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Burning peat and reworking loess contribute to the formation and evolution of a large Carolina-bay basin

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ABSTRACT

Carolina bays are nearly ubiquitous along ~1300 km of the North American Atlantic Coastal Plain, but relatively few bays have been examined in detail, making their formation and evolution a topic of controversy. The Lake Mattamuskeet basin, eastern North Carolina, USA, is a conglomeration of multiple Carolina bays that form a >162 km^2 lake. The eastern shoreline of the lake is made up of a 2.9-km-wide plain of parabolic ridges that recorded rapid shoreface progradation. The lower shoreface deposit contains abundant charcoal beds and laminae dated 6465–6863 cal yr BP, corresponding with initiation of a lacustrine environment in the eastern part of the lake. A core from the western part of the lake sampled a 1541–1633 cal yr BP charcoal bed at the base of the lacustrine unit, indicating formation of this part of the basin postdates the eastern basin. Lake Mattamuskeet has no relationship to the Younger Dryas or a linked impact event because rim accretion significantly postdates 12,000 cal yr BP. The shoreline progradation, and association of charcoal beds with the oldest lake sediment in both main parts of the basin, suggest that fire and subsequent hydrodynamic processes were associated with initial formation of these Carolina bays.

Introduction

There are about 500,000 elliptical lakes, wetlands, and depressions with elevated rims located on the Atlantic Coastal Plain named Carolina bays (Prouty, 1952). Carolina bays are most abundant in North Carolina, South Carolina, and Georgia, generally trend toward the northwest, and range from 0.15 km to 11.30 km across their long axis (Prouty, 1952). The elevated rim around Carolina bays is typically widest and highest in the east.

There have been many proposed theories on the processes that formed the depressions and rims including artesian springs (Prouty, 1952; LeGrand, 1953), dissolution of underlying material (Siple, 1960; May and Warne, 1999), and earthquakes (LeGrand, 1953). The origin of Carolina bays being attributed to an impact event has been the most controversial theory (Johnson, 1942; Prouty, 1952; Price, 1968; Kaczorowski, 1977; Savage, 1982). Firestone et al. (2007a, b) resurrected the impact hypothesis for Carolina-bay formation and/or evolution presenting evidence that 15 Carolina bays, including Lake Mattamuskeet, which is the focus of this study, contain markers of the Younger Dryas impact event throughout their entire 1.5- to 5-m-thick sandy rims (Kennett et al., 2009a,b). These findings have not gone uncontested (Pinter and Ishman, 2008; Surovell et al., 2009).

Field-based studies in South Carolina, North Carolina, Virginia, and Maryland aimed at deriving the process of Carolina-bay formation and evolution agree that they develop over time (i.e., are not the product of a single event) and that wave action, in addition to strong directional winds and associated eolian processes, are the main driving forces (Thom, 1970; Gamble et al., 1977; Bliley and Pettry, 1979; Stolt and Rabenhorst, 1987a; Bliley and Burney, 1988; Carver and Brook, 1989; Markewich and Markewich, 1994; Grant et al., 1998; Ivester et al., 2007). Thom (1970) recognized the association of Carolina bays with sandy substrates and interpreted the features as being the result of depressions within dune fields that are subsequently filled with water and modified by waves into their elongated morphology with raised rims, which developed as beaches. The varied depositional processes (eolian and lacustrine) invoked for Carolina bay formation and evolution implies that there were associated variations in effective moisture (precipitation minus evapotranspiration).

In a comprehensive study of Flamingo Bay, South Carolina, using GPR surveys, cores, radiocarbon dates, and archeological stratigraphy, Brooks et al. (1996) and Grant et al. (1998) show that multiple stages of rim accretion occurred during the Holocene (post Younger Dryas) as a result of wave action, fluctuating lake levels, and subsequent parabolic-dune accretion. Grant et al. (1998) do not address the process of initial basin formation, but argue, as did Thom (1970), that a water-filled basin must have formed prior to rim accretion because the nearshore zone is thought to be the sediment source for the raised beaches and parabolic dunes.

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Stolt and Rabenhorst (1987a) estimate that there are between 1500 and 2500 bays on the northern Delmarva Peninsula, Virginia. Unlike the bay rims in South Carolina that are composed of medium- to coarse-grained sand (Thom, 1970; Brooks et al., 1996; Grant et al., 1998), these bay rims are finer grained and typically contain >30% silt (Bliley and Pettry, 1979; Stolt and Rabenhorst, 1987a,b). The high silt content of the rims is likely related to the extensive loess deposit (<1.5 m thick and 9000 km^2) on the eastern shore of the Peninsula (Foss et al., 1978; Simonson, 1982; Stolt and Rabenhorst, 1987b). The loess overlies a regional organic-rich paleosol (Foss et al., 1978) and the contact is interpreted by Surovell et al. (2009) as the Younger Dryas boundary. Based on trenches and auger cores, bay formation is thought to be similar to that proposed by Thom (1970; Stolt and Rabenhorst, 1987a).

Here, we present a conceptual model of the formation and evolution of Lake Mattamuskeet, North Carolina, which was classified by Prouty (1952) as a large Carolina bay, based on sedimentological and chronostratigraphic data. The ubiquity of Carolina bays and the fact that they are not forming under present-day conditions implies that the landscapes on which they formed in the past were very different, particularly in terms of the dominant processes of sedimentation. A better understanding of those sedimentary processes will help evaluate possible linkages between Carolina-bay evolution and climate change events, like the Younger Dryas.

Study area

Lake Mattamuskeet is one of four Carolina bays on The Albemarle/Pamlico Peninsula. The peninsula is on the lower coastal plain and seaward of the last interglacial (Marine Isotope Stage 5e) shoreline or Suffolk Scarp (Brill, 1996). The Suffolk Scarp was also the shoreline during the subsequent MIS 5a sea-level highstand (Wehmiller et al., 2004; Mallinson et al., 2008), which indicates that the bays formed after ~80 ka. The peninsula is of very low elevation (56% of total area <1.5 m) and extensively covered by wetlands (53%) and hydric soils (90%; Moorhead and Brinson, 1995). The peninsula is composed of peat, which has an average thickness of about 1.2 m and is above Pleistocene shallow-marine sediment that likely was deposited ~80 ka (Ingram, 1987; Riggs et al., 1992; Mallinson et al., 2008).

Lake Mattamuskeet is the largest lake on the peninsula (162 km^2; Fig. 1A), is shallow (mean depth 1.0 m) and has been significantly affected by humans since ca. 1850 when European settlers constructed the first canal connecting the lake to nearby Pamlico Sound (Waters et al., 2009; 2010). This connection decreased the size of the lake from over 400 km^2 to its present size (Forrest, 2000; Fig. 1). The most dramatic change to the lake was a failed attempt to drain the lakebed in 1915 for farming. The effort resulted in the southern 25% of the lake being drained up until 1932 when the project was abandoned and the lake was allowed to refill. Lake Mattamuskeet was likely a closed lake prior to human modification given the continuous and narrow ridge that forms the rim of the basin at a mean elevation of 0.90 m.

The most prominent morphologic feature of the lake is a series of parabolic ridges located along the eastern shoreline and inside the outer rim of the basin (Fig. 1). The topography across this landform is asymmetric and the ridges are capped by cuspate dunes (Figs. 1 and 2). Elevations gradually increase on the west side from 0.15 m to 2.0 m over a linear distance of 2.85 km, and on the east side sharply decrease from 2.0 m to 0.50 m over a linear distance of 0.35 km. The parabolic ridges and the outer rim of the basin are among the highest features of the study area, which, based on a digital elevation model with a 15.2-m grid size (Fig. 1), has a median elevation of only 0.48 m.

The deep peat deposits around Lake Mattamuskeet are known to burn following lightning strikes during dry periods (Ingram, 1987). Regional oral history makes reference to Lake Mattamuskeet originating

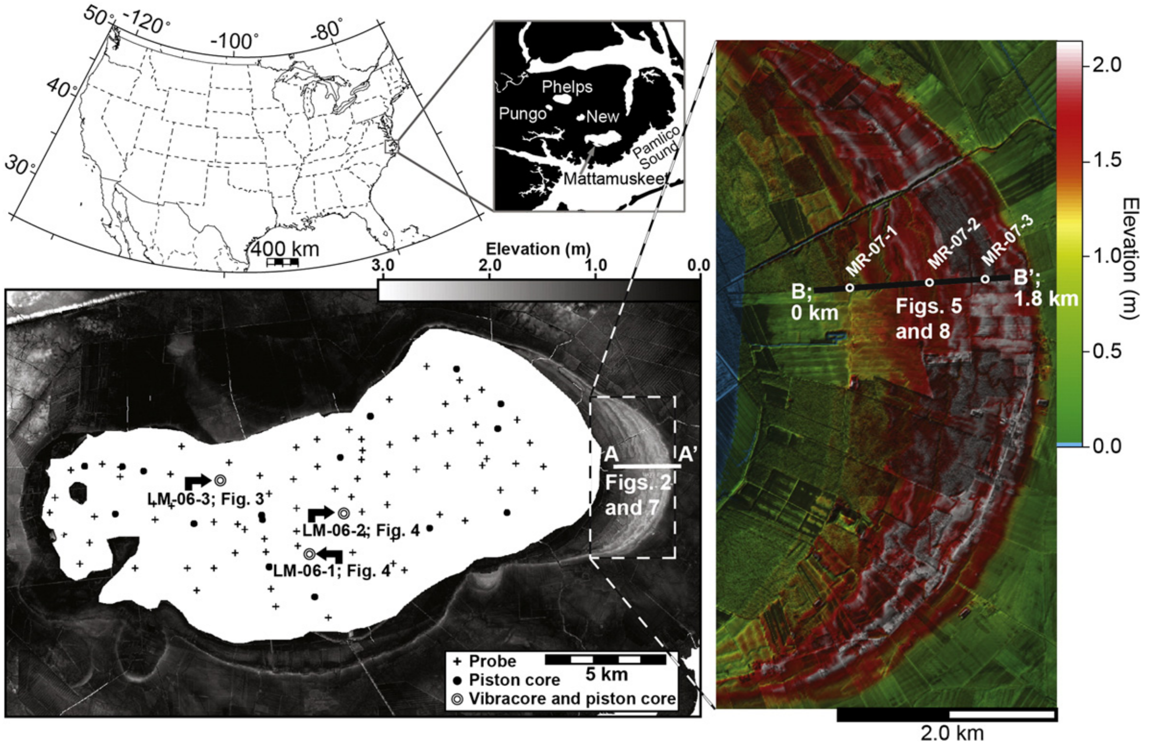


Fig. 1. The Lake Mattamuskeet study area is part of the Albemarle/Pamlico Peninsula. Elevation data displayed relative to NAVD88 and the expanded map of the eastern parabolic ridge is from draping elevation data over a black-and-white aerial photograph taken in 2000 (data are from the North Carolina Floodplain Mapping Program; www.ncfloodmaps.com). The sample locations in the lake are after Waters et al. (2009).

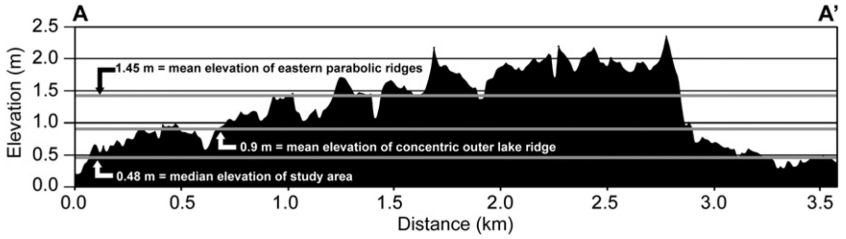


Fig. 2. The topographic profile across the eastern concentric ridges shows a gradual increase in elevation from the west to the highest elevation ridge and a sharp decrease in elevation continuing toward the east. Elevation is relative to NAVD88. See Fig. 1 for transect location and data source.

from a fire that burned for thirteen months (Barefoot, 1995). Whitehead (1972) hypothesized the origin of Lake Drummond as being from a deep peat burn, which is located 120 km north of the study area in the Dismal Swamp, Virginia.

Methods

To determine the timing and processes of lake basin and rim formation, vibracores and ground-penetrating radar data were collected along a transect oriented perpendicular to the trend of the eastern parabolic ridges, and vibracores were collected from the lake basin avoiding areas that were drained and farmed (Fig. 1). The vibracores are 7.6 cm in diameter, range between 270 cm and 415 cm in length, and were used to characterize depositional environments, ground truth radar facies to lithology, and provide material for radiocarbon dating. Vibracoring-site selection in the lake basin was based on bathymetric and soft-sediment thickness maps created from 96 measurements using a probe rod and 12 short (<1.0 m) piston cores (Waters et al., 2009; Fig. 1). Core LM-06-3, which was obtained from the deepest part of the lake where the sedimentary record is thickest, was analyzed in detail.

In the lab, we split the cores and photographed, described, and sampled them for lithological and radiocarbon analyses. A Cilas 1180 was used to measure particle sizes from 0.04 µm to 2500 µm in 100 size classes by laser diffraction. Percent organic carbon was measured by loss on ignition (Heiri et al., 2001). The National Ocean Sciences Accelerator Mass Spectrometry Facility at the Woods Hole Oceanographic Institution and Beta Analytic provided the radiocarbon ages on an individual piece of wood, sub-samples of bulk organic-rich sediment (silt size), sub-samples of medium to fine grained charcoal sand and silt, and articulated bivalves (Table 1). Ages (11 dates) were calibrated to calendar years using the Calib 5.0 program Northern Hemisphere terrestrial curve (Stuiver and Reimer, 1993).

Ground-penetrating radar (GPR) transects (~4.0 km) were collected using the pulse EKKO Pro system from Sensors and Software, Inc. configured with both 100 and 200 MHz antennae (Fig. 1). Traces were collected every 25 cm and 10 cm and antennae were held 1.0 m and 0.5 m apart for the 100 MHz and 200 MHz antennae, respectively. A velocity of 0.08 m/ns was used to convert time to depth for all profiles, which is between the values reported for saturated and unsaturated silt in Neal (2004). This velocity was verified from a common mid-point survey conducted at the middle of the transect and cores that show changes in lithology at the same depths as radar-facies transitions. Traces along the GPR transect were not adjusted vertically for variations in topography because the data were collected along the side of a relatively flat road. Data processing included applying a dewow filter, a tapered bandpass filter (20–40–300–600 MHz), and an automatic gain control (AGC), using EKKO View Delux software.

Results and interpretation

Lake-basin stratigraphy

Core LM-06-3, taken from the western part of the lake basin, sampled three general lithofacies (Fig. 3). The clay-sand sediment fraction of the basal 300 cm of the core shows an overall coarsening-upward trend to ~−120 cm and the percent of very fine sand, silt, and clay decreases abruptly at −190 cm. Shells, shell fragments, and/or articulated bivalves are present in overall decreasing abundance from the base of the core to −170 cm depth and a distinct shell-hash bed exists from −360 to −300 cm. The most abundant shell fragments at −324, −380 and −400 cm were identified as *Mulinia lateralis* (Say), a bivalve that lives in estuarine and shallow-marine environments. Articulated *Dosinia discus* (Disk Dosinia, Reeve) and *Divalinga quadrisulcata* (Cross-hatched Lucine, d'Orbigny) at −348 and −365 cm, respectively, were dated as >40,000 ^{14}C yr BP (radiocarbon dead). The upper part of the unit grades into a light gray (2.5 YR 7/1) sand with heavy mineral laminae from −150 to −120 cm. Due to the presence of marine shell fragments and articulated bivalves, heavy-mineral laminae, and pre-Holocene dates, the lower sandy unit from −120 to −400 cm is interpreted as a Pleistocene coastal–marine depositional environment.

Core LM-06-3 sampled a light brownish gray (10 YR 6/2) to dark yellowish brown (10 YR 4/6) medium grained (1.8–2.0 phi) massive

Table 1
AMS radiocarbon dates from the eastern parabolic ridges and Lake Mattamuskeet.

Lab number	Core name	Sample depth below surface	Material type	Conventional radiocarbon age (±1 STD)	cal yr BP (±2 sigma; Stuiver and Reimer, 1993)
Beta-251527	MR-07-3	0.57–0.58 m	Organic sediment	2780±40	2780–2965
Beta-251528	MR-07-3	1.24–1.25 m	Charcoal	5910±50	6635–6860
OS-66851	MR-07-3	1.69–1.71 m	Charcoal	5760±30	6485–6650
Beta-251529	MR-07-3	2.31–2.32 m	Organic sediment	7750±50	8420–8603
OS-68133	MR-07-1	1.07–1.08 m	Charcoal	5760±40	6465–6660
Beta-283049	MR-07-1	1.54–1.55 m	Wood	1270±50	14914–15136
Beta-283050	MR-07-1	2.74–2.75 m	Wood	38,060±260	N/A
OS-57953	LM-06-3	0.80–0.81 m	Charcoal	470±25	499–535
OS-57954	LM-06-3	1.20–1.21 m	Charcoal	1700±24	1541–1633
Beta-218380	LM-06-3	3.65–3.66 m	Shell (*Dosinia discus*)	>40,000	N/A
Beta-218381	LM-06-3	3.47–3.51 m	Shell (*Divalinga quadrisulcata*)	>40,000	N/A

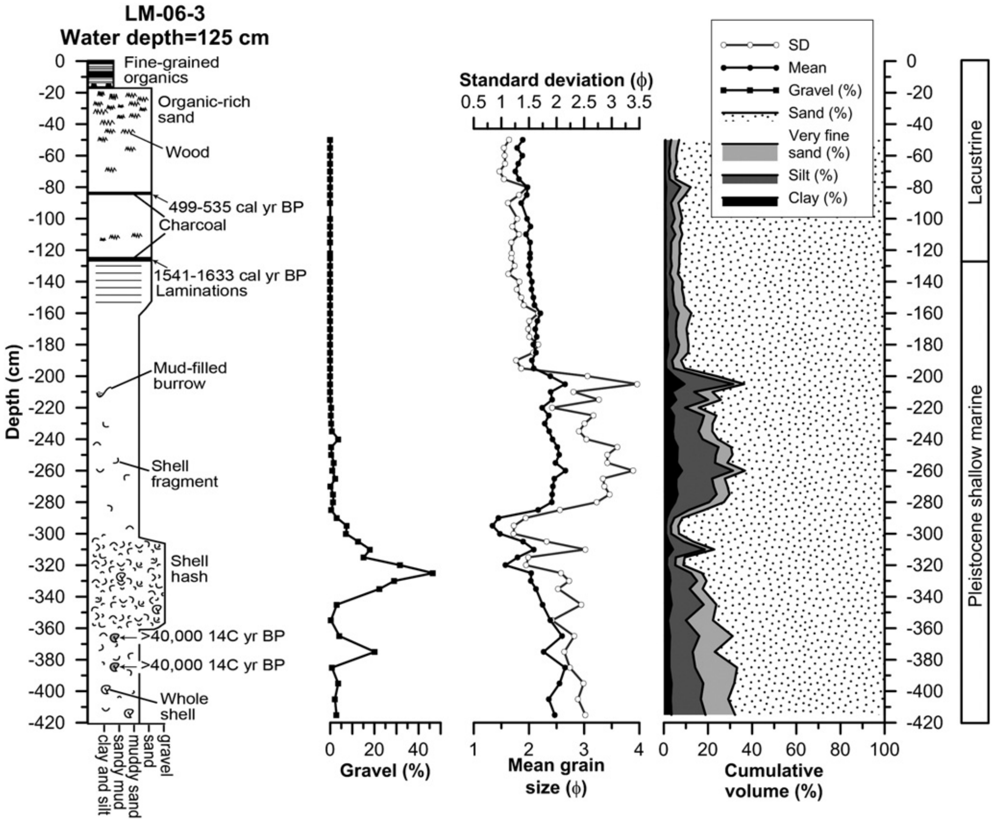


Fig. 3. Core LM-06-3 is from the center and deepest part of Lake Mattamuskeet. Mean grain size of the 2000–0.04 μm fraction is plotted with phi standard deviation (sorting). Cumulative% sand and very fine sand is defined as 125–2000 μm and 62–125 μm, respectively. See Fig. 1 for location and Table 1 for additional information on dates.

sand unit from −120 to −18 cm in sharp contact with the underlying coastal–marine unit. Organic content (mostly wood fragments) of the sand unit decreases with increasing depth down to −50 cm. Organic-rich charcoal beds (1-cm thick) at −80 cm and −120 cm were dated as 499–535 and 1541–1633 cal yr BP, respectively (dates on bulk sediment), with the basal bed marking the Holocene–Pleistocene contact. Based on the presence of wood, massive bedding, and algal-pigment data from the unit, presented in Waters et al. (2009), the sand unit was likely deposited in a water-filled lake basin. An overlying dark brown (7.5 YR 3/2) organic mud, interpreted as gyttja, is in sharp contact with the lacustrine sand unit, spans the upper 18 cm of the core, and is currently being deposited at the core location (Waters et al., 2009).

Cores LM-06-1 and LM-06-2, taken from the central part of the lake, sampled a basal gray (10 YR 5/1) clay to sandy clay unit that extends from the base of the cores at −415 cm and −327 cm to −81 cm and −26 cm, respectively (the entire extent of the cores are not displayed in Fig. 4). Marine shells and shell fragments are abundant below −349 cm in core LM-06-1 and −270 cm in core LM-06-2. This unit is very similar in appearance to the basal unit sampled in core LM-06-3 and is interpreted as Pleistocene coastal–marine sediment (Figs. 3 and 4). The coastal–marine deposit is in sharp contact with a brown (7.5 YR 4/3) organic rich, woody, sandy silt unit at −81 cm in core LM-06-1. This unit is interpreted as a paleosol and grades into a massive strong brown (7.5 YR 5/6) organic-rich sandy-silt unit, interpreted as lacustrine. The lacustrine sandy silt unit is present in both cores LM-06-1 and LM-06-2, where it extends to the sediment–water interface (Fig. 4); however, in core LM-06-2 the unit is in sharp contact with the coastal–marine deposit. Clay rip-up clasts at −26 cm in core LM-06-2, directly above the contact between coastal–marine and lacustrine deposits, indicate erosion likely removed the paleosol that was preserved in core LM-06-1 (Fig. 4).

Stratigraphy of the eastern parabolic ridges

The three cores from the eastern parabolic ridges each sampled a basal gray (10 YR 5/1) clay to sandy clay unit which is likely Pleistocene coastal–marine sediments, equivalent to what was sampled below the lake basin in cores LM-06-1, LM-06-2, and LM-06-3 (Figs. 3, 4, 5 and 6). The top of this unit increases in elevation (relative to NAVD88) toward the east, away from the lake basin (Fig. 7). Core MR-07-1 contains a more complete depositional record than the other two cores from the eastern parabolic ridges because it was obtained closest to Lake Mattamuskeet where the top of the Pleistocene coastal–marine deposit is deepest and accommodation space is greatest. This core sampled a mottled dark brown (10 YR 3/3) very-well sorted silty organic-rich unit with root and wood material interpreted as a paleosol in sharp contact with the coastal–marine deposit. A single piece of wood (not a root), sampled from the paleosol in core MR-07-1, was radiocarbon dated as 38,060 ^{14}C yr BP (which is likely radiocarbon dead). This paleosol correlates with the paleosol sampled above the coastal–marine deposit in core LM-06-1 from the middle of the lake. The basal paleosol sampled in core MR-07-1 either pinches out against the top of the coastal–marine deposit or was eroded toward the east.

Overlying the basal paleosol in core MR-07-1, a 40 cm massive sandy–silt unit was sampled (Fig. 5). Core MR-07-2 also sampled that unit but in sharp contact with the underlying Pleistocene coastal–marine deposit (Fig. 5). The massive sandy–silt unit either pinches out against the top of the coastal marine deposit or was eroded toward the east because it was not sampled in core MR-07-3 (Figs. 5 and 7). The massive sandy–silt unit is interpreted to be loess. In addition to glaciers, potential sources of loess in North America include nearby outcrops with silt-sized particles (Mason, 2001) and sand dunes (Whalley et al., 1982; Smalley, 1995; Mason et al., 2003); however, under arid climate conditions, coastal-plain deposits, including

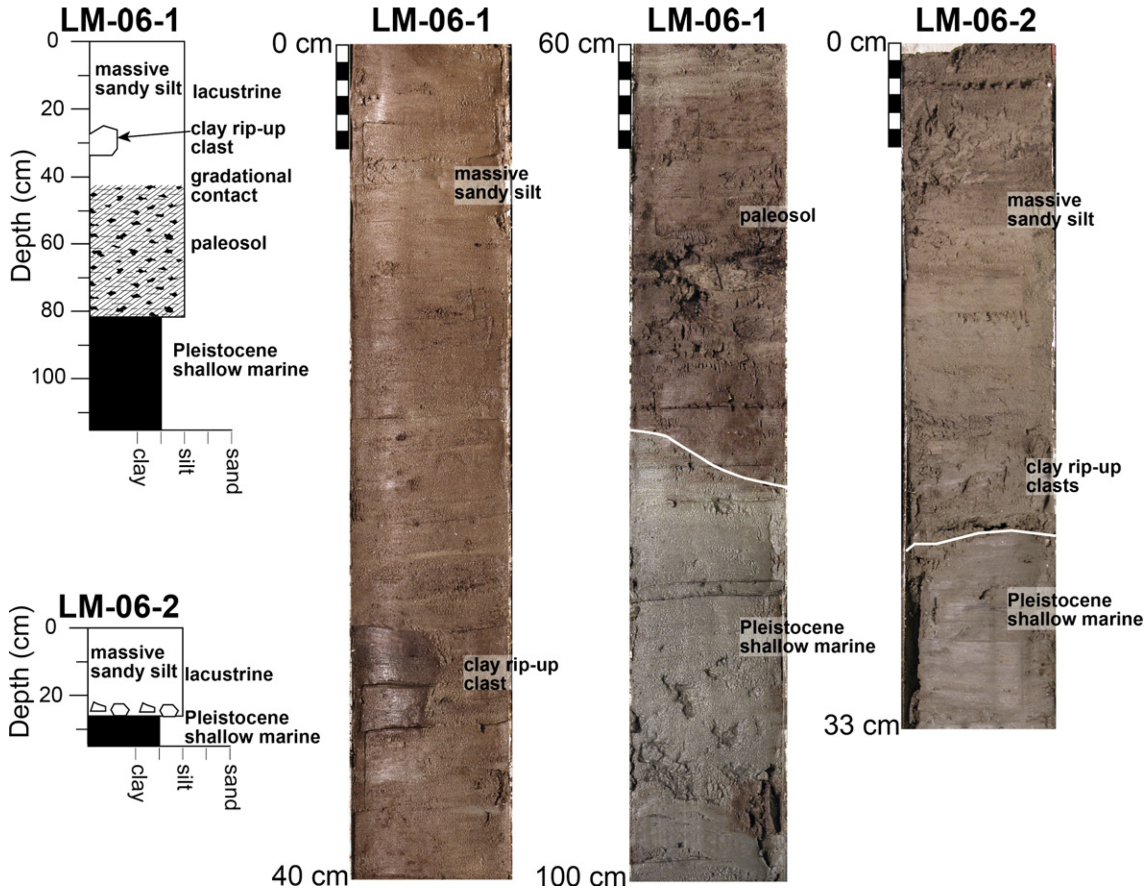


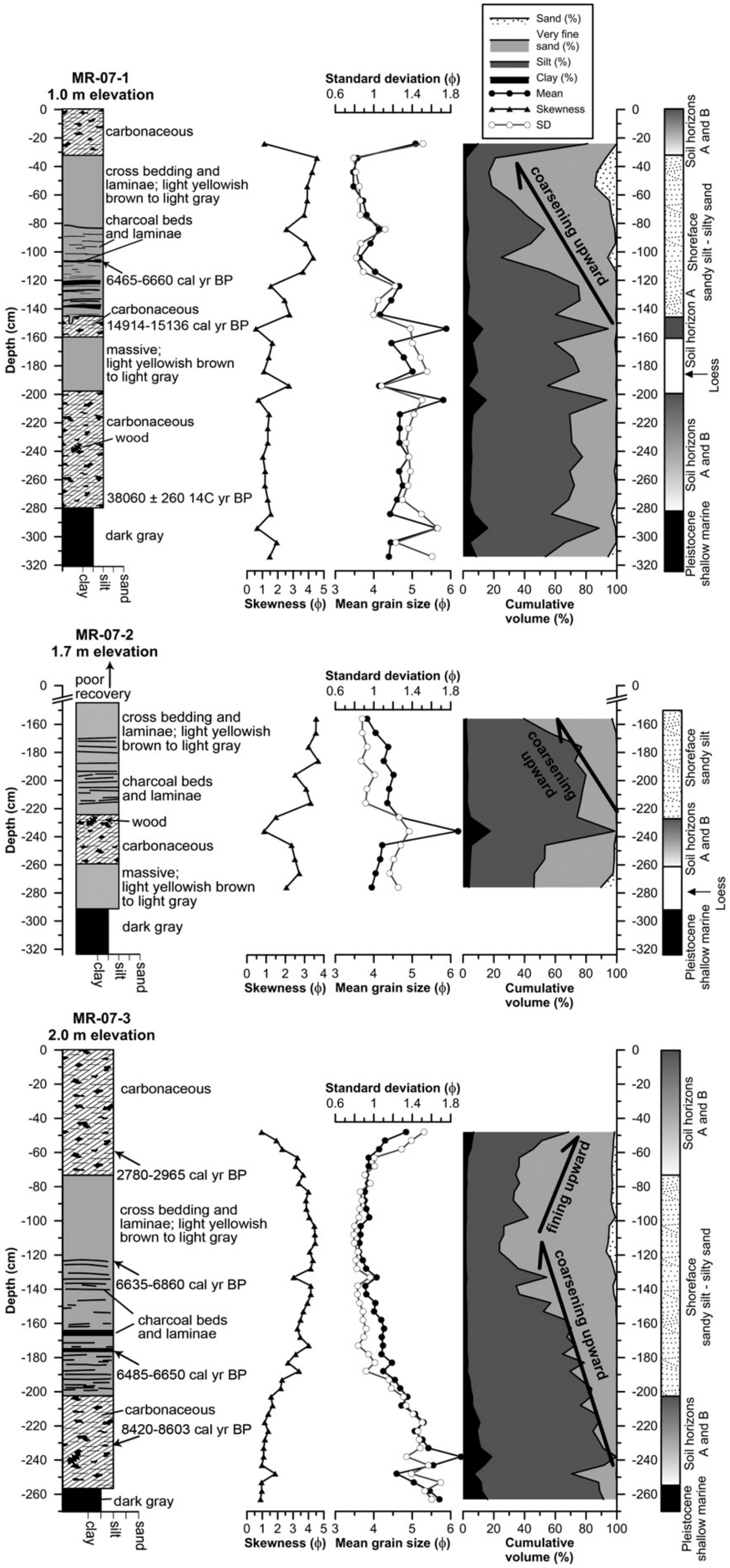
Fig. 4. Cores LM-06-1 and LM-06-2 are collected from the central part of Lake Mattamuskeet where the lake sediment is composed of organic-rich silt, as opposed to gyttja and sand as sampled from the western part of the lake in core LM-06-3. See Fig. 1 for location.

estuarine silt are potential loess source areas. The coastal–marine deposit is composed of 40–70% silt and is the likely sediment source for the loess (Fig. 5). The stratigraphy, sedimentology, and setting of Carolina bays on the Delmarva Peninsula are very similar to Lake Mattamuskeet (Bliley and Pettry, 1979; Stolt and Rabenhorst, 1987a, b) making the coastal loess deposit not unique to the Albemarle/Pamlico Peninsula.

Above the loess, cores MR-07-1 and MR-07-2 sampled a mottled dark brown (10 YR 3/3) very-well sorted silty organic-rich unit with root and wood material interpreted as a paleosol. The paleosol thickens toward the east and is dated as 14,914–15,136 cal yr BP from bulk fine-grained (silt size) organic material sampled in core MR-07-1 (Figs. 5 and 7; Table 1). Core MR-07-3 sampled the same paleosol, but at this eastern location the unit is in sharp contact with the underlying coastal–marine deposit. Bulk fine-grained (silt size) organic material sampled from the middle of the paleosol in core MR-07-3 was radiocarbon dated as 8420–8603 cal yr BP (Fig. 5, Table 1). Both paleosols are very similar in appearance to modern soil in the area, despite their lower total organic carbon (~6%). The two paleosols and middle loess deposit correlate with a laterally continuous GPR facies characterized by a planar, horizontal, and parallel reflection configuration (Fig. 8). The resolution of the GPR was not high enough to differentiate between those three units.

In sharp contact with the upper paleosol, cores MR-07-1, MR-07-2, and MR-07-3 sampled a ~125-cm-thick light yellowish brown (10 YR 6/4) to light gray (10 YR 7/1) sandy–silt unit at core depths of −143, −222, and −201 cm, respectively (Figs. 5 and 6). The sandy–silt unit is well sorted with a mean grain size typically between 4.0 and 4.5 phi (~60 and 40 μm), contains <2% grains that are larger than very fine sand, and coarsens upward (Fig. 5). Phi standard deviation and phi skewness decrease and increase upward, respectively. Very-thin planar- to lenticular-bedded charcoal is present only in the lower 70–80 cm of the sandy–silt unit but the entire unit contains climbing-ripple laminae, parallel laminae and cross laminae, indicative of a high sediment supply. Thin bed-laminae of sandy silt with higher percentages of organic carbon than the surrounding sediment (9–13% versus 0.2–4.5%) are also present in the lower 70–80 cm of the unit. Core MR-07-3 shows a lithologic transition to finer mean grain sizes and lower values of phi skewness with decreasing depth from ~ −100 cm (Fig. 5).

The sandy–silt unit correlates with a laterally continuous GPR facies characterized by oblique low angle (0.3°–0.4°) sigmoidal reflection configurations that dip toward the west and downlap onto a reflector that correlates with the top of the upper paleosol (Fig. 8). These reflection configurations are interpreted to be clinoforms that represent a westward-accreting shoreline. Foresets dip an order of magnitude less than other Carolina-bay (Grant et al., 1998) or shallow-lake (Fisher et al., 2007) paleoshorelines, which is likely due to the Lake Mattamuskeet shoreline and substrate being composed of silt as opposed to medium-fine grained sand (Brooks et al., 1996; Fisher et al., 2007). Erosional discontinuities characterized by erosional truncation below and downlap above are imaged throughout the eastern parabolic ridge set and correlate to individual beach ridges (Fig. 8). Discontinuity surfaces were likely formed by fluctuations in lake level or increases in the wave and/or current regime of the lake. Samples of sand- and silt-sized charcoal grains from three places in this unit have overlapping ages, indicating rapid deposition between 6465 and 6863 cal yr BP (Table 1). Based on textural similarity, the westward-accreting shoreline sediment


Sand (%)
Very fine sand (%)
Silt (%)
Clay (%)
Mean
Skewness
SD
MR-07-1
1.0 m elevation
carbonaceous
cross bedding and laminae; light yellowish brown to light gray
charcoal beds and laminae
6465-6660 cal yr BP
carbonaceous
14914-15136 cal yr BP
massive; light yellowish brown to light gray
carbonaceous
wood
38060 ± 260 14C yr BP
dark gray
Depth (cm)
clay
silt
sand
Skewness (ϕ)
Mean grain size (ϕ)
Standard deviation (ϕ)
Cumulative volume (%)
coarsening upward
Soil horizons A and B
Shoreface sandy silt - silty sand
Soil horizon A
Loess
Pleistocene shallow marine
MR-07-2
1.7 m elevation
poor recovery
cross bedding and laminae; light yellowish brown to light gray
charcoal beds and laminae
wood
carbonaceous
massive; light yellowish brown to light gray
dark gray
coarsening upward
Shoreface sandy silt
Soil horizons A and B
Loess
Pleistocene shallow marine
MR-07-3
2.0 m elevation
carbonaceous
2780-2965 cal yr BP
cross bedding and laminae; light yellowish brown to light gray
6635-6860 cal yr BP
charcoal beds and laminae
6485-6650 cal yr BP
carbonaceous
8420-8603 cal yr BP
dark gray
fining upward
coarsening upward
Soil horizons A and B
Shoreface sandy silt - silty sand
Soil horizons A and B
Pleistocene shallow marine

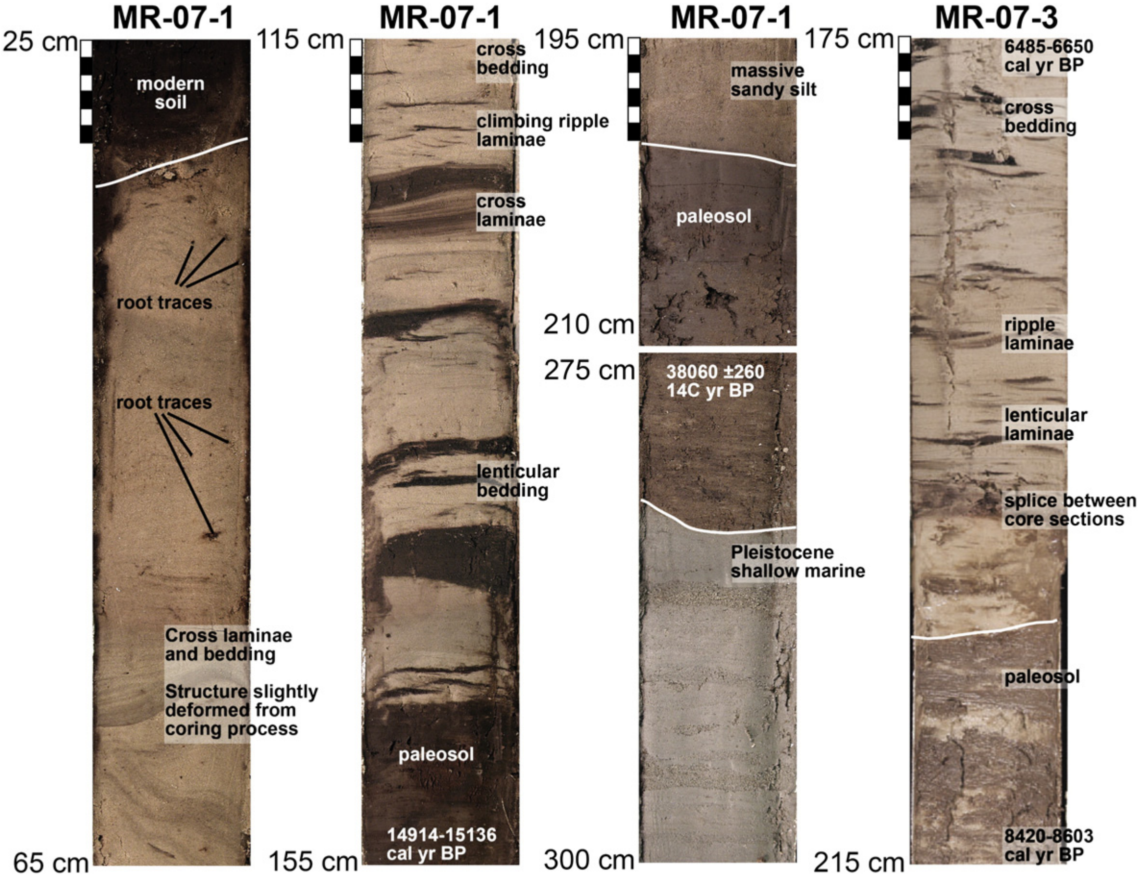


Fig. 6. Photographs of cores showing the different sedimentary units of the eastern parabolic ridges including the modern soil, shoreface sandy silt, paleosols, loess (massive sandy silt), and Pleistocene shallow marine. Depths are relative to the top of the core and correspond with Fig. 5. See Table 1 for additional information on dates.

was likely sourced from the underlying paleosols and loess and the lake-bottom sediment sampled in cores LM-06-1 and LM-06-2.

The surface of the parabolic ridge is mostly farmed and the modern soil is a 30–73 cm-thick layer of dark brown (10 YR 3/3), organic-rich (~12%) sandy silt to silty sand (Figs. 5 and 6). Core MR-07-3 shows that the modern soil is fining upward with decreasing phi skewness. The GPR facies of this upper unit is characterized by a moderately continuous to discontinuous subparallel reflection configuration. At each core location the modern soil is in sharp contact with the underlying deposit and the contact is a high-amplitude reflector that erosionally truncates the underlying shoreface clinoforms (Fig. 8). The fining upward sequence, erosional base, and cuspate dune surface morphology indicates that the soil parent material was transported by eolian processes and was likely sourced from the underlying laterally accreting shoreface deposit. Bulk fine-grained (silt size) organic sediment (no roots or macroscopic wood) is sampled from the base of the modern soil in core MR-07-3 and is 2778–2966 cal yr BP, which likely postdates eolian-dune accretion and estimates the time of initial pedogenesis.

Discussion

Late Pleistocene to early Holocene loess and soil formation

The depth to the Pleistocene coastal–marine deposit increases from the eastern edge of the parabolic ridges to the center of the lake and where this surface is low, an overlying extensive paleosol, which is >38,000 ^{14}C yr BP, has been preserved. The grain size of the paleosol is very similar to the overlying loess deposit and the parent material of the paleosol was likely loess. Eolian processes reworking the Pleistocene shallow-marine sedimentary unit, which in places is 40–70% silt, is a likely source for the loess and the sharp-based nature of the paleosol. Either this reworking formed the initial depression in the top of the coastal-marine deposit in the vicinity of Lake Mattamuskeet, or the depression pre-dates deposition of the loess and pedogenesis. The adjacent Albemarle and Tar-Pamlico sounds, which were not completely inundated by the sea until ~7 ka (Culver et al., 2007), were additional likely source areas for loess. Early Holocene coastal loess is not unique to the Albemarle/Pamlico Peninsula. Similarly, a loess deposit exists on the eastern shore of the Delmarva Peninsula (Foss et al., 1978; Simonson, 1982; Stolt and Rabenhorst, 1987b). The loess generally thins away from Chesapeake Bay, which is interpreted to be its source, and overlies an 11,603–12,920 cal yr BP paleosol (Foss et al., 1978).

During the late Pleistocene to early Holocene, the Albemarle/Pamlico Peninsula was likely composed of vegetated loess preserved as a paleosol overlying a massive sandy silt unit. The paleosol–loess–paleosol sequence likely reflects changing late Pleistocene to early Holocene climate. The upper well-developed soil had formed at the top of the loess by ~15,000 to 8500 cal yr BP and the area was likely highly vegetated. Major peat accumulation also initiated on the

Fig. 5. The locations of cores MR-07-1, MR-07-2 and MR-07-3 are oriented along a west–east transect across the eastern parabolic ridge. Mean grain size of the 2000–0.04 μm fraction is plotted with phi standard deviation (sorting) and phi skewness. Cumulative% sand and very fine sand is defined as 125–2000 μm and 62–125 μm, respectively. Core elevation (relative to NAVD88) was extracted from the DEM in Fig. 1 and is listed at the top of each log. See Fig. 1 for location and Table 1 for additional information on dates.

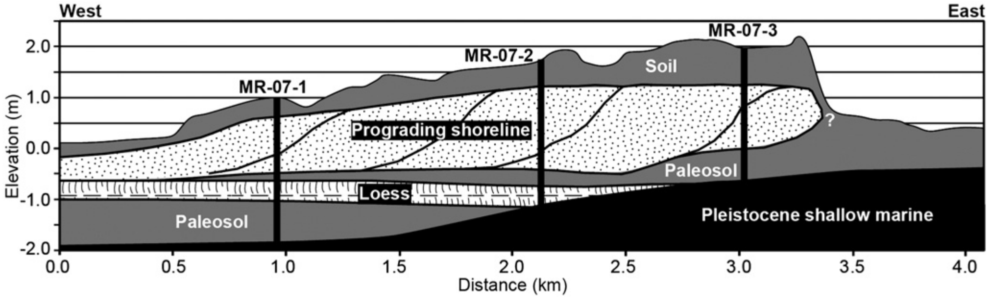


Fig. 7. Cross section showing the facies architecture of the eastern parabolic ridges based on the GPR data and cores. Location is the same as A–A′ in Figs. 1 and 2. Elevation is relative to NAVD88, based on the DEM of Fig. 1, and smoothed to remove human modifications to the landscape (e.g., drainage ditches).

Albemarle–Pamlico Peninsula 10,196–8630 cal yr BP (Cohen, 1979; Ingram, 1987; Fig. 9A). The age of the paleosol corresponds with wet conditions in southeast North America as suggested by palynological data 9000–6100 cal yr BP (Whitehead, 1972; 1981; Goman and Leigh, 2004) and overall dry conditions in the Great Plains ~9400–6500 yr (OSL dates; Miao et al., 2007) and northern Gulf of Mexico coast ~10,500–8500 yr (OSL dates; Otvos, 2004). A shift of the Bermuda High to the north and east of its present position is a likely explanation for these spatial differences in effective moisture (Forman et al., 1995).

Parabolic ridge accretion

The morphology of the eastern parabolic ridges is similar to concentric paleoshorelines. The shoreface and overlying eolian dune units are the sediment that comprises the topographic expression of the eastern landform (Fig. 7). The outer concentric rim, which marks the perimeter of Lake Mattamuskeet, is at the same mean elevation (~0.9 m) as the contact between the shoreface and eolian dune depositional environments, indicating that the lake basin filled with water prior to accretion of the eastern parabolic ridges (Figs. 2 and 7). The ridges decrease in elevation and the thickness of the upper eolian and soil unit thins toward the lake basin signifying lake levels were falling and/or sediment supply was decreasing during accretion. In addition, continuing sand transport by wind toward continually aggrading older dune ridges may have been a contributing factor in raising dune ridge elevations in the east.

Brooks et al. (1996) suggest that Carolina-bay ridges may form by a combination of processes and are composed of an internal shoreface unit that is capped by eolian-derived sediment. Ashton et al. (2009) presents a process-based numerical model of planform shoreline evolution (no vegetation at the shoreline) with resulting water bodies having similar morphologies as Carolina bays. They argue that the process of fetch-limiting self-organization is a probable explanation for the existence of chains of round lakes, like Carolina bays, in clastic settings (Ashton et al., 2009). The results presented here support both the Brooks et al. (1996) conceptual model and the Ashton et al. (2009) numerical model. The GPR facies clearly indicate lateral

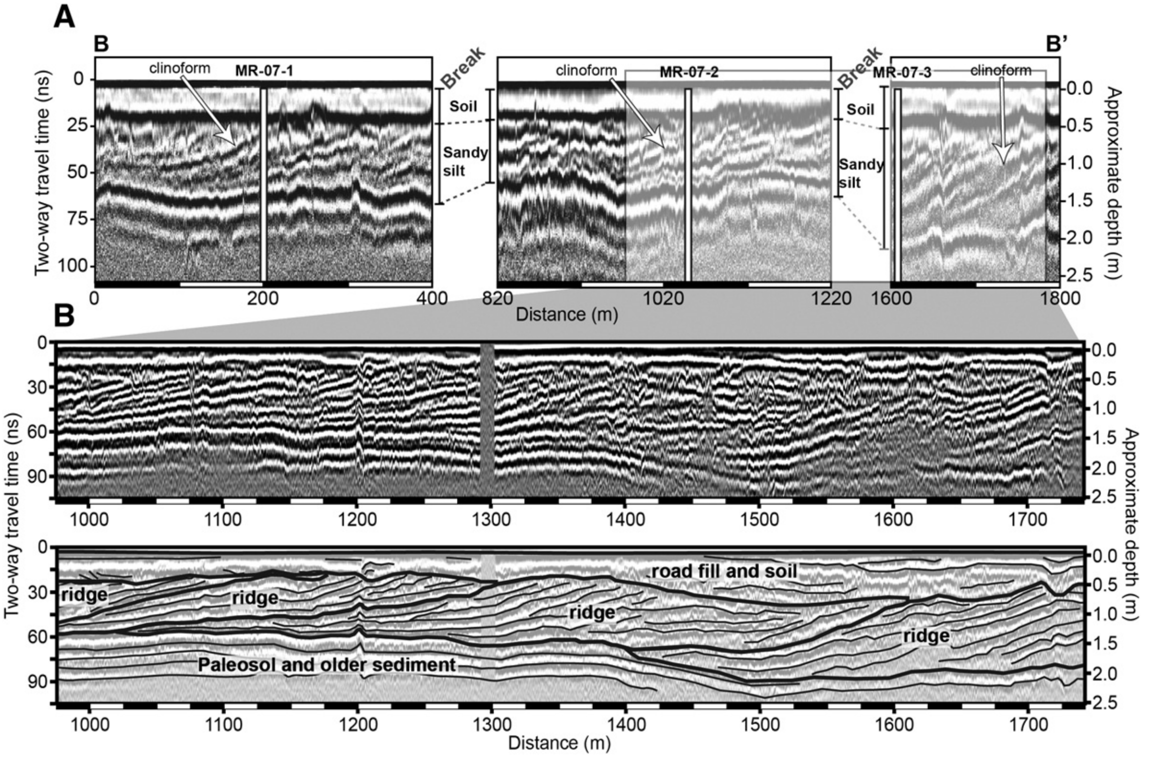


Fig. 8. Ground-penetrating radar (GPR) profile, collected using 100 MHz antennas, showing the shoreface sandy silt is imaged as westward-dipping reflectors downlapping onto a high-amplitude continuous reflector, which correlates with the top of the paleosol (A). GPR profile collected from the same location using 200 MHz antennas details the radar facies including the westward-dipping reflectors and erosional discontinuities marking each ridge (B).

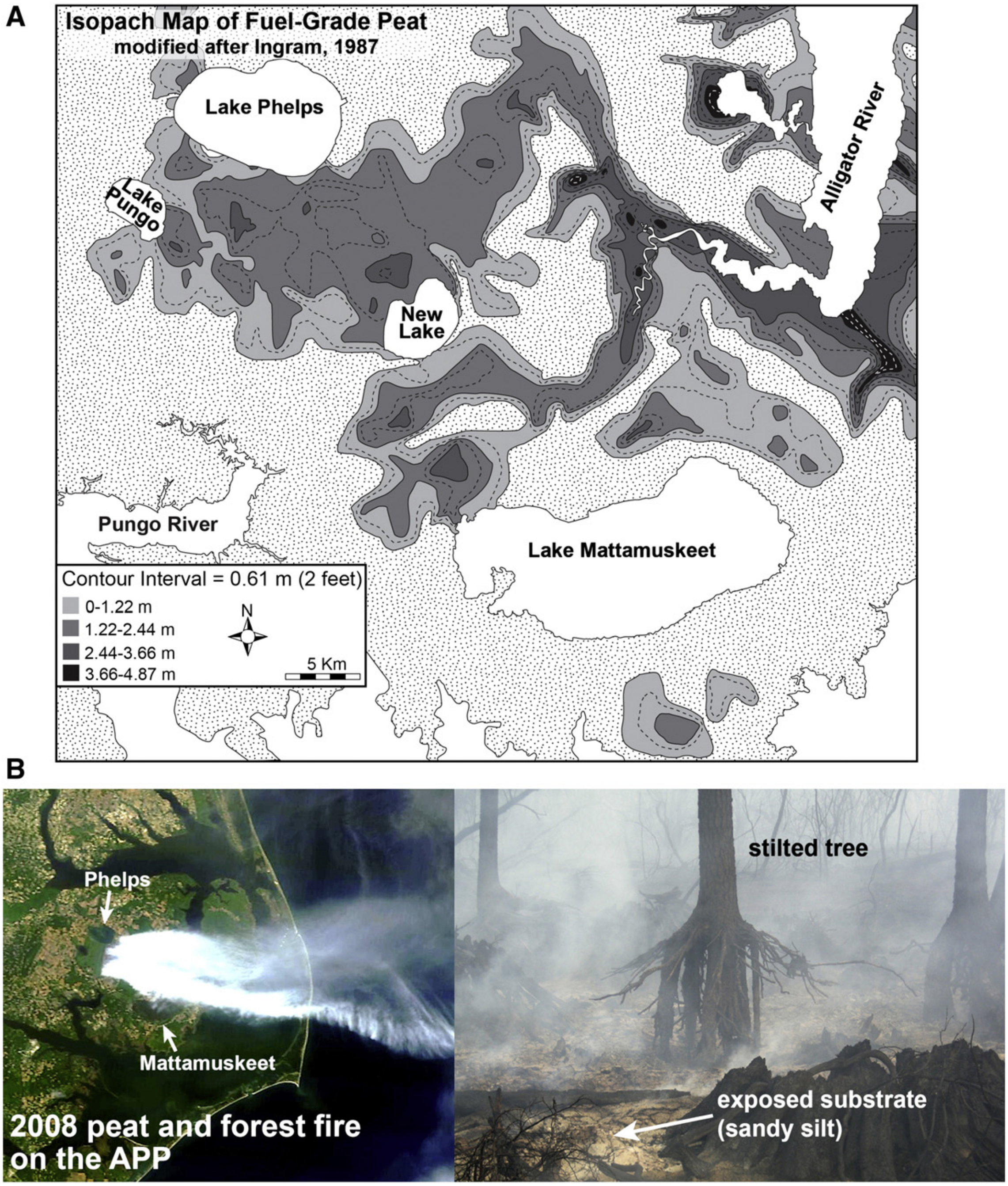


Fig. 9. The wide distribution of thick fuel-grade peat deposits on the Albemarle/Pamlico Peninsula (A) commonly burn after lightning strikes. On June 1, 2008 a lightning strike ignited and burned a total of 164.7 km^2 until it was extinguished on January 5, 2009 (B). Stilted trees, a result of burning peat over 1.5 m thick are now present across the landscape (photo courtesy of the U.S. Fish and Wildlife Service). The tree's roots were tapping the underlying sandy silt, which is now exposed. This event serves as a modern analog for the efficacy of burning soil at decreasing landscape elevation in the study area.

accretion toward the west, which is interpreted as shoreface progradation and the sediment was likely sourced from waves and currents reworking the bottom and margins of the water-filled basin.

Middle Holocene lake formation

Cores LM-06-3 from the western part of the lake and cores LM-06-2 and LM-06-1 from the central part of the lake sampled very different lake sediments (sand in the west and silt in the east). The charcoal bed at the contact between lacustrine (above) and Pleistocene shallow-marine units in core LM-06-3 (−120 cm depth; Fig. 3) is 1541–1633 cal yr BP and is the best estimate for initial sediment deposition in the western part of the lake. The ages of three charcoal layers in the lower part of the eastern shoreface unit, from different areas and depths, overlap (Fig. 5), indicating that initial accretion of the lake shoreline was rapid and began around 6500 cal yr BP. It is likely that the eastern part of the ridge plain formed shortly after inundation. Lake Mattamuskeet is the product of multiple Carolina-bay depressions that merged together, as evidenced by: 1) the large difference in age between the oldest lake sediment in the west and the oldest shoreline deposit in the east, 2) the difference in lithology of the lake sediment in the east and the lake sediment in the west, and 3) the morphology of the lake and outer rim that outlines small parabolic ridge plains (paleoshorelines) with wide high-elevation portions located in the south.

Fire may have played an important role in basin formation because charcoal beds are associated with the oldest lake sediment. Charcoal layers exist at the base of the western lake sediment in core LM-06-3 and multiple charcoal layers exist at the base of the easternmost shoreface deposit. Prior to lake formation, vegetation density of the Albemarle/Pamlico Peninsula was likely similar to today, where changing effective moisture significantly affects the landscape. A 30-year drought centered at 505 cal yr BP (Stahle et al., 1988) correlates with a charcoal layer at 80 cm in core LM-06-3 (Fig. 3; Waters et al., 2009) supporting a linkage between fire and dry periods in the study area. These observations lend some validity to the anecdotes of a peat burn occurring around the time of lake formation.

Historically, under dry conditions and low water-table elevations, the highly vegetated peat-producing area burns frequently and this accounts for most of the peninsula that is above mean sea level. As a result, the elevations at the burn sites decrease and underlying sediment is exposed. A recent fire on the Peninsula in 2008 lasted 7 months and burned 164.7 km^2 (Fig. 9B). When the fire was extinguished it left behind stilted trees that show up to 1.5 m of localized elevation loss as a result of burning peat, and exposed the underlying sandy silt unit. While the distribution of peat across the peninsula 6500 cal yr BP was likely less than it was 1541–1633 cal yr BP, when the charcoal layer was deposited in the western part of Lake Mattamuskeet, or than it is today, peat fires still may have contributed to formation of both the western and eastern parts of the lake basin. Inundation of the multiple Carolina bays that form Lake Mattamuskeet is likely related to rising groundwater levels associated with sea-level rise (Horton et al., 2009) and the multiple depressions merged when lake levels increased in response to climate transitioning to more humid present-day conditions (Gaiser et al., 2001).

Conclusions

A diverse assemblage of conceptual and numerical models exists that explains the formation and evolution of Carolina bays, which are common and abundant across the lower coastal plain of southeastern North America. Some of these models include formation of the elevated rim as being the result of hydrodynamic processes and data presented here for Lake Mattamuskeet supports that notion. Multiple lines of evidence link the formation of numerous concentric parabolic ridges with lake hydrodynamic processes including: 1) GPR imaging of clinoforms shows lateral accretion toward the lake (westward), 2) ridges become progressively lower in elevation toward the lake indicating deposition during falling lake levels, and 3) sediment is similar in the central part of the lake and on the ridges. Lake Mattamuskeet is the product of multiple Carolina bays that have merged. The eastern part of the Lake Mattamuskeet basin was inundated by at least 6500 cal yr BP, which predates inundation of the western part of the basin by >5000 yrs. The earliest lake sediment from both sides of the basin is associated with charcoal beds, suggesting that basin formation is associated with fires. Presently, peat fires on the Albemarle/Pamlico Peninsula are known to burn for months and to decrease land-surface elevations by >1 m. Although the extent of peat on the Peninsula was likely not as great during the early to middle Holocene as it is today, thick peats did exist locally. Lake Mattamuskeet formed when groundwater levels rose with rising sea levels and as climate became more humid.

Despite their abundance and long history of study, relatively few Carolina bays have been examined in detail and as a result their formation and evolution remain controversial. The evolutionary model presented here for Lake Mattamuskeet likely applies to the subset of Carolina bays in other coastal settings, like the Delmarva Peninsula, Virginia. Lake Mattamuskeet has no relationship to the Younger Dryas or an associated impact event because rim accretion significantly postdates 12,000 cal yr BP.

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