

SOILS AND NEAR SURFACE GEOLOGY OF CAROLINA BAYS: A REVIEW

Abstract: Carolina bays are oval depressions that vary in size, are oriented NW to SE and are found on the southeastern Atlantic coast. The purpose of this paper is to review the existing literature on soil properties of the rims, the depressions and the near surface geology of Carolina Bays. Over 45 papers containing information on Carolina bay soils in five states have been published. Carolina bays are found on undissected surfaces of sandy sediments. Underlying basin fill are geologic formations of the Pliocene and Cretaceous periods. The formation lying below the basin depends on which surface was exposed when the sand sheet was deposited. Low areas in the sand sheets and an impenetrable layer of humate or clay allowed water to perched at or near the surface resulting in conditions that favored the formation of Carolina bays identifiable oriented oval shape. Soil profiles on the rim consist of sand to sandy loam textures, have low amounts of organic matter and exhibit a range of profile development suggested by structure and clay translocation and accumulation. The soils tend to be acidic, have low CEC and base saturation. Carolina bay depressions contain soils that are dark in color and can range in texture from sandy loam to a silty clay loam, usually includes high levels of organic matter, and often has thick layers of peat. Profile development is usually weak and consists mainly of organic matter accumulation. The depressions tend to have high amounts of organic carbon providing high levels of organic acids resulting in low pH, high CEC, and low base saturation. Opposing theories on the origin of basin soil usually focus on one of three ideas; soils and sediments inside the basin are similar or different than the soils and sediment outside the basin, the soil in the surface of the basin are similar or different than the underlying sediment, or sediment in one bay is

similar to or different than sediment found in other bays. Peat and organic soil in Carolina bays vary in thickness from 10 cm to over 4 m. The peat usually consists of a fibric organic material lying over a black sapric muck, which lies over a mineral base. Buried surfaces and gravel have been found under both rims and depressions. The buried soils suggest periods of time when organic accumulation and profile development had sufficient time to occur, and was subsequently covered. Carolina bays are unique to the surface on which they form and have developed over time.

INTRODUCTION

Scattered about the southeastern Atlantic coastal plain of the United States are geomorphological features whose widespread extent was unknown until the development of aerial photography. These unusual features have inspired scientists to develop imaginative theories to explain their occurrence. Carolina bays are elliptical depressions that are dark in color because of high amounts of organic matter and are usually surrounded by a light colored sandy rim (Johnson, 1942). Johnson estimated the number of these bays to be as high as 500,000 (Prouty, 1952), but the actual number may be less than 100,000 (Nifong, 1998). They are all orientated with the long axis SE to NW, and range in size from 10 m to more than 4 km along the long axis. Carolina bays range from Northern Florida to Delaware with the highest concentration in North Carolina and South Carolina. Some of the more imaginative theories on the processes that formed the Carolina bay depressions and rims include meteor impact (Johnson, 1936), whale wallows (Grant 1945), artesian springs (Prouty, 1952; LeGrand, 1953), dissolution of underlying material (May and Warne, 1999; Siple, 1960), earthquakes (LeGrand 1983), and ice push (Bliley and Burney, 1988). Currently the most widely accepted explanation is that originally there were shallow depressions in the landscape with an aquitard that allowed water to perch above the surface. Prevailing winds then shaped the depression into the now familiar orientated shape (Kaczorowski, 1977; Thom, 1970; Odum, 1952). The origin of the original depression, however, is still uncertain. During the past century agricultural and community development have led to the drainage and use of these bays. It is estimated that 50% of all Carolina bays were drained and developed in some manner in Bladen County, NC, by 1982 (Weakley and Scott, 1982). This figure would be higher if other management practices such as logging

were included. As these bays are used for agriculture and other activities, their defining characteristics of sand rims and organic depression surfaces become blurred into the surrounding landscape, with smaller ones completely disappearing.

Due to their uniqueness in the landscape, Carolina bays have piqued scientists' curiosity leading to numerous studies over the years concerning various scientific aspects including: geology (Thom, 1970), wildlife (Scott et al., 1986), vegetation (Porcher, 1966), and soils (Stolt and Rabenhorst, 1987a,b). The first account concerning Carolina bay soils is from Glenn (1895) concerning bays in the area of Darlington, S.C. Concerning the rims, Glenn stated, "A sand ridge borders each bay . . . The sand on the ridges extends down into the surface of the adjacent sands and clays. No stratification is visible. It seems to be beach sand white in color and poor for agricultural purposes." Glenn describe the depressions as a ". . . perfectly flat, clayey area with a surface 2-4 ft below the general level of the country . . . [and it is] dark, fertile, and compact, impervious to water extending down 15 to 25 ft. Drilling through the clay layer, a sand aquifer with moderate-sized quartz pebbles is encountered." Since then, over 45 papers concerning Carolina bays containing information on soil properties have been published. Figure 1.1 shows a map of the Atlantic coast states and the counties in which these studies were conducted. The purpose of this paper is to review the existing literature on soil properties of the rims, the depressions and the near surface geology of Carolina Bays to provide a background for the studies presented in this dissertation.

RIMS

Carolina bay rims are the most distinguishing characteristic and are most apparent on the east to southeast side and tend to extend towards the south, while on the north to

northwest the rims tend to be less defined, but are still distinguishable. The rims have been described as resembling eolian dunes (Grant et al., 1998; Rodgers et al., 2000). The amount of rim distinguishable from the surrounding landscape tends to vary and ranged from 20-80% of the circumference of 10 bays in Horry County, S.C., (Knight et al., 1985). Despite being the most distinguishable feature, there is limited information on rim soils compared to the depressional soils. Much attention has been given to the geometric aspects of the rim (Prouty, 1952; Johnson, 1942) but will not be discussed here.

Profiles and Pedogenesis

Petry et al., (1979) found that, in general, rim soils in Virginia exhibited greater pedogenic development than the centers of the bays, reflected by the brighter colors, clay accumulation/movement, and distinct horizons. Bliley and Pettry (1979) provide thorough profile description of Carolina bay rims on a Pleistocene and a Holocene surface in Maryland. Rim soils on the Pleistocene surface were classified as coarse loamy, siliceous, mesic Typic Ochraquults and had brown or dark brown loamy sand to sandy loam surfaces that overlie a reddish brown, strong brown, or yellowish brown sandy loam to sandy clay loam subsoil. The substrata were sand to loamy sand. The soils also showed significant, relative to depressions, amounts of development with easily identified weak structure and presence of argillic horizons. They also noticed that the soils on rims found more than 10 m above mean sea level were thinner (45 cm) than lower lying rim soils (75 cm).

Bliley and Pettry (1979) did not classify the rim soils found on the Holocene surface but described them as having surface soils of dark grayish brown to brown loamy sand to sandy loam with a subsoil of brown olive or yellowish brown sandy loam or loamy sand, and a sandy or gravelly substratum. The soils had weakly developed B horizons with weak

structure and clay increases due to stratification during deposition rather than pedogenic processes. Clays from both surfaces consisted of vermiculite and kaolinite with some vermiculite-chlorite, mica, and gibbsite.

The rim profiles described by Bliley and Pettry (1979) are similar to what Gamble et al. (1977) described in the upper coastal plain of North Carolina: 50 cm of a sandy loam surface horizon over a sandy loam to sandy clay loam subsurface horizon to 1.2 m. Thom (1970) described rim soils as being poorly developed and compared them to well-drained beach sands. He noted that this suggested pedogenic equilibrium because the rim soils, which have been in place for many years, look like freshly deposited beach sands, which has not had time to develop soil profiles. In other words, the pedogenic processes are no longer occurring or are at very slow rates. There is minimal organic matter accumulation and clay translocation.

Secondary Rims

Gamble et al. (1977) suggested that the current visible rim might be a secondary rim in a bay in North Carolina. The secondary rim, the current rim, was formed later from eolian sand deposits which buried a primary rim that was the edge of an initial depression. The primary rim was exposed long enough to develop a soil profile before being buried by the formation of the current secondary rim. Grant et al. (1998), in South Carolina, and Stolt and Rabenhorst (1987b), in Maryland, also came to the conclusion that rims evolve over time and multiple epochs of rim accretion were possible. Grant et al. (1998) included in their hypothesis that the secondary rim was formed through the eolian deposition of sand into standing vegetation and was able to verify this with ground penetrating radar. Recently Zanner et al. (2002) proposed a process in which larger bays capture smaller bays in a

process analogous to stream capture. If such a process occurred, it could result in secondary rims.

Physical and Chemical Properties

Several studies included information on particle size analysis. There tends to be less than 15% clay and more than 75% sand in rim soils (Bliley and Pettry, 1979; Stolt and Rabenhorst, 1987a; Reese and Moorhead, 1996). The mean diameter of the rim soils was found to be 0.32 mm in Virginia (Bliley and Pettry, 1979). Brooks et al. (1996) found during an archeology dig in South Carolina that average grain size was 0.33mm (± 0.75 mm) to a depth of 170 cm and then decreased to 0.12 mm (± 0.33 mm) at a depth of 240 cm. They then estimated net sediment accumulation to be 0.07-0.26 mm yr⁻¹ based on Accelerator Mass Spectrometry (AMS) radiocarbon dating of charcoal found through the profile. Thom (1970) stated that grain size properties of rims revealed very little variation in mean sorting, skewness, and kurtosis values between bays. This means the rims had similar grain size distributions indicating they were formed with similar processes. However, there was some evidence that the east rim quadrants are finer and better sorted. Pettry et al. (1979) found that the clay fractions for rim and depression soils at elevations greater than 10 meters included kaolinite, vermiculite, vermiculite-chlorite, quartz, mica, and gibbsite, and that near sea level the suite was the same but included significant amounts of montmorillinite, possibly from ocean deposits after a storm surge.

There are few reports that specifically address the chemical characteristics of rim soils other than to identify them as nutrient poor and acidic to very acidic. Chemical characteristics for soil series usually found on rims can be found in soil surveys, but those soil series are not specific to rims. Reported pH values range from 4.1 (Stolt and

Rabenhorst, 1987a) to 5.3 (Reese and Moorhead, 1996). Organic carbon in the rims is low due to the localized droughty conditions that exist on the rim sands. Organic carbon was reported by Reese and Moorhead (1996) to be less than 2.7 g kg^{-1} , resulting in a low CEC of $13.9 \text{ cmol}_c \text{ kg}^{-1}$. The extractable nutrient values are below those necessary for crop production and other plant community environments, with a reported $2.44 \text{ cmol Ca}^{2+} \text{ kg}^{-1}$, $80 \text{ cmol Mg}^{2+} \text{ kg}^{-1}$, and $0.12 \text{ cmol K}^+ \text{ kg}^{-1}$ (Reese and Moorhead, 1996). As a result of the low values of exchangeable bases, the base saturation is low, less than 21% (Reese and Moorhead, 1996).

DEPRESSIONS

The areas inside the rims of Carolina bays tend to be slightly lower in elevation than the surrounding areas. The depressions of Carolina bays can be filled with water, as in the case of White Lake in North Carolina, can be partially filled with water (horseshoe lakes) as in the Bladen Lakes State Forest in North Carolina, can have a thick layer of peat and organic material, or have a high organic mineral soil. It is the depressions that have been the focus of most Carolina bay studies, whether dealing with water quality, vegetation and wildlife surveys, or soil classification studies.

Profile Descriptions

Bliley and Pettry (1979) classified Carolina bay depression soils found on a Pleistocene surface in Virginia as coarse loamy, siliceous, mesic Typic Ochraquults. These soils were described as having a gray to very dark gray sandy loam or loam surface overlaying an olive gray to gray sandy clay loam to clay loam subsoil, with the substrata being sand or loamy sand. The profiles showed a significant degree of development with weak structure and argillic horizons. Bliley and Pettry (1979) did not classify depressional

soils on a Holocene surface in Virginia but did describe them as a black to very dark gray loam or sandy loam surface overlaying a gray or very dark gray loam or clay loam subsurface, with substrata of sand or gravel. These soils had very weak structure with profile discontinuities and irregular clay distributions, which are more indicative of sedimentation than of profile development. The increased profile development on the Pleistocene surface compared to the Holocene surface is supported by Pettry et al. (1979) who reported that depressional bay soils lower (<10 m) in elevation near the coast of Virginia were less developed than those higher in elevation (>10 m).

Lide et al. (1995) classified depressional soils of a bay in South Carolina as loamy, siliceous, thermic Arenic Ochraquults, with 20 cm of black mucky loam grading to 20-60 cm of grayish loam, overlaying 60-90 cm of loose white sand over a clayey hardpan. Stolt and Rabenhorst (1987a) found that out of 53 bays examined in Maryland, 26 had Histic epipedons, 2 were Histosols, and the remaining were Humaquepts, Umbraquults, or Umbraqualfs. They reported that those soils formed from sandy textured sediments or silty textured basin fill with accumulation and translocation described as the two major soil forming processes. However, Ingram et al. (1959) found only a minor variation existed in the relative abundance of clay in the profile in a North Carolina bay, indicating that translocation may not play a significant role in the bays.

Source of Basin Fill

Studies of basin soils and sediments have been based on one of three comparisons:

- 1.) Comparing inside of bays to adjoining outside areas.
- 2.) Comparing the surface soils/sediments to the underlying sediment.
- 3.) Comparing soils in different bays.

Theory one: soils and sediments inside the basin are similar or different than the soils and sediment outside the basin. Bryant and McCracken (1964) found that surface sediments in three bays in North Carolina basins are transported sediments from surrounding areas, and that the soils outside the bays were more differentiated, had thicker profiles, higher Fe content, higher degree of interlaying 2:1 minerals, and exhibited a higher degree of clay movement than the soils found inside the basin. Preston and Brown (1964) stated that the surficial sediment of the bay basins in South Carolina are enriched with clay from peripheral sediments. Stolt and Rabenhorst (1987b) hypothesized that sediment material in the basin is a result of continuous deposition of loess material from outside the basin.

Theory two: the soil and sediment in the surface of a basin are similar or different than the underlying sediment. Ingram et al. (1959) stated that the formations under the bays have a different mineralogy than the surface sediments, concluding that they are washed or blown in with little alteration since deposition. In addition Shartz and Gibbons (1982) in South Carolina, and Bryant and McCracken (1964) in North Carolina, found that sediment in the Carolina bays basins have no consistent relationship to subsurface strata types. However, Spradlin and Johnson (2000) found that sediments in two bays in Virginia were both texturally and mineralogically similar to the parent material on which they formed.

Theory three: sediment in one bay is similar to or different than sediment found in other bays. Knight et al. (1985) stated that the sediment of bays adjacent to each other were as different from each other as bays further apart in South Carolina. Saunders and Brown (1992) reported on three bays that had different internal sediments or subsoil type, which were related to their location with respect to geomorphic surfaces in North Carolina. However, Stolt and Rabenhorst (1987a) found that the mineralogy of the three basins they

sampled were almost identical suggesting that the sediments were from similar sources in Maryland.

The theories presented tend to intertwine with one another because of the complex geology that is associated with the coastal plain and the wide extent where Carolina bays are found. The lateral and vertical variation that is often found in the coastal plain reflects the energy present in the environment at the time of sediment deposition, and the incision and infilling that occurred during different periods of ocean transgression and regression (Zanner, 2003). This variation can explain the difference between substratum and surface sediments and differences from bay to bay. Zanner et al. (2002) also suggested that there could be periods of surface stability in which soil formation can occur followed by influxes of new material, and that periods of erosion can complicate recreating the history of a bay. The theories indicate that each bay can have variations or similarities based on localized conditions and events.

Peat and Organic Soils

Peat or organic soils are often described as the surface layers of many Carolina bay depressions (Table 1.1). A typical description was given by Knight et al. (1985) for Carolina bays in South Carolina. There was a 0.5 m root mat over organic or mineral soil. Beneath the root mat was black peat up to 80 cm thick, which was a soft to firm organic ooze containing plant debris, under which was a dark brown to brown peat. In places the peat was hard, compact, dry, and often had many plant and root fragments. Shartz and Gibbons (1982) found that peat had between 14 and 76% organic matter in South Carolina bays. Thom (1970) stated that the peat tended to be evenly thick across the depressions.

Buell (1939) described Carolina bays in Bladen County, N.C. as filling in rapidly from the north and west and slowly from the south and east, as suggested by the bottom profile. The depth of the water was shallower, i.e., a broad gently sloping shelf, in the north and west while the southern end was deep. This can be seen in the horseshoe shaped lakes in Bladen County, NC. He described peat formation into the bays as vegetation from the margin through the stoloniferous and spreading superficial root systems of shrubs and other “bog plants” slowly advancing out into the water along the sloping shelf of the underlying sediments. Frey (1949) reported that peat appears to fill from the NW. Buell (1946) described the soil in Jerome Bay as having 125 cm of peat in the center and with a thick coarse tough mat of tree roots and rhizomes at the surface. Below this mat the peat varied from place to place. There was no stratification and the peat type ranged from a brown peat that had an abundance of logs, to a black peat that was very fine, soft and sticky when wet. He also described small bits of charcoal and attributed the black color of the peat to fire events. Today we know the peat that Buell described as hemic and sapric organic material, and that the color is due to the organic carbon in the soil, rather than fire. Still Buell made an important point about fire in Carolina bays. “The coastal plain has never been completely free from fire during the history of the bog since small amounts of charred fragments are found even to the bottom of the peat.” Fire in the Carolina bays can and does influence the formation of organic soil through subsidence and influence of vegetation communities. Cohen et al. (1999) and Grant et al. (1998) also reported organic layers in a South Carolina bay rich in charcoal.

There have been attempts at estimating the age and rate of organic matter accumulation. The charcoal Brooks et al. (1996) found in South Carolina came from 15, 25,

and 40 cm depths, and were dated to 2550, 3050 and 4505 B.P. using AMS radiocarbon dating. This allowed them to estimate organic accumulation to be between 0.07 and 0.26 mm yr⁻¹. Cohen et al. (1999) were able to estimate accumulation rates of 70-100 cm of peat to be 0.75 cm yr⁻¹ based on Cs¹³⁷ and 0.18cm yr⁻¹ based on Pb²¹⁰. The peat accumulation reflected alternating wet and dry periods in the laminated mineral deposits and relatively thin layers of peat with different compositions. Rodgers et al. (2000) in Georgia dated *Nymphaea* seeds found in muck at 215 to 225 cm to 7850 B.P. using AMS radiocarbon dating.

Whitehead (1965) noticed that a series of alternating organic and inorganic zones could be identified in a bay in North Carolina. The uppermost organic horizon was dated at 10224 ± 510 B.P. and the second organic horizon was dated 38000 B.P.

Mineralogy

Not all bays had organic soil interiors, and there is some clay mineralogy associated with the interior of Carolina bays. Gamble et al. (1977) and Bliley and Burney (1988) in North Carolina, and Brooks et al. (2001) in South Carolina describe most or part of the interior sediments as being mineral in nature, usually consisting of a silt, loam, or sandy loam surface over a loamy sand to sandy clay loam B horizon. The mineral content of the bay depressions are dominated by quartz, but can include various of clay minerals. Bliley and Pettry (1979) found vermiculite-chlorite, vermiculite, and kaolinite to be the dominant clay mineralogy with minor amounts of gibbsite and mica in bay depressions on a Pleistocene surface in Virginia, while kaolinite was the dominant mineral along with some vermiculite-chlorite in the bays on Holocene surfaces. Stolt and Rabenhorst (1987a) found feldspars, mica, kaolinite, and quartz. Preston and Brown (1964) identified a full suite of heavy minerals from inside a Carolina bay in South Carolina including; tourmaline, sillimanite,

staurolite, kyanite, zircon, rutile, and epidote, monazite, titanite, spinel, and opaque minerals that included; magnetite, ilmenite, hematite, leucozenc, opaque rutile, and authigenic marcasite-pyrite.

Chemical Properties

Several studies have focused on the chemical and nutrient aspects of the soil and water found in the depressions. High organic carbon (OC) content in the surface horizons is a common characteristic of Carolina bays. Knight et al. (1985) found over 29.1% OC in northern South Carolina. Shartz and Gibbons (1982) reported the surface peat layer had a OC content of 8.1 - 44.2% in North Carolina. Stolt and Rabenhorst (1987a) found depressions with trees had a higher OC value, 372 g kg^{-1} , at the surface than those with bushes, 50 g kg^{-1} . The large amount of organic acids produced in the decomposition of organic matter results in Carolina bay soils often being described as very strongly to extremely acidic. Stolt and Rabenhorst (1987a) reported a pH of 3.6 in the Oa horizon in Maryland, Knight et al. (1985) reported a pH range of 3.4 to 3.8 in northern South Carolina, and Reese and Moorhead (1996) found a pH of 4.6 in southern South Carolina. However, there are some bays that have been influenced by the underlying calcareous strata resulting in an alkaline pH. Lake Waccamaw Bay in North Carolina has a pH of 7.1 with alkalinity of 12.0 mg l^{-1} (Stager and Cahoon, 1987). In addition to the acidic conditions, the high organic content lends itself to high CEC values as reported by Reese and Moorhead (1996), $26 \text{ cmol}_c \text{ kg}^{-1}$, and Stolt and Rabenhorst (1987a), $100 \text{ cmol}_c \text{ kg}^{-1}$. Despite the high CEC, nutrient levels are low in general. Reese and Moorhead (1996) reported $0.18\text{-}0.72 \text{ cmol}_c \text{ kg}^{-1}$ exchangeable Ca, $0.19\text{-}0.62 \text{ cmol}_c \text{ kg}^{-1}$ exchangeable Mg, and $0.21 \text{ cmol}_c \text{ kg}^{-1}$ exchangeable K. Knight et al. (1985) reported Total Kieldahl Nitrogen of 1.0 to 14.8 g kg^{-1} , extractable P

<0.013 g kg⁻¹, extractable Ca of 0.3 g kg⁻¹, extractable Al of 0.023 to 1.28g kg⁻¹, and extractable Fe of 0.003 to 0.124 g kg⁻¹. Because of low amounts of base cations, base saturation (BS) tends to be low, as reported by Reese and Moorhead (1996), with a BS of 4-11%. However, Stolt and Rabenhorst (1987a) reported that as depth increased BS increased, not due to the increase in base cations but from decreasing CEC that is a result of decreasing organic matter.

Several studies have included chemical information on the water that is associated with Carolina bays. Knight et al. (1985) reported a water pH range of 2.6 to 3.0 in a bay in South Carolina. Newman and Schalles (1990) related peat depth to water quality. They found that peat depth was positively correlated with dissolved organic carbon (DOC), Fe²⁺, SiO₂, and negatively with K, HCO₃⁻ and pH. As peat depth increased pH, HCO₃⁻ and Ca²⁺ decreased and DOC increased. Bays from sandy terraces were dominated by monovalent cations, and those associated with river terraces or back barrier areas, which had finer soils, had higher proportions of divalent cations (Newman and Schalles, 1990).

Some Carolina bay studies have been conducted on bays that have been drained and placed in agricultural production, which has led to chemical changes in the soils. Ewing et al. (2003) found that organic soils of a drained Carolina bay under agricultural production had higher extractable P (no values reported) in the surface 45 cm compared to natural bays but were similar below 45 cm. They also showed trends for increasing extractable Ca levels with increasing amounts of time that the soils have been under production; natural, 0.5 meq cm⁻³; 15 years, 3 meq cm⁻³; 20 years, 9 meq cm⁻³; 30 years, 10 meq cm⁻³. Hanchey et al. (2000) also showed an agriculturally induced shift in the organic soils of Carolina bays, shifting from an organic soil with a pH of 3.7 and 0.10 g kg⁻¹ exchangeable Ca to a mineral

soil with a pH of 5.0-5.5 and 0.600 g kg⁻¹ exchangeable Ca. Carbon and nitrogen were depleted through the profile and oxalate extractable Fe was lower while oxalate extractable Al was increased.

Physical Properties

Physical property data on the soils in Carolina bay depressions are sparse mostly due to the difficulty of obtaining samples and working with saturated organic and mineral soils in the field. The soils of bay depressions are often described as having low bulk density; however, only one value was found in the literature. Stolt and Rabenhorst (1987a) used a McCauley peat sampler to determine a mean bulk density of 0.35 g cm⁻³ in Maryland. Ewing et al. (2003) found the bulk density at the surface of a drained Carolina bay in North Carolina to be higher than an undrained bay; however, no values were given. Saturated hydraulic conductivity (K_{sat}) is often described as being high in the peat, low in the sapric material and variable in the underlying strata. Rizzuti and Cohen (2000) found that K_{sat} increased with depth to a depth of 25 cm and then decreased in a bay in South Carolina; again, no values were given. In their study, they found that K_{sat} was positively influenced by an increase in macropore percentage found in the upper 25 cm of peat material. This information corresponds with the porosity reported by Cohen et al. (1999) for the upper 42 cm of a bay in South Carolina, which was found to be between 0.90 and 0.94 cm³ cm⁻³. Lide et al. (1995) report a clayey hard pan underlying the organic surface horizon that had K_{sat} range of 0.396 to 0.001 cm hr⁻¹. This hard pan provides an aquitard on which water can perch near the surface. Particle size data is also sparse. Shartz and Gibbons (1982) reported the horizon under the surface peat layer, 33-100 cm had 61-73% sand and 17-18% clay.

COMMON SOIL CHARACTERISTICS

Along with their easily identified shape and position in the landscape, Carolina bays have some common soil characteristics.

Buried Soils

Quite a few studies of Carolina bay soils have found indications of buried soil surfaces under the rims and in the depressions. Stolt and Rabenhorst (1987b) found buried organic rich horizons beneath 25% of the rims in 53 bays examined in Maryland. The buried A or Oa horizons were silt loam to silty clay loam underlain by dark horizons of sandy loam, which dipped towards the depression. Gamble et al. (1977) mention a buried soil profile under the current secondary rim. Wright et al. (2000) found that the rim in a South Carolina bay overlies an organic rich mud lens and basal humate cemented sands that were dated to 30-35,000 B.P. Bliley and Burney (1988) described a buried surface in a bay in Johnson County, N.C., dated to 21,920 B.P., as having conspicuous dark colors with organic accumulation and little evidence of profile development. Stolt and Rabenhorst (1987a) found major discontinuities in basin fill between 140 and 215 cm in the basin fill of Bear Pond Bay in Maryland, suggesting a buried A horizon. Frey (1950) mentioned secondary organic layers below a mineral layer of sand or clay in a study of 33 bay depressions in North Carolina. Jenkins et al. (2001) were able to distinguish a buried surface throughout a bay in North Carolina by using ground-penetrating radar. This buried surface was verified by Ewing et al. (2001), who found it at depths between 1.0 and 2.7 m. Grant et al. (1998) described a truncated paleo B/C horizon through the depression with ground penetrating radar in South Carolina. Brooks et al. (1996) found a buried surface horizon at 80-100 cm using grain size distributions in South Carolina and also found two distinct Hydric A

horizons in the profile of a Carolina bay in South Carolina. Finally, Whitehead (1965) described a layer of peat under an inorganic silt layer. The sum of the evidence on buried soils indicates that at some point in the past the surface was exposed at a lower elevation long enough for soil profiles to develop and organic matter to accumulate. At some point the surfaces were then covered with new material.

Gravelly Deposits

Several studies have mentioned gravelly deposits. These gravel deposits were first mentioned by Glenn (1895), who found moderate sized quartz pebbles in the sands under the rim. The gravel has been described as rounded quartz pebbles 0.2 to 5 cm in size in Virginia (Pettry et al. 1979), as up to 6-20% rounded to angular vein quartz (>0.2 cm) similar to that which caps the saprolite in the area on the edge of the piedmont in North Carolina (Bliley and Burney, 1988), and as quartz pebbles up to 0.5 cm at the base of the rim in the upper coastal plain of North Carolina (Gamble et al., 1977). Bliley and Burney (1988) described the deposits of gravel as ice push deposits. Brooks et al. (1996) suggested the gravel areas to be a shoreline. These theories address how the gravel came to be under the rim, but not where it came from? It is hypothesized that it originated from the depositional surface in which the bays were formed. The type of material, in this case gravel, is a result of the energy present at the time of deposition. This high-energy environment is often related to the distance from a river mouth and/or the location of the coast and covered large areas resulting in regional deposition of gravel. The hypothesis of regional deposition of gravel is supported by Stolt and Rabenhorst (1987b), who found that in gravelly sediments tended to extended across most of the depression and under the rim, maintaining an approximately level gradient. Such a regionalized deposition is also supported by Grant et al. (1998), who found

a regional Upland sedimentary unit that is gravel rich, and Thom (1970), who reported that the sub-surface sediments of bays found on former coastal flats are mainly interbedded sands and gravels. Evidence that deposition of gravel occurred during different periods of the past was provided by Bliley and Pettry (1979) who found gravel under rims of bays on a Holocene surface, but not a Pleistocene surface in Virginia.

Impermeable Layer

One common trait of the underlying strata is an impermeable layer underlying the basin sediments. This layer can be clay to sandy clay material (Buell, 1946; Glenn, 1895; Ingram et al., 1959; Stager and Cahoon, 1987; Grant et al., 1998; and Lide et al., 1995) or a sandy stratum that is cemented by humate (Thom, 1970; Wright et al., 2000; and Knight et al., 1985). This impenetrable layer perches water and forms a base for sediment fill. The perched water table allows for shaping of the bay, sediment accumulation, and formation of high organic soils. However for the bay to be formed there has to be a depression that allows water to be exposed because the impermeable layer has been shown to be a continuous stratum that runs between bay and interbay areas (Bliley and Pettry, 1979) resulting in a regionalized perched water table.

UNDERLYING STRATA AND REGIONAL GEOLOGY

The underlying strata and regional geology of Carolina Bays provides a clearer picture concerning the formation of the bays and the development of their soils. One of the more thoroughly studied areas is the Savanna River Station in South Carolina. Surface sediments and soils overlie sandy clay to sandy clay loams of the fluvial Miocene Upland Unit, which overlies the Tobacco Road Sand formation, which is upper Eocene in age (Lide et al. 1995). Cohen et al. (1999) described the Upper Unit complex as a gravel-rich unit

interpreted to be between upper Oligocene and lower Miocene in age. Brooks et al. (1996) found that a BC horizon in the surface sediments had a generally flat topography inside and outside a bay and constituted a regional stratigraphic marker.

Geologic Formations

Brooks et al. (2001) found three depositional packages in South Carolina, the Duplin Formation at the base, an intervening organically rich bay fill sequence and the overlying sand sheet that is fluvial in nature. The abrupt boundary between the Duplin and the overlying bay fill is an erosional unconformity. Bay fill sediments were 4.5 m thick and 4.5 m below the present surface. Ewing et al. (2001) found a stratum between 3.6 and 7.3 m that contained fossilized shells from the Duplin Formation (Pliocene). Coarse sand or laminated clay also occurred near those depths throughout the bay. A wavy-flaser unit, the Black Creek Formation (Cretaceous) extended downward from depths between 6.8 and 7.3 m. Interpretations suggest that the Black Creek Formation underlies the bay, and is overlain by an eroded member of the Duplin Formation, which is overlain by bay fill sediments. LeHocky and Colquhoun (1969) found the Black Mingo Formation underlying a very clayey unit, underlying a coarse sand and clay containing a weathering profile, and a fluvial unit in South Carolina. Bryant and McCracken (1964) found that the surface soils and bay sediments overlie the basal sands of Pleistocene sediment, which overlies the micaceous clays of the Tuscaloosa Formation (often associated with the Black Creek Formation). Bliley and Burney (1988) presented a unique stratigraphy of a Carolina bay in Johnston County, NC, where saprolite underlies a clayey, sticky, smectitic coastal plain sediment, which underlies the sandy basin fill. Preston and Brown (1964) described three sand facies that underlies the bay and surrounding area near Sumter County, SC. Bed A was a fine to

medium sand starting at 2.1 m below the surface, Bed B was a slightly argillaceous coarse to very coarse granular starting 6.1 to 10.7 m below the surface, and Bed C was an argillaceous fine to medium sand commonly micaceous with the presence of marcasite-pyrite starting around 13.7-15.2 m below the surface. Ingram et al. (1959) stated that Singletary Lake overlies the Black Creek Formation and three other bays in Scotland County overlie the Middendorf/ Tuscaloosa. Thom (1970), in South Carolina, found that bays on former barrier islands were found to rest on a shell rich facie 5.1-7.7 m thick, which overlies the Pee Dee Formation of dark gray marl. Bays on former clay flats had non-calcareous organic clay at the depth of the Pee Dee and possibly the Black Creek Formation. Bays found on fluvial terraces have sandy and gravelly bay deposits overlying the soft calcarenite Duplin Formation that overlies the impermeable marl of the Pee Dee formation. Occurrence of the Carolina bay is common to those areas underlain by formations of middle Miocene to early Pliocene age, predominantly the Duplin marl (Siple, 1960).

Erosional incision and subsequent infilling that occurred during different periods of ocean transgression and regression can affect the lithology seen in the field (Zanner, 2003). However, the geology from southern South Carolina to eastern North Carolina is relatively similar. The Pee Dee, Black Creek, Tuscaloosa, and Middendorf Formations are identified upper Cretaceous depositional units that underlie Carolina bays. Where all three are present, the Pee Dee formation overlies the Black Creek, which overlies the Middendorf. The Tuscaloosa, which was identified by Ingram et al. (1959) and Bryant (1965) has been correlated to the Black Creek Formation (Nystrom et al., 1991). The Black Mingo Formation is a Paleocene formation that lies above the Cretaceous sediments. The Duplin is Pliocene in

age and often overlies the Upper Cretaceous strata in North Carolina (Ward et al., 1991). Holocene material has been deposited on top of this and this is where the bays are formed.

Typical Surfaces on Which Bays Form

The underlying strata of Carolina bays tend to be undisturbed (Preston and Brown, 1964; Jenkins et al., 2001; Gamble et al., 1977). The strata in which Carolina bays have formed tend to be restricted to sandy surfaces (Shartz and Gibbons, 1982; Gamble et al., 1977; Daniels et al., 1999). Carolina bays are absent on valley slopes and modern flood plains in North Carolina (Daniels et al., 1999). Thom (1970) recognized three geologic surfaces on which bays were found in South Carolina; flat interfluves, dune depressions, and terrace contacts. Flat interfluves included former coastal barrier islands or broad clay flats, with most of the bays located on areas that were sandy barrier islands. Terrace contacts include surfaces that are fluvial in nature and are composed of poorly sorted sands of bars and swales of ancient braided streams. Bays on terrace contact surfaces were usually on broad undissected fluvial areas. Dune depression surfaces are located in well-sorted eolian sediment developed from the sand and gravel of ancient flood plain channels. These bays in the dune depressions occupy the lowest topography in the dune fields.

CONCLUSIONS

Carolina bays are found on undissected surfaces of sandy sediments. Underlying the basin fill are geologic formations of the Pliocene and Cretaceous periods. The formation that lies below the basin depends on which surface was exposed when the sand sheet was deposited. Low areas in the sand sheets and an impenetrable layer of humate or clay allowed water to perched at or near the surface resulting in conditions that favored the formation of Carolina bays' unique shape. In addition to the unique oriented oval shape of Carolina bays,

a light colored sandy rim and a dark colored center of peat or loamy mineral material are also identifying features.

Soil profiles on the rim have sand to sandy loam textures, with low amounts of organic matter, and exhibit a range of profile development suggested by structure and clay translocation and accumulation. Clay minerals present in rim soils include kaolinite and vermiculite. The soils tend to be acidic and have low CEC and base saturation. There is also evidence that supports a buried primary rim of an original depression and a current secondary rim that formed over time through wind or wave action.

Carolina bay depressions contain soils that are dark in color and can range in texture from sandy loam to a silty clay loam, usually include high levels of organic matter, and often have thick layers of peat. Profile development is usually weak and consists mainly of organic matter accumulation. The depressions tend to have high amounts of organic carbon providing high levels of organic acids, resulting in low pH, high CEC, and low base saturation. However, there are some exceptions like Lake Waccamaw Bay, which has a calcareous base resulting in near neutral pH and high base saturation. Bays that have been drained and in agricultural production show increased pH and base saturation, and decreased organic carbon and nitrogen. The surface horizons have very high porosity, low bulk density, and a high K_{sat} in fibric and hemic organic material but a low K_{sat} in sapric organic material. Most bays have an underlying impermeable layer, although not always.

Studies of basin soils and sediments have been based on one of three comparisons: comparing inside of bays to adjoining outside areas, comparing the surface soils/sediments to the underlying sediment, and comparing soils in different bays. There are supporting data for

each point of view but all provide information that Carolina bays have characteristics that link them to the varied geologic depositional units in which they were formed.

Peat and organic soils in Carolina bays vary in thickness from 10 cm to over 4 m. The peat usually consists of a black sapric muck lying on a mineral base. The black sapric muck underlies a reddish brown sapric to hemic muck that underlies a hemic to fibric muck consisting of roots and plant debris. There have been several estimates on sedimentation and accumulation rates (0.18 to 0.75 cm yr⁻¹) and age (2550 to 38000 B.P. depending on depth) estimated from radiocarbon dating and pollen analysis. Fire has been a part of Carolina bay history and has occurred periodically since organic matter has been accumulating indicating that fire is a process to account for in studying the soils of Carolina bays.

Buried soil surfaces and gravel have been found under both rims and depressions. The buried soils suggest periods of time when organic accumulation and profile development had sufficient time to occur. Then some environmental event occurred that resulted in an accumulation of bay fill to bury the original surface. The gravel accumulations near the rim have been suggested to be deposited by wave action or ice push. The source of the gravel is believed to be a regionalized deposition in a high-energy environment of the underlying strata, or possibly fluvial material from the piedmont. Carolina bays have evolved over time as environmental conditions have changed.

Information gathered in this review establishes an over all view of Carolina bay soils their position in the landscape, and near surface geology. This information will also be evaluated against the studies that have been conducted in the following chapters. We hope that the information for this dissertation will add to the knowledge base presented here and will be useful in establishing a working model on Carolina bay formation and evolution.

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Table 1.1. Peat and organic soil depths for Carolina Bays from various studies.

State	Depth of Organic	Number of Bays in Study	Source
	(cm)		
North Carolina	62-100	Lake Waccamaw	Stager and Cahoon, 1987
North Carolina	10-200	33	Frey, 1950
North Carolina	125	Jerome Bay	Buell, 1946
Georgia	225	1	Rodgers et al., 2000
South Carolina	1-200	45	Newman and Schalles, 1990
South Carolina	50-400	10	Knight et al., 1985
South Carolina	Up to 400	Unknown	Kaczorowski, 1977
South Carolina	30-460	5	Sharitz and Gibbons, 1982
South Carolina	60- 380	Unknown number of Large bays	Thom, 1970
South Carolina	<60	Unknown number of Small bays	Thom, 1970

Figure 1.1. Counties in the southeastern United States where studies on Carolina bays have included information on soils.

