transgression farther north (Ward and Blackwelder 1980).

3.2.2. Goose Creek Limestone

The Goose Creek Limestone was first described (but not named) by Tuomey (1848), originally referred to as the Goose Creek Phase by Sloan (1908), and formalized by Weems et al. (1982). The type section of the Goose Creek Limestone is a bluff, 0.3 km east of the Seaboard Coastline railroad bridge over Goose Creek, Berkeley County, South Carolina (text-figure 2C). The Goose Creek Limestone can be biostratigraphically separated into lower and upper parts, separated by an unconformity (Campbell and Campbell 1995). According to McCartan (1990), the Goose Creek Limestone (stratotype), or lower Goose Creek [= Givhans beds] lies below the stratotype of the Bear Bluff Formation and above the Wabasso beds. The short ranging *Chesapecten septenarius*, which first appears at the base of the Rushmere Member of the Yorktown Formation as well as the Duplin Formation at Natural Well, also occurs in the Raysor Formation and Goose Creek Limestone in South Carolina (Campbell and Campbell 1995). With the Raysor Formation, Duplin Formation, and Goose Creek Limestone having limited exposures with which to view stratigraphic context, and all being *similar* in age based upon microfossils and mollusks (Weems et al. 1982; Dowsett 2024), we include the Goose Creek Limestone as part of the Raysor Formation *sensu lato*.

3.2.3. Raysor Formation

The Raysor Formation was named for a 1 meter section of shelly, dark-blue marl on the right bank of the Edisto River, 0.4 kilometers downriver from the Raysor Bridge, 12.9 kilometers southwest of St. George, South Carolina (Cooke 1936), based upon a description by Sloan (1908). Mansfield (1943) correlated the Raysor beds to his Zone 1 Yorktown in southeastern Virginia. Since the location of the original type section was lost, Blackwelder and Ward (1979) designated a neostratotype section at Givhans Ferry State Park, on the left bank of the Edisto River, 1.1 km above the Route 61 bridge crossing, Dorchester County, South Carolina (text-figure 2C). In that same publication, they indicated the Raysor was correlative to Zone 2 Yorktown, based upon mollusks. The Raysor is recognized from Georgia to southeastern South Carolina and grades into the Duplin Formation to the north (Ward and Huddlestun 1988; Ward et al. 1991). Cronin (1991) suggested the Raysor and Duplin Formations correlate with each other and together represent a marine transgression that occupied the Orangeburg scarp. Ward et al. (1991) described the Raysor Formation as a shallow-shelf calcareous lithofacies that interfingers with the correlative Duplin Formation, a more nearshore clastic-rich shelly unit. Huddlestun (1988) identified a diverse planktic foraminiferal assemblage indicating a Late Pliocene age for the Raysor Formation in Georgia. The presence of both *Dentoglobigerina altispira* and *Sphaeroidinellopsis seminulina* preclude an age younger than PL4, and the presence of *Globorotalia puncticulata* suggests the Raysor Formation is no older than PL2. No other marker species defining the lower bounds of the Raysor Formation are present. A similar planktic foraminiferal assemblage was identified by Ward and Huddlestun (1988) and Dowsett (2024) from South Carolina. Based upon current planktic foraminiferal biochronology, the Raysor Formation most likely records deposition somewhere within Zone PL3, equivalent to the Rushmere and Morgarts Beach Members of the Yorktown Formation (Zone 2 Yorktown) in Virginia and North Carolina.

3.2.4. Bear Bluff Formation

The Bear Bluff Formation (DuBar 1969) was originally described as a gray to cream, fossiliferous, coarse-grained calcareous sand and sandy limestone present in northeastern South Carolina and southeastern North Carolina. The type section is located on the left bank of the Waccamaw River at Bear Bluff, ∼3 km east of Conway, Horry County, South Carolina (text-figure 2C). The definition was modified by DuBar et al. (1974) and Owens (1989) to include a range of marine facies. The Bear Bluff Formation is unconformably overlain by the Waccamaw Formation in South Carolina and the James City Formation in North Carolina. The Bear Bluff Formation is contemporaneous with the lower Chowan River Formation found in North Carolina and southeastern Virginia based upon a number of molluscan taxa stratigraphically restricted to the Chowan River Formation (Blackwelder and Ward 1979; Ward et al. 1991; Ward and Gilinsky 1993). Conversely, Campbell (1992) considered the upper Goose Creek Limestone and Bear Bluff Formation to be the same unit based upon the occurrence of a single molluscan subspecies restricted to the upper Goose Creek.

Weems et al. (1982) indicate the Bear Bluff Formation falls within Nannofossil Zones NN16-NN18, making the Bear Bluff younger than the Goose Creek Limestone. Further south in Georgia, Markewich et al. (1992) indicate the Bear Bluff Formation to be equivalent to the Cypress Head Formation, which unconformably overlies the Raysor Formation. Planktic foraminifera from the Cypress Head Formation indicate an age no younger than Early Calabrian (PT1a) based upon the presence of *Globigerinoides obliquus* and *Globigerina apertura* (Huddlestun 1988). These taxa place the Cypress Head and Bear Bluff Formations in Planktic Foraminiferal Zone PL5, suggesting a Late Pliocene age somewhere between 3 Ma and 2.4 Ma. Planktic foraminifer assemblages recovered from the Bear Bluff Formation at Elizabethtown, North Carolina, and Parkers Landing, South Carolina, include specimens of *Globigerina decoraperta* and *Globorotalia inflata*, which support placement in Zone PL5 (Late Piacenzian to Early Gelasian). We tentatively place the Bear Bluff at ∼2.75 Ma.

3.2.5. Waccamaw Formation

Dall (1892) named the "Waccamaw Beds" for exposures along the Waccamaw River, Horry County, South Carolina. In North Carolina (south of the Neuse River) the name was applied to Pliocene marine beds equivalent to the Croatan sand north of the Cape Fear Arch. Blackwelder (1979) redefined the Waccamaw to include shelly medium-grained quartz sands of the original type area not included in the Bear Bluff Formation. An exposure 180 m downstream from Tilly Lake on the Waccamaw River, Horry County, South Carolina, was designated as the lectostratotype (text-figure 2C). There, the Waccamaw Formation sits unconformably on Cretaceous sediments. Elsewhere (e.g., an exposure on the shore of Lake Waccamaw in North Carolina) the Waccamaw Formation is unconformably overlain by the Canepatch Formation (Pleistocene) and is underlain by the Bear Bluff Formation (Upper Pliocene). In such places, the Waccamaw Formation consists of two beds of similar lithology but somewhat different molluscan faunas, and separated by a disconformity. This is interpreted as deposition during two separate sea level high stands (Ward et al. 1991; Campbell and Campbell 1995).

Akers (1972) recorded diverse Waccamaw planktic foraminifera assemblages from Walkers Bluff, sections in Columbus County, North Carolina, and North Myrtle Beach, South Carolina (Crescent Beach Airport), south of the Intracoastal Waterway. A sample from the Waccamaw Formation along the intracoastal waterway near Myrtle Beach produced many of the same taxa with the addition of *Turborotalita quinqueloba* (Dowsett 2024). The presence of *Globorotalia truncatulinoides* and *Globigerinoides obliquus* (Akers 1972; Huddlestun 1988; Dowsett 2024) places the Waccamaw in the Pleistocene, within the lower part of Zone PT1a (~1.9-1.3 Ma). Mollusks found in the Waccamaw suggest placement in Zone M3 of Blackwelder (1981a), and these are in agreement with the planktic foraminifer occurrence data.

3.2.6. Canepatch Formation

DuBar et al. (1974) defined the Canepatch Formation as marginal marine shelly sands, silts, clays, and peats unconformably overlying the Waccamaw or Bear Bluff formations in northeastern South Carolina. The type section is on the south bank of the Intracoastal Waterway near Canepatch Swamp, 10.4 km northeast of Myrtle Beach, Horry County, South Carolina (text-figure 2C). Molluscan assemblages place the Canepatch Formation in Zone M3 of Blackwelder (1981a). Hollin and Hearty (1990) used amino acid racemization to place the Canepatch Formation within MIS 5e.

3.3. Georgia

In Georgia the Early Pliocene Wabasso beds are unconformably overlain by the Raysor Formation. The Raysor extends southward from South Carolina where it correlates to the Duplin Formation. The Cypress Head Formation unconformably overlies the Raysor Formation, and unconformably underlies the Late Pleistocene Satilla Formation. It should be noted that the Pliocene is well represented in western Florida (i.e. the Gulf Coastal Plain) and that mollusc-based correlations with the ACP sequence have been made (Petuch and Roberts 2007). However, our current study is restricted to the ACP from Virginia to Georgia.

3.3.1. Wabasso beds

Named by Huddlestun (1988), the Wabasso beds are known from the subsurface in southeastern South Carolina, Georgia, and eastern Florida. They are described as phosphatic, calcareous, and microfossiliferous, silty, fine-grained sands disconformably overlying the Coosawhatchie Formation in Georgia, and are disconformably overlain by the Satilla Formation. The reference section of the Wabasso beds is located between 65 and 39 m in the Florida Geological Survey core Phred 1 (W-13958), located 5.6 km south of Wabasso, Indian River County, Florida (text-figure 2D). A diverse assemblage of planktic foraminifera were identified from the Wabasso beds in Georgia and Florida by Huddlestun (1988). The occurrence of *Globigerina nepenthes* (LAD ~4.37 Ma) indicates the Wabasso beds are no younger than Zone PL1 or Early Pliocene (Zanclean) (Raffi et al. 2020). The occurrence of *Globorotalia margaritae* (range 6.08–3.85 Ma) suggests an age no older than Planktic Foraminiferal Zone M13 or Late Miocene (Messinian). This planktic assemblage potentially correlates the Wabasso beds in South Carolina, Georgia, and Florida with Zone 1 Yorktown (Sunken Meadow Member) in southeast Virginia and northeast North Carolina. The age of 4.4 Ma from the Sunken Meadow at Lee Creek Mine corroborates this correlation.

3.3.2. Cypresshead Formation

Huddlestun (1988) named the Cypresshead Formation for fossil-poor sediments above the Raysor Formation in Georgia. The Cypresshead Formation was described as a “thin-to-thick bedded and massive, planar to cross bedded, variably burrowed and bioturbated, fine-grained to pebbly, coarse-grained sand in the terrace region of eastern Georgia. The type locality is on Goose Creek, 0.4 km southeast of the junction of Cypresshead Branch and Goose Creek, 7.5 km north-northwest of Jessup, Wayne County, Georgia (text-figure 2D). The Cypresshead Formation disconformably overlies the Miocene Coosawhatchie Formation and the Raysor Formation along the Altamaha River. The Cypresshead is disconformably overlain by the Satilla Formation.

Planktic foraminifera are rare in the unit, but the assemblage recovered, combined with the stratigraphic relationships to other formations, indicates a probable assignment to Zone PL5. The presence of *Globigerina decoraperta* (LAD in the middle of PL5) in the Cypresshead Formation suggests an age no younger than 2.75 Ma. This fits with Markewich et al. (1992) who correlate the Cypresshead Formation to the Bear Bluff Formation in the Carolinas.

3.3.3. Satilla Formation

The Satilla Formation was named and described as unconsolidated greenish and bluish marine clays, gray, white, and yellow sands, and thin layers of gravel in Georgia by Veach and Stephenson (1911). Since a type section was not named, a lectostratotype was designated by Huddlestun (1988) on the Satilla River at Satilla Bluff, 5 km downriver of Woodbine, Camden County, Georgia (text-figure 2D). Markewich et al. (1992) suggested an age younger than 200 ka, based on previous work by McCartan et al. (1982), McCartan et al. (1984), Owens (1989) and McCartan (1990). A planktic foraminiferal assemblage recovered by Huddlestun (1988) from Chatham County, Georgia, while not age diagnostic, is compatible with a Late Pleistocene age.

4. DISCUSSION

The foregoing summary of Pliocene and Pleistocene units forms the basis of a stratigraphic framework for the ACP within which the MPWP can be located. The correlations shown in Figure 4 have for the most part been proposed by others (e.g. Blackwelder and Ward, 1979; Hazel, 1983; Cronin and others, 1984; Huddlestun, 1988; Ward and others, 1991; Campbell and Campbell, 1995; Ward, 2007; etc.). Here we have updated the stratigraphic framework through a reanalysis of planktic foraminiferal data available from coastal plain localities (Dowsett 2024) and recent additions to the ACP stratigraphic literature (e.g. Denison and others, 1993; Graybill and others, 2009; McGregor and others, 2011; Dowsett and others, 2021).

4.1. Biostratigraphy and Biochronology

A recurring issue in coastal plain stratigraphy is the mixing of litho- and bio- stratigraphic concepts. Both lithostratigraphic formations and biostratigraphic zones are time transgressive, and therefore age plays no proper role in their definitions (North American Commission on Stratigraphic Nomenclature, 2021). On the ACP, where absolute age estimates (radiometric dates) are rare, and successive lithologies have minor differences (one shelly sand looks like another), distinguishing one formation from another can be difficult. In a practical sense it becomes necessary to use fossil occurrences and similarity of fossil assemblages to assess temporal equivalence and to place approximate ages on units (Kauffman and Hazel 1977). However, comparison of the presence or absence of benthic taxa (generally more sensitive to substrate and otherwise local conditions than planktic organisms) between two localities, may represent environmental differences as much or more so than temporal diachrony. Though generally rare in shallow environments, planktic microfossil events (evolutionary first and last appearances) have higher relative biostratigraphic value due to their extensive spatial distributions and facies independence. Thus, events are often calibrated to geologic time scales and used to estimate ages of units (Berggren 1973; Berggren et al. 1985; Wade et al. 2011). Since biostratigraphic events are to some degree diachronous (Shaw 1964; Dowsett 1989a, 1989b; Wade et al. 2011; Lam et al. 2022), calibrated biochronologies can, and sometimes do, add additional uncertainty to correlations. Scott (1978) put it plainly: "the logical distinction between sequence and time, so well made by Huxley, has not been appreciated and the "double-talk" about synchroneity continues unabated."

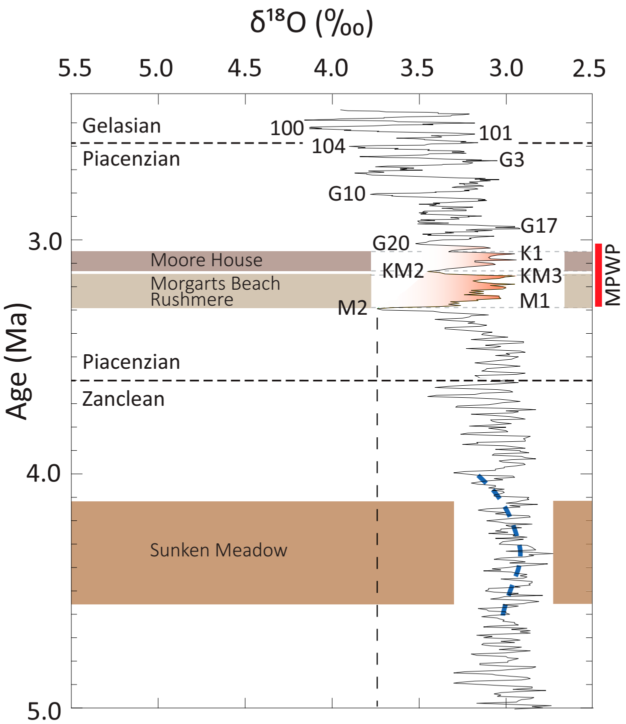
Another complication in evaluating age of Coastal Plain units based largely upon calibrated fossil events is that our understanding of when individual taxa evolved and became extinct, as well as the geologic time scale itself, has changed over historical time. Ever more refined data from many sources, including the Deep Sea Drilling Project (DSDP) and its successors, have provided a wealth of quantitative data on the temporal, geographic, and ecologic distribution and paleoceanographic implications of microfossils (Saitō and Burckle 1975; Kennett 1978; Talwani et al. 1979; Berggren et al. 1985; Bolli et al. 1989; Dowsett 1989a, Berggren et al. 1995). Many previous ACP planktic foraminifera-based age assignments relied upon the original N-zones of Blow (1969) or PL-zones of Berggren (1973). Changes to nominate species of some zones over time, or new information on the times of origination and extinction of taxa, resulted in confusion over age estimates. In one example, the presence of the planktic foraminifer *Dentoglobigerina altispira* in samples from the Raysor Formation in South Carolina was used to estimate the formation as being older than 3.9 Ma (Bybell 1990). This was based upon an assumed LAD of 3.9 Ma. Today we recognize the *Dentoglobigerina altispira* LAD to be closer to 3.13 Ma. Thus, interpreting and assessing age assignments from previous workers requires knowledge of the historical development of biostratigraphic zonations, as well as the geologic time scales used to calibrate fossil events. In this work, we have relied primarily on foraminiferal occurrence data to determine placement of units in the zonation of Wade et al. (2011) as presented in GTS2020 (Gradstein et al. 2020).

4.2. Pliocene sea level

Coastal Plain outcrops generally represent spatially discontinuous records of fleetingly short intervals of time, separated by intervals of uncertain duration, or in some cases, highly condensed and time averaged beds (Barrell 1917; Dott 1983; Davies et al. 2019; Zimmt et al. 2022). Sedimentary units from the Coastal Plain of Virginia through Florida also record marine deposition over a warped and evolving surface (Ward et al. 1991). Depositional sequences are controlled in large part by glacioeustatic sea level and a combination of mantle dynamics (dynamic topography) and glacial isostatic adjustment (GIA). Rowley et al. (2013) showed that dynamic topography has a significant effect on ACP sea-level estimates based upon analysis of the elevation of the Orangeburg Scarp, a marker for the mid-Piacenzian shoreline. Dowsett and Cronin (1990) used the Orangeburg Scarp to estimate a late Pliocene sea-level of +35 (±17) m. That work used simple assumptions about rates of tectonic uplift. Moucha and Ruetenik (2017) demonstrated that in addition to dynamic topography, inclusion of flexural isostasy is required to fully explain deformation of the Orangeburg Scarp within the ACP. That work suggested an estimated sea level rise of +15 m. Miller et al. (2012) obtained global sea level estimates of +22 (±5) m (68% confidence level) from backstripping in Virginia, New Zealand, and Enewetak Atoll. Dowsett et al. (2016) presented a paleogeographic reconstruction based upon GIA, adjustments due to mantle convection, and estimated ice-volume to suggest a global mean sea level (GMSL) +24 m relative to present day. Halberstadt et al. (2024) indicate a dynamic Pliocene Antarctic ice sheet revealing 25m of GMSL rise. Conversely, a recent estimate of mid-Piacenzian GMSL, based upon geodynamically corrected Pliocene shoreline elevations in Australia, is +16.0 m (±5.5 m) (Richards et al. 2023), and another by Dumitru et al. (2019), based upon phreatic overgrowths on speleothems from the western Mediterranean, suggests GMSL +16.2 m to +17.4 m relative to present day. Despite the spread, these estimates of past GMSL provide critical paleoclimatic information by bracketing global ice volume.

While documentation of the elevation of the Orangeburg Scarp along its length has been made (Rovere et al. 2015), for the purpose of determining the stratigraphic position of the MPWP, it is the spatial location of the scarp that is most important. Regardless of the GMSL, the ACP was submerged during parts of the Pliocene with the western-most extent of marine sediments occurring at the toe of the Orangeburg Scarp (DuBar et al. 1974; Winker and Howard 1977; Colquhoun 1986; Huddlestun 1988; Owens 1989; Dowsett and Cronin 1990).

Obliquity driven sea level cyclicity during the Pliocene suggests transgressive-regressive cycles on the ACP of around 40,000 years. Given the 1 My length of the Late Pliocene (Piacenzian), there could have been ~ 25 Piacenzian transgressive-regressive cycles. The correlation of the Duplin, Raysor, and Goose Creek formations differs between authors (Ward et al. 1991; Campbell and Campbell 1995; Willoughby et al. 1999). What has been described in the literature are three cycles that can be accurately attached to type sections. Thus, at most, only three of these potential Piacenzian transgressive-regressive cycles have been described based on type sections, leaving 22 cycles not covered by any of



TEXT-FIGURE 5
The Pliocene portion of the LR04 benthic stable isotope stack of Lisiecki and Raymo (2005). Horizontal dashed lines indicate the Zanclean – Piacenzian and Piacenzian – Gelasian (also the Pliocene – Pleistocene) boundaries. Numbers refer to selected marine isotope stages. Horizontal shaded bands do not represent duration of sedimentation of respective units, but rather indicate the temporal interval within which the units most likely reside. Vertical red line at right indicates the interval covered by the PRISM3 mid-Piacenzian Warm Period (Dowsett et al. 2010).

the existing lithostratigraphic terminology. This implies that any new Late Pliocene exposure may represent a transgressive-regressive cycle not previously described in the existing literature. We are dealing with many short transgressive-regressive cycles that are nearly impossible to separate based upon observed faunal successions (R. Weems, USGS, written communication, 2024).

Krantz (1991) discussed the chronology of Pliocene sea-level fluctuations on the U.S. Middle ACP based on marine and marginal-marine sediments. Considering the ACP records the feather edge of transgressions due to changes in sea level, he correlated transgressions onto the ACP with deep-ocean benthic stable isotopic records. This was a particularly elegant way to determine relative (and to estimate absolute) ages of units. Krantz presented the model as a hypothesis to be tested when additional data became available. The Krantz model has since been applied to sedimentary sequences in Virginia, North Carolina, and South Carolina to help determine relative age and to facilitate correlation throughout the ACP (Ward et al. 1991; Campbell 1993; Campbell and Campbell 1995; Harding et al. 2015; Spivey et al. 2022).

Our summary of Pliocene ACP stratigraphy and identification of the MPWP is also based, in part, upon the deep-sea oxygen isotopic record. Krantz (1991) used available oxygen isotope records at that time (Deep Sea Drilling Project Sites 552A, 572C, 588, 606, 607 and Ocean Drilling Program Site 665A) to develop a sea level curve, tying the Yorktown Formation and its members to specific times of estimated high sea level. The global oxygen isotopic record of the past 5 million years has since been synthesized in a seminal paper by Lisiecki and Raymo (2005), and for the past two decades the so called "LR04 stack" has been the *de facto* standard for marine age models.

4.3. Isotope Stratigraphy

The single largest δ^{18}O enrichment in the LR04 record during the first two million years of the Pliocene occurs at ~3.3 Ma and is designated marine isotope stage (MIS) M2 (text-figure 5). The M2 event can be interpreted as an increase in global ice volume and concomitant decrease in GMSL. The magnitude of sea-level drop associated with the M2 event has been estimated at ~60 m by Dwyer and Chandler (2009) using coupled Mg/Ca and oxygen isotope analyses in North Atlantic deep sea cores. Many have analyzed the M2 event, its possible causes, and the role it may have played in the development of Pliocene paleoceanographic and paleoclimatic changes (De Schepper et al. 2009; Dolan et al. 2015; de la Vega et al. 2020).

The increase in global ice volume associated with MIS M2 led to widespread regression on the ACP (Dowsett et al. 2021). The ensuing transition from MIS M2 to MIS M1 resulted in an extensive transgression occurring over ~0.04 My. Following MIS M1 the benthic isotope record remains depleted with low amplitude variability through MIS KM3. Marine Isotope Stage KM2 is the next strong δ^{18}O enrichment occurring ~3.15 Ma (text-figure 5). The time interval between MIS M2 and MIS KM2 (~0.16 Ma) is equivalent to the first half of the MPWP of Dowsett et al. (2010).

4.4. Atlantic Coastal Plain mid-Piacenzian Warm Period

By definition, the MPWP lies between the transition of MIS M2/M1 (3.264 Ma) and MIS G21/G20 (3.025 Ma), in the middle part of the Gauss Normal Polarity Chron (Dowsett et al. 2010). The MPWP ranges from C2An.2r (Mammoth reversed polarity) to near the bottom of C2An.1n (just above Kaena reversed polarity). This interval correlates in part to Planktic Foraminiferal Zones PL3 (*Sphaeroidinellopsis seminulina* Highest Occurrence Zone), PL4 (*Dentoglobigerina altispira* Highest Occurrence Zone) and PL5 (*Globorotalia miocenica* Highest Occurrence Zone) of Wade et al. (2011). The MPWP sits within the limits of Calcareous Nannofossil Zones NN16 of Martini (1971), CM12a of Okada and Bukry (1980), and Mollusk Zone M5 of Blackwelder (1981a) (text-figure 4).

In southeastern Virginia, the Yorktown Formation rests unconformably on the Late Miocene Eastover Formation, which is placed in Nannofossil Zones NN11 of Martini (1971) or CN9 of Okada and Bukry (1980) (M. Utsunomiya, JGS, written communication, 2024) (text-figure 4). The basal Sunken Meadow Member of the Yorktown Formation is dated at ~4.3 Ma. Planktic foraminiferal assemblages indicate assignment to Zone PL1 (Robinson and Dowsett 2023), and the molluscan assemblage is placed in Zone M6. Any number of regressions may be responsible for removing large parts of the Lower Pliocene sedimentary record (prior to 3.3 Ma), but the MIS M2 event was the strongest δ^{18}O enrichment since the beginning of the Zanclean.

The reduction in GMSL and concomitant regression removed part, in some cases all, of the Sunken Meadow Member (Yorktown Zone 1), so that the Rushmere Member locally sits on Miocene units. Mollusk faunas are different across the unconformity, suggesting an appreciable amount of time missing from the geologic record (Ward and Blackwelder 1980). Based upon biochronology and the few dates available for the Yorktown Formation (Bender 1973; Hazel 1983; Denison et al. 1993; Browning et al. 2009), the Sunken Meadow Member of the Yorktown Formation is separated by ~1 My from the overlying Rushmere Member. In Georgia and Florida, the Wabasso beds, like the Sunken Meadow, can be placed in Planktic Foraminiferal Zone PL1. The Wabasso beds are unconformably overlain by the Duplin and Raysor Formations, both of which fall within Zone PL3, showing a similar stratigraphic arrangement as seen in southeast Virginia and northeast North Carolina within the Yorktown Formation.

Deposition during the MIS M2-M1 glacioeustatic rise in sea level marks the start of the MPWP (text-figure 5). This rapid transgression is recorded by the Rushmere Member of the Yorktown Formation in Virginia and northern North Carolina (Ward and Blackwelder 1980; Dowsett et al. 2021). The Rushmere-Morgarts Beach transgression was the most extensive of Pliocene depositional events, covering an area inland to just west of the Tidewater fall line (Ward and Blackwelder 1980; Fig. 12 of Ward, 2008) and thus comprises the extent of the modern ACP in southeastern Virginia and northeastern North Carolina (Weems 1998). Following relatively high stands of sea level associated with MIS M1, KM5, and KM3, the next major glacial event, and presumed drop in sea level (MIS KM2, text-figure 5), could be a candidate for the regression resulting in the unconformable contact between the Morgarts Beach and Moore House members of the Yorktown Formation. This would put the age of the Moore House Member within the interval of ~3.1 Ma to 3.0 Ma (Dowsett et al. 2021). Thus, while multiple short transgressive-regressive cycles were probably responsible for the existing sediments, there are at least two pulses of relative rise in sea level evident in southeastern Virginia and northeastern North Carolina during the first half of the Piacenzian.

Cronin et al. (1984), Dowsett and Cronin (1990), and Ward et al. (1991) suggested the Raysor, Duplin, and Yorktown Formations were correlative and represented parts of a marine transgression that occupied the Orangeburg Scarp. A large amount of time is missing between the Early Pliocene Wabasso beds of Georgia and the overlying Raysor Formation (Huddlestun 1988). Elsewhere on the ACP, the Raysor and Duplin Formations rest unconformably on much older (Cretaceous, Eocene, Oligocene, and Miocene) units (Ward et al. 1991).

The Chowan River Formation and age equivalent Bear Bluff Formation may have been deposited following the MIS G20 glacial event or possibly the MIS G10 glacial event, which is followed by nearly 100,000 years of relatively high sea levels (Dowsett et al 2021). However, at present these correlations are conjectural and additional chronologic data are required to accurately date post-MPWP units.

Blackwelder (1981a) Mollusk Zone M5 is defined by the occurrence of *Chesapecten septenarius*, which first occurs at the base of the Rushmere Member of the Yorktown Formation (=Zone 2 Yorktown) but it is not present in the overlying Moore House Member. This short ranging taxon has thus been used as a marker for the transgression that deposited the Late Pliocene Rushmere and Morgarts Beach Members of the Yorktown. *Chesapecten septenarius* is also found at the type locality of the Duplin Formation at Hidden Well (Dall 1903), in the Raysor Formation at its type locality on the Edisto River (Ward and Huddlestun 1988), and in the informal upper and lower beds of the Goose Creek Limestone (Campbell and Campbell 1995). This suggests the Duplin Formation, Raysor Formation, and Goose Creek Limestone are at least in part equivalent, fall within Mollusk Zone M5, were deposited post 3.3 Ma, and represent the MPWP on the southeastern ACP.

5. SUMMARY AND CONCLUSIONS

We reinterpreted existing and generated new planktic foraminiferal occurrence data for Pliocene-Pleistocene units of the ACP (Dowsett, 2024) using the presently accepted zonation schemes calibrated to GTS2020 (Raffi et al. 2020). These data were used to confirm correlations and, to the extent possible, ages of Coastal Plain units. We recognize there is no *a priori* reason to assume synchroneity of fossil first and last appearance events (Shaw 1964; Hazel 1977; Scott 1978; Dowsett 1989a, Lam et al. 2022) and therefore use the calibrated ages of evolutionary events provided in Raffi et al. (2020) only as a general guide to age.

The MIS M2 event was of large enough magnitude that the associated regression removed sediments along the length of the southeastern ACP. Thus, in most cases, post-MIS M2 sedimentary units rest unconformably on Miocene or older rocks. The base of the MPWP is coincident with the MIS M2-M1 transition and the MPWP is probably represented by several transgressive-regressive cycles on the ACP. Our review of the stratigraphy of the coastal plain suggests this extensive transgression is recorded by the Rushmere and Morgarts Beach Members of the Yorktown Formation of Virginia and North Carolina, the Duplin Formation in North Carolina, and the Raysor and Goose Creek Formations in South Carolina and Georgia (text-figure 4).

The ACP provides a unique and accessible fossil-rich laboratory within which detailed and nuanced analyses of marine paleobiology and paleoenvironments can take place (Stanley and Campbell 1981; Allmon et al. 1996; Saupe et al. 2014; Friend et al. 2023; Anderson et al. 2024). We identify several peri-MPWP intervals: the Sunken Meadow Member of the Yorktown Formation and the correlative Wabasso beds in Georgia represent a pre-MPWP interval within the Zanclean that may be equivalent in age to the 4.474 Ma PRISM 5.1 time-slice (Dowsett et al. 2023), one of two Early Pliocene targets currently being analyzed by paleoclimate modeling groups (Haywood et al. 2024). The Rushmere (and Morgarts Beach) Member of the Yorktown Formation in Virginia and North Carolina was deposited during the MPWP. The Duplin and Raysor Formations, and Goose Creek Limestone, are correlated to the Rushmere Member of the Yorktown Formation and represent the MPWP and PRISM4 paleoenvironmental reconstruction focused on 3.205 Ma or MIS KM5c (Dowsett et al. 2016). A post-MPWP interval near the Pliocene-Pleistocene boundary is represented by the Chowan River, Bear Bluff and Cypress Head Formations from Virginia to Georgia. A second, younger post-MPWP interval is represented by the James City Formation in the north and Waccamaw Formation further south. Based upon mollusk faunas, both units can be separated into a first and second pulse. This provides four (and possibly 5) time bands within which comparative paleobiological, paleoenvironmental, and paleoclimatic research can be pursued.

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DATA AVAILABILITY

Occurrences of planktic foraminifera and information on localities discussed in the text are available here: https://doi.org/10.5066/P14THAU8.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Harry Dowsett: Writing – original draft, review & editing, Visualization, Methodology, Formal analysis, Conceptualization, and Funding acquisition. **Whittney Spivey**: Writing – review & editing, Visualization, Validation, Formal analysis, Data curation, Resources.

REFERENCES

AKERS, W. H., 1972. Planktonic Foraminifera and biostratigraphy of some Neogene formations, northern Florida and Atlantic Coastal Plain. *Tulane Studies in Geology,* 9: 1–139.

ALLMON, W. D., ROSENBERG, G., PORTELL, R. W. and SCHINDLER, K., 1996. Diversity of Pliocene-Recent mollusks in the western Atlantic: extinction, origination, and environmental change. In: JACKSON, J. B. C., BUDD, A. F. and COATES, A. G. Eds., *Evolution and environment in tropical America*, 1626–1629. Chicago, IL: University of Chicago Press.

ANDERSON, B. M., PETSIOS, E., BEHN, J., BETZ, A., ALLMON, W. D., LIEBERMAN, B. S. and HENDRICKS, J. R., 2024. Body-size evolution in gastropods across the Plio-Pleistocene extinction in the western Atlantic. *PLoS ONE*, 19 (12): e0313060.

BARRELL, J., 1917. Rhythms and the measurements of geologic time1. *Geological Society of America Bulletin*, 28 (1): 745–904.

BARTRAM, W., 1791. *Travels through North and South Carolina, Georgia East & West Florida, the Cherokee country, the extensive territories of the Muscogulges, or Creek Confederacy, and the country of the Chactaws*, Philadelphia, PA, USA: *James and Johnsons.*

BENDER, M. L., 1973. Helium-uranium dating of corals. *Geochimica et Cosmochimica Acta*, 37 (5): 1229–1247.

BERGGREN, W. A., 1973. The Pliocene Time Scale: Calibration of planktonic foraminiferal and calcareous Nannoplankton zones. *Nature*, 243 (5407): 391–397.

BERGGREN, W. A., KENT, D. V., SWISHER, C. C. and AUBRY, M.-P., 1995. A revised Cenozoic geochronology and chronostratigraphy. In: Berggren, W. A., Kent, D. V., Aubry, M.-P., and Hardenbol, J., Eds., *Geochronology, Time Scales, and Global Stratigraphic Correlation*, 54: 129–212. SEPM Special Publication.

BERGGREN, W. A., KENT, D. V. and VAN COUVERING, J. A., 1985. Neogene geochronology and chronostratigraphy. In: Snelling, N. J. Ed. *The Chronology of the Geological Record*, 10: 211–260. Geological Society of London Memoir.

BLACKWELDER, B. W., 1979. Stratigraphic revision of Lower Pleistocene marine deposits of North and South Carolina. *U.S. Geological Survey Bulletin*, 1482-A: A52–A61.

——, 1981a. Late Cenozoic Stages and Molluscan Zones of the U.S. Middle Atlantic Coastal Plain. *Memoir (The Paleontological Society)*, 12: 1–34.

——, 1981b. Stratigraphy of upper Pliocene and lower Pleistocene marine and estuarine deposits of northeastern North Carolina and southeastern Virginia. *U.S. Geological Survey Bulletin*, 1502-B: B1–B19.

BLACKWELDER, B. W. and WARD, L. W., 1979. Stratigraphic revision of the Pliocene deposits of North and South Carolina. *Geological Notes*, 23: 33–49.

BLOW, W. H., 1969. Late middle Eocene to recent planktonic foraminiferal biostratigraphy. *Proceedings of the 1st International Conference on Planktonic Microfossils*, 199–422. Leiden, The Netherlands: Brill, E. J.

——, 1979. *The Cainozoic Foraminiferida*, Leiden, The Netherlands: *E. J. Brills.*

BOLLI, H. M., SAUNDERS, J. B. and PERCH-NIELSEN, K., 1989. *Plankton Stratigraphy. Volume 1, Planktic Foraminifera, Calcareous Nannofossils and Calpionellids.* Cambridge: Cambridge University Press.

BRITT, R. J., CAMPBELL, L. D., CAMPBELL, M. R., and CARTER, J. G., 1992. Molluscan Biostratigraphy of the Robeson Farm site, Tarheel, Bladen County, North Carolina. In: Dennison, J. M. and Stewart, K. G., Eds., *Geologic Field Guides to North Carolina and Vicinity*, 1: 153–157. Chapel Hill, NC, USA: Department of Geology, University of North Carolina at Chapel Hill.

BROWNING, J. V., MILLER, K. G., MCLAUGHLIN, P. P., J. R., EDWARDS, L. E., KULPECZ, A. A., POWARS, D. S., WADE, B. S., FEIGENSON, M. D., WRIGHT,. and J., D., 2009. Integrated sequence stratigraphy of the postimpact sediments from the Eyreville core holes, Chesapeake Bay impact structure inner basin. In: Gohn, G. S., Koeberl, C., Miller, K. G. and Reimold, W. U. Eds., *The ICDP-USGS Deep Drilling Project in the Chesapeake Bay impact structure: Results from the Eyreville Core Holes*, 775–810. Geological Society of America.

BURKE, K. D., WILLIAMS, J. W., CHANDLER, M. A., HAYWOOD, A. M., LUNT, D. J. and OTTO-BLIESNER, B. L., 2018. Pliocene and Eocene provide best analogs for near-future climates. *Proceedings of the National Academy of Sciences*, 115 (52): 13288–13293.

BYBELL, L. M., 1990. Calcareous nannofossils from Pliocene and Pleistocene deposits in South Carolina, in Studies related to the Charleston, South Carolina, Earthquake of 1886-Neogene and Quaternary Lithostratigraphy and Biostratigraphy. *U. S. Geological Survey Professional Paper*, 1367-B: 1–9.pp.

CAMPBELL, L. D., 1993. Pliocene molluscs from the Yorktown and Chowan River Formations in Virginia. *Virginia Division of Mineral Resources*, 127: 1–259.

CAMPBELL, L. D., CAMPBELL, D. C., CARTER and J. G.,. 1995. Molluscs of the Natural Well Locality, Duplin Stratotype, Near Magnolia, North Carolina, and Rediscovery of Carinorbis Quadricostata (Emmons, 1858) (Gastopoda: Amathinidae). *Tulane Studies in Geology and Paleontology*, 27: 165–182.

CAMPBELL, M. R., 1992. Molluscan biostratigraphy of the Pliocene beds of eastern South Carolina and southeastern North Carolina. In: Dennison, J. M. and Stewart, K. G., Eds., *Geologic field guides to North Carolina and vicinity: University of North Carolina-Chapel Hill, Department of Geology Geologic Guidebook, Joint annual meeting of Geological Society of America, Southeastern Section, Society of Economic Paleontologists and Mineralogists, Eastern Section, and Paleontological Society, Southeastern Section*, 145–151. Winston-Salem, NC: Geological Society of America.

CAMPBELL, M. R. and CAMPBELL, L. D., 1995. Preliminary biostratigraphy and molluscan fauna of the Goose Creek Limestone of Eastern South Carolina. *Tulane Studies in Geology and Paleontology*, 27: 53–100.

CLARK, W. B., 1894. Origin and classification of the Greensands of New Jersey. *The Journal of Geology*, 2 (2): 161–177.

——, 1906. A brief summary of the geology of the Virginia Coastal Plain. *Virginia Geological Survey Bulletin*, 2: 11–24.

COLQUHOUN, D. J., 1986. The geology and physiography of the Orangeburg Scarp. In: Neathery, T. L. Ed. *Southeastern Section of the Geological Society of America, Centennial Field Guide*, 6: 321–322. Boulder, Colorado: Geological Society of America.

CONRAD, T. A., 1841. Observations on the Secondary and Tertiary formations of the southern Atlantic states. *The American Journal of Science and Arts*, 41: 332–348.

COOKE, C. W., 1936. Geology of the coastal plain of South Carolina. *U. S. Geological Survey Bulletin*, 867: 1–196.

COOKE, C. W., GARDNER, J. and WOODRING, W. P., 1943. Correlation of the Cenozoic formations of the Atlantic and Gulf Coastal Plain and the Caribbean region. *Geological Society of America Bulletin*, 54 (11): 1713–1722.

CRONIN, T. M., 1980. Biostratigraphic correlation of Pleistocene marine deposits and sea levels, Atlantic Coastal Plain of the southeastern United States. *Quaternary Research,* 13 (2): 213–229.

——, 1991. Pliocene shallow water paleoceanography of the North Atlantic Ocean based on marine Ostracodes. *Quaternary Science Reviews*, 10 (2-3): 175–188.

CRONIN, T. M., BYBELL, L. M., POORE, R. Z., BLACKWELDER, B. W., LIDDICOAT, J. C. and HAZEL, J. E., 1984. Age and correlation of emerged Pliocene and Pleistocene deposits, U.S. Atlantic Coastal Plain. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 47 (1-2): 21–51.

CRONIN, T. M., DOWSETT, H. J., GOSNELL, L. B., and ROSS, R. M., 1989. Pliocene marine micropaleontology of Southeastern Virginia and Northeastern North Carolina. *U.S. Geological Survey, Open-File Report, 89-678*: 1–16.

CURRAN, H. A. and PARKER, P. L., 1983. Observations on the paleoecology and formation of the "Upper Shell" Unit, Lee Creek Mine. In: Ray, C. E. Ed., *Geology and paleontology of the Lee Creek Mine, North Carolina, I. Smithsonian Contributions to Paleobiology*, 53:219–228. Washington, DC: Smithsonian Institution Press.

DALL, W. H., 1892. Contributions to the Tertiary fauna of Florida, with special reference to the Miocene Silex beds of Tampa and the Pliocene beds of the Caloosahatchie River. *Wagner Free Institute of Science Transactions*, 3:1654.

——, 1896. Diagnoses of new species of mollusks from the southern United States. *Proceedings of the United States National Museum*, 18:21–46.

——, 1903. Contributions to the Tertiary Fauna of Florida: With Especial Reference to the Miocene Silex-beds of Tampa and the Pliocene Beds of the Caloosahatchie River. *Transactions of the Wagner Free Institute of Science,* 3: 1–1654.

DALL, W. H. and HARRIS, G. D., 1892. Correlation papers: Neogene. *United States Geological Survey Bulletin*, 84: 349.

DANA, J. D., 1862. *Manual of Geology: Treating of the Principles of the Science, with Special Reference to American Geological History, for the Use of Colleges, Academies, and Schools of Science.* Philadelphia, PA: T. Bliss & Company, 798 pp.

DAVIES, N. S., SHILLITO, A. P. and MCMAHON, W. J., 2019. Where does the time go? Assessing the chronostratigraphic fidelity of sedimentary geological outcrops in the Pliocene–Pleistocene Red Crag Formation, eastern England. *Journal of the Geological Society*, 176 (6): 1154–1168.

DE LA VEGA, E., CHALK, T. B., WILSON, P. A., BYSANI, R. P. and FOSTER, G. L., 2020. Atmospheric CO_2 during the Mid-Piacenzian Warm Period and the M2 glaciation. *Scientific Reports*, 10 (1): 11002.

DE SCHEPPER, S., HEAD, M. J. and GROENEVELD, J., 2009. North Atlantic Current variability through marine isotope stage M2 (circa 3.3 Ma) during the mid-Pliocene. *Paleoceanography*, 24 (4) PA4206.

DENISON, R. E., HETHERINGTON, E. A., BISHOP, B. A., DAHL, D. A. and KOEPNICK, R. B., 1993. The use of Strontium isotopes in stratigraphic studies: An example from North Carolina. *Southeastern Geology*, 33: 53–69.

DOLAN, A. M., HAYWOOD, A. M., HUNTER, S. J., TINDALL, J. C., DOWSETT, H. J., HILL, D. J. and PICKERING, S. J., 2015. Modelling the enigmatic Late Pliocene glacial event—Marine isotope stage M2. *Global and Planetary Change*, 128: 47–60.

DOTT, R. H., 1983. Episodic sedimentation; how normal is average? How rare is rare? Does it matter? *Journal of Sedimentary Research*, 53 (1): 5–23.

DOWSETT, H. J., 1989a. Application of the Graphic Correlation method to Pliocene marine sequences. *Marine Micropaleontology*, 14 (1-3): 3–32.

——, 1989b. Improved dating of the Pliocene of the eastern South Atlantic using graphic correlation: Implications for paleobiogeography and paleoceanography. *Micropaleontology*, 35 (3): 279–292.

——, 2024. Occurrences of Planktic Foraminifera from the Pliocene - Pleistocene of the Atlantic Coastal Plain. *U.S. Geological Survey Data Release.* http://dx.doi.org/10.5066/P14THAU8.

DOWSETT, H. J. and CRONIN, T. M., 1990. High eustatic sea level during the middle Pliocene: Evidence from the southeastern U.S. Atlantic Coastal Plain. *Geology*, 18 (5): 435–438.

DOWSETT, H. J., DOLAN, A., ROWLEY, D., MOUCHA, R., FORTE, A. M., MITROVICA, J. X., POUND, M., SALZMANN, U., ROBINSON, M., CHANDLER, M., FOLEY, K. and HAYWOOD, A., 2016. The PRISM4 (mid-Piacenzian) paleoenvironmental reconstruction. *Climate of the Past*, 12 (7): 1519–1538.

DOWSETT, H. J. and POORE, R. Z., 1991. Pliocene sea surface temperatures of the North Atlantic Ocean at 3.0 Ma. *Quaternary Science Reviews*, 10 (2-3): 189–204.

DOWSETT, H. J., ROBINSON, M., HAYWOOD, A., SALZMANN, U., HILL, D., SOHL, L., CHANDLER, M., WILLIAMS, M., FOLEY, K. and STOLL, D., 2010. The PRISM3D paleoenvironmental reconstruction. *Stratigraphy*, 7 (2-3): 123–139.

DOWSETT, H. J., ROBINSON, M. M., FOLEY, K. M. and HERBERT, T. D., 2021. The Yorktown Formation: Improved Stratigraphy, Chronology, and Paleoclimate Interpretations from the U. S. Mid-Atlantic Coastal Plain. *Geosciences*, 11 (12): 486.

DOWSETT, H. J., ROBINSON, M. M., FOLEY, K. M., HERBERT, T. D., OTTO-BLIESNER, B. L. and SPIVEY, W., 2019. The mid-Piacenzian of the North Atlantic Ocean. *Stratigraphy*, 16 (3): 119–144.

DOWSETT, H. J., ROBINSON, M. M., FOLEY, K. M., HUNTER, S. J., DOLAN, A. M. and TINDALL, J. C., 2023. Early Pliocene (Zanclean) Stratigraphic Framework for PRISM5/PlioMIP3 Time Slices. *Stratigraphy*, 20 (3): 225–231.

DOWSETT, H. J. and SPIVEY, W., 2021. Planktonic foraminifer census data from type section of Yorktown Formation at Rushmere, Virginia. *U. S. Geological Survey Data Release*, http://dx.doi.org/10.5066/P9QKSO4W.

DOWSETT, H. J. and WIGGS, L. B., 1992. Planktonic foraminiferal assemblage of the Yorktown Formation, Virginia, USA. *Micropaleontology*, 38:75–86.

DUBAR, J. R., 1969. Biostratigraphic significance of Neogene macrofossils from two dug ponds, Horry County, South Carolina. *South Carolina Division of Geology, Geologic Notes*, 13: 67–71.

DUBAR, J. R., JOHNSON, H. S., THOM, B. and HATCHELL, W. O., 1974. Neogene stratigraphy and morphology, south flank of the Cape Fear Arch, North and South Carolina. In: Oaks, R. Q. and DUBAR, J. R. Eds. *Post-Miocene Stratigraphy of Central and Southern Atlantic Coastal Plain.* Logan, Utah: Utah State University Press, 139–173.

DUBAR, J. R. and SOLLIDAY, J. R., 1963. Stratigraphy of the Neogene deposits, lower Neuse Estuary, North Carolina. *Southeastern Geology*, 4: 213–233.

DUMITRU, O. A., AUSTERMANN, J., POLYAK, V. J., FORNóS, J. J., ASMEROM, Y., GINéS, J., GINéS, A. and ONAC, B. P., 2019. Constraints on global mean sea level during Pliocene warmth. *Nature*, 574 (7777): 233–236.

DWYER, G. S. and CHANDLER, M. A., 2009. Mid-Pliocene sea level and continental ice volume based on coupled benthic Mg/Ca palaeotemperatures and oxygen isotopes. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 367 (1886): 157–168.

EMMONS, E., 1858. *Report of the North Carolina geological survey; together with descriptions of the fossils of the marl beds Agriculture of the eastern counties.* Raleigh: H.D. Turners, 314 pp.

FAUTIN, D., DALTON, P., INCZE, L. S., LEONG, J. A., PAUTZKE, C., ROSENBERG, A., SANDIFER, P., SEDBERRY, G., TUNNELL, J. W., ABBOTT, I., BRAINARD, R. E., BRODEUR, M., ELDREDGE, L. G., FELDMAN, M., MORETZSOHN, F., VROOM, P. S., WAINSTEIN, M. and WOLFF, N., 2010. An overview of marine biodiversity in United States waters. *PLoS ONE*, 5 (8): e11914.

FINCH, J., 1823. Geological Essay on the Tertiary Formations in America. *American Journal of Science*, 7: 31–43.

——, 1833. *Finch's travels in the United States: and Canada, Containing some account of their scientific institutions, and a few notices of the Geology and Mineralogy of those countries*. London, Longman, Rees, Orme, Brown, Green, and Longman, 455 pp.

FRIEND, D., ANDERSON, B., ALTIER, E., SANG, S., PETSIOS, E., PORTELL, R. and ALLMON, W., 2023. Systematics and Phylogeny of Plio-Pleistocene Species of Turritellidae (Gastropoda) from Florida and the Atlantic Coastal Plain. *Bulletins of American Paleontology*, 402 (402): 1–74.

GIBSON, T. G., 1967. Stratigraphy and paleoenvironment of the phosphatic Miocene strata of North Carolina. *Geological Society of America Bulletin*, 78:631–650.

——, 1983a. Key foraminifera from upper Oligocene to lower Pleistocene strata of the central Atlantic Coastal Plain. In: *Geology and Paleontology of the Lee Creek Mine, North Carolina, I. Smithsonian Contributions to Paleobiology*, 53: 355–453. Washington, DC: Smithsonian Institution Press.

——, 1983b. Stratigraphy of Miocene through Lower Pleistocene strata of the United States central Atlantic Coastal Plain. In: *Geology and Paleontology of the Lee Creek Mine, North Carolina; I: Smithsonian Contributions to Paleobiology*, 53: 35–80. Washington, DC: Smithsonian Institution Press.

——, 1987. Miocene and Pliocene Pectinidae (bivalvia) from the Lee Creek Mine and adjacent areas. In: *Geology and Paleontology of the Lee Creek mine, North Carolina, II: Smithsonian Contributions to Paleobiology*, 61: 31–112. Washington, DC: Smithsonian Institution Press.

GOHN, G. S., 1988. Late Mesozoic and early Cenozoic geology of the Atlantic coastal plain: North Carolina to Florida. In: Sheridan, R. E. and Grow, J. A. Eds., *The Atlantic Continental Margin.* U.S. Geological Society of America. Boulder, CO, 107–130.

GRADSTEIN, F. M., OGG, J. G., SCHMITZ, M. D. and OGG, G. M., 2020. *Geologic time scale 2020.* Amsterdam: Elseviers, 1357 pp.

GRAYBILL, E. A., HARRIS, W. B., KELLEY, P., DIETL, G. and VISAGGI, C. C., 2009. Age of the Duplin and Waccamaw Formations, Cape Fear River basin, North Carolina [abs]. *Geological Society of America Abstracts with Programs*, 2009:41.

GULLAND, F. M. D., BAKER, J. D., HOWE, M., LABRECQUE, E., LEACH, L., MOORE, S. E., REEVES, R. R. and THOMAS, P. O., 2022. A review of climate change effects on marine mammals in United States waters: Past predictions, observed impacts, current research and conservation imperatives. *Climate Change Ecology*, 3: 100054.

HALBERSTADT, A. R. W., GASSON, E., POLLARD, D., MARSCHALEK, J. and DECONTO, R. M., 2024. Geologically constrained 2-million-year-long simulations of Antarctic Ice Sheet retreat and expansion through the Pliocene. *Nature Communications*, 15 (1): 7014.

HARDING, J. M., STRAUBE, B. A., GRIMM, B. L., VERMEIJ, G. J. and SPERO, H. J., 2015. Shells and fossils collected by the earliest settlers of Jamestown, Virginia, USA. *The Nautilus*, 129: 77–82.

HAYHOE, K., EDMONDS, J., KOPP, R. E., LEGRANDE, A. N., SANDERSON, B. M., WEHNER, M. F. and WUEBBLES, D. J., 2017. Climate models, scenarios, and projections. In: Wuebbles, D. J., Fahey, D. W., Hibbard, K. A., Dokken, D. J., Stewart, B. C. and Maycock, T. K. Eds., *Climate Science Special Report: Fourth National Climate Assessment*, I. Washington, DC: U.S. Global Change Research Program.

HAYWOOD, A. M., BURTON, L. E., DOLAN, A. M., DOWSETT, H. J., FLETCHER, T. L., FOLEY, K. M., HILL, D. J., HUNTER, S. J., ROBINSON, M. M. and TINDALL, J. C., 2024. Pliocene model intercomparison project phase. PlioMIP3): Science plan and experimental design. *Global and Planetary Change*, 3: 232.

HAYWOOD, A. M., TINDALL, J. C., DOWSETT, H. J., DOLAN, A. M., FOLEY, K. M., HUNTER, S. J., HILL, D. J., CHAN, W.-L., ABE-OUCHI, A., STEPANEK, C., LOHMANN, G., CHANDAN, D., PELTIER, W. R., TAN, N., CONTOUX, C., RAMSTEIN, G., LI, X., ZHANG, Z., GUO, C., NISANCIOGLU, K. H., ZHANG, Q., LI, Q., KAMAE, Y., CHANDLER, M. A., SOHL, L. E., OTTO-BLIESNER, B. L., FENG, R., BRADY, E. C., von der HEYDT, A. S., BAATSEN, M. L. J. and LUNT, D. J., 2020. The Pliocene Model Intercomparison Project Phase 2: large-scale climate features and climate sensitivity. *Climate of the Past*, 16 (6): 2095–2123.

HAZEL, J. E., 1971. Ostracode biostratigraphy of the Yorktown Formation (upper Miocene and lower Pliocene) of Virginia and North Carolina. *U.S. Geological Survey Professional Paper*, 704: 13.

——, 1977. Use of certain multivariate and other techniques in assemblage zonal biostratigraphy: examples utilizing Cambrian, Cretaceous, and Tertiary benthic invertebrates. In: Kauffman, E. G. and Hazel, J. E., Eds., *Concepts and methods of biostratigraphy*, 187–212. Pennsylvania, Dowden, Hutchinson & Ross.

——, 1983. Age and correlation of the Yorktown (Pliocene) and Croatan (Pliocene and Pleistocene) Formations at the Lee Creek Mine. *Geology and Paleontology of the Lee Creek Mine, North Carolina, I*, 53:81–200.

HODGSON, W. B., 1846. *Memoir on Megatherium and other extinct gigantic quadrapeds of the coast of Georgia, with observations on its grologic features.* New York: Bartlett and Welfords, 47 pp.

HOLLIN, J. T. and HEARTY, P. J., 1990. South Carolina interglacial sites and stage 5 sea levels. *Quaternary Research*, 33 (1): 1–17.

HUDDLESTUN, P., 1988. A revision of the lithostratigraphic units of the coastal plain of Georgia, the Miocene through Holocene. *Georgia Geologic Survey Bulletin*, 104: 1–162.

IPCC, 2013. *Climate Change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change.* New York, NY, USA: Cambridge University Presss, 1535 pp.

KAUFFMAN, E. G. and HAZEL, J. E., 1977. *Concepts and methods of biostratigraphy.* Stroudsburg: Dowden, Hutchinson and Ross, 658 pp.

KENNETT, J. P., 1978. The development of planktonic biogeography in the Southern Ocean during the Cenozoic. *Marine Micropaleontology*, 3 (4): 301–345.

KRANTZ, D. E., 1991. A chronology of Pliocene sea-level fluctuations: The U.S. Middle Atlantic coastal plain record. *Quaternary Science Reviews*, 10 (2-3): 163–174.

LAM, A. R., CRUNDWELL, M. P., LECKIE, R. M., ALBANESE, J. and UZEL, J. P., 2022. Diachroneity rules the mid-latitudes: A test case using late Neogene Planktic Foraminifera across the Western Pacific. *Geosciences*, 12 (5): 190.

LISIECKI, L. E. and RAYMO, M. E., 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic δ^{18}O records. *Paleoceanography,* 20 (1): PA1003.

LYELL, C., 1845a. On the Miocene tertiary Strata of Maryland, Virginia, and of North and South Carolina. *Quarterly Journal of the Geological Society,* 1: 413–429.

——, 1845b. *Travels in North America: With geological observations on the United States, Canada, and Nova Scotia*, 2. London: J. Murray.

MANSFIELD, W. C., 1929. New fossil mollusks from the Miocene of Virginia and North Carolina, with a brief outline of the divisions of the Chesapeake group. *Proceedings of the United States National Museum*, 74 (2759): 1–11.

——, 1943. Stratigraphy of the Miocene of Virginia and the Miocene and Pliocene of North Carolina: Mollusca from the Miocene and lower Pliocene of Virginia and North Carolina: Part 1. Pelecypoda. With a summary of the stratigraphy. *U.S. Geological Survey Professional Paper*, 199-A: 1–178.

MARKEWICH, H. W., HACKE, C. M. and HUDDLESTUN, P. F., 1992. Emergent Pliocene and Pleistocene sediments of Southeastern Georgia: An anomalous, fossil-poor, clastic section. In: Fletcher, C. H., III and Wehmiller, J. F., Eds., *Quaternary Coasts of the United States: Marine and Lacustrine Systems*, 173–189. SEPM Special Publication.

MARTINI, E., 1971. Standard tertiary and Quaternary calcareous nannoplankton zonation. In: Farinacci, A. Ed., *Proceedings 2 Planktonic Conference.* Rome: Techno-Scienza.

MCCARTAN, L., 1990. Introduction; Studies related to the Charleston, South Carolina, earthquake of 1886: Neogene and Quaternary lithostratigraphy and biostratigraphy. *U.S. Geological Survey Professional Paper*, 1367: 1–5.

MCCARTAN, L., LEMON, E. M., J. R., and WEEMS, R. E., 1984. Geologic map of the area between Charleston and Orangeburg, South Carolina. *U.S. Geological Survey Miscellaneous Investigations Series Map Series I-1472*.

MCCARTAN, L., OWENS, J. P., BLACKWELDER, B. W., SZABO, B. J., BELKNAP, D. F., KRIAUSAKUL, N., MITTERER, R. M. and WEHMILLER, J. F., 1982. Comparison of amino acid racemization geochronometry with lithostratigraphy, biostratigraphy, uranium-series coral dating, and magnetostratigraphy in the Atlantic Coastal Plain of the southeastern United States. *Quaternary Research*, 18 (3): 337–359.

MCGREGOR, D., HARRIS, W., DIETL, G. and KELLEY, P., 2011. Strontium isotopic dating of the Waccamaw Formation at Acme, NC, and the Duplin Formation at Tar Heel, NC: A Plio-Pleistocene Research Progress Report. *Geological Society of America Abstracts with Programs,* 43: 4.

MEHVAR, S., FILATOVA, T., DASTGHEIB, A., DE RUYTER VAN STEVENINCK, E. and RANASINGHE, R., 2018. Quantifying economic value of coastal ecosystem services: A review. *Journal of Marine Science and Engineering*, 6 (1): 5.

MILLER, B. L., 1912. The tertiary formations. In: Clark, W. B., Miller, B. L., Stephenson, L. W., Johnson, B. L. and Parker, H. N. Eds., *The Coastal Plain of North Carolina*, 171–258. North Carolina Geological and Economic Survey.

MILLER, K. G., WRIGHT, J. D., BROWNING, J. V., KULPECZ, A., KOMINZ, M., NAISH, T. R., CRAMER, B. S., ROSENTHAL, Y., PELTIER, W. R. and SOSDIAN, S., 2012. High tide of the warm Pliocene: Implications of global sea level for Antarctic deglaciation. *Geology*, 40 (5): 407–410.

MILLER, W., 1985. The Flanner beach formation (middle pleistocene) in Eastern North Carolina. *Tulane Studies in Geology and Paleontology*, 18: 93–122.

MOUCHA, R. and RUETENIK, G. A., 2017. Interplay between dynamic topography and flexure along the U.S. Atlantic passive margin: Insights from landscape evolution modeling. *Global and Planetary Change*, 149: 72–78.

NACSN. 2021. North American stratigraphic code. *Stratigraphy*, 18: 153–204.

OECD. 2016. *The Ocean Economy in 2030.* Paris: OECD Publishings.

OKADA, H. and BUKRY, D., 1980. Supplementary modification and introduction of code numbers to the low-latitude coccolith biostratigraphic zonation (Bukry, 1973; 1975). *Marine Micropaleontology,* 5: 321–325.

OWENS, J. P., 1989. Geologic map of the Cape Fear region, Florence 1° x 2° quadrangle and northern half of the Georgetown 1° x 2° quadrangle, North Carolina and South Carolina. *U.S. Geological Survey*, MI-1948A.

PARHAM, P. R., RIGGS, S. R., CULVER, S. J., MALLINSON, D. J., JACK RINK, W. and BURDETTE, K., 2013. Quaternary coastal lithofacies, sequence development and stratigraphy in a passive margin setting, North Carolina and Virginia, USA. *Sedimentology*, 60 (2): 503–547.

PETUCH, E. J. and ROBERTS, C., 2007. *The Geology of the Everglades and Adjacent Areas*, Boca Raton: CRC Press, 212 pp.

RAFFI, I., WADE, B. S., PäLIKE, H., BEU, A. G., COOPER, R., CRUNDWELL, M. P., KRIJGSMAN, W., MOORE, T., RAINE, I., SARDELLA, R. and VERNYHOROVA, Y. V., 2020. Chapter 29—The Neogene Period. In: GRADSTEIN, F. M., OGG, J. G., SCHMITZ, M. D. and OGG, G. M. Eds. *Geologic Time Scale 2020.* Amsterdam: Elsevier BV.

RICHARDS, F. D., COULSON, S. L., HOGGARD, M. J., AUSTERMANN, J., DYER, B. and MITROVICA, J. X., 2023. Geodynamically corrected Pliocene shoreline elevations in Australia consistent with midrange projections of Antarctic ice loss. *Science Advances*, 9 (46): eadg3035.

ROBINSON, M. M. and DOWSETT, H. J., 2023. Pliocene Planktic foraminiferal census data from the Northeast Indian Ocean and Southeast Virginia. *U.S. Geological Survey Data Release.* http://dx.doi.org/10.5066/P9PZJMDM.

ROVERE, A., HEARTY, P. J., AUSTERMANN, J., MITROVICA, J. X., GALE, J., MOUCHA, R., FORTE, A. M. and RAYMO, M. E., 2015. Mid-Pliocene shorelines of the US Atlantic Coastal Plain—An improved elevation database with comparison to Earth model predictions. *Earth-Science Reviews*, 145: 117–131.

ROWLEY, D. B., FORTE, A. M., MOUCHA, R., MITROVICA, J. X., SIMMONS, N. A. and GRAND, S. P., 2013. Dynamic topography change of the Eastern United States since 3 million years ago. *Science*, 340 (6140): 1560–1563.

SAITŌ, T. and BURCKLE, L. H., 1975. *Late Neogene Epoch Boundaries.* New York, USA: Micropaleontology Press.

SAUPE, E. E., HENDRICKS, J. R., PORTELL, R. W., DOWSETT, H. J., HAYWOOD, A., HUNTER, S. J. and LIEBERMAN, B. S., 2014. Macroevolutionary consequences of profound climate change on niche evolution in marine molluscs over the past three million years. *Proceedings of the Royal Society of London B: Biological Sciences,* 281(1795): 20141995.

SCHOEPF, J. D., 1787. *Contributions to the mineralogical knowledge of the eastern part of North America and its mountains.* Erlanger, Germany: J.J. Palm.

SCOTT, G., 1978. Concepts and methods of biostratigraphy. *New Zealand Journal of Geology and Geophysics*, 21 (4): 537–537.

SHAW, A. B., 1964. *Time in stratigraphy*, New York: McGraw-Hill Book Co., 365 pp.

SLOAN, E., 1908. Catalogue of the mineral localities of South Carolina. *South Carolina Geological Survey Bulletin*, 2: 1–505.

SMITH, E. A., 1914. Pioneers in gulf coastal plain geology. *Geological Society of America Bulletin*, 25 (1): 157–178.

SNYDER, S. W., MAUGER, L. L. and AKERS, W. H., 1983. Planktonic foraminifera and biostratigraphy of the Yorktown Formation, Lee Creek Mine. *Geology and Paleontology of the Lee Creek Mine, North Carolina, I*, 53: 455–481.

SNYDER, S. W., MAUGER, L. L. and AMES, D., 2001. Benthic foraminifera and paleoecology of the Pliocene Yorktown and Chowan River Formations, Lee Creek Mine, North Carolina, USA. *Journal of Foraminiferal Research*, 31 (3): 244–274.

SPIVEY, W. E., CULVER, S. J., MALLINSON, D., DOWSETT, H. J. and BUZAS, M. A., 2022. Benthic foraminiferal and sedimentologic changes in the Pliocene Yorktown Formation, Virginia, USA. *Journal of Foraminiferal Research*, 52 (4): 278–305.

STANLEY, S. M. and CAMPBELL, L. D., 1981. Neogene mass extinction of Western Atlantic molluscs. *Nature*, 293 (5832): 457–459.

TALWANI, M., HAY, W. and RYAN, W. B. F., 1979. Deep drilling results in the Atlantic Ocean: Continental margins and paleoenvironment. *American Geophysical Union Maurice Ewing Series,* 3: 1–410.

TUOMEY, M., 1848. *Report on the geology of South Carolina.* Columbia: A.S. Johnston, 293 pp.

VEACH, O. and STEPHENSON, L. W., 1911. Preliminary report on the geology of the coastal plain of Georgia. *Georgia Geological Survey Bulletin*, 26: 1–466.

WADE, B. S., PEARSON, P. N., BERGGREN, W. A. and PÄLIKE, H., 2011. Review and revision of Cenozoic tropical planktonic foraminiferal biostratigraphy and calibration to the geomagnetic polarity and astronomical time scale. *Earth Science Reviews*, 104: 111–142.

WARD, L. W., 2007. Synthesis of Paleontological and Stratigraphic Investigations at the Lee Creek Mine, Aurora, N.C. (1958-2007). In: WARD, L. W. Ed., *Lee Creek Mine, Aurora, North Carolina: History, mining operations, geology, stratigraphy and paleontology: A synthesis, Carolina Geological Society annual field trip, November 9-11, 2007.* Martinsville: Virginia Museum of Natural History.

——, 2008. *Geology and paleontology of the James River: Richmond to Hampton Roads, Virginia Museum of Natural History Guidebook 7.* Martinsville: Virginia Museum of Natural History.

WARD, L. W. and ALLMON, W. D., 2019. History of paleontology in Virginia: 1607-2007. *Bulletins of American Paleontology*, 397: 196 pp.

WARD, L. W., BAILEY, R. H., and CARTER, J. G., 1991. Pliocene and early Pleistocene stratigraphy, depositional history, and molluscan paleobiogeography of the coastal plain. In: HORTON, J. W. and ZULLO, V. A. Eds. *The geology of the Carolinas: Carolina Geological Society Fiftieth Anniversary Volume*, 274–289. Knoxville: University of Tennessee Press.

WARD, L. W. and BLACKWELDER, B. W., 1980. Stratigraphic revision of upper Miocene and lower Pliocene beds of the Chesapeake Group, Middle Atlantic Coastal Plain. *U.S. Geological Survey Bulletin*, 1482-D: 61.

——, 1987. Late Pliocene and early Pleistocene Mollusca from the James City and Chowan River Formations at Lee Creek Mine. In: *Geology and Paleontology of the Lee Creek Lake, North Carolina, IL*, 61: 113–283. Washington D.C.: Smithsonian Institution Press.

WARD, L. W. and GILINSKY, N. L., 1993. Molluscan Assemblages of the Chowan River Formation, Part A: Biostratigraphic Analysis of the Chowan River Formation (Upper Pliocene) and adjoining units, the Moore House Member of the Yorktown Formation (Upper Pliocene) and the James City Formation (Lower Pleistocene). *Virginia Museum of Natural History Memoir*, 3:1–33.

WARD, L. W. and HUDDLESTUN, P. F., 1988. Age and stratigraphic correlation of the Raysor Formation, late Pliocene, South Carolina. *Tulane Studies in Geology and Paleontology*, 21: 59–75.

WEEMS, R. E., 1998. Newly recognized en echelon fall lines in the Piedmont and Blue Ridge provinces of North Carolina and Virginia; with a discussion of their possible ages and origins. *U.S. Geological Survey Open-File Report 98-374*, 40 pp.

WEEMS, R. E., LEMON, E. M., J. R., MCCARTAN, L., BYBELL, L. M., SANDERS,. and A., E.,. 1982. Recognition and formalization of the Pliocene “Goose Creek phase” in the Charleston, South Carolina, area. *U.S. Geological Survey Bulletin*, 1529-H: 137–138.

WEEMS, R. E., SELF-TRAIL, J. and EDWARDS, L. E., 2019. Cross section of the North Carolina coastal plain from Enfield through Cape Hatteras. *U. S. Geological Survey Open-File Report 2019-1145*, 2 sheets.

WHITE, G. W., 1953. Early American geology. *The Scientific Monthly*, 76: 134–141.

WILLOUGHBY, R. H., NYSTROM, P. H., CAMPBELL, L. D., KATUNA, M. P., WEEMS, R. E. and SANDERS, A., 1999. *Cenozoic Stratigraphic Column of the Coastal Plain of South Carolina.* Columbia, South Carolina.

WINKER, C. D. and HOWARD, J. D., 1977. Correlation of tectonically deformed shorelines on the southern Atlantic coastal plain. *Geology*, 5 (2): 123–127.

ZIMMT, J. B., KIDWELL, S. M., LOCKWOOD, R. and THIRLWALL, M., 2022. Strontium isotope stratigraphy reveals 100 Ky-scale condensation, beveling, and internal shingling of transgressive shell beds in the Maryland Miocene. *Palaios*, 37 (10): 553–573.

ZUBAKOV, V. A. and BORZENKOVA, I. I., 1983. *Paleoclimate of the Late Cenozoic*, Saint Petersburg: Leningrad, Gidrometeoizdat, 215 p.