Reevaluating the Geologic Formations of the Upper Coastal Plain in Chesterfield County, South Carolina

Bradley Aaron Fitzwater
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REEVALUATING THE GEOLOGIC FORMATIONS OF THE UPPER
COASTAL PLAIN IN CHESTERFIELD COUNTY, SOUTH CAROLINA

by

Bradley Aaron Fitzwater
B.S. December 2011, James Madison University

A Thesis Submitted to the Faculty of
Old Dominion University in Partial Fulfillment of the
Requirements for the Degree of

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ABSTRACT

REEVALUATING THE GEOLOGIC FORMATIONS OF THE UPPER COASTAL PLAIN IN CHESTERFIELD COUNTY, SOUTH CAROLINA

Bradley Aaron Fitzwater
Old Dominion University, 2016
Director: Dr. G. Richard Whittecar

Data from a new geological map of the Patrick, S.C. 7.5 minute quadrangle (1:24,000) and detailed descriptions of two cores collected nearby (Middendorf and Cheraw, S.C.) permit improved interpretation of the geology of this portion of the Carolina Sandhills. Geologic mapping incorporated analyses of outcrops with LiDAR data, soil survey maps, ground-penetrating radar transects, and hand auger borings. Micro- and macrofossil identification and optically-stimulated luminescence (OSL) dating provided age control.

Four distinct mappable units occur throughout the Patrick quadrangle. Resting unconformably on schist of the Paleozoic Persimmons Fork Formation, the Cretaceous Middendorf Formation is more than 85.3 m thick and underlies the entire quadrangle. It consists of five related lithofacies that range in texture from pebbly sands to silty clay, all deposited by braided and meandering fluvial systems. Now dissected by streams and deeply weathered, the Middendorf sediments consist mostly of quartz and kaolinite. Although none of the clay beds seem to form extensive aquitards, some of them are of minable thickness (> 9 m). The Pinehurst Formation lies unconformably on the Middendorf Formation and covers hilltops, side slopes, and older terraces associated with the modern stream drainages. Mostly medium-fine sand, the Pinehurst consists of sand sheets and dunes up to 7 m thick. OSL dates (69 ka – 7 ka) from the Pinehurst indicate the area experienced relatively dry and windy conditions during the cold
periods of the Late Pleistocene. Strath stream terraces rest on valley side slopes up to 15 m (50 ft) above the modern flood plain.
ACKNOWLEDGMENTS

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# TABLE OF CONTENTS

LIST OF TABLES............................................................................................................. vii

LIST OF FIGURES .......................................................................................................... viii

Chapter

I. INTRODUCTION .......................................................................................................... 1
   OVERVIEW OF THE STUDY AREA ............................................................................. 1
   GEOLOGIC SETTING ................................................................................................... 6

II. GEOLOGIC HISTORY .................................................................................................. 10

III. METHODS .................................................................................................................. 15
   FIELD MAPPING ........................................................................................................ 15
   DRILL CORE ANALYSIS ........................................................................................... 19
   GROUND-PENETRATING RADAR (GPR) DATA COLLECTION AND
   PROCESSING ............................................................................................................. 22
   AGE DATING ............................................................................................................. 23
   CLAY MINERAL ANALYSIS USING X-RAY DIFFRACTION (XRD) ....................... 24
   GRAIN SIZE ANALYSIS ........................................................................................... 24

IV. RESULTS ..................................................................................................................... 26
   STRATIGRAPHY OF THE PATRICK QUADRANGLE ............................................... 26
   CRETACEOUS MIDDENDORF FORMATION ............................................................ 27
      LITHOFACIES (DETERMINED FROM OUTCROP DATA) .................................... 28
      LITHOFACIES 1 ..................................................................................................... 29
      LITHOFACIES 2 ..................................................................................................... 40
      LITHOFACIES 3 ..................................................................................................... 43
      LITHOFACIES 4 ..................................................................................................... 46
      LITHOFACIES 5 ..................................................................................................... 50
   DRILL CORE ANALYSIS (SUBSURFACE) ................................................................ 53
   CLAY MINERAL ANALYSIS (MIDDENDORF FORMATION) ..................................... 56
   QUATERNARY PINEHURST FORMATION ............................................................. 59
      GROUND PENETRATING RADAR PROFILES ....................................................... 62
      OPTICALLY STIMULATED LUMINESCENCE (OSL) DATING ............................ 69
   QUATERNARY AND NEOGENE (?) STREAM TERRACES ....................................... 75
   QUATERNARY FLOODPLAINS ............................................................................... 81

V. DISCUSSION ............................................................................................................... 82
   INTERPRETATION OF MIDDENDORF FORMATION LITHOFACIES ................. 82
LITHOFACIES 1 (CROSS-BEDDED OR STRUCTURELESS, MEDIUM-TO-COARSE SAND TO PEBBLY SAND) ........................................ 82
LITHOFACIES 2 (ALTERNATING LAMINATIONS AND (OR) THIN BEDS OF SAND AND CLAY (TOTAL LITHOFACIES UNIT THICKNESS < 1.5 M)) .......................................................... 88
LITHOFACIES 3 (CLAY AND SILTY CLAY BEDS OR LENSES NOT ASSOCIATED WITH) ................................................... 88
LITHOFACIES 4 (QUARTZ SANDSTONE WITH MUD MATRIX) ........ 89
LITHOFACIES 5 (FERRUGINOUS SANDSTONE TO PEBBLY SANDSTONE) ............................................................................. 90

INTERPRETATION OF THE MIDDENDORF FORMATION IN A LARGER CONTEXT ................................................................ 92
USE OF THE STRATIGRAPHIC NAME “MIDDENDORF FORMATION” ........ 98
INTERPRETATION OF THE PINEHURST FORMATION IN A LARGER CONTEXT ................................................................. 104

VI. CONCLUSIONS .............................................................................................................................................. 109
REFERENCES CITED .............................................................................................................................................. 113
APPENDICES ..................................................................................................................................................... 121
  A. STATEMENT ABOUT ECONOMIC RESOURCES ......................................................................................... 122
  B. STATEMENT ABOUT GEOHYDROLOGIC FRAMEWORK ........................................................................ 124
  C. CORE DESCRIPTIONS .............................................................................................................................. 125
     CHERAW CORE DESCRIPTION ...................................................................................................................... 126
     PATRICK CORE DESCRIPTION ..................................................................................................................... 149
  D. ADDITIONAL PINEHURST, TERRACE, AND FLOOD PLAIN DEPOSIT DESCRIPTIONS ........................................ 177
  E. SETUP PARAMETERS AND POST-PROCESSING FILTER CONSTRAINTS (RADAN 7 SOFTWARE) ............... 183
  F. GEOLOGIC AND MINERAL RESOURCES OF THE PATRICK QUADRANGLE, SOUTH CAROLINA ......... 186

VITA .................................................................................................................................................................... 189
<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Grain Size Data from the Middendorf Formation (Lithofacies 1 and 2) within the Patrick 7.5 Minute Quadrangle, Chesterfield County, South Carolina</td>
<td>44</td>
</tr>
<tr>
<td>2. Grain Size Data from the Pinehurst Formation within the Patrick and Middendorf 7.5 Minute Quadrangles, Chesterfield County, South Carolina</td>
<td>62</td>
</tr>
<tr>
<td>3. Optically Stimulated Luminescence (OSL) Data from the Patrick and Middendorf 7.5 Minute Quadrangles, Chesterfield County, South Carolina</td>
<td>73</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Generalized Map of the Geologic Provinces of South Carolina</td>
<td>4</td>
</tr>
<tr>
<td>2. Location of the Patrick, S.C. Quadrangle (1:24,000) within the Sand Hills Ecosystem Region, a zone that extends into Georgia and North Carolina</td>
<td>5</td>
</tr>
<tr>
<td>3. Location of the Patrick 7.5-Minute quadrangle (1:24,000) within Chesterfield County, South Carolina and relation to the fall line</td>
<td>9</td>
</tr>
<tr>
<td>4. Optically Stimulated Luminescense (OSL) and X-Ray Diffraction sample locations in and around the Patrick 7.5-Minute quadrangle</td>
<td>18</td>
</tr>
<tr>
<td>5. The U.S. Geological Survey wire-line drill core rig positioned at the Patrick (CTF-320) drill core site</td>
<td>20</td>
</tr>
<tr>
<td>6. Location of the Patrick Core and the Cheraw core in relation to the Patrick 7.5-Minute quadrangle</td>
<td>21</td>
</tr>
<tr>
<td>7. Generalized stratigraphic column of units found within the Patrick 7.5-Minute Quadrangle</td>
<td>27</td>
</tr>
<tr>
<td>8. Multiple sets of stacked cross-strata (5-23 cm thick) in coarse-to-medium sands associated with lithofacies 1</td>
<td>30</td>
</tr>
<tr>
<td>9. Beds of sand to pebbly sand related to the Middendorf Formation (Lithofacies 1)</td>
<td>30</td>
</tr>
<tr>
<td>10. Photomosaic of the Cretaceous Middendorf Formation that contains many of the characteristics found in lithofacies</td>
<td>32</td>
</tr>
<tr>
<td>11. Cretaceous outcrop along Brown Springs Church road that displas the vertical extent, horizontal extent, and some of the variation of cross bedding and structureless sands found within lithofacies 1</td>
<td>33</td>
</tr>
<tr>
<td>12. Stratigraphic log from A-A’ (Fig. 11) of the Cretaceous Middendorf Formation</td>
<td>34</td>
</tr>
<tr>
<td>13. A curved piece of fossilized conifer wood collected from the Middendorf Formation along the Seaboard Coast Line Railroad outcrop (Fig. 14)</td>
<td>35</td>
</tr>
<tr>
<td>14. Railroad outcrop approximately 1 mile southwest of the town of Patrick</td>
<td>38</td>
</tr>
<tr>
<td>15. Two strip logs (A-A’) and (B-B’) approximately 66 feet apart as whon by the outcrop in Figure 14</td>
<td>39</td>
</tr>
</tbody>
</table>
16. Large planar crossbeds showing a true dip towards the west/northwest direction with animal burrows and mm thick clay laminations (drapes?) on the tops of some of the crossbeds

17. Gray clay bed (below) in contact with an orange pebbly sand bed (above) forming flame structures at the top of the hammer

18. Alternating clay and sand beds of variable thicknesses (all < 1.5 m). Rock hammer for scale

19. Alternating clay and sand beds or laminations of variable thicknesses (< 1.5 m) at the Middendorf Type Section

20. A clay bed related to lithofacies 3 pinches out between the two markers (garden hoe shovel), infilling a channel-like depression within the Middendorf sands

21. A sandstone bed along route 1 southwest of the town of Patrick

22. A sandstone bed that sits on top of Cretaceous sands in the northwest corner of the Patrick quadrangle

23. Photomicrographs of thin sections associated with the outcrop exposures in figures 21 and 22 in plain polarized light (left) and cross-polarized light (right)

24. Ferruginous sandstone to pebbly sandstone at the top of Sugar Loaf Mountain

25. Iron-cemented sandstone to pebbly sandstone beds that make up Sheep Head Rock in the southwestern area of the Patrick quadrangle

26. Photomicrograph of a thin section associated with the rocks at the top of Sugar Loaf Mountain

27. Core correlations with a schematic of larger outcropping beds within the Patrick quadrangle

28. Typical clay minerals found within the Patrick quadrangle using X-Ray Diffraction (XRD)

29. Typical clay minerals found within the Patrick core using X-Ray Diffraction (XRD)

30. Typical clay minerals found within the Cheraw core using X-Ray Diffraction (XRD)

31. LiDAR derived from point cloud data showing GPR transects (A, B, C, D, and E) within the Pinehurst Formation
32. GPR transect (top) located in the Sand Hills State Forest in the western part of the Patrick quadrangle near Sugarloaf Mountain ........................................................................................................... 66

33. GPR transect (above) located on the Wilkes Farm Site approximately 12 m uphill from Juniper Creek ........................................................................................................................................ 67

34. 324 GPR profile within the Sand Hills State Forest Showing the slight undulatory nature of the contact between the Pinehurst and underlying Middendorf Formation .......... 68

35. A 3 m deep soil pit located approximately 30.5 m (100 feet) from the beginning of the GPR transect in figure 33 .................................................................................................................. 74

36. An outcrop within the borrow pit where the Patrick drill core was taken .................. 74

37. Lidar point cloud data shows the extent of a lower terrace in the Patrick quadrangle .... 78

38. Cumulative trough and planar crossbed measurements from the upper portion of the Middendorf Formation .................................................................................................................... 85

39. A series of rose diagrams displaying trough and planar crossbed measurements from the upper portion of the Middendorf Formation .................................................................................. 86

40. Two models for distal braided river systems proposed by (Miall, 1977)96 .................. 96

41. A redrafted cross-section of Swift and Heron’s (1969) cross-section of the Middendorf type section ................................................................................................................................. 100

42. Measured section by Sloan (1904, p. 107-108) at Sugarloaf Mountain (Swezey et. al., 2016) .................................................................................................................................................. 101

43. A redrafted version of Heron’s (1958) hypothetical cross section across Chesterfield and Darlington Counties, South Carolina ................................................................................................. 102

44. Optically Stimulated Luminescence (OSL) Age Dates for the Pinehurst Formation throughout the Middendorf and Patrick 7.5-minute quadrangles ............................................................................. 107
CHAPTER 1
INTRODUCTION

Overview of the Study Area

The purpose of this project is to produce a geologic map of the Patrick 7.5-minute quadrangle (Chesterfield County, South Carolina) to gain a better understanding of the geologic framework and minable resources in the area. This study area lies within the U.S. Atlantic Coastal Plain Province (Fig. 1), and also the Sand Hills Ecosystem Region (Griffith and others, 2002), which extends along the upper Coastal Plain from central North Carolina to the western border of Georgia (Fig. 2). The study area is also part of the recharge zone for the Middendorf aquifer, a large regional aquifer that underlies and supplies significant volumes of fresh water for the Coastal Plain of South Carolina. An increased understanding of the nature and extent of the sand and clay resources in this area could be used for multiple applications (e.g., paper and brick manufacturing, golf course sands, construction materials, and groundwater hydrology). Finally, the study area contains much of the Sand Hills State Forest, and a better understanding of the geology should lead to improved management of the State Forest.

Because this work was supported from the USGS EDMAP Program USGS scientists from the Coastal Plain Mapping program participated in this project and their contributions will be noted throughout this report. Of particular note is that the adjacent Middendorf S.C. quadrangle was mapped by Dr. Chris Swezey (USGS) concurrently with the Patrick quadrangle and the two maps will be published together.

Geologic mapping in this portion of the Atlantic Coastal Plain has been sparse due to the low economic demand for raw materials in this area. Nevertheless, it is broadly understood that the study area contains Cretaceous strata (sand and clay) overlain by a younger unit of predominantly sand.
There is great disagreement about many details of the Cretaceous strata. Several studies in North and South Carolina have relied on regional lithostratigraphy or biostratigraphy to separate distinct units within the Cretaceous strata along the upper Atlantic Coastal Plain (Berry, 1914; Cooke, 1926; Heron, 1958; Swift and Heron, 1969; Christopher, 1979; Owens and Gohn, 1985; Nystrom et al., 1991; Prowell, 2003). These studies provide information pertaining to regional lithological characterization, interpretations of depositional environments and sequences, and correlations of the Cretaceous strata from the upper Atlantic Coastal Plain to the Gulf Coastal Plain. Despite this previous work, variations in scientific approaches have resulted in conflicting ideas about the number of formations present, the details of subsurface stratigraphy, and the depositional models and ages of the unit(s).

There is also much disagreement about the younger (post-Cretaceous) sand that unconformably overlies the Cretaceous strata. Regional studies (Cooke, 1926; Cooke and others, 1961; Nystrom, 1989) from Aiken County to Chesterfield County, SC and into North Carolina provide some detailed geologic information on the regional distribution, depositional environment, and lithology of this unit. Nystrom (1989) correlates this post-Cretaceous unit with the Pinehurst Formation of North Carolina (Conley, 1962) but the timing of deposition and origin have remained in question due to age dating limitations and lack of provenance studies.

This study aims to build upon existing geologic interpretations of the formations within the Patrick quadrangle, and to provide new details about the characteristics, ages, and depositional environments of these units. Rooted in geologic mapping of the Patrick 7.5 minute quadrangle at a scale of 1:24,000, this study also incorporates data derived from subsurface drilling reports, LiDAR images, use of fossil interpretations, and detailed soil survey maps. Furthermore, new age dating techniques and modern field and laboratory analyses have helped to
solve some of the remaining questions related to the strata in this area. These data will be used to address two major hypotheses; (1) that the cretaceous unit(s) in the mapping area can be subdivided based on lithologic properties, and (2) that the Pinehurst Formation is much younger than previously thought, and it can be put into a regional context based on similarly aged eolian deposits throughout the southeastern Atlantic Coastal Plain.
Figure 1. Generalized map of the geologic provinces of South Carolina (North American Datum (NAD) 1983 StatePlane South Carolina FIPS 3900 (US Feet)). The study area (black box) is located in the northeast corner of the Upper Coastal Plain province directly south of the North Carolina and South Carolina state line boundary.
Figure 2. Location of the Patrick, S.C. quadrangle (1:24,000) within the Sand Hills Ecosystem Region, a zone that extends into Georgia and North Carolina (NAD 1983 StatePlane South Carolina FIPS 3900 (US Feet)). (Modified from Griffith and others, 2002)
Geologic Setting

Several topics need to be addressed in order to describe the geology of the Patrick 7.5-minute quadrangle properly. After discussing the location of the Patrick quadrangle, this thesis introduces the topography of the area, and the distribution of the geological units throughout the landscape. Lastly, the geologic resources and current land use are described in order to provide a context for understanding how they are being exploited.

The Patrick 7.5-minute quadrangle is positioned between 34° 37’ 30” N and 34° 30’ 00” N latitude and 80° 07’ 30” W and 80° 00’ 00” W longitude. Located 115.0 km to the northeast of Columbia, South Carolina, the study area lies in Chesterfield County just southeast of the fall line (Fig. 3). The quadrangle is northwest of the Orangeburg Scarp (Doering, 1960) and to the southwest of the Cape Fear Arch (LeGrand, 1961) within the upper Coastal Plain province of South Carolina.

The Patrick Quad topo map shows a rolling landscape that has been deeply incised by modern streams. Although the study area has not been affected by extensional tectonics, isostatic uplift may have played a part in shaping the region. This dissected landscape is characterized by incised valleys and rolling topography, where exposed sedimentary geologic formations are commonly highly weathered and fossil-poor. Regional-scale mapping indicates that the sedimentary units here on the western side of the Coastal Plain have been very gently warped by long-term crustal uplift patterns, notably isostatic uplift of the Appalachian Mountains to the northwest, and the rise of the Cape Fear Arch to the northeast (Gohn, 1988).

The terrain within the Patrick quadrangle has elevations ranging from 513 ft (e.g., Sugarloaf Mountain) to 150 ft (e.g., eastern part of Juniper Creek). Several of the hilltops in the area are marked by an irregular lumpy topography. Many of the hills have steep slopes that
transition into valley bottoms lined with terraces and flood plain deposits. As the streams here cut through the local strata, they flow east towards the Peedee River away from a minor drainage divide on the western side of the quadrangle. Small man-made dams modify the local base level of streams in many localities, resulting in the deposition of legacy sediments in upstream valley bottoms.

Even though the streams can reach elevations as low as 150 ft, none of the underlying Cambrian to Neoproterozoic Formations associated with the Piedmont terrain are exposed within the Patrick quadrangle. Instead, Cretaceous sediments overlie an unconformity on the older Piedmont rocks and cover a large percentage of the mapping area. Many of the Cretaceous deposits are fossil-poor and highly weathered, making both local and regional correlations difficult. In addition, some of the Cretaceous strata have been reworked by subsequent fluvial and eolian processes. For example, stream channels carved into the sandy Cretaceous strata have left younger Quaternary alluvial deposits on strath terraces. In addition, eolian processes have worked some of the Cretaceous sand and re-deposited this sand as eolian sand sheets and dunes. These windblown deposits were first described by Conley (1962) in North Carolina and are referred to as the Pinehurst Formation.

With only small-scale economic activity in the region, few demands have arisen for geologic resources in this area. The sandy, low-nutrient, well-drained nature of the Pinehurst Formation (Alpin-Candor soil series) only allows certain agricultural practices (e.g., peach trees and dairy farming), and is the main reason that much of the study area is used for growing longleaf and loblolly pine trees. Historically, this sand has been excavated in small borrow pits for road construction, but no demands have arisen for large-scale industrial operations within the Patrick quadrangle. However, sand and gravel mining operations are present further to the
northwest near Pageland, South Carolina. Cretaceous deposits near Patrick support small kaolin pits where clay has been mined for road repair, local medicinal and cosmetic purposes, and clay modeling. Larger kaolin deposits in the adjacent Middendorf quadrangle are currently being used for brick and paper manufacturing, but no such operations currently occur inside the Patrick quadrangle. Compared to the sands of the Cretaceous and Pinehurst Formations, younger stream terraces in the valley bottoms appear to be better suited for agricultural purposes according to Morton (1995), and are currently being used for row crop and cattle farming.

The Patrick 7.5 minute quadrangle falls within a unique coastal plain setting where there has been very little previous geologic mapping. A detailed geologic map, and associated data on the geologic units of the study area will increase an awareness of both the geologic history and economic possibilities in the area. If sufficient geologic resources can be identified, there is the potential to bring additional jobs to the Patrick area.
Figure 3. Location of the Patrick 7.5-Minute quadrangle (1:24,000) within Chesterfield County, South Carolina and relation to the fall line (NAD 1983 StatePlane South Carolina FIPS 3900 (US Feet)).
CHAPTER 2
GEOLOGIC HISTORY

Previous reports from the northern and central Sand Hills in South Carolina indicate that the Patrick area landscape is underlain by thick arkosic sand of Cretaceous age that is deeply weathered, incised by streams, and overlain by eolian sand of variable thickness. Berry (1910; 1914) followed the work of Sloan (1904) and described the Cretaceous Middendorf beds at the type section (McKennon railroad stop along the Seaboard Coast Line, approximately 3.2 km northeast of the community of Middendorf) as having cross-bedded arkosic sands with a clay lens that contained more than 40 species of Cretaceous leaf fossils. From this data Berry (1910) assigned a Turonian age to the Middendorf Formation. Later, Swift and Heron (1969) and Prowell (2003) expanded on Sloan’s (1904) work by providing detailed illustrations and descriptions of the area generally accepted as the Middendorf type section. Cooke (1926) states that Berry (1914) concluded that there is an overlap between the Cretaceous flora within the Middendorf Formation and the overlying Black Creek Formation, but in Cooke’s early work he separated the Middendorf and Black Creek strata into two separate units. Cooke (1936) and Stephenson (1942) later dropped the name Middendorf in favor of correlating the strata with the Tuscaloosa Formation in Tuscaloosa, Alabama.

Heron (1958; 1960) proposed that the Middendorf unit be brought back to formational rank and suggested a fluvial origin based on sedimentary structures. Swift and Heron (1969) traced the general lithology at the Middendorf type section throughout North and South Carolina. From their work they distinguished several facies throughout the Middendorf Formation and denoted them as “Middendorf materials.” Within the Patrick quadrangle, Swezey et al. (2016)
rafted a stratigraphic column of Sugarloaf Mountain from Sloan’s (1904) measured section showing the upper extent 156.4 m (513 ft) ASL of the Cretaceous deposits within the mapping area.

Swift and Heron (1969) also used clay mineral analyses to show that the Middendorf Formation differs from the Cretaceous Cape Fear Formation (which underlies the Middendorf Formation in North Carolina). They found that throughout North and South Carolina the Middendorf Formation is kaolin-rich with minor amounts of illite and montmorillonite, whereas the Cape Fear Formation is a kaolinitic clay with a montmorillonite fraction.

Geologists have found it difficult to agree upon the appropriate formation name for the Cretaceous strata in the upper Coastal Plain of South Carolina, and they have also found it difficult to agree on the exact age of the strata. After the work of Berry (1910: 1914), there was a long hiatus of paleontological work on the Cretaceous strata until Christopher (1979), who correlated existing palynology zones from Cretaceous strata in New Jersey to help establish ages and biostratigraphic control for the Cape Fear, Middendorf, and Black Creek Formations within North and South Carolina. According to Christopher (1979), deposition of the Middendorf Formation took place during pollen zone 5 (Middle Turonian to late Santonian). Subsequent investigators (Prowell and others 1985; Owens and Gohn 1985; Nystrom and others 1991) continued to use biostratigraphy to separate the timing of depositional sequences within the upper Coastal Plain of South Carolina. Prowell (2003) divided the Cretaceous unit(s) at the type section into the up-dip portion of the Pee Dee and Bladen Formations on the basis of paleontological data collected from drill core and outcrop samples in Chesterfield and surrounding counties.
Previous geologic mapping in Chesterfield County has been at a relatively coarse scale. Howell and Butler (1977) Open-File Report – 17, produced a 1:100,000 scale geologic map of Chesterfield County, and a 1:62,500 scale geologic map of the Patrick quadrangle. The text accompanying the Patrick and Chesterfield County maps provided very brief descriptions of topography, and identified the following three units in the Patrick quadrangle: (1) the Cretaceous Middendorf Formation (Km); (2) the Tertiary Pinehurst Formation (Tp); and (3) Quaternary alluvium (Qal). Howell and Butler (1977) described the dominant lithology of the Middendorf Formation as being orange, poorly sorted kaolinitic sandy clay or clayey sand with thin gravel layers and scattered kaolinitic clay balls. They described the Pinehurst Formation as much less weathered fine-to-medium sand that covers many hill tops and side slopes with dunes and colluvium. Approximately 80 km to the southwest of the Patrick quadrangle, Ridgeway et al. (1966), working in the 7.5 minute Blaney quadrangle (Kershaw County and Richland County, South Carolina), interpreted the sand beds within the Middendorf that were not kaolin-bound as the sources of the younger eolian sand. They also claimed that the similarity of heavy mineral sand compositions (tourmaline, rutile, zircon, ilmenite, limonite, monazite, epidote) between the two units supported that conclusion. Where possible, they used stipple patterns on their map to note areas with thick accumulations of eolian sand.

Other descriptions of the Cretaceous strata include a regional summary by Gohn (1988), who reported that Cretaceous outcrops in northern South Carolina represent delta-plain and delta-margin deposits assigned to the Black Creek Formation. Nystrom and others (1991) mapped the Fort Jackson North 7.5 minute quadrangle, next to the Blaney quadrangle, and described Middendorf-correlative (“Tuscaloosa”) Cretaceous units as follows:
“The outcropping sediments of the upper Coastal Plain are mostly micaceous, kaolinitic sands, with lenses of clay of variable thickness. Sands are mostly coarse sand to granule size, angular to subangular and poorly sorted, but some fine-grained, fairly well-sorted sands do occur. Rounded pebbles occur in thin lenses or are scattered through the sand. The mineral grains are mostly quartz, with smoky quartz fairly common. Ubiquitous white mica constitutes no more than a few percent of the material. Dark, heavy minerals are common, and feldspar grains are rare. Rock fragments may occur at the base. Kaolinitic clay occurs as clay coating on sand grains, as matrix supporting ‘floating’ sand grains and as rounded clasts or ‘balls.’” (Nystrom et al., 1991, p. 221)

Sohl and Owens (1991) provide the most recent compilation of the regional studies that have been published on the chronologic nomenclature and age assignment of the Cretaceous lithostratigraphic units in the Coastal Plain of North and South Carolina.

On top of the Middendorf Formation lie eolian sands of variable thickness. Cooke (1936) used the name “Congaree Sand Hills” to denote extensive sand accumulations across the inner Coastal Plain that “correspond approximately to the area in which the Upper Cretaceous Tuscaloosa formation is exposed (p. 11).” He noted that the Sand Hills are cut by river valleys but that eolian action appears to have had a considerable effect in shaping the topography. Johnson (1961), Pooser and others (1961), and Otwell and others (1966) also provided brief descriptions of “post-Eocene” sand hills in Richland and Kershaw Counties, near Columbia, South Carolina. They speculated that part of these sand accumulations were of eolian origin and part were of subaqueous origin.

As Ivester and others (2011) explained, eolian sands lying atop the Cretaceous sediments are reported by several authors. Nystrom and others (1991) interpreted sand bodies on the upper
Coastal Plain of South Carolina as dunes based on good sorting and lack of mica in the sand. They suggested a Late Miocene to Pliocene age for the deposits. Nystrom and Kite (1988) followed Bartlett (1967) in designating these sands as the Pinehurst Formation.

Modern geophysical, aerial, and dating techniques have allowed scientists to address a suite of heretofore unanswered questions within the upper Coastal Plain. Moore and Brooks (2011) reported that LiDAR imagery shows eolian dunes are generally widespread in the upper Coastal Plain. According to them, first-order stream heads are the source of some eolian features across this hilly landscape. Inland sand dunes identified elsewhere in South Carolina (e.g. Ivester and Leigh, 2003) formed on broad valley-bottom plains where large paleo-braided river deposits appear to be source of the windblown sand. A few relatively recent studies have documented ca. 14,000-year records of palynological changes in ponds among dunes in Richland and Kershaw Counties (Watts, 1980; Taylor and others, 2011). Farther east on the terrace flats planed off by repeated Pleistocene and Pliocene marine transgressions across the middle and lower Coastal Plain of South Carolina, dunes and eolian rims associated with Carolina Bays have yielded OSL ages that suggest a dry, windy climate existed across the region during many episodes between 80 and 18 ka (Ivester and others, 2004).

Most recently, Markewich et al. (2015) has shown that late-middle and Late Pleistocene, and Holocene inland eolian sand and loess blanket a large area of the unglaciated eastern United States of America (USA). OSL data from Markewich et al. (2015) suggests that eolian activity along the southeastern Atlantic Coastal Plain may have been episodic in nature during the Late Pleistocene.
CHAPTER 3

METHODS

Three sets of investigative approaches were followed to achieve the goals of this research project. The first involved gathering data through field mapping, drill core analyses, ground-penetrating radar (GPR), grain size analysis, and petrographic analyses to improve the understanding of the thickness, lateral extent, stratigraphy, and lithology of the geologic units in the study area. The second involved optically stimulated luminescence (OSL) dating to investigate the timing and origin of the surficial Pinehurst Formation that overlies an unconformity on the Cretaceous Middendorf Formation. The third component employed X-Ray powder Diffraction (XRD) to characterize the clay content of the Cretaceous sediments (both at the surface and at depth).

Field Mapping

Prior to field mapping, preliminary field reconnaissance work was performed to gain a general understanding of landforms and stratigraphy in the study area and how they related to Coastal Plain strata across the region. This reconnaissance involved a review of existing publications, topographic maps, LiDAR imagery, soil maps, and previously unpublished maps of the study area. As stated previously the most recent geologic map of the Patrick quadrangle (1:65,000) is an Open-File Report (OFR) by Howell and Butler (1977). U.S. Geological Survey (USGS) topographic maps (1:24,000) and U.S. Department of Agriculture (USDA) soil maps (1:20,000) available on Topoquest (www.topoquest.com/map-detail.php?usgs_cell_id=34400) and Web Soil Survey (http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx) were combined with LiDAR imagery as multiple layers in ArcGIS to identify landforms and potential
sites with known geologic contacts before starting field work. Google Earth images were used to locate large outcrops within the study area. The preliminary work led to data collection in the field, collecting samples for lab analyses, and constructing a geologic map and cross section.

Geologic mapping of the 7.5 minute Patrick quadrangle was carried out over 60+ days from the summer of 2013 through the spring of 2015. A topographic map of the Patrick 7.5 minute quadrangle at a scale of 1:24,000 was used as a base map to plot and record field data from 300+ outcrops and subsurface exposures (e.g., soil auger cuttings, hand pits, and back hoe dug trenches). The location, thickness of the units, lithology, sedimentary structures, and soil horizons were used to describe the outcrops and subsurface data. A Brunton compass was used to record true and apparent dip angles from cross-beds in weakly lithified to unconsolidated sands. Few strike and dip angles of bedding were measured due to the scarcity of non-horizontal beds throughout the quadrangle.

Several outcrops, borings, trenches, and pits were sampled for more detailed laboratory analysis during field mapping. Samples were chosen on the basis of the location within the landscape, the geologic unit, sedimentary facies present (only in Cretaceous unit), unit thickness, and lithology in order to meet the objectives of the project. Three lithified rocks were collected from outcrops within the Patrick quadrangle and sent to National Petrographic Service, Inc. to be made into thin sections. These thin sections were analyzed and photographed under a petrographic microscope. Twenty-six outcrops were sampled for clay analysis in order to be analyzed using x-ray diffraction (Fig. 4). In addition, seven sites were sampled for OSL dating, four outcrops were sampled by both Old Dominion University and the USGS (Fig. 4), and three sites were sampled solely by the USGS. Thirteen samples were collected for grain size analysis in order to characterize both the Pinehurst and Middendorf Formations. Petrified wood fossils
with iron and silica replacement were collected and photographed at several localities in the quadrangle. One locality along the Eastern Seaboard railroad (at approximately 34° 33’ 53.84” N, 80° 3’ 34.24” W) yielded an approximately 1.5 m long fossilized log. Unfortunately, no fossilized leaves were identified as described by Berry (1914).

Multiple geodatabases were created to keep track of the inputs and outputs for this project. A topographic map from the Topoquest website was downloaded, stored, and brought into the map document as a layer in order to show natural and man-made objects within the Patrick quadrangle. The soils maps for Chesterfield County were downloaded from Web Soil Survey to show the extent of certain soil series that correlate with the geological units. Previously processed LiDAR data from the USGS was used in the form of a raster data set. The LiDAR data set was georeferenced using an underlying base map within ArcMap. Once the data layers were put into the table of contents, the Patrick topographic boundary layer and the soils layer were combined using the intersect tool into one layer in order to analyze the possible extent of the geologic units. Outcrop data were brought into ArcMap from Excel, and converted into a feature class point layer within the Patrick geodatabase. Lastly, the geologic units polygon shapefile that was created using the editor and snapping tools was brought into the geodatabase and made into a feature class polygon layer. All of the data layers were projected in North American Datum 1983 (NAD 1983) State Plane South Carolina “on the fly.” The editor tool was used to make necessary updates to the map over the course of the project. The finished map in ArcGIS was transferred to Adobe Illustrator version CS5 version 15.1.0 to be made into a working PDF.
Figure 4. Optically Stimulated Luminescence (OSL) and X-Ray Diffraction sample locations in and around the Patrick 7.5-Minute quadrangle (NAD 1983 StatePlane South Carolina FIPS 3900 (US Feet)).
Drill Core Analysis

Drill cores collected across the Atlantic Coastal Plain have historically provided detailed information for litho- and bio-stratigraphic analysis as well as valuable hydrological information. During this project, a 85.34 m (280.0 ft) drill core named the Patrick core (CTF-320) was collected from March 8, 2014 to March 11, 2014 at 34° 33’ 10.94” N, 80° 37’ 40.52” W by the U.S. Geological Survey drill team run by Eugene F. Cobbs III using a wire line drill rig (Fig. 5). The site was chosen due to its close proximity to the Middendorf type section, located approximately 0.40 km (0.25 mi.) away. The core was immediately cleaned of drilling mud, logged, cut into sections, and placed into pre-labeled boxes. Each box was described, photographed in the field, and later transferred to the USGS core laboratory in Reston for additional descriptions and analyses.

Once in the core laboratory, the entire core was laid out and photographed again before it was split into working and nonworking pieces. Each piece of the core was split down the middle using a trough, a piece of piano wire, or a saw depending on the compaction and hardness of the sediment. The working side of the core was meticulously described into a stratigraphic log showing lithology, bed thickness, and sedimentary structures. Nine clay beds were sampled and marked for bulk clay mineral analysis at different depths (Appendix C). Additionally, Christopher Bernhardt (USGS) extracted two samples from dark gray clay beds for pollen analysis. The entire stratigraphic log was drafted in 3.05 m (10 ft) sections (Appendix C).

A second drill core CTF-81 was collected in 1995 by the U.S. Geological Survey drill team run by Eugene Cobbs II and Eugene F. Cobbs III in coordination with the South Carolina Geological Survey. The drill site was located roughly 22.2 km (13.8 miles) northeast of the Patrick core (CTF-320) in Cheraw State Park at approximately 34° 38’ 35.79” N, 79° 54’ 41.73”
W (Fig. 6). A simplified, unpublished description by David Prowell (USGS retired) of this core does exist, but for thoroughness the core was re-described during this project. Prior to this re-description the Cheraw core (CTF-81) was never split into working and non-working pieces, but appeared lightly scraped with a pocketknife. Therefore, once the Cheraw core was photographed an attempt was made to split the core into a working and non-working side. The dry condition of the core made it difficult to split and much of the core fell apart during the process. After the core was split, it was described, sampled, and drafted using the same process and tools as used on the Patrick core. The entire stratigraphic log was drafted in 3.05 m (10 ft) sections (Appendix C).

Figure 5. The U.S. Geological Survey wire-line drill core rig positioned at the Patrick (CTF-320) drill core site.
Figure 6. Location of the Patrick Core and the Cheraw core in relation to the Patrick 7.5-Minute quadrangle (NAD 1983 StatePlane South Carolina FIPS 3900 (US Feet)).
**Ground-Penetrating Radar (GPR) Data Collection and Processing**

Ground Penetrating Radar (GPR) is a noninvasive geophysical method used to produce high-resolution cross-section images of subsurface features along a surveyed profile. GPR enables the visualization of certain sedimentary structures (e.g. cross-bedding) and stratigraphic contacts that may not be visible at outcrop scale, and served as a critical supplement to borehole data and outcrop data throughout the study area.

GPR data were collected along 12 pre-selected survey transects at four separate sites within the Patrick 7.5 minute quadrangle. GPR survey sites were chosen based on available LiDAR imagery, Chesterfield County soil maps, and geological field mapping data applied in ArcGIS. The objective of these surveys was to investigate stratigraphic thickness, depositional contacts, and sedimentary structures within the Quaternary eolian and Quaternary river terrace deposits that lie above an unconformity on the older Cretaceous sediment. GPR survey data were collected with a towed-array system using a GSSI SIR-3000 and 200 Megahertz (MHz) antenna outfitted with an integrated survey wheel that was calibrated in the field. Locations of survey transects were recorded with a survey grade Trimble Geo XH GPS (horizontal accuracy ± 4 inches (10.2 cm)). Depth calibration to known stratigraphic contacts was performed with a 4.88 m (16 ft) hand auger at select locations along each profile to insure accurate interpretation of post-processed survey data. Post-processing and examination of GPR data was conducted using RADAN 7 processing software. Post-processing of data from each transect involved time-zero depth correction (air-wave removal), background removal (reduction of horizontal frequency noise), frequency filtering (reduction of vertical high-frequency noise), and surface normalization (topographic correction). Elevation data for surface normalization was derived
from Chesterfield County LiDAR data. Specific GPR setup parameters and post-processing filter constraints are described in Appendix E.

Age Dating

Recently developed during the last 30 years, Optically Stimulated Luminescence dating has proven to be an effective tool to date young (Quaternary) sediments. During this project, OSL dating was used to estimate the age(s) of the Pinehurst Formation and to provide an age constraint on the unconformity between the Pinehurst Formation and underlying Cretaceous Middendorf Formation. OSL sites were selected based on field mapping, LiDAR data, and GPR data. A total of 18 OSL samples were collected at seven different sites throughout the Patrick and Middendorf 7.5 minute quadrangle. Fifteen of the eighteen samples were processed by Shannon Mahan (USGS, Denver, Colorado) using the Single Aliquot Regenerative-dose (SAR) protocol. The remaining three samples were collected from trenches (backhoe dug) and processed by George A. Brook (University of Georgia, Athens, Georgia) using the Single Aliquot Regenerative-dose (SAR) protocol described by Aiken (1998). Samples were sent to separate laboratories in an attempt to verify reported ages. Each of the OSL samples was collected by hammering a 2-inch diameter PVC pipe horizontally into the sediment at a depth of approximately 2 m (see Table 3 for complete depths) to avoid bioturbation effects from plants and animals. To minimize light exposure, OSL samples were capped, sealed, and labeled with the GPS location, elevation above sea level, depth below surface, sampling date, and sampling time. A moisture sample was collected at each site and the average moisture content of each sample was determined in the laboratory for the samples sent to the University of Georgia.
Clay Mineral Analysis using X-Ray Diffraction (XRD)

X-Ray powder Diffraction (XRD) is a nondestructive tool used to generate unique patterns (diffractograms) by the diffraction of x-rays from different crystal faces within a bulk sediment sample. Traditional field techniques can be used to describe particle size and basic mineralogy, but grain size cards and hand lenses are used primarily for sediment > 63 µm. For smaller grain sizes, XRD can be used for the rapid identification and quantification of mineralogy.

A total of forty-three clay samples (26 throughout the field mapping site, 9 from the Patrick core, and 8 from the Cheraw core) were collected to provide a representation of the horizontal and vertical spatial distribution of the Cretaceous clay minerals. Samples were prepared according to Eberl (2004; RockJock) in order to produce diffractograms associated with random oriented sediments. All of the samples were run by Frank T. Dulong (USGS, Reston, VA). These samples were prepared using a standard back loading technique and analyzed on a Phillips Panalytical X’Pert Pro Powder Diffractometer. The XRD was equipped with a Copper tube, 10 mm slit, and phase array accelerator for processing samples quickly and efficiently. Clay samples were run from 5-65° 2θ using a step of 0.017° 2θ, and processed using X’Pert Highscore Pro software integrated with Reitveld Analysis to identify minerals present, mineral percentages, and crystallinity.

Grain Size Analysis

A total of 13 samples were processed at Old Dominion University using a Malvern Mastersizer 2000 laser diffractometer with a Hydro 2000G dispersion unit to provide a high-resolution particle size analysis of the Cretaceous and Quaternary sediments within the study.
site. Mastersizer 2000 version 5.60 software was used to collect and view the results of the data. All the data were exported from the Mastersizer 2000 software into an Excel spreadsheet. Each sample was prepared using water as a dispersant (refractive index 1.33). If a sample contained a greater percentage of clay, then an admixture of sodium hexametaphosphate was added to the dispersant at 1 g/l to avoid additional peaks within the data from bubbles (usually 100 µm in size). Each sample treated with sodium hexametaphosphate was allowed at least 24 hours to defloculate before being sonified and loaded into the Hydro 2000G dispersion unit. A Standard Operating Procedure (SOP) was set up in the Mastersizer software prior to each sample being measured to insure sampling consistency. A pre-measurement time of 60 s was used before each sample ( aliquot) was measured three times using a refractive index of 1.549 (Quartz) and a measurement time of 50 s with 50,000 snaps.
CHAPTER 4

RESULTS

Stratigraphy of the Patrick Quadrangle

Stratigraphic interpretations were made on the basis of geologic field mapping (surface data) and data from drill cores and logs (subsurface data). These two techniques (along with X-Ray Diffraction, petrographic analysis, and sediment texture analysis) helped to characterize and describe the Cretaceous Middendorf Formation. Additional data from hand augered cores, LiDAR, and Chesterfield County soil maps provided the necessary information to characterize the Pinehurst Formation, modern stream terraces, and flood plains. GPR profiles and OSL ages helped to resolve questions about the age and stratigraphic position of the Pinehurst Formation.

Geologic mapping of the study area revealed four distinct units that range from Cretaceous to Quaternary in age (Appendix F). The Cretaceous units are the oldest, thickest, and most widespread strata within the quadrangle. The Cretaceous strata are capped by an unconformity, above which are the younger Quaternary deposits at many localities (Fig. 7). The geologic units within the Patrick 7.5-Minute quadrangle are described in chronological order in the following sections.
Figure 7. Generalized stratigraphic column of units found within the Patrick 7.5-Minute Quadrangle. Unit thickness is relative to one another.

**Cretaceous Middendorf Formation**

The Cretaceous Middendorf Formation extends throughout the Patrick quadrangle, where outcrops are numerous but are of limited exposure. Despite the limited exposure, the outcrop data revealed the presence of several distinct lithofacies (described below). Two drill cores (Patrick core, Cheraw core) in the vicinity revealed that these lithofacies determined from outcrop data can be recognized in the subsurface.
Lithofacies (Determined from Outcrop Data)

The Middendorf Formation is mostly weakly consolidated sand, sandstone, mud, and gravel. Some of the units of sands contain variable amounts of clay matrix, whereas other units of sand do not contain any clay matrix. The units of uncedmented mud are mainly silty clay with sparse grains of quartz sand. Most sandy beds are dominated by quartz with minor amounts of mica and opaque heavy minerals. Where the sandy units are unweathered, they are predominately white. Where the sandy units are weathered, however, they are usually a combination of orange, yellow, brown, red, and purple. Clay units within the area are predominantly white and light to dark gray, with minor amounts of purple, yellow, brown, pink, and red hues within.

The more typical units of the Middendorf Formation are very coarse to fine grained (subangular-to-rounded pebbles occur in certain places), angular-to-subrounded, and poor to moderately sorted sand with occasional well-sorted beds in places. At some places, sandy beds display evidence of scour, planar and (or) trough cross-bedding, fining-upward sequences, and (or) laminations. Massive, uniform sands are present at several localities. Multiple outcrops contain silty clay beds with sparse quartz grains throughout. The white, gray, and purple clay beds are generally lens-shaped and pinch out laterally over short distances, making correlation difficult from one outcrop to another. Clay rip-up clasts are common in multiple outcrops. Many of the quartz sand grains are coated with a clay matrix.

Some outcrops contain secondary features such as flame structures, animal burrows, weathered feldspar grains, fossilized conifer wood fossils, and iron concretions. At certain localities, soil profile development has obliterated primary features due to mottling, increased clay content, and presence of plinthitic nodules. In certain cases, sand and clay beds are
indurated. Iron oxide, clay matrix, and silica act as cement in certain deposits. Geologic mapping indicates that five lithofacies exist within the study area. These lithofacies are described below in more detail.

Lithofacies 1

Of the five lithofacies associated within the Middendorf Formation, the most abundant one within the mapping area is the medium-to-coarse sand to pebbly sand, with cross-bedding in some places, and structureless in others. Outcrops of Lithofacies 1 are commonly weathered, and the unit is predominantly orange but also may display combinations of white, tan, brown, yellow, orange, red, and purple. Unweathered outcrops are usually mostly white. The large number of outcrops that contain this lithofacies can be found at a wide range of elevations throughout the study area. Outcrops containing this lithofacies can exist at elevations in excess of 121.9 m (400 ft) as shown by the outcrop on Brown Springs Church Road or can rest at elevations below 76.2 m (250 ft) as found in the borrow pit off of Scotch Road in the northwest corner of the quadrangle. Several smaller outcrops show the variation that can occur within this lithofacies (Figs. 8 and 9). However, one large outcrop south of the town of Patrick on Brown Springs Church Road provides an excellent example of the characteristics exhibited by this lithofacies (Figs. 10, 11, and 12).
Figure 8. Multiple sets of stacked cross-strata (5-23 cm thick) in coarse-to-medium sands associated with lithofacies 1. The rock hammer to the right of the white rectangle rests directly below a sloping, silty clay bed associated with lithofacies 3.

Figure 9. Beds of sand to pebbly sand related to the Middendorf Formation (Lithofacies 1). (Top Bed) Burnt orange, poorly sorted, subangular, very coarse-to-medium, quartz sands to pebbly sands with rounded-to-subrounded kaolin rip-up clasts (up to 8 cm). (Lower Bed) Predominately white, moderately sorted, subangular, coarse-to-fine, cross-bedded, quartz sands.
Lithofacies 1 consists of fine-to-very coarse grained, angular-to-subrounded, poorly-to-moderately sorted sand to pebbly sand (pebbles are commonly subangular-to-rounded), with occasional well sorted beds in certain localities. A light colored matrix (kaolin) is present in most outcrops, but at some places the sand may contain little to no matrix. Most sand grains consist of quartz with minor amounts of mica and heavy minerals. Kaolin rip-up clasts, weathered feldspars grains, iron concretions, and subrounded-to-rounded quartz pebbles are found in certain localities.

Primary sedimentary structures are common in outcrops, but are much harder to distinguish within drill cores. These primary sedimentary structures include tabular (planar) cross-bedding and trough cross-bedding. Cross-bed data were recorded throughout most of the quadrangle. Only the northeastern portion of the mapping area did not have many outcrop exposures with cross-beds. Paleocurrent direction of the Middendorf Formation was determined using the dip direction from 148 cross beds at 11 exposures scattered throughout the quadrangle. Overall the paleocurrent direction for the Middendorf Formation has a mean value of 158° towards the southeast. However, when the cross-bed data were split into individual outcrops or into a combination of closely associated outcrops (Fig. 38) the flow direction was more erratic and the mean values ranged from southeast to southwest.
Figure 10. Photomosaic of the Cretaceous Middendorf Formation that contains many of the characteristics found in lithofacies 1. The outcrop can be found at 34° 30’ 46.79” N and 80° 03’ 29.39” W. Person for scale in photograph is 6 feet tall. See the cross section and stratigraphic log on the following pages for a more detailed description.
Figure 11. Cretaceous outcrop along Brown Springs Church road that displays the vertical extent, horizontal extent, and some of the variation of cross bedding and structureless sands within lithofacies 1.
Figure 12. Stratigraphic log from A-A’ (Fig. 11) of the Cretaceous Middendorf Formation. Sands exhibit a fining upward sequence that starts with a scour at 3.8 ft and is masked by soil processes at 7.3 ft. Colors are taken from a Munsell Soils Color book.
In addition to primary bedding features, outcrops related to lithofacies 1 displayed secondary features as well. A number of conifer tree fossils were found within beds associated with lithofacies 1 (Fig. 13). Multiple outcrops contained iron concretions and small, weathered, monoclinic shaped kaolinitic clasts that resemble feldspar clasts. Pedogenic processes such as mottling and plinthite formation may obscure primary bedding features within outcrops related to lithofacies 1.

Figure 13. A curved piece of fossilized conifer wood collected from the Middendorf Formation along the Seaboard Coast Line Railroad outcrop (Fig. 14) (Note: The cellular pattern in the lower left portion of the fossil). This particular fossil contains iron oxide replacement, but occasional fossils were found to contain silica.

One outcrop within the quadrangle contained multidirectional cross-bedded sands with mm-thick clay laminations (drapes?) on the cross-beds. This exposure is positioned along the
Seaboard Coast Line Railroad at (34°, 33’ 53.74” N, 80° 03’ 34.31” W) approximately 1.61 km (1 mile) southwest of the town of Patrick (Fig. 14). Woollen and Colquhoun (1977) originally described this outcrop, but did not mention the clay laminations on the cross-beds in their description. Below are the lithological descriptions, cross bed data, and Malvern data collected from this the railroad outcrop.

The exposure along the Seaboard Coast Line Railroad appears to have been recently excavated within the last 50 years based on its proximity to the railroad and lack of extensive weathering. Given the low amount of weathering the colors at the site can be described as predominately white with purple, yellow, brown, tan, and orange staining in places. Sands are predominately medium-to-coarse grained, moderate-to-well sorted, and subangular-to-subrounded in nature. The sand is unconsolidated with little to no matrix present. Sands are composed of quartz, mica 0-5% and minor < 1% opaque heavy minerals in places. Sands contain large planar cross beds (up to 2 meters thick) with mm-thick clay laminations (drapes?) overlying certain beds (Fig. 16). Additionally the cross beds may be multi-directional and contain visible animal burrows on the tops of some of the beds. A clay bed at the base of the outcrop on the western end contains flame structures (Figs. 14 and 17). All of these characteristics are displayed in the cross section shown in (Fig. 14).

The railroad outcrop rests between 59.4 – 68.6 m (195 and 225ft) in elevation, but the multidirectional cross-beded sands with mm-thick clay laminations were only found in the lower 4.57 m (15 ft) of the outcrop towards the base. Many of these measured cross beds were found to have a true dip towards the west/northwest direction. However, some of the beds did exhibit a true dip towards the south/southeast direction. The rose diagram in Fig. 40 shows these findings.
Grain-size analysis of 4 samples in a Malvern Mastersizer 2000 (Table 1) reveal that the mean grain size was between 0.67Φ and 2.82 Φ, which is fine to medium sand [According to Folk (1980), 0.67 Φ is coarse sand]. Additionally, these analyzed samples were moderate-to-poorly sorted, fine to strong-fine skewed, and mesokurtic to extremely leptokurtic.

The fine-to-coarse (mainly medium-to-coarse) sand to pebbly sand, with cross-bedding in some places, and structureless in others is widespread throughout the Patrick quadrangle. The outcrops described above (Figs. 8, 9, 10, and 14) display features commonly associated by lithofacies 1. The cross-bed measurements from these outcrops show a southeastern flow for the streams that deposited these sediments. One outcrop found along the Eastern Seaboard Railroad exhibits multidirectional and mm-thick clay laminations (drapes?) (Fig. 14). This outcrop was the only one found that exhibits these characteristics and the reasoning for placing it within this lithofacies will be explained in a later section.
Figure 14: Railroad outcrop approximately 1 mile southwest of the town of Patrick. The black square (1) corresponds to Figure 16 and shows large west to northwest dipping planer crossbeds with mm thick clay laminations (Drapes?) in places. The second black square (2) corresponds to figures 17 and shows flame structures. A-A’ and B-B’ are shown in Figure 15.
Figure 16. Large planar crossbeds showing a true dip towards the west/northwest direction with animal burrows and mm thick clay laminations (drapes?) on the tops of some of the crossbeds. Pointer finger rests on one of the clay laminations.

Figure 17. Gray clay bed (below) in contact with an orange pebbly sand bed (above) forming flame structures at the top of the hammer. Exposure is located on the western side of Fig. 14. The clay bed was sampled for XRD analysis.
**Lithofacies 2**

Lithofacies 2 is < 1.5 m thick units of alternating beds or laminations of sand and clay. In outcrops of Lithofacies 2, the sand is typically tan to orange, whereas the clay is typically gray. This lithofacies was found at a handful of outcrops within the quadrangle. Outcrops of lithofacies 2 are present at elevations in excess of 400 ft (e.g. Sugarloaf Mountain) and at elevations as low as 91.4 m (300 ft) as shown by the outcrop in Fig. 18. Figure 18 is located in the southeastern corner of the topographic map just northeast of Plainview School in an abandoned clay pit.

Typically the sandy beds and laminations of Lithofacies 2 consist of coarse to fine sand that is moderate-to-poorly sorted, subangular-to-subrounded in nature. A light colored matrix (kaolin) is present in most outcrops, but at some places the sand may contain little to no matrix. Most sand grains are composed mainly of subangular-to-subrounded quartz with minor amounts of mica and heavy minerals.

Grain-size analysis of 2 samples in a Malvern Mastersizer 2000 reveal that the mean grain size was between 2.13Φ and 2.19Φ, which is fine sand. These sands are poorly to very poorly sorted, strongly-fine skewed and leptokurtic to very leptokurtic in nature (Table 1).

The clayey beds of Lithofacies 2 consists of silty clay with sparse floating quartz grains in certain samples. Clay mineral analysis shows that the clays by the Middendorf type section (Fig. 19) are composed of 77.4% well crystallized kaolinite, 0.7% anatase, and 21.9% amorphous material. In comparison the clays from the abandoned pit (Fig. 18) close to Plainview School contain 17.4% illite, 45.3% moderate to well-crystallized kaolinite, 24% quartz, and 13.4% amorphous material.
Alternating beds or laminations of sand and clay < 1.5 m thick can be seen at different intervals within the Patrick and Cheraw drill cores (Appendix C). One example of this lithofacies within the Patrick core is between 109.2 m to 109.1 m ASL. Similarly, in the Cheraw core interbedded sand and clay beds are visible from 39.8 m to 39.7 m and from -6.2 m to -6.8 m towards the base of the Cheraw core. Here sands to pebbly sands and clay with visible black specks that have been interpreted as plant debris.

Fossils and iron concretions were absent within this lithofacies. However, many of the beds are thoroughly oxidized and iron stained. Pedogenic processes were not apparent factors on this lithofacies, but the black specks of debris within the Cheraw core are likely related to previous subaerial exposure processes.

Lithofacies 2 is less abundant throughout the Patrick quadrangle and within the Cheraw and Patrick cores in comparison to Lithofacies 1. Drill core data and field mapping suggests that the lithofacies can exceed elevations of 121.9 m (400 ft) ASL and can be found at -6.8 m (-22.3 ft) below sea level. Clay analysis and samples from the drill cores and Patrick quadrangle suggest that the primary minerals within these beds are illite, kaolinite, quartz, and amorphous material with minor amounts of anatase. The majority of the clay analysis in the quadrangle was performed on lithofacies 3 as explained within the next section.
Figure 18. Alternating clay and sand beds of variable thicknesses (all < 1.5 m). Rock hammer for scale.

Figure 19. Alternating clay and sand beds or laminations of variable thicknesses (< 1.5 m) at the Middendorf Type Section. A fingernail points to a scour in the lower clay bed.
<table>
<thead>
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<th>Sample Name</th>
<th>Location</th>
<th>Elevation (ft)</th>
<th>Mean (Φ)</th>
<th>Mean (μm)</th>
<th>Sorting</th>
<th>Skewness</th>
<th>Kurtosis</th>
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<tr>
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<td>34°31’ 24.16” N, 80° 04’ 10.66” W</td>
<td>397.00</td>
<td>0.98</td>
<td>508.0</td>
<td>1.51</td>
<td>0.42</td>
<td>3.09</td>
</tr>
<tr>
<td>Sandy Hill Rd. (Lithofacies #1)</td>
<td>34°30’ 11.06” N, 80° 03’ 47.81” W</td>
<td>332.00</td>
<td>2.82</td>
<td>141.9</td>
<td>2.36</td>
<td>0.51</td>
<td>1.06</td>
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<tr>
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<td>34°30’ 11.06” N, 80° 03’ 47.81” W</td>
<td>394.00</td>
<td>0.67</td>
<td>628.6</td>
<td>1.00</td>
<td>0.19</td>
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</tr>
<tr>
<td>Seaboard Coastline Railroad (Lithofacies #1)</td>
<td>34°, 33’ 53.74” N, 80° 03’ 34.31” W</td>
<td>203.00</td>
<td>1.63</td>
<td>324.2</td>
<td>1.57</td>
<td>0.33</td>
<td>2.12</td>
</tr>
<tr>
<td>Abandoned Clay Pit (Lithofacies #2)</td>
<td>34°31’ 06.23” N, 80° 02’ 08.17” W</td>
<td>311.00</td>
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<td>224.7</td>
<td>2.27</td>
<td>0.39</td>
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<tr>
<td>Middendorf Type Section (Lithofacies #2)</td>
<td>34°32’ 59.85” N, 80° 07’ 46.60” W</td>
<td>356.00</td>
<td>2.13</td>
<td>227.9</td>
<td>1.70</td>
<td>0.58</td>
<td>2.47</td>
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<tr>
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<td>385.00</td>
<td>2.40</td>
<td>189.4</td>
<td>2.32</td>
<td>0.47</td>
<td>1.24</td>
</tr>
<tr>
<td>Candor Cut Profile C (N/A)</td>
<td>34°36’ 45.72” N, 80° 01’ 04.61” W</td>
<td>257.00</td>
<td>4.11</td>
<td>59.76</td>
<td>3.49</td>
<td>0.17</td>
<td>0.85</td>
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</tbody>
</table>

Table 1. Grain size data from the Middendorf Formation (lithofacies 1 and 2) within the Patrick 7.5 Minute Quadrangle, Chesterfield County, South Carolina. Samples that contain an N/A below the name have been altered by soil forming processes.

**Lithofacies 3**

Lithofacies 3 can be described as flat-to-lens shaped, discontinuous, gray, beds of clay and (or) silty clay that are ≥ 1 m thick. These beds are not part of the clay beds associated with lithofacies 2. Geologic mapping, drill core analysis, and clay mineral analysis have allowed for a better understanding of the lithology, and distribution of this lithofacies.

Beds associated with lithofacies 3 are predominately white and light to dark gray, with minor amounts of purple, yellow, brown, pink, and red, although beds usually weather to white and light gray when exposed at the surface. The beds consist mainly of silty clay that may or may not contain sparse floating grains of quartz. The floating quartz is very coarse-to-very fine sand that is subangular-to-subrounded. The quartz grains may have purple and red stains around them in certain hand samples. Beds may contain up to < 5% mica and minor amounts (< 1%) of
heavy minerals. Pure clay beds are rare, but are present as shown in the Cheraw and Patrick drill cores (Appendix C).

None of the clay beds produced the leaf fossils described by Berry (1914). Two darker gray clay beds at (34° 36’ 45.72” N, 80° 01’ 04.61” W) that contain charcoaled plant fragments, were sampled and are currently being processed at the USGS by Chris Bernhardt. Clay beds in the Patrick core and quadrangle displayed laminations and disrupted bedding. Secondary structures such as flame structures, animal burrows, root structures, and pieces of organic debris were discovered in the mapping area and drill cores.

The clay beds within the quadrangle were found to show some degree of weathering, induration, and (or) are only partially exposed at the surface. Bed thickness can range from 1.0 m to > 9.0 m, as shown by the large clay bed found within the Patrick core (Appendix C), but the beds tend to pinch out laterally over short distances (Fig. 20). Clay beds that are < 1.0 m thick, not associated with lithofacies 2 were considered to small to map and are part of the surrounding lithology. Few beds over 1.0 m are exposed at the surface, and only three locations contained clay beds > 9 m (found during geologic mapping). One in the southeast corner of the quadrangle showed the possibility of being a thick bed similar to a > 9 m thick clay bed in the Patrick Core. The discovery of this potentially large bed was made on the basis of several outcrops that were partially exposed at the surface at different elevations. Further confirmation of the large clay bed in this area came from the landowner who claims that he has been approached in the past about uncovering the clay bed for mining.

Only two clay beds in the mapping area may correlate with each other. The first one is the 1.5 m (5 ft) thick clay bed shown in the cross section of the outcrop along the Seaboard Coastline Railroad (Fig. 14), and the second clay bed is located at (34° 36’ 45.72” N, 80° 01’
04.61” W) approximately 1.10 km (0.70 miles) southwest of the railroad outcrop on route 1. These beds are between 71.0 m – 67.1 m (200 ft-220 ft) elevation with similar thickness and lithology. It is possible that a thick clay exposure in the Middendorf quadrangle from 91.4 m (300 ft) to 86.0 m (282 ft) correlates with the thick clay bed in the Patrick drill core that exists from 87.3 m (286 ft) to 77.4 m (254 ft) ASL. If so, this clay bed spans roughly 4.83 km (3 miles) in length and rests beneath the drainage divide that separates the southerly-flowing Big Black Creek in the Middendorf quadrangle from the eastward-flowing streams throughout the Patrick quadrangle.
Clay mineral analysis shows that the major clays minerals associated with lithofacies 3 are kaolinite (75.9 - 26.7%), illite (24.2% - 4.9%; some samples do not have any illite present), quartz (39.4% - 8.0%), and amorphous material (37% - 7.2%), with minor amounts of sodalite and anatase. None of the beds associated with the third lithofacies contains montmorillonite, smectite or any type of feldspars.

Geologic mapping, drill core analysis, and clay mineral analysis show that beds associated with lithofacies 3 are predominately kaolinitic, fairly wide spread throughout the quadrangle and two cores, and difficult to correlate.

**Lithofacies 4**

Lithofacies 4 is a quartz sandstone with a mud (kaolin) matrix. The sandstone is typically gray to pinkish gray, white, or tan, but weathers to a darker gray. The sandstones are typically
composed of coarse-to-medium, and subangular-to-subrounded sand grains. Lesser amounts of
fine sand and quartz pebbles are present in a few locations. In some hand samples, quartz sand
grains are floating within a mud matrix. Most of the sand grains consist of quartz with minor
amounts of mica and heavy minerals. Beds are primarily massive, but there are hints of
horizontal to slightly undulatory beds that are 0.2 – 0.6 m (0.7 – 2.0 ft) thick. Beds are primarily
flat lying and may show scouring at the base.

All of the sandstone beds were found at elevations between 61.0 and 91.4 m (200 and 300
ft) ASL. None of these outcrops were found in the southern portion of the mapping area.
Several beds were found to span the length of the outcrop, but many do not extend far beyond
this point. All of the beds related to this lithofacies were found as the top bed at each outcrop.
These beds cap hilltops and form local ledges as shown by Figs. 18 and 19. In some cases, beds
may form larger regional ledges (currently discontinuous) as shown by the sandstone bed in the
Northeast corner of the geologic map (Appendix F). A portion of this sandstone bed is located at
(34°, 36’ 30.74” N, 80° 06’ 17.15” W) and spans a total area of approximately 6,200 sq. ft.
(Fig. 22). Several of the beds do not extend far into the hill behind the outcrop. Both rock types
were found to be in close proximity (less than 100 ft) to each other at (34°, 33’ 35.01” N, 80° 04’
46.89” W). The thicknesses of the beds can range from < 0.30 m (1 ft) to < 1.5 m (5 ft).
Figure 21. A sandstone bed along route 1 southwest of the town of Patrick. Directly across the road in an opposite facing outcrop lies a separate sandstone bed.

Figure 22. A sandstone bed that sits on top of Cretaceous sands in the northwest corner of the Patrick quadrangle. This bed is part of a larger discontinuous ledge that was sampled for thin section analysis in a nearby location.
Thin section analysis (Fig. 23) of samples collected from the outcrops in Figs. 21 and 22 show that these rocks are poorly sorted sand grains surrounded in a matrix material (kaolinite), with minor amounts of cement and porosity present. The rock from the outcrop in Fig. 21 contains 50% framework grains that are composed of 99% quartz (monocrystalline and polycrystalline), 0% feldspar, and 1% lithic grains (this includes mica and opaque minerals). This rock contains 40% matrix material, 5% cement (silica and authigenic kaolinite rinds around quartz grains), and 5% porosity (intergranular). The rock from Fig. 22 has a similar assemblage of 60% framework grains that are composed of 97% quartz (monocrystalline and polycrystalline), 0% feldspar, and 3% lithic grains (this includes mica and opaque minerals). Additionally, this rock contains 30% matrix material, 5% cement (silica and authigenic kaolinite rinds around quartz grains), and 5% porosity (intergranular). Some of the quartz grains have inherited quartz overgrowths and contain voids that are filled with matrix material due to dissolution.
Figure 23. Photomicrographs of thin sections associated with the outcrop exposures in figures 21 and 22 in plain polarized light (left) and cross-polarized light (right). Fig. 21 is associated with letter (A) and Fig. 22 is associated with letter (B). The thin sections show poorly sorted, Monocrystalline (MQ) and Polycrystalline (PQ) Quartz, Muscovite mica (M), and Opaque (O) grains that are completely separated by a Kaolinitic Matrix (KM).

All of the rocks associated with lithofacies 4 were found at the surface; none were recovered from the subsurface. Similarly, lithofacies 5 was only discovered in surficial exposures within the Patrick quadrangle, and are not present within the subsurface.

**Lithofacies 5**

Lithofacies 5 is ferruginous sandstone to pebbly sandstone. Weathered outcrops of this lithofacies are brown, red, and purple, whereas freshly broken surfaces are primarily shades of purple. Most of the deposits consist of poorly sorted, subangular-to-subrounded quartz sand
grains and pebbles that are cemented together by iron oxides. A few deposits contain rip-up clasts of kaolinite and weathered feldspars.

Ferruginous sandstone outcrops are present in the southern and in the northern portion of the mapping area (Appendix F). All of the sandstone beds were found at the surface. These sandstone beds commonly cap hills, form ledges (Figs. 21 and 22), or establish small knolls within the landscape (i.e., on side slopes). Beds of iron-cemented sandstone are up to 1.43 m (3.75 ft) thick in certain locations (e.g. Sugarloaf Mountain). At Sugarloaf Mountain the 1.43 m ferruginous sandstone caps a hilltop, but larger blocks of sandstone appear to have slide down from previously higher elevations. These displaced pieces of sandstone were up to 2.7 m (9 ft) thick. A measured section by Sloan (1904) was redrafted by Swezey et al. (2016) shows the position of lithofacies 5 at Sugar Loaf Mountain in relation to lithofacies 1, 2, and 3 (Fig. 42). A thin section from one of the iron-cemented sandstones higher in the section is described below.

Thin section analysis of a ferruginous sandstone from the top of Sugarloaf Mountain contains 55% framework grains that are composed of 99% quartz (monocrystalline), 0% feldspar, and 1% lithics (this includes mica and opaque minerals). Additionally, this rock contains 5% matrix material, 30% cement (iron oxides), and 10% porosity (intergranular). The thin section of the ferruginous sandstone (below) shows that this rock is poorly sorted, with quartz grains that rarely touch each other (Fig. 26).
Figure 24. Ferruginous sandstone to pebbly sandstone at the top of Sugar Loaf Mountain. This sandstone is believed to be in place.

Figure 25. Iron-cemented sandstone to pebbly sandstone beds that make up Sheep Head Rock in the southwestern area of the Patrick quadrangle. Notice the gnarly weathering pattern on the iron-cemented beds. Rock hammer for scale. This rock is part of a larger discontinuous iron-cemented ledge.
Ferruginous sandstone to pebbly sandstone beds exist throughout the Patrick quadrangle, but are not as abundant as other lithofacies within the study area. All of the Cretaceous lithofacies described above were used to distinguish the Middendorf formation from the overlying Pinehurst formation during geologic mapping.

**Drill Core Analysis (Subsurface)**

The Cheraw and Patrick cores revealed beds with similar characteristics to those of the Cretaceous strata mapped in the Patrick quadrangle. The Patrick core started at a ground elevation of 113.7 m above sea level (ASL), and was terminated at a depth of 85.3 m (ASL) before reaching bedrock. The Cheraw core started at a ground elevation of 58.8 m (ASL) and reached an elevation of 15.5 m below sea level. A contact between the Middendorf Formation and the Paleozoic schist was found at a depth of 66.4 m. Pebbles [up to 5 cm in diameter] of smoky quartz and milky quartz can be found at this contact.
In both cores, the strata are predominately sands to pebbly sands. Other lithologies throughout the cores are \( \leq 1.5 \) m thick units of alternating sand and beds of clay to silty clay (lithofacies). One thick bed composed mainly of clay to silty clay was found at 26.8 to 38.1 m depth in the Patrick core. Fining-upward sequences (FUS) ranging from \(< 1 \) m up to 3.7 m were discovered throughout both cores. Occasionally, the smaller FUS are stacked, and appear to be part of a larger FUS. A good example of this type of sequence occurs from 36.2 m to 44.6 m within the Cheraw core. Cross-strata along with low angle-to-horizontal laminations lie within a few of the sandy beds. An assemblage, unusual in these two cores of coarse-to-very fine sand with disrupted bedding, mottled texture (moderate red 5R 5/4, pale yellowish orange 10YR 6/6, and very light gray N8), and downward tapering vertical structures is present in the Cheraw core at 36.3 to 38.1 m depth (20.7 to 22.5m ASL). Likewise, a similar distinctive assemblage is present in the Patrick core at 81.7 to 85.3 m depth (27.5 to 31.1 m ASL). In both cores, clay beds are more common above this interval, and gravel is more common below. Additional work may show that this interval denotes buried soils formed on a regional unconformity (Fig. 27).

Pollen was successfully extracted from both cores, but only the palynomorphs from the Cheraw core have been identified by Chris Bernhardt (USGS) thus far. The pollen and spores were found in a silty clay bed at the base of the Cheraw core at 65.5 m depth (6.7 m below sea level). Swezey et al (2015) has shown that the palynomorphs within this bed are Late Cretaceous and some of the fossils appear to be associated with intermittently flooded, poorly drained flood plains within freshwater environments.
Figure 27. Core correlations with a schematic of larger outcropping beds within the Patrick quadrangle.
Clay Mineral Analysis (Middendorf Formation)

The clay samples collected from the Patrick quadrangle, Patrick core, and Cheraw core show the spatial distribution of the clay minerals throughout the Middendorf Formation within this study site. X-ray diffraction using X’Pert Highscore Pro software integrated with Reitveld Analysis provided the minerals present, mineral percentages, and crystallinity (kaolinite only).

Twenty-six samples from the Patrick quadrangle were analyzed by XRD. The major minerals found in the mapping area are kaolinite (up to 77.4%), quartz (up to 64%), illite (up to 24.9%), and amorphous material (up to 37%). Minor amounts of sodalite (up to 4.2%), and anatase (up to 1%) occur in 19 of the 28 samples. One sample (found at 34°, 31’ 05.21” N, 80° 04’ 42.83” W) contains 6% zeolite. None of the other samples contain this mineral. The presence of zeolite might have been introduced via sampling processing, given the grinding process that the clay minerals go through. Of the 28 samples 17 are well crystallized when compared to the reference standard KGa-1, a well crystallized kaolinite from Washington Co., GA. Eleven samples are moderately to poorly crystallized when compared to reference standard KGa-2, a poorly crystallized kaolinite from Warren Co. GA. KGa-1 and KGa-2 were originally described by Van Olphen and Fripiat (1979) as well crystallized and poorly crystallized, respectively.
Figure 28. Typical clay minerals found within the Patrick quadrangle using X-Ray Diffraction (XRD). This sample was collected from the clay bed on the north side of the outcrop on Brown Springs Church Road (Figure 11).

Nine samples were run from the Patrick core at different depths. The Patrick core contains kaolinite (up to 62.5%), quartz (up to 50.1%), and amorphous material (up to 32.6%). Seven of the nine samples contain a minor amount of anatase (up to 0.8%). Six out of the nine samples from the Patrick core are moderate to well crystallized, and 3 are poorly crystallized when compared to the KGA-1 and KGA-2 reference standards. The three poorly crystallized samples are at a depth of 72.9m to 79.4m below the surface. Four samples were collected from the 11.3 m thick clay bed in the Patrick core and the samples contain (57.1-62.5%) kaolinite, (14.2-22.3%) quartz, (18.1-25.0%) amorphous material, and 0.7% anatase.
Eight samples were run from the Cheraw core at different depths. Six contain the same major minerals—quartz (up to 49.1%), kaolinite (up to 69.8%), and amorphous material (up to 44.2%). A sample taken at 45.2 m contains 7.1% illite in addition to the other major clay minerals. Weathered minerals collected close to the bedrock were run and found to be microcline feldspars. The other sample from the core was collected from the saprolitized bedrock (a metasiltstone), and it is composed of 17.3% illite, 2.0% kaolinite, 62.5% quartz, and 18.2% amorphous material. Two of the samples have well-crystallized kaolinite, and 5 of them are poorly crystallized when compared to the two Georgia standards.
The clay mineralogy in the Patrick quadrangle, Cheraw core, and Patrick core are very similar and only contain differences within the minor minerals present. The three sites provide a surficial and subsurface representation for the entire Middendorf Formation within the immediate area. None of the samples collected within the quadrangle, or two cores contain smectite, chlorite, and (or) montmorillonite, as found within other Cretaceous strata in the Carolinas.

**Quaternary Pinehurst Formation**

The Pinehurst Formation (Fig. 7) is composed of unconsolidated sands, with minor amounts of silt and clay that form hills or sheet-like deposits throughout the landscape. Beds are
typically unweathered, and can be tan, brown, white, and yellow within an outcrop. Deposits are composed of quartz sand with minor amounts (< 1%) of mica and opaque heavy minerals. The sandy deposits are predominately coarse-to-fine grained, subangular-to-subrounded, and poor-to-moderately sorted. Very coarse and granule-sized quartz grains are sparsely scattered throughout several deposits.

Primary structures were absent in all of the exposures of the Pinehurst Formation’s surficial deposits; their absence is attributed to bioturbation, soil profile development, and/or insufficient outcrop thickness. Large cross-bedding does appear at depth in nearly all of the GPR transects made across this formation. Secondary features such as krotovinas, soil lamellae, and paleosols with argillic horizons exist in certain exposures. Modern root structures were visible in many localities.

Across the Patrick quadrangle Pinehurst Formation deposits were discovered on hilltops, side slopes, and older terraces. All of these sand deposits rest unconformably on the older Quaternary or Neogene(?) terraces or on top of the Middendorf Formation or as shown in Figs. 35 and 36, respectively. All outcrops of Pinehurst sands found during mapping were < 3 m thick, and were only mapped in areas where they are ≥ 2 m.

USDA soils maps were one of several tools used to delineate the boundaries of the Pinehurst formation. The Alpin sand and Candor sand soil series definitions include at least 2 m of uniform sand. The mapped soil boundaries were used as formation boundaries initially, but those contacts were critically assessed and adjusted wherever possible by GPR and LiDAR data, outcrops, and additional auger hole information.
Sand dune deposits only appear on terraces that are > 6 m above the modern stream channel. Additionally, none of the lower terraces (< 4.6 m) or modern flood plains contained sand sheets or dunes related to the Pinehurst Formation.

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Location</th>
<th>Elevati on (ft)</th>
<th>Mean (Phi)</th>
<th>Mean (μm)</th>
<th>Sorting</th>
<th>Skewness</th>
<th>Kurtosis</th>
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<td>1.87</td>
<td>300.37</td>
<td>0.99</td>
<td>0.08</td>
<td>1.15</td>
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<tr>
<td>Pit 2 on Tommy Wilkes Property (C Horizon)</td>
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</tbody>
</table>

Table 2. Grain size data from the Pinehurst Formation within the Patrick and Middendorf 7.5 minute quadrangles, Chesterfield County, South Carolina. All of the samples were collected from parent material below eluviated or argillic horizons unless otherwise noted.

Size analysis from six separate locations has shown that the Pinehurst Formation is predominately fine-to-medium sand with moderate-to-poor sorting. Three of the deposits have grain-size distributions that are near-symmetrical with the other three being fine to strongly-fine skewed. Two out of the three nearly-symmetrical deposits are mesokurtic, and the other four deposits are leptokurtic to very leptokurtic. Additionally, Pinehurst sands at the Candor roadcut and the borrow pit at the drill site show better sorting than the underlying Middendorf Formation.
Size frequency distributions were determined for the Pinehurst Formation at each OSL site (table 3) by Chris Swezey (USGS). The sieving was performed at 0.5 phi intervals and these data show that the Pinehurst sands at these sites are moderately-to-poorly sorted, coarse-to-fine sands.

**Ground Penetrating Radar Profiles**

Subsurface data on the Pinehurst Formation using GPR were collected from three separate locations during June of 2014 (Fig. 31). LiDAR imagery, USDA soils maps, and geologic mapping data were effective in characterizing each locality before it was investigated via GPR. A total of five transects were recorded at three sites. All of the transect profiles revealed supplementary subsurface data that were not available through traditional geologic mapping. Two representative profiles (A-A’; C-C’) shown in Figures 32 and 33 were collected on the western side of the Sand Hills State Forest and on private farmland, respectively. The location of the other three profiles (B-B’, D-D’, and E-E’) are shown in the LiDAR map below (Fig. 31). Interpretation of GPR data collected along a 323 m transect in the Sandhills National Wildlife Refuge (Middendorf quadrangle) shows evidence that may support multi-directional cross-bedding within the Pinehurst Formation.
The 324 m transect from A-A’ is located on the western side of the Patrick quadrangle within the Sand Hills State Forest. The hilly landscape starts below 106.7 m (350.0 ft) and reaches an elevation of > 121.9 m (> 400.0 ft). Here geologic mapping and auger hole data confirmed that the surficial material is the Pinehurst Formation and the underlying material is the Middendorf Formation. The GPR profile (Fig. 34) shows that up to 8.5 m of relief exists locally on the surface between the Pinehurst sands and the underlying Cretaceous sands. Similar to the Pinehurst deposits seen in outcrop, the uppermost 2 m of many of the sand hills do not display sedimentary structures, but 2-to-5 m thick sets of southeast-dipping cross-bedding are visible at depths below 2 m (Figs. 32 and 33). Data from a separate transect B-B’ run in the opposite direction of A-A’ confirmed that the cross strata are indeed dipping towards the southeast. GPR also revealed that the sandy deposits that form hills are up to 7 m thick. Additionally the GPR profile from A-A’ revealed that up to three separate deposits may exist within the Pinehurst.
Formation at this locality (Fig. 34). The interpretation that multiple deposits exist within the GPR profile was confirmed by the data collected from a 4.9 m auger hole 313 m from the beginning of the transect. The underlying Cretaceous topography at this site is primarily flat, but does show some degree of undulation due to weathering and incision (Fig. 34). GPR revealed that the underlying Cretaceous strata appear to be interbedded clays and sands with channel scour-and-fill.

A 313 m transect collected from C-C’ was run 16.4 m across a low terrace near Juniper Creek. This transect was collected by running GPR off of a side slope and on to a relatively broad, flat surface adjacent to the modern stream channel. The GPR profile generated from the subsurface strata shows at least two distinct deposits within the first 64 m of the profile. Sands associated with the Pinehurst Formation are clearly recognizable on the side slope with 3-4.5 m thick cross strata visible at depths below 2 m. Two trenches confirmed that these sands are indeed part of the Pinehurst Formation, and also uncovered the existence of two separate soil profiles within the second trench. The buried soil profile was not originally evident in the GPR profile, but upon further inspection there is a small reflector that intersects the second trench at a depth of 1.9 m. Beneath these cross strata, the GPR signal hit several strong horizontal reflectors that are interpreted as horizontal beds. The GPR signal is attenuated in places along these deposits due to an increase in silt and clay within certain beds. Bore hole data coupled with GPR data revealed that the horizontal beds are composed of modern stream deposits, as well as the Middendorf Formation. All of the data collected along this transect clearly show that the Pinehurst Formation rests unconformable on both the Middendorf Formation and stream terrace deposits that exist at higher elevations.
Figure 32. GPR transect (top) located in the Sand Hills State Forest in the western part of the Patrick quadrangle near Sugar Loaf Mountain. Cross section (bottom) shows distinct features found within the two sandy formations.
Figure 33. GPR transect (above) located on the Wilkes Farm Site approximately 12 m uphill from Juniper Creek. The cross section (above) shows the three separate deposits uncovered using GPR, backhoe dug trenches, and hand auger data. These deposits contain three disconformities. One disconformity is between the two deposits within the Pinehurst formation, one is between the Pinehurst formation and the Quaternary or Neogene terrace, and one is between the two Quaternary/Neogene (?) units and the underlying Middendorf formation. The change within the terrace material on the right side of the cross section was interpreted through data collected from a separate trench taken ~227 m east of the 4.9 m auger hole. The terrace material found in the 4.9 m auger hole and in the trench to the east both start at ~59.4 m (195 ft) above sea level (ASL) and have been interpreted as the same surface. The water table (WT) was identified through GPR and hand augering and is represented by a dashed line.
Figure 34. 324 m GPR profile within the Sand Hills State Forest showing the slight undulatory nature of the contact between the Pinehurst and underlying Middendorf Formation. Auger data was used to confirm the contact between the two Formations.
Optically Stimulated Luminescence (OSL) Dating

Eighteen age dates were generated from Optically Stimulated Luminescence (OSL) age dating from six sites within the Patrick and Middendorf 7.5-minute quadrangles. Chris Swezey (USGS) and I collected all of the samples between 2012-2014. The samples were run by the USGS lab in Denver, Colorado, and the University of Georgia using the Single Aliquot Regenerative (SAR) procedure. The labs used quartz grains from 150μm to 250μm. The samples were collected from 40 cm to 250 cm below the surface and yielded ages between 8.83 ± 1.33 ka and >117 ka. The Lab in Denver provided ages using the OSL minimum age model-3, the weighted mean OSL value, and the mean OSL value, all using equivalent dose (DE) determinations (appendix). Only the weighted mean OSL value was reported in Table 3. The University of Georgia only provided ages using the weighted mean values, which are reported in Table 3.

Eight samples were collected at three separate locations within the Patrick quadrangle and all of them are within the Pinehurst Formation. Two samples were collected from a 1 m deep soil pit within the Sand Hills State Forest (34° 35’ 0.78” N, 80° 06’ 15.48” W). The soil pit contained a thin O horizon (0-1 cm) with a hue of 10YR 8/1 white, clean sand, and a thin layer of pine needles. Directly beneath the O horizon rests a coarse-to-fine, sandy A horizon (1-24 cm) with a hue of 10YR 3/3 dark brown. A clear wavy boundary separates the A horizon and a coarse-to-fine sandy E horizon (24-62 cm) with a hue 10YR 6/6 brownish yellow. A gradual wavy boundary exists between the E horizon and the underlying coarse-to-fine sandy B horizon (62-100 cm) with a hue of 10YR 5/8 yellowish brown. Each of the soil horizons had modern tree roots throughout. The OSL sample taken at a depth of 42 cm within the E horizon produced a date of 9.60 ± 0.89 ka and another sample taken at a depth of 85 cm in the B horizon produced
a date of 22.74 ± 1.91 ka. The location of this soil pit can be viewed on the GPR transect in Fig. 32.

A road cut along Isaac Road (34° 36’ 45.72” N, 80° 01’ 04.61” W) generated three of the oldest age dates recorded within the Pinehurst formation. Because the soil series at this site is the Candor sand, this location is known as the “Candor site.” The youngest deposits crop out at the southern most portion of the road cut, and the oldest deposit is exposed at the bottom of the northern edge. One OSL sample was collected at a depth of 210 cm within a loose, sandy C horizon with a hue of 10YR 8/6 yellow, and thin soil lamellae throughout. This deposit produced an age date of 51.3 ± 2.85 ka. A very distinct wavy boundary can be seen between this C horizon and the underlying Btₜ horizon. The Btₜ horizon is a loamy sand with a hue of 7.5YR 5/8 strong brown. This horizon has been interpreted as a buried soil and can be traced throughout the exposure laterally. Below the Bt horizon rests another loose sandy deposit, this deposit is part of a Cₜ horizon with a hue of 7.5YR 8/4 pink. This horizon contains visible lamellae. The Cₜ horizon was sampled at depths of 259 cm and 238 cm and produced ages of 67.1 ± 5.46 and 56.1 ± 4.90, respectively. A photomosaic was constructed in order to show the location of all three samples within the outcrop (Appendix D).

On private farmland at a location known as “Wilkes farm site” a backhoe was used to dig two trenches into the sandy hill slope deposits identified through GPR and bore hole data (Fig. 33). The trenches were roughly 18.3 m apart and located at (34° 34’ 44.2” N, 80° 01’ 43.2” W) on private farmland. The first trench was 2.5 m deep and contained only one deposit. The soil profile contained a thin O horizon, a 0.2 m thick sandy Aₚ horizon with a hue of 10YR 5/3 brown, a 0.3 m thick sandy E horizon with a hue of 10YR 6/6, a 1.0 m thick loamy sand B horizon with a hue of 7.5YR 5/8 strong brown. The B horizon is separated from the underlying
C horizon by a gradual wavy boundary with visible root structures. The underlying 1 m thick sandy C horizon has a hue of 10YR 6/6 brownish yellow. One OSL sample was taken at a depth of 2.5m within the C horizon and produced an age date of 33.8 ± 3.39 ka.

The second trench (Fig. 35) reached a total depth of 3 m and contained three separate deposits. The pit contained a thin O horizon as well as a 0.4 m thick sandy A_p horizon with a hue of 10YR 5/3 brown. Directly below the A_p horizon from 0.4 m to 1.9 m there is a loose, sandy C horizon that has a hue of 10YR 8/1 white and 10YR 8/6 yellow. This soil horizon contains multiple soil lamellae that have a hue of 10YR 6/8 brownish yellow, and start at a depth of 0.8 m below the surface. The soil lamellae are up to 1cm thick in places. This material was sampled at a depth of 1.9 m for OSL dating and produced an age date of 12.06 ± 2.05 ka. An abrupt boundary separates the C horizon from the underlying deposit. The underlying deposit is 0.8 m thick, and is a loamy sand with a hue of 10YR 6/8. This deposit was interpreted as a B_{th} horizon. This deposit was sampled at a depth of 2 m for OSL dating and produced an age date of 29.18 ± 4.86 ka. A wavy boundary separates the B_{th} horizon from an underlying sandy loam deposit that contains mottling. The sandy loam is exposed in the bottom 0.3 m of the trench. The ages confirmed the assumption that the sands from the first pit and the sandy loam from the second pit were deposited around the same time.

The borrow pit where the Patrick core was taken was also sampled for OSL dating. This pit is not within the Patrick quadrangle, but is important to mention given its close proximity to the Middendorf type section. This pit shows an abrupt boundary between the loose yellow, tan, and white sands of the Pinehurst Formation and the underlying oxidized and mottled surface of the Middendorf sands (Fig. 36). This boundary also provides evidence for small animal borrows no more than 2 cm in diameter. The pit was sampled at 60 cm and 200 cm from the surface
within the Pinehurst formation, and was found to be 25.94 ± 2.30 ka and 46.77 ± 4.00 ka, respectively.
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<th>Longitude (West)</th>
<th>Stratigraphy</th>
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<th>Depth (cm)</th>
<th>Water content(%)</th>
<th>U (ppm)</th>
<th>Th (ppm)</th>
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Table 3. Optically Stimulated Luminescence (OSL) data from the Patrick and Middendorf 7.5-minute quadrangles, Chesterfield County, South Carolina. Age (ka) = age in thousands of years (ka) ago using the weighted mean OSL value for equivalent dose (DE) determinations. These ages and other ages presented in this table are reported in years before AD 2012-2015 (the date of age determination). Paleodose (Gy) = equivalent dose (grays) using the weighted mean; Dose Rate (Gy/ka) = total dose rate (grays per thousand years); K (%) = potassium content (percentage); Th (ppm) = thorium content (parts per million); U (ppm) = uranium content (parts per million); water (%) field moisture (complete sample saturation percentage in parentheses); Depth (cm) = sample depth (centimeters below surface); Elevation (m) = sample site elevation (meters above sea level); Stratigraphy = geologic formation present; Method = Single Aliquot Regenerative (SAR) method; Lab No. = ID for each lab; Lab = lab that processed sample; Quadrangle = Patrick or Middendorf 7.5-minute quadrangle. Samples above a depth of 200 cm may be subject to bioturbation.
Figure 35. A 3 m deep soil pit located approximately 30.5 m (100 feet) from the beginning of the GPR transect in figure 33. Distinct, irregular boundary lines (white) separate three separate deposits within the soil pit. OSL dating techniques were used to sample the first two deposits (white circles). Soil lamellae are clearly visible in the youngest deposit.

Figure 36. An outcrop within the borrow pit where the Patrick drill core was taken. Here the Pinehurst Formation rests unconformably on the Middendorf Formation (white line). The boundary line contains multiple animal burrows (krotovinas). The OSL sample of 46.07 ± 2.67 ka was taken at 2 m in order to avoid bioturbation. Upper OSL date at ~ 1 m may be subject to bioturbation.
Quaternary and Neogene (?) Stream Terraces

Outcrops related to the modern stream terraces are extremely limited in the Patrick quadrangle, and hard to trace downstream given the small mapping area. The lack of observable outcrops does not provide the level of detail necessary for a thorough understanding of the deposits at the surface. Therefore, multiple subsurface techniques (e.g. bore hole data, GPR, and trench data) combined with the few available outcrops in the quadrangle were used to investigate the different levels of terrace surfaces in the study area. Data collected from the terraces revealed the lithology as well as the soil characteristics, thicknesses, and position within the landscape of these deposits. Terraces were found at different elevations within the quadrangle, but in order to keep it simplistic for mapping purposes the terrace deposits were mapped as a terrace complex. Additional analyses of terraces on tributaries leading east towards the Peedee River are needed before the multiple surfaces can be differentiated into mappable units.

The stream terraces within the Patrick quadrangle are composed of unconsolidated, very coarse-to-fine, subrounded-to-angular, moderately to poorly sorted sand, silt, and clay. The sands are composed of quartz with minor amounts of mica (< 1%). Many deposits contain rounded-to-angular quartz pebbles (up to 1.9 cm). Smoky, milky, and clear quartz pebbles were visible within deposits, but no rose quartz grains were found within these valley units. Within many of these deposits the coarser sands and pebbles were located towards the base as part of an overall fining-upwards sequence. A few of the sands to pebbly sands contain light gray clay clasts (up to 2 cm). Deposits that are closer to the modern flood plains are typically shades of browns and yellows, while higher deposits contain hues of reddish yellows and browns. Small, broken iron concretions appear reworked in a small outcrop along Juniper Creek just southwest of the town of Patrick.
Thirty auger holes and 2 backhoe trenches dug into different terrace surfaces revealed the range of characteristics between soil profiles on these terrace surfaces. These data suggest that three groups of terraces exist in the Patrick Quadrangle – lower terraces (0 - 4.6 m above the river level (ARL)), mid-level terraces (4.6-9.1 m ARL), and high level terraces (more than 9.1 m ARL).

Deposits up to 4.6 m ARL can be ≥ 2 m thick, but are commonly ≤ 2 m. These lower deposits typically contain little to no organic matter below the O and A/Ap horizons of the soil profiles. The more mature soil profiles at these lower elevations contain E horizons (up to 8 cm) and Bt horizons (up to 68 cm) thick. Most of the soil profiles have two different C horizons. Pebbly sands, sands, loamy sands, sandy loams and sandy clay loams are commonly associated with the C horizon from the terrace deposits. These parent materials contain yellow and brown hues. Very commonly these deposits are underlayin by a different parent material composed of coarse-to-fine sands, loamy sands, sandy loams, or silty clays with light gray and white hues. An example of a soil sampled on a lower terrace that does not appear to be disturbed lies in the Sand Hills State Forest (Appendix D). According to Morton (1995) the Pelion soil series is mapped here, but this profile appears closer to the Ailey soil series, a soil series that commonly displays a distinct A, E, BE, Bt, Btx, 2C and 2Cd horizon. All of the horizons above the light gray, silty clay, 2C horizon are thought to be part of the modern terrace. The 2C horizon has been interpreted as the Middendorf Formation. The C horizon is distinct with its alternating sandy clay loam and sandy loam deposits.

A separate deposit on a lower level terrace 1.2 m ARL at the Wilkes Farm site shows less soil profile development than a lower terrace found within Sand Hills State Forest (Appendix D).
The profile at the Wilkes Farm Site contains an O, A, and C horizon, all composed mostly of sand to pebbly sand. Slight but notable differences in grain size and color occur within the C horizons (Appendix D). Towards the bottom of the profile the pebble size increases and small clay clasts occur. This deposit would be considered a sandy inceptisol given its light colored A horizon and few diagnostic features. Differences between this lower terrace deposit and the deposit from within the Sand Hills State Forest show the range of soil profile development between the lower level terraces in the study area. Visualizing the parent materials from these two deposits proves helpful when trying to identify older terrace units at higher elevations.

The most distinct lower terrace surface in the quadrangle rests < 1.6 km SE of the town of Patrick on the Wilkes Cattle Field site at the confluence of Juniper and Mill creek. This site is distinguishable on the topographic map and LiDAR imagery given its flat, broad, and elongated shape that is parallel with both streams (Fig. 37). Analyses of GPR transects and hand auger data show a thin terrace deposit underlain by silty clays associated with the Middendorf Formation throughout most of the pasture fields. A pebbly sand deposit rests parallel to Mill Creek and has been interpreted as a levee deposit. This site shows some of the variation in terrace deposit thickness across larger surfaces (Fig. 37). None of the lower terrace deposits contain sands associated with the Pinehurst Formation. Given the youngest OSL age date recorded from the Pinehurst Formation (8 ka) the age of the lower terrace is restricted to < 8 ka years.
Figure 37. Lidar point cloud data shows the extent of a lower terrace in the Patrick quadrangle. Hand auger data A was taken to the left of the GPR profile A-A’’. Information collected from 0-104 cm from sample A has been interpreted as a terrace deposit and the silty clay below 104 cm has been interpreted as the Middendorf Formation. Hand auger data B was taken to the right of profile B-B’ and the entire 183 cm profile has been interpreted as a Quaternary terrace deposit. Hand auger data in sample A shows how thin the modern deposits can be over the Cretaceous strata.
Several mid-level terrace surfaces exist from 4.6 m to 9.1 m above the modern flood plain. A bench roughly 7.6 m (25 ft) above Juniper Creek’s flood plain on the Wilkes Farm Site (34° 34’ 39.02” N, 80° 01’ 31.35” W) was sampled using a 1.8 m hand auger (Appendix D). The borehole data from this deposit indicates presences of a thin O horizon, followed by a thick A/Aₚ horizon, an E horizon, Bₕ horizon, and a BC (?) or C horizon. Soil colors associated with these deposits are typically in the 10YR to 7.5YR range and contain hues of yellows and browns. Pebbles (up to 5 mm) exist in the C horizon. The mid-level terrace soil profiles show thicker A, E, and Bₕ horizons then the deposits associated with the lower terraces, but the colors of well-drained profiles are not markedly more orange on the older terraces. None of the deposits associated with the Pinehurst Formation were mapped on mid-level terrace surfaces. However, thinner eolian sand sheet deposits could help explain the thick (0.81 m) A and E horizons shown in (Appendix D). It is more likely that these A and E horizons are part of the fluvial package, and their thickness can be attributed to soil forming processes, but an eolian influence should not be ruled out. The presence of over thickened E horizons within mid level terrace deposits suggests that eolian processes may have influenced their formation. However, given the lack of thick eolian deposits related to the Pinehurst Formation it is likely that these deposits formed during the late Pleistocene to Holocene.

Thin, terrace deposits (remnants) exist > 9.1 m above Juniper Creek’s flood plain. Additionally, the smaller streams in the mapping area were investigated, but did not produce any surfaces similar to the ones above Juniper Creek. Two broad flat surfaces, roughly 13.7 m above Juniper Creek’s flood plain, contain deposits that have gravel at the base, and are underlain by sands and clays of the Middendorf Formation (Appendix D).
One of these sites, located off of U.S. Route 1 on the eastern side of the quadrangle within the Sand Hills State Forest (34° 35’ 27.10” N, 80° 00’ 36.28” W), contains a thin deposit with rounded gravel (up to 1.9 cm diameter) at the base. The deposit has lighter 10YR hues of browns and yellows in the O, A, E, Bt, and C horizons, but the light colors in the Bt and C horizons may be contributed to the increase in light gray, clay matrix between the coarse sand grains. The light colors are believed to be atypical for such a deposit, but the elevation, thickness, and gravel at the base were used to make the assumption that it is part of a high terrace surface. A light gray, silty clay that is part of a 2C horizon and which contains redoximorphic features underlies the deposit.

The Wilkes Farm site contains the other high terrace deposit. This site was investigated using bore hole, GPR, and trench data. Borehole data show 2.6 m thick (eolian) sands lie on top of a 1.53 m thick (fluvial) deposit composed of clays and pebbly sands. These buried terrace deposits contain a paleosol with a Bt and Cb horizon. The sediments here show colors in the 7.5YR range with hues of reddish yellow and strong brown. The lower Cb horizon contains subrounded-to-subangular quartz pebbles (up to 1.5 cm). The terrace deposit shows a distinct color and composition change in comparison to the overlying and underlying deposits. The overlying deposit is associated with the Pinehurst Formation and the underlying deposit is part of the Middendorf Formation. The GPR revealed that the terrace deposit is thin (1.53 m thick) and extends underneath of the eolian sands associated with the Pinehurst Formation (Appendix D). The trench data taken in the area shows that as the terrace deposit extends to the east, there is a facies change. This facies change is depicted in the GPR transect (Fig. 33) as the deposit becomes more clay-rich and loses the pebbly sands laterally. This transition from a pebbly sand to a more clay-rich sand makes it extremely difficult to differentiate the older terraces from the
underlying Middendorf Formation.

**Quaternary Floodplains**

The boundaries of Johnston and Bibb soil series from the USDA Soils Maps for Chesterfield County were effectively used to help map the modern flood plain deposits in the Patrick quadrangle. These deposits coupled with LiDAR imagery show clear boundary lines between the lower terraces and the modern flood plain deposits. Hand auger data collected on the modern flood plain shows that the alluvium is composed of unconsolidated gravel, sand, silt, and clay. Sands are typically subrounded-to-angular and moderately-to-poorly sorted. Quartz is the dominant mineral type with up to 2% mica and minor amounts of heavy minerals. Deposits are commonly composed of sandy clay loams, sandy loams, loamy sands, and sands. The deposits are unweathered and are in the 10YR range with hues of browns, blacks, grays, and yellows. Fining-upward sequences are common with subrounded-to-angular pebbles (up to 1cm) towards the base, as well as deposits that are rich in organic matter (Appendix D). The water table is usually close to the surface, and therefore hand augering is difficult due to slumping within the bore hole. The characteristics found within the flood plain deposits were used to help identify older alluvium related to the terrace deposits.
CHAPTER 5

DISCUSSION

In addition to the development of a geologic map of the Patrick quadrangle, these data gathered from geologic mapping, detailed drill core analyses, and clay mineral analysis of the sedimentary units within the quadrangle permit interpretations to be made of the depositional environments and timing of the strata. Geologic mapping of the late Cretaceous (Turonian) Middendorf Formation found five separate lithofacies whose depositional environments help to re-establish the notion that the Middendorf Formation was deposited within a fluvial environment. Geologic mapping and drill core analyses suggest that this system contains features that are indicative of a distal braided river system that flowed towards the southeast during the late Cretaceous. These data also allow for the late Cretaceous sediments in the study area to be put into a sequence stratigraphy context. Additionally, these data reinforce the use of the formational name Middendorf and show that the lithofacies found at the type section can be successfully applied throughout the study area. Geologic mapping data and drill core analysis also suggests that only one late Cretaceous formation exists within the study area, and that this formation contains many local unconformities and possibly a larger regional unconformity. In addition to the information collected from the Middendorf Formation, geologic mapping, LiDAR, ground-penetrating radar, and Optically Stimulated Luminescence (OSL) data provide an informed framework for interpreting the origin and significance of the Pinehurst Formation within the Patrick 7.5-minute quadrangle.

Interpretation of Middendorf Formation Lithofacies

Lithofacies 1 (Cross-bedded or structureless, medium-to-coarse sand to pebbly sand)

Cross-bedded sands related to the Middendorf Formation have been described by several
authors (Sloan, 1904; Berry, 1914; Cooke, 1936; Heron, 1958; Heron 1960; Ridgeway, 1966; Wollen and Colquhoun, 1977; Prowell, 2003). Swift and Heron (1969) described cross-bedded sands with good framework and overall sorting as part of their Middendorf materials.

Lithofacies 1 is composed of cross-bedded or structureless, medium-to-coarse sands to pebbly sands and is interpreted as fluvial channel fill, dunes (lower flow regime), and bar deposits. A fluvial interpretation matches similar interpretations by Heron (1958; 1960), Ridgeway (1966), Swift and Heron (1969) with the lithofacies interpretations similar to those of Miall (1977) and Cant and Walker (1978). Some individual sand units fill distinct channels cut into underlying units, and cross bedding is visible in some outcrops. Pebbles, clay chip rip-up clasts, and weathered feldspar clasts (?) are present at the bottom of some channel deposits and follow cross-bedding in certain localities. The clay clasts up to 7.5 cm in length are rounded-to-subangular and appear locally derived on the basis of their size, shape, and kaolinitic composition. Some of the smaller kaolin clasts (< 1.5 cm in length) are believed to be weathered feldspar grains due to the similarities in shape between the clasts and microcline feldspars that were collected and analyzed in the Cheraw core. Subrounded-to-angular smoky, clear, and milky quartz pebbles and gravel make up the rest of the coarse deposits, and the lack of rounding suggests the sediment was transported only a short distance before being deposited. Many of the sand and pebbly sand deposits contain channel material that has been eroded or cut by subsequent deposition of a new channel deposit, as shown by the outcrop on Brown Springs Church road (Fig. 11).

Cumulative crossbed measurements from the upper portion of the Middendorf Formation in the Patrick quadrangle show that streams were flowing predominately southeast during the late Cretaceous. The aggregate of all of the crossbed measurements from the upper portion of
the Middendorf formation show a unimodal azimuthal pattern (Fig. 38). These types of patterns have been associated with fluviatile environments (Selley, 1968), but it is not possible to distinguish braided or meandering channel patterns from these types of data. Shukla et al. (1999) provides paleocurrent analysis for a meandering and braided channel from the Ganga River and shows the variability of crossbed readings within different portions (upper, middle, lower) of each channel type. The ability of each channel type to display polymodal, bimodal, and/or unimodal patterns may help explain the wide variety of patterns (Fig. 39). Given the data in (Fig. 38) a channel sinuosity of 2.4 was determined for the upper Middendorf Formation using Le Roux’s (1992) method, suggesting that the late Cretaceous streams were highly sinuous, and not braided. However, Le Roux (1992) states that as the number of paleocurrent measurements increases (n), the more accurate the sinuosity number is for the system. The low number of measurements (i.e. n = 148) from only partially exposed meander belts (i.e. the Middendorf Formation within the Patrick quadrangle), may lead to a less accurate sinuosity value. An increase in paleocurrent measurements (n) should lead to a more accurate sinuosity value as well as a more accurate representation of the paleocurrent direction for the Middendorf Formation. Additional studies may show that the Middendorf Formation contains multiple river systems and that each one should be assigned its own sinuosity value. Combining the paleocurrent readings of multiple river systems, as done in this study, the sinuosity value may over-or-under estimate the sinuosity value. If the higher sinuosity value is proven correct eventually, it would significantly impact interpretation of the type of river system that deposited the Middendorf Formation.
Figure 38. Cumulative trough and planar crossbed measurements from the upper portion of the Middendorf Formation.
Figure 39. A series of rose diagrams displaying trough and planar crossbed measurements from the upper portion of the Middendorf Formation. The circles outside of the diagrams display the location and proximity of each outcrop visited. The sum of the measurements recorded from these outcrops is displayed in Fig. 38.
The exposure along the Seaboard Coast Line Railroad that displays mm-thick clay laminations on the tops of cross-bedded sands is interpreted as being part of lithofacies 1. The mm-thick clay laminations have been interpreted as allogenic clay particles deposited shortly after deposition by clay infiltration from a fluvial system with a highly suspended sediment concentration, fluctuating water tables, and minimal sediment reworking (Matlack et al. 1989). If the clay were deposited during initial deposition, then the clay would be considered draped across the beds and the deposit could be interpreted as estuarine (Woollen and Colquhoun, 1977). Additional authors have suggested marine influences within the Middendorf Formation (Siple et al., 1956; Pavich et al., 1980), therefore it is possible that the Middendorf Formation experienced brief periods of estuarine conditions due to eustatic sea level rise and subsequent flooding of river valleys.

However, the abundance of coarse-to-medium, cross-bedded sands to pebbly sands, suggests fluvial channel fill, dunes (lower flow regime) and bar deposits were the dominant deposit types during the Late Cretaceous. The abundance of these deposits suggests that steady, vertical aggregation took place over several periods of erosion and deposition, while multiple streams migrated through the landscape. The cross-bedding facies is the most abundant facies, and the persistence of this facies both horizontally and vertically (throughout Patrick quadrangle and in the Patrick and Cheraw cores) suggests a widespread and persistent fluvial environment of deposition.
Lithofacies 2 (Alternating laminations and (or) thin beds of sand and clay (total lithofacies unit thickness < 1.5 m))

The laminated sand and clay deposits within the Middendorf Formation have previously been described by multiple authors (Heron, 1960; Swift and Heron, 1967; Woollen and Colquhoun, 1977; Prowell et al., 2003). The alternating laminations and (or) thin beds of sand and clay (total lithofacies unit thickness < 1.5 m) are interpreted as fluvial flood plain and crevasse splay deposits. These deposits of lithofacies 2 are much less abundant than those of lithofacies 1 in the quadrangle and drill cores. The scarcity of lithofacies 2 may be attributed to erosion during subsequent channel migration or avulsion. This erosion is then subsequently followed by deposition of sand of lithofacies 1 or clay of lithofacies 3. In the Cheraw core at depth of 6.7 m below sea level, a clay bed of lithofacies 2 produced pollen that is interpreted as characteristic of an intermittently flooded, poorly drained flood plain within a freshwater environment (Swezey et al., 2015). Miall (1977) describes and interprets deposits similar to these as minor facies within a larger fluvial system.

Lithofacies 3 (Clay and silty clay beds or lenses not associated with lithofacies 2)

Clay and silty clay beds or lenses (lithofacies 3) are interpreted to be the final stage of accumulation in an abandoned channel or flood plain deposits within a fluvial environment. The 9.9 m thick clay bed within the Patrick core may represent stabilization within the landscape and retention of muds associated with a large flood plain or an oxbow lake deposit with a few silty and sandy lenses throughout. Another possibility is that large mud beds within the Middendorf Formation are mechanisms of lateral channel restriction on the flood plain, coupled with rapid subsidence (Miall, 1977). Many of the smaller clay beds, like the one shown in Fig. 20, fill smaller U-shaped depressions, and are interpreted as abandoned channel fill deposits. Two dark
gray clay beds were found to contain charcoaled plant fragments and could represent swamp deposits. Relatively flat-lying clay beds within the mapping area that are not associated with lithofacies 2 (Fig. 8) represent the end of fining-upward sequences and are interpreted as flood plain deposits. Due to the high amount of oxidation within the sediments, organic material within the deposits is rare, and therefore the environmental interpretation for many of the deposits is based on the clay bed shapes and sizes.

**Lithofacies 4 (Quartz sandstone with mud matrix)**

Gray to Pinkish grey beds of quartz sandstone < 1.5 m. Beds contain horizontal bedding within some outcrops, and were only found at the surface. The muddy matrix, sedimentary structures, and flat lying nature of these deposits suggest that these sandstones (lithofacies 4) could be a product of rapid deposition from sporadic flood deposits (Pe-piper et al., 2005). The light nature and lack of organic material within the deposits suggests a history of oxidation; this is consistent with most of the Middendorf Formation. A few of the deposits are only partially exposed at the surface and therefore their shape and thickness could not be determined. These unexposed deposits warrant a similar flood plain interpretation, but could be considered channel fill, swamp (?), or lacustrine (?) deposits within a fluvial environment given the lack of available data collectable from these outcrops.

The kaolinitic cement within the sandstones (Fig. 23) demonstrates the textural immaturity of the muddy sandstone beds. Given the high percentage of kaolinitic matrix (30-40%) the kaolinite is potentially the product of rapid deposition from mud rich streams and/or is a product of early soil formation due to percolating meteoric water (Pe-piper et al., 2005). Bent mica between quartz sand grains with silica cement are indicators of mechanical and chemical
compaction as illustrated by Worden and Burley (2003). The mica grains within the rocks are primarily straight suggesting little to no compaction has taken place. The slightly bent mica grain in Figure 23 may have been bent before burial or is an indicator of very slight compaction. Thin sections show that the quartz sand is not tightly packed, suggesting that there has not been a lot of burial (Fig. 23). The lack of cements may also be an indicator of shallow burial. Quartz overgrowths are not abundant suggesting that they may be inherited. The two types of quartz grains (monocrystalline (more abundant) and polycrystalline) suggest at least two different sources. In addition, the sand is poorly sorted which suggests that it has not travelled far. The angular, subangular, and even rounded grains suggests multiple sources as well (i.e. Appalachian piedmont schist and granite, and Mesozoic rift basin sands).

**Lithofacies 5 (Ferruginous sandstone to pebbly sandstone)**

The most prominent lithofacies is the study area is the ferruginous sandstone to pebbly sandstone. With such a low percentage of iron-bearing minerals within the Middendorf Formation < 1%, most of the iron associated with the ferruginous sandstone beds may have accumulated from allochthonous sources, rather then autochthonous processes (Widdowson, 2007). Two possible outside sources of iron include older, higher Cretaceous surfaces (i.e. plinthitic paleosols) that have been eroded or Piedmont sediments. The distribution and characteristics of the ferruginous sandstones to pebbly sandstones allows for a formational and environmental interpretation of this lithofacies.

As shown in Fig. 24 many of these beds rest unconformably at the top of the Middendorf Formation (i.e. Sugar Loaf Mountain (156.4 m) (513 ft)), and tend to exhibit primary structures such as cross-bedding (Fig. 25). The presence of cross-bedding, and absence of pedogenic features (i.e. soil horizons) suggests that these rocks did not form as a result of pedogeneic
processes (*in situ* weathering profiles), but rather non-pedogenic processes. Bourman (1993) and Tanner and Khalifa (2009) described ferruginous sandstones that contain primary sedimentary structures as products of allochthonous iron deposited by groundwater activity. Tanner and Khalifa (2009) suggest that iron cementation is preferential in bedding planes and that iron distribution via groundwater is controlled by sediment permeability. Furthermore, iron cementation via groundwater activity fills the intergranular porosity of the ferruginous sandstones described by Tanner and Khalifa (2009).

Much like Tanner and Khalifa’s (2009) study, thin section analysis shows that much of the intergranular porosity of the ferruginous sandstones to pebbly sandstones within the Middendorf Formation is filled by iron cementation. Furthermore, geologic mapping shows that iron cementation is restricted to coarser, more poorly sorted beds, and does not exist in within finer grained deposits, suggesting that permeability played a role in the formation of these deposits. These beds show characteristics that should warrant a similar environmental interpretation as lithofacies 1 (i.e. fluvial channel fill, dunes (lower low regime), and bar deposits). Most probably these ferricretes cement formed after sediment deposition and at some notable depth below the surface. However, it is possible that the ferricretes formed near the surface. Widdowson (2007) shows that allochthonous iron deposits such as ferricretes can form in topographic depressions such as valley floors, swamps, and lakes. These lower deposits are dependent on iron-rich debris or solutes from higher landscape positions. Therefore, sandstones related to lithofacies 5 may have been deposited through groundwater interactions in topographic low settings. These rocks that now rest at some of the highest elevations within the Patrick quadrangle may indicate a geomorphic history of stream incision and topographic inversion that changed previous lowlands into current uplands (Eze et al. 2014) after their initial deposition.
Substantial pedogenic overprint exists within the uppermost Middendorf Formation and the unconformity that caps it. These types of features may form as a result of pedogenic processes. Within these highly weathered soil profiles iron-rich mixtures of kaolinitic clay with quartz, and commonly reticulate mottling, may form and are known as plinthitic masses (Soil Survfey Staff, 2006). Plinthites commonly form in oxisols today in humid tropical and subtropical environments within poorly and somewhat poorly drained soils (Eze et al., 2014; Schaetzl and Thompson 2015). A stable landscape position with abundant moisture, high temperatures, and a fluctuating water table seem to be favorable conditions for their formation (e.g., Osher and Buol, 1998). The availability of iron aids the process considerably (e.g., Smith, 2007). Thus the presence of plinthite may indicate that the landscape at the site used to be a lowland in a tropical or subtropical climate. The common occurrence of plinthitic soils on dissected uplands (such as here in the Carolina Sandhills) would indicate a geomorphic history of stream incision and topographic inversion that changed lowlands into an upland plateau (Eze et al., 2014). If these deposits contributed to the formation of the ferruginous sandstone to pebbly sandstones within the Middendorf Formation, then the geomorphic history of the Carolina Sandhills is far more complex than originally thought.

**Interpretation of the Middendorf Formation in a Larger Context**

Fluvial systems have classically been described as having braided or meandering channel patterns. However, this classification system potentially poses a problem when describing geological formations. As noted by Adams and Bhattacharya (2005), several variables determine the channel type of modern fluvial systems and gradational differences within these variables result in a continuum of channel patterns. Therefore, it is not unreasonable to believe that similar variables influenced channel types within ancient fluvial systems, and that multiple channel
patterns may exist within the late Cretaceous deposits. The Middendorf Formation is composed of fluvial sediments that display features that can be associated with both braided and meandering channel patterns. For example, there are occasional fining-sequences within the two cores and the quadrangle that could be interpreted as point bar deposits. However, given the abundance of stacked cross-bedded sand to pebbly sand deposits, the lack of fine sand and silt deposits, and the presence of higher width-to-depth ratios (i.e. 10:1) for paleochannels, it is more likely that the Middendorf deposits were deposited within a braided river setting. Here two distal braided river models from the Donjek and South Saskatchewan rivers (Fig. 40) (Miall, 1977) are proposed to help explain the fluvial system that is responsible for the deposition of the Middendorf Formation. Most of the evidence found during geologic mapping and drill core analysis helps to support this interpretation.

The Middendorf Formation is interpreted to be fluvial sediments derived from highlands to the west including the uplifted margins of Mesozoic rift basins, Piedmont schist and granite, and (or) the Appalachian Mountains. The two facies models for distal braided river systems mentioned above may help explain the distribution of the deposits within the Middendorf Formation. Here the Middendorf Formation is separated into a lower (coarser sediment) portion and upper (finer sediment) portion, in a way that is very similar to Ridgeway’s (1966) geologic map. The distinction between the lower and upper contact is defined by two intervals within the Patrick and Cheraw Cores that are interpreted to be paleosols (?). As shown in Fig. 27 these paleosols may represent a larger regional unconformity. A combination of the Donjeck and South Saskatchewan models are used to describe the lower portion of the Middendorf Formation, but only the South Saskatchewan is needed to describe the upper package of sediments.
The lower portion of the Middendorf Formation is primarily represented by the deposits below the paleosol at 38.1 m depth in the Cheraw core. These deposits show several small, stacked fining-upward sequences (0.2 m - 2.1 m) that are dominated by gravel and coarse sand. The core shows gravel and sand beds that are vertically stacked on top of one another and appear truncated in places. These deposits have been interpreted as minor channel fills, dunes, and bars within a braided environment. The silty clay and finer beds in the core are interpreted as overbank and waning flood deposits. These beds appear to be minor throughout much of the lower Middendorf (Appendix C). Both river models are considered here in order to construct a more open interpretation due to the absence of lower Middendorf outcrop exposures in the mapping area.

As mentioned earlier, between the lower and upper Middendorf rests two intervals that are interpreted as possible paleosols. The paleosol within the Cheraw core is coarse-to-very fine sand with disrupted bedding, mottled texture, and downward tapering vertical structures at 38.1 to 36.3 m depth (20.7 to 22.5 m ASL). A similar lithology is present in the Patrick core at 85.4 to 75.5 m depth (28.7 to 38.5 m ASL), though this interval is not as clearly defined as the Cheraw core. In comparison to the Patrick core, the beds that represent the paleosol within the Cheraw core show an upward increase in clay content, differentiated soil horizons, and an abrupt grain size change at the top of the soil profile. These characteristics are typically associated with more well-developed soil profiles (Kraus, 1999). The interval within the Patrick core contains less clear pedogenic features (i.e. soil horizonation), but appears to be a surface that set out long enough to accumulate features that require some stabilization within the landscape (i.e. animal burrows or root traces). These two intervals may represent a time of stabilization of the Cretaceous landscape in the immediate area and possibly on a regional scale (Kraus, 1999).
Additional drill core analysis within the Middendorf Formation should help solidify or differentiate the interpretation of these deposits. Above these two intervals, throughout both cores the mean grain size generally becomes finer. A reduction in grain size in the upper portion of the Middendorf Formation is also consistent with the outcrop data collected from the Patrick quadrangle. This change is interpreted as having been caused by a decrease in gradient across this area as sea level continued to rise.

The upper portion of the Middendorf Formation consists of the deposits above the two paleosols within the cores. This includes all of the deposits found within the Patrick quadrangle. Deposits within the upper portion are consistently dominated by the cross-bedded or structureless, medium-to-coarse sand to pebbly sand lithofacies, but fine-grained deposits (silty clays and interbedded clays and sands) appear to be more common than below the paleosols. Occasional fining-upward sequences do exist within the cores and throughout the Patrick quadrangle, but nice gradational fining-upward sequences are not as abundant as they would be in a predominately meandering system. The major facies (coarser grained) within the upper portion have been interpreted as dunes (lower flow regime), channel fill, scour deposits, and bar deposits, while the minor facies (finer grained) have been interpreted as flood plain, crevasse splay, and possibly swamp deposits. Using the two models shown in Figure 40 for comparisons, the major and minor facies presented here seem to be more indicative of the South Saskatchewan distal river model, and not as closely related to the Donjeck, given the smaller amount of gravel throughout the deposits.
Figure 40. Two models for distal braided river systems proposed by (Miall, 1977).

The presence of meandering river systems can be attributed to a decrease in slope, an increase in vegetation, and formation of more cohesive flood plain deposits within the landscape (Cant, 1982). These types of river systems are often confined laterally by abandoned mud filled
oxbox lake deposits (Cant, 1982). The increase in fining-upward sequences (FUS) and thicker, silty clay deposits within the upper Middendorf Formation potentially represents a shift to a predominately meandering channel patterns during the late Cretaceous. These deposits seem to be more abundant throughout the Patrick core and Patrick quadrangle between 61.0 m – 91.4 m (200 ft – 300 ft) in elevation. Though these deposits here are interpreted as being part of a braided river system, some of these deposits may be associated with more meandering-dominated river channels. This idea may help explain the high sinuosity value (2.4) estimated from the upper Middendorf paleocurrent data (Fig. 38). Further detailed studies of the Middendorf Formation should help solidify whether these sediments were deposited in a predominately braided river system, or if these deposits experienced time periods where the rivers transitioned from predominately braided to predominately meandering and vice-versa.

The geologic mapping and drill core data also allow for the Middendorf Formation to be applied within a sequence stratigraphy context. During the time period represented by the oldest sediments studied, an initial base level fall during the late Cretaceous created a steeper overall gradient for the Cretaceous fluvial systems. This base level fall allows streams in the area to prograde into the basin leaving a deposit of very coarse gravel on top of the Paleozoic rocks of the Persimmons Fork Formation (see Cheraw core at 66.4 m depth (7.6 m below sea level)).

Above this thin gravel lie deposits of coarse to medium sand to pebbly sand up to 2 m thick. This would be the result of a subsequent sea level rise that created accommodation space within the basin resulting in Lower Systems Track (LST) deposits. The lack of flood plain deposits within the lower portion of the Cheraw core suggests that the increase in accommodation space may not have been rapid within the basin, forcing streams to rework sediments laterally during this time period. Mature, well-drained paleosols (see Cheraw core at
38.1 to 36.3 m depth (20.7 to 22.5 m ASL)) may have developed on fluvial terraces during this time (Wright and Marriott, 1993). A rapid rise in sea level helped to create accommodation space for the early part of the Transgressive Systems Tract (TST). The high rate of increase in accommodation space from rapid sea level rise allowed vertical accretion and flood plain deposits to form and be preserved within the rock record. The possible weakly developed soils (see Patrick core at 85.3 to 81.7 m depth (27.5 to 31.1 m ASL) and prominent thick flood plain deposits (see Patrick core at 36.6 to 26.7 m depth (77.4 to 87.3 m ASL) formed this interval. The middle to later portion of the TST would be marked by a decrease in accommodation space. This decrease resulted in a large number of channel deposits in the study area, a greater degree of interconnectedness with a dominance of sand throughout the stratigraphic section, and a decrease in soil preservation. All of these features are very common within the Patrick quadrangle.

According to the global sea level curve of Hallam and Cohen (1989) a global sea level drop occurred around 100 ma followed by a rise in sea level towards the end of the Cretaceous time period. This sea level curve helps support the assumption that the sediments are of Turonian age and that the sediments represent a drop in sea level followed by a subsequent rise in sea level.

Use of the Stratigraphic Name “Middendorf Formation”

In this study, the Cretaceous sediments are mapped as the Middendorf Formation, and the Middendorf type section is located in the adjacent quadrangle to the west (Middendorf 7.5 minute topographic quadrangle). The same lithofacies at the Middendorf type section are present throughout the Patrick quadrangle and in both the Patrick core and the Cheraw core. In fact, the Patrick core was drilled within sight of the Middendorf type section.
At its highest point the Middendorf type section reaches an elevation that is between 115.8 – 118.9 m (380 – 390 ft) ASL. Although the Middendorf type section is overgrown with vegetation at present, several previous studies have provided descriptions of this type section (Sloan, 1904; Swift and Heron, 1969, Prowell 2003). The most complete representation of the type locality by Swift and Heron (1969) shows cross-bedded, coarse basal sands to the northeast that are directly overlain by roughly 3 m (10 ft) of sand and clay deposits that span at least 45.7 m (150 ft). Laterally to the southwest, an 18.3 m (60 ft) leaf bearing, clay bed overlies the coarse, basal sands, and visibly pinches out within the outcrop. Towards the southwest end of the deposit wood fragments and clay clasts are shown within “loose sands” that appear massive (?) in nature. Swift and Heron’s (1969) cross-section displays three out of the five lithofacies found throughout the study area (Fig. 41); the massive to cross-bedded sand to pebbly sand facies (lithofacies 1), the alternating sand and clay facies (lithofacies 2), and the clay facies (lithofacies 3). The upper 3 m (10 ft) of the cross-section shows the extent of soil forming processes and further displays how pedogenic processes have altered the Middendorf Formation in many places.
Figure 41. A redrafted cross-section of Swift and Heron’s (1969) cross-section of the Middendorf type section. Lithofacies identified during this study have been labeled where they are more prominently displayed.

As previously shown, the five lithofacies of the Middendorf Formation can be applied to the deposits throughout both the Patrick and Cheraw cores, as well as to outcrops throughout the Patrick quadrangle including the Middendorf type section (Fig. 41). Above the Middendorf type section, the highest elevation that the Middendorf Formation reaches within the Patrick quadrangle is 156.4 m (513 ft) (i.e. Sugarloaf Mountain). Here the lithofacies of the Middendorf Formation are applied to Sloan’s (1904) measured section description (Fig. 42) to show the upper extent of the strata within the mapping area.
Figure 42. Measured section by Sloan (1904, p. 107-108) at Sugarloaf Mountain (Swezey et. al., 2016). Sloan (1904) describes a “drab clay” bed 6.1 m (20 ft) in a pit at the based of Sugarloaf Mountain (not shown above). This clay bed is related to lithofacies 3.
The lithologies of the Cheraw core are very similar to those of the Patrick core and to outcrops within the Patrick quadrangle, and thus do not support Prowell’s (2003) claim that the lower portion of the Cheraw core is the Cretaceous Cape Fear Formation (which has its type section on the Cape Fear River in Cumberland County, North Carolina). In fact, there is no lithologic evidence to suggest that the Cape Fear Formation is present within the Cheraw core, Patrick core, or Patrick quadrangle. However, it is possible that beds within the Middendorf Formation in the Patrick quadrangle are the same age as the Cape Fear Formation. The findings from this study and Woollen and Colquhoun (1977) confirm Heron’s (1958) hypothetical cross section of the Cretaceous beds within Chesterfield and Darlington Counties (Fig. 43).

Figure 43. A redrafted version of Heron’s (1958) hypothetical cross section across Chesterfield and Darlington Counties, South Carolina. The approximate location and area of this study has been shaded light gray and the contact between the Middendorf Formation and the Persimmon Fork Formation in the Cheraw core is shown.

Irrespective of lithology, there is some evidence that the Middendorf Formation at the Middendorf type section may be the same age as the Cape Fear Formation at the Cape Fear type section. For example, Christopher’s (1979) work on the Cape Fear River suggests that the Cape Fear Formation and the lower portion of the Middendorf Formation share a similar pollen zone (V) that is Middle Turonian to late Santonian in age. Similar studies should be completed
towards the Cape Fear River in order to understand how the two formations are related biostratigraphically and lithostratigraphically.

Furthermore, geologic mapping and drill core data suggest that sediments of the Middendorf Formation can be distinguished and delimited on the basis of lithic characteristics and stratigraphic position following the rules of the North American Stratigraphic Code (1983). Prowell (2003) states that the Middendorf Formation may span through much of the Late Cretaceous, but additional geologic formation names should probably be avoided for practical geologic mapping purposes.

The five lithofacies in the Middendorf Formation represent fluvial processes or possibly post depositional processes within a fluvial environment. This study uses two distal braided river models by Miall (1977) to explain the facies found within the Middendorf Formation, but suggests that more detailed geologic mapping and paleocurrent analysis should be done within the formation in order to resolve the discrepancies found regarding channel morphology. In a sequence stratigraphic context the findings from this study suggests that these deposits only represent a sea-level drop followed by deposition of lowstand sediments that are capped by a possible regional unconformity, and followed by an early to middle transgression. The Middendorf Formation can be successfully mapped and identified using the lithofacies found at the Middendorf type section and from this study. By applying these lithofacies throughout the Patrick 7.5-minute quadrangle and two drill cores, it has been concluded that only one late Cretaceous formation exists within the study area. The findings from the surfical and subsurface clay mineralogy also support this conclusion. Additional palynology work may show that the Middendorf Formation spans through a length of the late Cretaceous, but this should not warrant separate formational names.
Interpretation of the Pinehurst Formation in a Larger Context

Geologic mapping, LiDAR, and ground-penetrating radar data within the Patrick quadrangle, agree with regional interpretations (Cooke, 1936; Cooke and Pooser and Johnson, 1961; Nystrom and Kite, 1988) that the Pinehurst Formation is eolian in origin. Chesterfield County USDA soils maps and LiDAR point cloud data were successfully coupled with geologic field mapping to identify dunes and sand sheets within the study area. Thicker dune and sand sheet deposits within the mapping area show internal structures that suggest a northwest to southeast pattern for paleowind direction. Buried soils identified within these thicker deposits suggest sand remobilization and deposition occurred at multiple times to help shape the landscape. OSL age dates confirm sand remobilization and deposition during the late Pleistocene and early Holocene, and not during the Miocene as hypothesized by previous authors (Nystrom et al., 1991). These data add to regional data by Markewich et al. (2015) along the southeastern Atlantic Coastal Plain, and may show that both local and regional paleoclimate factors played a role in landscape evolution within the mapping area.

Morton (1995) mapped two major soil series within Chesterfield County that delineate deposits interpreted to be sand dunes and sand sheets. Within the Patrick quadrangle Morton (1995) mapped 28% of the soils as part of the Alpin soil series, and 11% as part of the Candor soil series, both soil series representing sandy deposits that are ≥ 2 m thick. This study used these two major soil series as well as some minor soil series (e.g., Ailey, Troupe, Vaucluse) to help identify and delineate eolian deposits associated with the Pinehurst Formation that are ≥ 2 m. These major soils are not previously mentioned as soils associated with eolian deposits along the southeastern Atlantic Coastal Plain (Markewich et al., 2015), but these data presented here show that these deposits are of eolian origin. The prudence suggested by Markewich (2015)
proved necessary because not all of the deposits associated with these soils should be considered eolian and field checking is required to insure accuracy.

Whittecar et al. (2016) shows that degraded parabolic dunes, transverse dunes, and eolian sand sheets mantle more than 80% of the Patrick quadrangle. The composition, sorting and rounding of these sands paired with their position within the landscape suggest that deposits of the Pinehurst Formation were locally derived from the underlying Middendorf Formation. The lack of eolian sands on lower valley deposits suggests that these deposits formed after the last episode of eolian sand mobilization. The distribution of the Pinehurst Formation is visible on the geologic map of the Patrick 7.5-minute quadrangle (Appendix F).

Ground-penetrating radar (GPR) shows that deposition of the Pinehurst sands took place on top of the highly dissected Middendorf Formation, and up to 8.5 m of relief exists locally between the two formations. LiDAR data shows that Quaternary sand forms subdued hills of up to 6 m of relief, with steeper sides predominantly on the southeast. The large 2-5-m thick southeast dipping cross-bedding within the GPR profiles (Figs. 32 and 33) is consistent with the dip of the steepest side of the sandhills. These data suggest that wind was coming from the northwest and going to the southeast; this wind direction is consistent with a paleowind model presented by Markewich (2015) during the Last Glacial Maximum (LGM). Age dates collected from pits and trenches along the GPR profiles in Figs. 32 and 33 support this model.

The absence of internal structures within the top 2 m of the thicker eolian deposits (i.e. dune deposits) is attributed to bioturbation from vegetation that stabilized the bedforms and/or may have been affected by soil forming processes (i.e. illuviation). The effects and extent of these processes are visible within the GPR transects, and explain the lack of bedding features seen within outcrop exposures around the Patrick quadrangle. Bioturbation processes must be
taken into account when using OSL age dating, as they move sediment around after deposition. If exposed to sunlight the ages of the sediment can be altered resulting in a younger age date.

In previous studies, the age of the Pinehurst Formation has been rather speculative and poorly constrained. Nystrom et al. (1991) used the stratigraphic position and river incision rates from the Congaree River to estimate a Late Miocene age for the Pinehurst Formation. However, the lack of well-developed soil horizons within some of the soil profiles associated with the Pinehurst Formation (i.e. Figs. 35 and 36) here show that the ages of the deposits are much younger than Miocene. OSL age dates agree with the interpretation that these soil profiles are indeed much younger than previously believed.

OSL age dates from this study show that the age of the Pinehurst Formation is late Pleistocene to Holocene. The OSL data shown in Table 3 and Figure 44 show different ages that cluster around three, possibly four time periods, three during the late Pleistocene and one during the Holocene. These data suggest that at any one location sands associated with the Pinehurst Formation could have been mobilized and deposited at multiple stages throughout the late Pleistocene to Holocene. The existence of the buried soils and eroded soils seen in outcrop and GPR help explain the multiple age dates found throughout different exposures within the quadrangle. For example in and around the Patrick quadrangle, several sites with thick eolian sands have a brown argillic buried paleosol below a brown B argillic surface soil, all resting on an eroded orange-red paleosol. At one site (Wilkes Farm), the eolian sands associated with the surface soil are 12.06 ± 2.05 ka, but sands below an unconformity and a buried brown paleosol are notably older (29.18 ± 4.86 ka – 33.80 ± 3.93 ka). In contrast, at Isaac Road the older eolian sediments developed a significant argillic soil before the dune was eroded and then a new argillic soil formed across the eroded dune surface. Dates in the base of the dune (69.60 ± 5.65 ka) are
notably older than dates above and below the buried (older) argillic horizon (47.30 ± 2.78 ka and 47.30 ± 4.19 ka). The presence of similar ages at shallow depths but different age dates at greater depths below the surface at multiple places within the quadrangle indicates that deposition of the Pinehurst Formation may have been a result of local destabilizing events (e.g., forest fires that obliterated vegetation and activated the underlying dunes over large parts of the quadrangle), perhaps related to larger regional events such as the LGM. Another possibility is that the clustering of OSL data is an artifact of incomplete sampling.

Figure 44. Optically Stimulated Luminescence (OSL) Age Dates for the Pinehurst Formation throughout the Middendorf and Patrick 7.5-minute quadrangles. Sample numbers correspond to age dates recorded in Table 3.
One indication that the OSL data may not be simply artifacts of sampling is the observation that the data from the Carolina Sandhills agree with published age dates in southeastern Georgia (Markewich et al., 2015) that show three or possibly four major eolian dune-forming periods on the southeastern Atlantic coastal plain. Additionally age dates from this study are consistent with reported OSL ages collected from parabolic eolian dunes in river valleys of the Coastal Plain from Georgia through Delaware that were active ca. 40-19 ka (Ivester et al., 2001; Swezey et al., 2013; Markewich et al., 2015). Below the Orangeburg scarp, raised rimed basins (i.e. Carolina bays) in Georgia, North Carolina, and South Carolina agree with the OSL dates from inland dunes and sand sheets in Georgia and South Carolina. These raised rim basins are thought to have formed by eolian deflation and show several periods of mobilization during the late Pleistocene and Holocene. All of the data included in Markewich (2015), plus the findings from this study (Fig. 44), suggest that inland dunes and sand sheets, as well as raised rim basins and dunes associated nearby river valleys (i.e. Pee Dee and Cape Fear), were episodically active on the southeastern Atlantic Coastal Plain during the late Pleistocene and Holocene.
CHAPTER 6

CONCLUSION

The detailed geologic mapping, along with other field and laboratory techniques, performed in this study helped to resolve questions related to the depositional environment, stratigraphic name, stratigraphic position, and timing of the geologic units located within the Patrick 7.5-Minute quadrangle in Chesterfield County, South Carolina. In this area the Middendorf Formation unconformably overlies the Paleozoic basement rocks of the Persimmons Fork Formation, and is unconformably overlain by younger sediments associated with the Pinehurst Formation and modern drainages in many localities. The Middendorf Formation contains five lithofacies that are interpreted to be part of a braided fluvial environment.

The results from this study show that the Middendorf Formation is the only late Cretaceous Formation present throughout the study area, as hypothesized earlier by Heron (1958), and that the lithofacies described at the Middendorf type section by Swift and Heron (1969) (Fig. 41) in the adjacent Middendorf quadrangle are recognizable as the Middendorf Formation throughout the mapping area and into the subsurface.

Though many local unconformities are present throughout the mapping area, two subsurface intervals interpreted as paleosols in the Patrick and Cheraw cores may represent a larger regional unconformity. Potentially the Middendorf Formation might consist of an upper Middendorf and a lower Middendorf based on the presence of these paleosols. Below and above the paleosols the grain size of the deposits seems to change from mostly coarser grained (lower Middendorf) to mostly finer grained (upper Middendorf), respectively. In a sequence stratigraphy context the lower and upper portions of the Middendorf Formation may represent a sea level drop, followed by a depositional lowstand and early transgression. Future work may
reveal that these textural differences extend into adjacent regions, and the possible paleosols identified in the two cores are indeed useful stratigraphic concepts for this region.

Degraded dune and sand sheet deposits associated with the Pinehurst Formation unconformably overlie the Middendorf Formation on hilltops and side slopes. The evidence found here supports the notion that the Pinehurst Formation was derived locally and transported only a short distance by eolian processes before being deposited. Available OSL age dates suggest the dunes and sand sheets were episodically active during the late Pleistocene and early Holocene. The OSL age data and buried soils of the Pinehurst Formation show that the eolian sands were episodically remobilized throughout this time period, likely due to regional climate changes (e.g. LGM) that set the stage for local influences (e.g. high winds; fires) that created large landscape disturbances. GPR profiles and LiDAR images illustrate that the dominant wind direction for deposits within the Patrick quadrangle was from northwest to southeast, and that the leesides of the dunes are consistently towards the southeast. OSL, GPR, and hand augering data show that the older and thicker deposits ($\geq 2$ m) related to the Pinehurst Formation are restricted to hill tops, side slopes and older terraces. Along the mid-level terraces eolian sand sheets are ($< 2$ m) and are likely the result of weaker winds and possibly a more stabilized landscape. The lower terraces and flood plains associated with the modern drainages are void of eolian deposits. Given the absence of these older, thicker deposits on mid-level terraces, lower terraces and flood plains associated with the modern drainages, the ages of these deposits can be constrained from the late Pleistocene to the present day.

The following chronology summarizes the history of the Patrick quadrangle:

1) Deposition of Middendorf fluvial system: During the Late Cretaceous, base level dropped and predominately braided fluvial systems prograded out into the basin over an unconformity
overlying a metasiltstone associated with the Carolina slate belt. A subsequent base level rise allowed sediments associated with the Middendorf to retrograde back into the basin. At some point the rise in sea level stalled and the Late Cretaceous landscape was dominated by erosion, weathering, and soil formation. Later, renewed sea level rise caused a decrease in the regional gradient and more silts and clays were preserved as the basin continued to fill up towards the end of the Late Cretaceous.

(2) Erosion of regional unconformity at the top of the Middendorf Formation: A long period of erosion formed a broad low-relief surface on top of the Middendorf Formation throughout the Patrick area.

(3) Pedogenesis on regional unconformity: Plinthite formed on low-relief surface during a long period of landscape stability (Paleocene - Miocene). New stream incision, soil formation, and other processes shaped the Middendorf landscape from mid-Miocene until the present.

(4) Formation of older terraces: The oldest terraces preserved may date to the end of the Neogene (?) and later ones continued to form throughout the Pleistocene. These terraces are eroded strath terraces that are broad and clearly visible primarily along the largest streams. Many of the higher surfaces may be buried by eolian sands.

(5) Deposition of Pinehurst Formation: Episodic eolian events during the late Pleistocene covered the hilltops and higher terraces with dunes and sand sheets.

(6) Pedogenesis on Pinehurst Formation: Well-drained argillic soils formed within the Pinehurst Formation under temperate climates. In addition, bioturbation and loss of sedimentary structures affected the Pinehurst throughout the late Pleistocene.

(7) Formation of younger terraces: Mid-level terraces formed during the Late Pleistocene are covered with thin sand sheets. Lower terraces and the modern flood plain with out sand sheets
formed throughout the Holocene and into the present day.
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APPENDICES
STATEMENT ABOUT ECONOMIC RESOURCES

Historically the Patrick quadrangle has produced minimal amounts of raw materials for economic purposes. There are currently no large-scale quarries within the quadrangle, but significant sand and kaolin mining operations have existed or currently exist in adjacent quadrangles (e.g. Middendorf quadrangle) and throughout Chesterfield County. Small borrow pits for road reconstruction and small community kaolin pits were found to be widespread throughout the quadrangle during field mapping.

Aiken County is the leading producer of high quality kaolinite within the upper coastal plain of South Carolina. Many kaolin pits both historical and current exist along this NE-SW trending belt, but the overall quality diminishes away from Aiken County. The Middendorf quadrangle, which lies directly adjacent to the Patrick quadrangle, contains one active mining operation that is primarily used in brick and paper manufacturing. Similar kaolin deposits to the one in the Middendorf quadrangle exist in the Patrick quadrangle, but significant overburden, current land use, or both prohibit the development of such operations. Clay mineral analyses from the thickest beds (samples X, X, X, and X) can be found in the table in appendix X. The percentage of kaolin varies within deposits and many clay beds contain a percentage of quartz (Appendix x).

Sand resources that could be used as construction materials are extensive throughout the quadrangle. All of the sand deposits are rich in quartz with minor amounts of mica and heavy minerals. Unconsolidated, homogeneous sand deposits, up to 6+ m thick, exist on hilltops within the quadrangle, and could potentially be used for multiple applications (e.g. bunker sand, road reconstruction, play sand).
study suggest that sands related to the Pinehurst Formation contain characteristics that are highly favorable to golf companies (e.g. subangular-to-subrounded particles, predominately coarse-to-fine sand, light colors, high in silica, highly permeable, small amounts of silts and clays). Many of the Cretaceous sand beds contain greater amounts of clay matrix, and contain a high degree of particle size variability.
APPENDIX B

STATEMENT ABOUT GEOHYDROLOGIC FRAMEWORK

The Middendorf Formation is composed of interconnected sands and gravels with discontinuous clay beds and lenses of variable sizes. Additionally, sands contain a clay matrix in certain beds throughout the Middendorf quadrangle and subsurface (see both drill cores appendix C). The upper portion of the Middendorf Formation (above paleosol) contains an increase in clay and silt, while the lower portion contains an increase in coarse sands and gravel. The beds in the area thicken from 0 m at the fall line to (66.4 m thick) in the Cheraw core to the east. Sands and clays within the Patrick core are (85.3 m thick), but did not reach bedrock. A core drilled to the west in the town of McBee reached bedrock at 116.5 m. Therefore, the sands and clays within the Patrick area are approximately 97.5 m thick.
APPENDIX C
CORE DESCRIPTIONS

Legend:
- = Sand
- = Silt and clay
- = Pebby sand
- = Metasiltstone
- = Single sand sized grains
- = Modern roots, plant debris, and charcoal
- = Horizontal bedding or laminations
- = Crossbedding and or inclined laminations
- = Possible plant debris
- = Mottling
- = Unconformity
- = Kaolin rip-up clast (with or without sand grains)
- = Opaque Minerals
- = Iron Cement
- = Color change or significant break within a bed (i.e. a zone of possible organic material)
CHERAW CORE DESCRIPTION
100% vc to vf (mostly c to f) quartz sand, poorly sorted.
90%–99% vc to vf (mostly c to m) quartz sand, moderately to poorly sorted; 1%–2% twigs, roots, and charcoal (1%–2%).

100% mostly c to m quartz sand; moderately sorted; no visible sedimentary structures; rare opaque grains and organic debris.

100% vc to f (mostly c to m) quartz sand, moderate sorting, no visible sedimentary structures.

No Recovery

100% vc to f (mostly c to m) quartz, moderate sorting, no visible sedimentary structures.

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<th>Gravel</th>
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- **100% vc to m quartz sand, moderate to poor sorting, mostly poor sorting, no apparent sedimentary structures.**
- **No Recovery**
- **100% vc to m quartz sand, vf sand to clay matrix, poorly sorted.**
- **Silty clay, with sparse floating c to m quartz grains.**
- **97% m to f (mostly f) quartz sand, 2% vf opaque grains, 1% f to vf mica, well sorted, no apparent bedding.**
- **100% vc to m quartz sand, occasional pebbles 1 cm across, poorly sorted.**
Feet
20
21
22
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24
25
26
27
28
29
30

Color
white 90

C1

Silt

vf

Sand

Gravel

Description

97% m to v(f mostly) quartz grains, 2% of opaque heavy mineral grains, 1% f to v(mica grains, well sorted, no apparent bedding.

97% m to quartz sand, 1-2% f to v opaque grains, m to v mica (1-2%), moderate to well sorted, color stains may follow cross bedding.

97-98% f to v quartz sand, 1% f to v opaque grains, 1% m to v mica, areas with clay matrix (pinkish gray SYR 8/1).

97-98% f to v quartz sand, 1-2% f to v opaque grains, 1% m to v mica, well sorted.

Silty clay, no apparent bedding.

97% m to v quartz sand, 1% f to v opaque grains, 1% m to f mica, one lamination with kaolinitic clay matrix.

Silty clay, no apparent bedding

98% m to v quartz sand, 1% f opaque grains, 1% m mica, well sorted, mm thick cross strata with a kaolinitic matrix that follows some of the cross-strata, occasional mm thick blobs of concentrated kaolinitic matrix in places.

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<td>98% vc to f (mostly m) quartz sand, 1% f opaque grains, 1% m mica, well sorted, occasional scattered mm thick blobs of kaolinite matrix.</td>
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<td>moderately cemented sand</td>
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<td>Silty clay, no apparent bedding.</td>
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<td>32</td>
<td>very pale orange</td>
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<td>100% vc to c quartz sand, occasional scattered mm-cm thick blobs of kaolinite matrix, no apparent bedding, moderately sorted.</td>
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<td>iron cemented sand grains</td>
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<td>100% vc to m quartz sand, mm-cm thick blobs of kaolinite matrix (white N9), subrounded to angular, no apparent bedding, iron cemented sand grains found at the top of the bed, dashed lines represent color changes.</td>
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<td>very pale orange</td>
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<td>100% vc to m quartz sand with occasional pebbles up to 26 mm in length x 10 mm in width, poorly sorted, rounded clear framework quartz pebbles present.</td>
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<td>(Upper 0.0-0.4 m) 99% cto m quartz, 1% f opaques, occasional areas of 1-5 mm kaolinite matrix, moderately sorted. (Lower 0.4-0.6 m) 100% vc to m quartz sand with some pebbles present, 50% kaolinite matrix (white N9), quartz grains are subrounded to subangular. Top 0.1 in on bottom FUS dark yellow-orange 10 YR 7/4.</td>
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<td>100% f to vf quartz sand with a few cto m grains present, poorly sorted, kaolinite (white N9) (0.5-1.0 cm long x 0.3-0.6 cm wide), cleats are along horizontal bedding.</td>
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<td>100% c to m quartz sand with occasional concentrated blobs of kaolinite matrix, moderate sorting, no apparent bedding.</td>
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<td>Silty clay, no apparent bedding, floating grains of c to m, subrounded quartz sand.</td>
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</table>
Silty clay, rare mica, floating grains of c to f quartz sand.

99% c to f quartz sand, 1% f to v opaque grains, rare mica, kaolin matrix present, moderate sorting, no apparent bedding.

No Recovery

99% c to f quartz sand, 1% f to v opaque grains, rare mica, kaolin matrix present, moderate sorting, no apparent bedding.

99% vc to m gravelly quartz sand, (gravel up to 7 mm in length) 1% f to v opaque grains, 1% m mica, kaolin matrix, poor sorting, no apparent bedding, subangular to subrounded.

99% vc to m quartz sand, 1% f to v opaque grains, 1% m mica, kaolin matrix present, moderate to poor sorting, no apparent bedding, subangular to subrounded.

No Recovery
<table>
<thead>
<tr>
<th>Feet</th>
<th>Color</th>
<th>Clay</th>
<th>Silt</th>
<th>f</th>
<th>Sand</th>
<th>m</th>
<th>c</th>
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<th>Gravel</th>
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</table>

**Description**

99% to quartz sand, 1% f to v f opaque grains, rare m to f mica, kaolinite matrix present, well sorted, no apparent bedding.

98% c to m quartz sand, 1% m to f opaque grains, rare m to f mica, occasional mm sized flakes of kaolinite matrix present, moderately sorted, no apparent bedding.

99% c to m quartz sand, 1% m to f opaque grains, rare m to f mica, 1.2 mm thick horizontal low angle laminations.

No Recovery

98% c to m quartz sand, 1% f to v f opaque grains, 1% c to m mica, horizontal to low angle laminations, moderately sorted, some kaolinite matrix between grains.

No Recovery
100% vc to c quartz sand, 1 cm diameter areas of kaolin matrix (white N9) present, poorly sorted, possible low angle bedding, scattered gravel 6 mm x 3 mm.

99% vc to m (mostly cl) quartz sand, 1% f to vf opaque grains, c to m) rare mica, moderate to poor sorting, some 1-3 mm diameter blots of kaolin matrix (white N9).

99% vc to m quartz sand, 1% f to vf opaque grains, (c to m) rare mica, subrounded to subangular, 3-5 mm patches of kaolin matrix (white N9), occasional 0.5 x 1 cm pebbles, smoley quartz present.

98% vc to c quartz sand, 1% m to vf opaque grains, rare mica, kaolin matrix (white N9) moderate sorting, no apparent bedding.

98% vc to c quartz sand, 1% m to vf opaque grains, rare mica, 3-4 mm gravel, a few 4 mm x 10 mm) kaolin clasts (white N9), poor sorting, no apparent bedding.

No Recovery
Silty clay bed 1 cm thick

98% m to f quartz sand, 1% f to vf opaque grains, 1% m to f mica, clay around quartz grains, moderate to well sorted, no apparent bedding.

Coarse grains (vc to f), 2-5 mm thick laminations of dark yellowish orange 10YR 6/6
Same as overlying unit (65.1 to 67.0)
98% m to f quartz sand, 1% f to vf opaque grains, 1% c to f mica, moderate to poor sorting, no apparent bedding.
Coarse grains are sparse at the top of the bed and more abundant at the bottom

6-10 mm clay rip-up clasts

98% m to f quartz sand, 1% f to vf opaque grains, 1% vc to f mica, moderate sorting, vc to c sand follows (0.5-2.0 cm) thick cross bedding

No Recovery
# Description

98% c to f (mostly m) quartz sand, 1% f to v f opaque grains, 1% v f mica, moderate to poor sorting, (0.5-2 cm) thick color bands, possible cross bedding, kaolinite matrix between some grains.

100% v f m quartz sand, rare opaque grains, rare mica, moderate to poor, possible 1 cm thick color bands that may be bedding, occasional smoky quartz grains, subangular to subrounded.

99% c to m quartz sand, 1% c to m mica, rare f to v f opaque grains, moderate to poor sorting, color bands may follow possible bedding.

Increase in grain size v c to m.

C to m only

98% v c to m quartz sand, 1% f to v f opaque grains, 1% c to m mica, no apparent bedding, kaolinite matrix in pieces, bands of moderate orange-pink 10R 7/4.

99% c to f quartz sand, 1% f to v f opaque grains, rare mica, moderate sorting, possible cross bedding 1 cm thick.

100% v c to m quartz sand, rare opaque grains, rare mica, poorly sorted, no apparent bedding, kaolinite matrix.

99% c to f quartz sand, 1% f to v f opaque grains, rare mica, moderate sorting, no apparent bedding, kaolinite matrix (white N9).

No Recovery

99% v c to m quartz sand, 1m to v f opaque grains, rare mica, a few scattered pebbles up to 6 cm in length, oblique to horizontal 1 cm thick laminations with more abundant kaolinite matrix bedding (7%), poorly sorted, kaolinite matrix.

99-97% v c to m quartz sand, 1-3% f to v f opaque grains, rare mica, occasional pebbles up to 4 mm in length, opaque grains may follow bedding in places, poorly sorted, kaolinite matrix.

98% c to f quartz sand, 2% m to v f opaque grains, rare mica, a few scattered pebbles, possible low angle bedding (?), poorly sorted.

100% v c to m quartz sand, f to v f of rare opaque grains, rare mica, with occasional pebbles up to 7 mm in length with kaolinite matrix in places, poorly sorted, smoky quartz present.

99% m to f quartz sand, 1% c to m mica, f to v f of rare opaque grains, moderate sorting, kaolinite matrix in places.

1.5 cm thick clay chip with f to v f of opaque minerals, concentrated at base.

See description on next page.
100% vc to m quartz sand, rare opaque grains, rare mica; kaolin matrix (white N19) moderate to poor sorting, mm sized blobs of kaolin matrix present, mostly subrounded.

Increase in coarse grains (c to f)

Increase in kaolin matrix

98% c to m quartz sand, 1% c to m mica, 1% f to v f opaque grains, poor sorting.

99% vc to m quartz sand, 1% c to m mica, rare f to v f opaque grains, poorly sorted.

Greater concentration of pebbles into fines to vc sand

100% vc to m quartz sand, rare vc to m mica, rare f to v f opaque grains with occasional vc to m opaque grains, a few scattered pebbles in places, kaolin matrix is thicker in some places.

Increase in vc c grains

Increase in vc c grains

99% vc to m (mostly c to m) quartz sand, 1% f to v f opaque grains, rare (c to f) mica, moderate to poor sorting, no apparent bedding, (1-2 mm) blobs of kaolin (white N19) matrix, subrounded to subangular.
See description on previous page from 88.6-90.0 ft.

Increase in grain size vc to m with a few pebbles up to 5 mm in length.

96-98% m to f quartz sand, 1-3% f to vc opaque grains concentrated in places, 1% c to m mica, kaolin matrix (white N9) in places, moderate sorting, no apparent bedding.

Increase in grain size vc to m.

99% f to v, quartz sand, 1% f to vc opaque grains, rare c to f mica, clayey clay matrix, occasional floating (c to m) quartz grains, mostly well sorted, 2 cm diameter vertical burrow or root structure (most likely) filled with vc to m quartz sand, opaque grains, and clay. Length of burrow or root structure is at least 0.9 ft with a 2 mm thick rim (moderate red to dark yellowish-orange). No obvious sedimentary structures, occasional 1-3 mm flecks of black material (organic matter? altered plant debris?) and see color on quartz grains.

99% m to f quartz sand, 1% f to vc opaque grains, 1% c to f mica, well sorted, no apparent bedding.

99% c to f (mostly m to f) quartz sand, 1% f to vc opaque grains, 1% c to m mica, moderate sorting, possible 0.5 cm thick low angle laminae, occasional 1 mm x (1-6 mm) areas of black sand (plant debris).

No Recovery.
98% m to f quartz sand, 1% f to v of opaque grains, 1% vc to m mica, moderate sorting, possible low angle laminations 2-6 mm.

Increase in c to f quartz sand

No Recovery

100% vc to f quartz sand

No Recovery

Separate clast or bed 100% vc to m quartz sand in a clay matrix, rare mica, poorly sorted.

99% vc to m quartz sand, 1% f to v of opaque grains, rare m to f mica, poorly sorted, kaolin matrix (very light gray NB).

98% vc to m (mostly c to m) quartz sand, 1% f to v of opaque grains, 1% c to m mica, moderate sorting, kaolin matrix, no apparent bedding

No Recovery
No Recovery

100% vc to m quartz sand, rare vc to f mica, occasional pebbles (up to 6 mm), smoky quartz present in matrix, poorly sorted, no apparent bedding.

99% vc to f (mostly c to f) quartz sand, 1% vc to m mica, smoky quartz present, mm sized blebs of kaolinite matrix (white Hb), poorly sorted, possible horizontal bedding.

Horizontal laminations 0.5 cm. 1 cm thick. 97-98% m to f quartz sand, 1% m to f mica, 1-2% f to v of opaque grains. 96-98% quartz sand, 1-3% f to v of opaque grains, 1% m to f mica. Both are well sorted.
Same description as 116.6-116.4 ft.

Vague horizontal laminations: 97-98% m to f quartz sand, 1% m to f mica, 1-2% f to v of opaque grains, 96-98% quartz sand, 1-3% f to v of opaque grains, 1% m to f mica. Both are well sorted.

5-20 mm size clasts of silt, clay with floating grains of c to m quartz sand, one 6 mm long feldspar grain.

90% m to f quartz sand with occasional pebbles (2 to 6 mm), 1% vc to m mica, possible for angle laminations that are white Hb due to presence of kaolinite.

Pebbley sand, pebbles (2-10 mm).
Vague horizontal laminations: 97-98% m to f quartz sand, 1% m to f mica, 1-2% f to v of opaque grains, 96-98% quartz sand, 1-3% f to v of opaque grains, 1% m to f mica. Both are well sorted.
Mottled transition zone between upper and lower units, moderately red SR 6.6.

Sandy, silty clay, with occasional floating grains of c to m quartz sand, roughly 1% f to v mica.

No Recovery
99% f to v silt sand, 1% m to f mica, silt and clay matrix, and occasional floating grains of c to m quartz sand, well sorted.

99% f to v quartz sand, 1% m to f mica, 1% f to v opaque grains occasional floating grains of c m sand, well sorted, no apparent bedding, mottled colors.

99% f to v quartz sand, 1% m to f mica, floating grains of c to m quartz sand, mostly well sorted.

99% c to f (mostly m to f) quartz sand, 1% f to v opaque grains, rare mica, kaolin matrix, well sorted, no apparent bedding.

99% c to f (mostly m to f) quartz sand, 2-6% c to m mica, moderate sorting. Light areas very light grey NB contain more mica (~5% mica, c. to m.), but fewer coarse quartz grains that are mostly m to f quartz sand.

No Recovery
130 Fees

Gravel Description

99% c to m quartz sand, 1% c to m mica, moderate sorting, no apparent bedding, smoky quartz present.

100% vc to m quartz sand, rare c to m mica, occasional pebbles up to 3 mm in length, kaolin matrix, poorly sorted, no apparent bedding.

99% c to m quartz sand, 1% c to f mica, moderate sorting, mm blobs of kaolin matrix, horizontal to low angle bedding (0.5-3.0 cm) thick, smoky quartz present.

99% vc to m quartz sand, 1% c to fmica, poor sorting.

96% c to f quartz sand, 3% c to f mica, 1% f to f opaque grains, moderate sorting, mm to cm thick horizontal to low angle laminae, band of color very light grey NB and dark yellowish orange 10YR 6/6.

99% c to f quartz sand, 1% c to fmica, moderate sorting.

99% vc to m quartz sand, 1% vc to fmica, areas of smoky quartz, mm sized blobs of kaolin matrix, poor sorting.

FUS

99% vc to m quartz sand, 1% vc to m mica, mm sized blobs of kaolin matrix, areas of smoky quartz, poor sorting, no apparent bedding.

More abundant vc to c grains with less abundant kaolin matrix, possible cm thick cross bedding.

140
142

Feet | Color | CI | Silt | vf | f | Sand | m | c | vc | Gravel |
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160 |  |  |  |  |  |  |  |  |  |  |

Description

No Recovery

100% c to f quartz sand; rare m to f mica; rare m to f opaques, well to moderately sorted, kaolin matrix, no apparent bedding.

Silty clay

93% m to f quartz sand; 1% f to v f opaque grains; 1% m to f mica; kaolin matrix, occasional c grains of quartz sand, well to moderately sorted.

99% vc to f f mica; vc to f f mica; 1% m to f opaque grains; rare mica, isolated mm size blocks of kaolin matrix.

99% vc to m (mostly c) quartz sand; 1% m to f opaque grains; rare m to f mica; opaques and mica grains concentrated along mm thick laminations, poorly sorted, isolated mm size blocks of kaolin (white N9), possible 1-2 cm thick low angle to horizontal beds.

95-99% vc to m (mostly c, but a few more vc) quartz sand; 5% m to f opaque grains; opaque grains are concentrated along laminations, poor sorting, a few mm size blocks of kaolin matrix (white N9).

No Recovery
Sandy gravel or gravelly sand, with gravel up to 1 cm across, 99% vc to c quartz sand, 1% f to vf opaque grains, smoky quartz present, gravel is subrounded to rounded, patches of kaolinitic matrix, 0.5-1 cm sized clasts of kaolinite (white N0).

99% c to f (mostly c to m) quartz sand, 1% f to vf opaque grains, rare f to vf mica, smoky quartz present, moderate sorting, subrounded to subangular, kaolinitic matrix.

99% m to f quartz sand, 1% f to vf opaque grains, rare f to vf mica, kaolinitic matrix, well to mod. sorted, rounded to subrounded.

See description from 161.7-161.8 ft.

See description from 161.1-161.7 ft.

Pebbly sand, pebbles are up to 2 cm long (smoky quartz).

99% vc to m quartz sand, 1% f to v opaque grains, rare f to vf mica, kaolinitic matrix, poorly sorted.

97% c to f quartz sand, 2% m to vf opaque grains, 1% f to vf mica, kaolinitic matrix, moderate to poor sorting, occasional vc quartz sand, smoky quartz present.

No Recovery.

100% vc to m (mostly c to m) quartz sand, rare m to fnica, rare f to vf opaque grains, moderate sorting, possibly some mm kaolinitic clasts.

Pebbly sand, 98% vc to m quartz sand, 1% c to fnica, 1% m to vf opaque grains, pebbles and kaolinitic clasts up to 15 mm across, kaolinitic matrix, poorly sorted, smoky quartz present.

98% vc to m quartz sand, 1% c to fnica, 1% f to vf opaque grains, kaolinitic matrix, possibly some 1 mm kaolinitic clasts, poorly sorted.

99% vc to m quartz sand, 1% opaque grains, rare m to fnica, clays of 2 mm kaolinitic clasts, kaolinitic matrix, poorly sorted.

No Recovery.

See description from 163.1-163.9 ft.

See description from 165.0-165.4 ft.

See description from 165.4-165.7 ft, 10 mm smoky quartz pebble present.

See description from 165.0-165.4 ft.

See description from 165.4-165.7 ft.

Clay bed.

99% m to f quartz sand, 1% f to vf opaque grains, rare f to vf mica, moderate to well sorted, subrounded to subangular, 1 cm thick horizontal beds at the top.

No Recovery.
99% m to f quartz sand, 1% f to v f opaque grains, moderate sorting, no apparent bedding.

99% c to f (mostly m) quartz sand, 1% f to vf opaque grains, moderate to well sorted, subangular to subrounded.

Pebbles up to 5 mm, 100% vc to m quartz sand, smoky quartz present.

99% c to m quartz sand, 1% m to vf opaque grains.

Pebbles and kaolin clasts up to 8 mm, 99% vc quartz sand, 1% f to vf opaque grains, poorly sorted.

99% c to m quartz sand, 1% f to vf opaque grains, well sorted, no apparent structures.

Kaolin clasts up to 4.5 x 1 cm and pebbles 5 mm across, 99% vc to m quartz sand, 1% f to vf opaque grains, no apparent bedding.

No Recovery

100% vc to m (mostly c to m) quartz sand, rare f to vf opaque grains, moderately sorted, very occasional kaolin matrix biobeds, no obvious sedimentary structures, pebbles up to 14 mm long at base, smoky quartz present.

100% c to m quartz sand, rare f to vf opaque grains, 0.5-1.0 cm thick laminations some kaolin along laminae, kaolin matrix.

98% vc to f (mostly c to m), 2% f to vf opaque grains, opalines are concentrated in some places along laminae, coarse grains near base of unit, some pebbles up to 6 mm near base, pebbles and vc sand are smoky quartz, 0.5-1.0 cm thick cross laminations, kaolin matrix.

No Recovery
100% c to m quartz sand, rare mica, rare opaque grains, well to moderately sorted, rare mm size blocks of kaolin matrix, 0.5 to 2 cm thick cross-bedding.

Laminations of opaque
medium light gray N9
Contact pebbles up to 12
mm and oscillation of
opaque grains (m to f) and
f to quartz sand.

99% vc to m quartz sand, 1% opaque grains, kaolin matrix
white N9, some kaolin clasts 1x5 mm of kaolin.

No Recovery

94% vc to m quartz sand, 3% m to f opaque grains, rare f to vf
mica, 3% kaolin clasts 1x7 mm, scattered pebbles up to 5 mm
throughout, vague horizontal bedding, poorly sorted.

99% c to f (mostly c to m) quartz sand, 1% f to vf opaque
grains, moderate sorting, small amounts of kaolin matrix,
meander to subrounded.

Scattered pebbles up to 5 mm, 97% vc to f quartz sand, 1% f to
vf opaque grains, 2% kaolin clasts up to 5 mm, poorly sorted.
97% c to quartz sand, 1% f to vf opaque grains, 2% kaolin
clasts (1 mm), moderate sorting, subrounded to subangular.

See description from 186.4-186.6f.

See description from 186.6-186.9f.

Pebbles (5x15 mm), 97% vc to c quartz sand, 1% f to vf
opaque grains, rare f to vf mica, 2% kaolin clasts up to 9 mm,
no apparent bedding, poorly sorted.

No Recovery
190

**Feet**

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<th>Color</th>
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**Description**

Pebbles up to 5 mm, 96-94% vc to m quartz sand, 1-4% ft to vf opake grains, kaolin clasts up to 50 cm, poorly sorted.

191

97-94% vc to m quartz sand, 2% kaolin clasts 1-2 mm, 1% ft to vf opake grains, rare mica, pebbles present, poorly sorted, no apparent bedding.

Silty clay with scattered black specks (plant debris). A

Sandy clay with black specks (plant debris).

192

Silty sand to sandy silt, 98% of quartz sand, 1% ft to vf mica, 1% ft to vf opake grains, well sorted, no black specs.

Horizontal 1-3 cm thick beds of sandy silt and silty sand, 160% ft to vf occasional m quartz sand, rare m to vf mica, rare ft to vf opake grains, well sorted.

193

Sands: 160% ft (mostly m to f) quartz sand, rare f to vf mica, rare m to vf opake grains, well sorted, kaolin matrix, subrounded to subangular Class: Silty clay, mostly clay.

Sandy silt clay (mostly a silty clay), floating m quartz sand, 1% ft to vf opake grains, rare mica, well sorted, scattered 1-5 mm long black specks (plant debris), white N8 to very light grey N8 (more towards top), slight increase in sand towards top of bed.
100% vc to f (mostly vc to m) quartz sand, rare opaque grains, a few mm size blocks of kaolin matrix, moderate sorting, no obvious sedimentary structures.

Pebby sand, pebbles up to 4 mm in length, 100% vc to f (mostly vc to m) rare opaque grains, rare lithic fragments. No obvious sedimentary structures, 3-2 cm size areas of light gray N7 kaolin matrix, milky quartz, smoky quartz, and clear quartz present.

Sandy silt clay (to vf) quartz sand, rare mica, scattered lines of black fragments (plant debris). Pebby sand, pebbles up to 2.5 cm, 100% vc to m quartz sand, rare m to f mica, rare f to vf opaque grains, poorly sorted.

See description from 213.6 to 213.8 ft. 100% m to f quartz sand, rare f to vf opaque grains, rare m to vf mica, well sorted.

See description from 213.6 to 213.8 ft. See description from 214.2 to 214.8 ft.

See description from 213.6 to 213.8 ft. Pebby sand, pebbles up to 7 mm, milky, smoky, and clear quartz, poorly sorted. 100% vc to f (mostly mi) quartz sand, rare mica, rare opaque grains, poorly sorted.

Pebby sand, pebbles up to 1.8 cm, 99% vc to m (mostly vc to quartz sand, rare m to f mica, 1 mm size blocks of kaolin matrix, poorly sorted, no apparent bedding, ~1% white feldspars (more common at base)."
PATRICK CORE DESCRIPTION
90% mostly s to m quartz sand, 1% f&v of opaque grains, rare mica, scattered accumulations of kaolin matrix (1%), moderate sorting, subrounded to subangular sand grains, no apparent sedimentary structures.
151

Footage | Color | Clay | Silt | M | t | f | c | vc | Gravel | Description
---|---|---|---|---|---|---|---|---|---|---|
10 | &lt;25% quartz sand, 97% f to t white grains, scattered accumulations of kaolin matrix (1%), moderate sorting, no apparent sedimentary structures.
| kaolin yellowish-gray | S3 B1/1 |
| increase in coarse grains |
| S3 B1/1 |
| No Recovery |
11 | 100% &lt;25% quartz sand, rare opaque grains, rare kaolin, moderate sorting, subrounded to subangular sand grains, no apparent sedimentary structures.
| light brown | S1 YR 6/3 |
12 | All cm to rem: thick beds of sand and clay, most sand beds are m to f (apparent bed is sc to m). 100% quartz sand, rare mica, kaolin, rare f to t opaque grains. Clay colors: pale yellowish-orange 10 YR 6/6, yellowish-gray 5 YR 8/1, and very pale orange 10 YR 8/2.
| 99% &lt;25% quartz sand, 1% f to t opaque grains, rare mica, cm thick bands of different colors (pale red 10 R 5/2, pale reddish-brown 10 R 5/4, grayish-yellow 5 YR 8/4, pinkish gray 5 YR 8/1), well to moderately sorted, kaolin matrix present.
| No Recovery |
13 | 14 |
15 | 16 |
17 | 18 |
19 |
20 |
No Recovery

98% m to f quartz sand, 2% f to vf opaque grains, rare mica, moderate to well sorting, possible horizontal bedding 1 cm thick, clayey sand (top) to sandy clay (bottom), moderate red 5R 5/4 in places.

98% c to m quartz sand, 2% f to vf opaque grains, rare mica, moderate sorting, no apparent sedimentary structures.

97% f to vf quartz sand, 2% f to vf mica, 1% f to vf opaque grains, well sorted, no apparent sedimentary structures, colors alternate in 1 to 3 cm bands.

99% m to f quartz sand, 1% f to vf opaque grains, rare mica, well to moderate sorting, 5 to 10 cm thick sand to clayey sand beds, kaolinite matrix present in places.

99% c to f quartz sand, 1% f to vf opaque grains, rare mica.

97% m to f quartz sand, 2% f to vf opaque grains, 1% m to f mica, moderate to well sorting, horizontal to low angle (f) bedding 5-10 mm thick.

Clay, 5-10% quartz grains with iron stained rims (dusky red 5R 3/2).
Clay to silt clay (mostly clay), no sedimentary structures. Sampled for XRD analysis at 30.9 feet.

100% m to f quartz sand, rare opaques, rare opaque grains, rare inorganic clay matrix (abundant clay matrix) streaks of incomplete red (SR 5/4) concentrated along coarse sand grains.

100% ve to m quartz sand, moderate to poor sorting, subangular to subrounded, oblong, no obvious sedimentary structures, streaks of moderate red (SR 3/4).

100% ve to m quartz sand, some clay matrix (not as pervasive as overlying unit), moderate to poor sorting, no obvious sedimentary structures.

100% ve to m quartz sand, rare fines to very fine opaque grains, some clay matrix, moderate to poor sorting, no obvious sedimentary structures.

No Recovery.
100% vc to m (mostly c to m) quartz sand, rare f to vf opaque grains, moderate to poor sorting, some clay matrix, no obvious sedimentary structures.

99% vc to m quartz sand, 1% m to vf opaque grains, rare mica, moderate to poor sorting, some clay matrix, no obvious sedimentary structures.

100% c to m quartz sand, rare vf opaque grains, moderate sorting, subrounded to subangular (mostly subrounded) some clay matrix, no obvious sedimentary structures.

99% c to m quartz sand, 1% vf opaque grains, moderate sorting, some clay matrix, no obvious sedimentary structures.

99% c to m quartz sand, 1% vf opaque grains, rare mica, moderate sorting, some clay matrix, no obvious sedimentary structures.

No Recovery
100% c to m quartz sand, rare f to v opaque grains, kaolin matrix, moderate to poor sorting, no obvious sedimentary structures.

100% c to f quartz sand, poorly sorted, no sedimentary structures, 99% c to m quartz sand, 1% f to v opaque grains, 0.5-1.0 cm thick bed, moderately sorted, some kaolin present.

No Recovery
Description

Sand (mottled) to clayey sand; 97-98% f quartz sand, 2-3% vf opaque grains; rare mice, moderately sorted, 1 cm iron concentration present.

0.5-1.0 cm disrupted clay beds (?disturbance?), lighter beds (pinkish-gray 5 YR 6/1) and darker beds (pale yellowish brown 10 YR 6/6).

100% m to f quartz sand, rare f to vf opaque grains, moderate to well sorted.

99% m to f quartz sand, 1% f to vf opaque grains, moderately sorted.

100% vc to m quartz sand, f to vf opaque grains, moderate sorting.

Gravel present, 100% vc to c quartz sand, f to vf opaque grains, moderate sorting.

100% m to f quartz sand, moderate to well sorted; streaks of pale yellowish-orange 10 YR 8/6.

No Recovery
99% m to f quartz sand, 1% f to vf opaque grains, rare mica, moderate to well sorted, subangular to subrounded (mostly subrounded), possible laminations 0.5 to 1.0 cm thick.

99% c to f quartz sand, 1% f to vf opaque grains, moderate sorting.

99% m to f quartz sand, 1% opaque grains, moderate sorting.

100% m to f quartz sand, rare f to vf opaque grains, rare m mica, well sorted.

99% c to f quartz sand, 1% f to vf opaque grains, moderate to poor sorting, subangular to subrounded.

99% m to f quartz sand, 1% f to vf opaque grains, 1% m to f mica, moderate to well sorted.

Clay cemented sand, 100% c to m quartz sand, moderate to poor sorting.

98-99% m to f quartz sand, 1-2% c to f mica, rare opaque, some kaolin matrix, laminated sands (some laminations have a clay matrix), matrix (pinkish gray 5YR 6/2).

Clay with fine quartz sand (dark reddish brown 10YR 3/4).

Alternating disrupted (bioturbated) laminations of light gray and medium gray clay. Sampled for XRD analysis at 89.0 feet.

Clay

No Recovery
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Clay, massive with no sedimentary structures.

Area with dark yellowish orange 10YR 6/6 blobs of sandy clay; blobs consist of vI quartz sand and silt.

Alternating laminations of light gray clay and dark yellowish orange 10YR 6/6 sandy clay; sandy clay contains of quartz sand and silt.

Clay with blobs and laminations of sandy clay; sandy clay contains of quartz sand and silt and is dark yellowish orange 10YR 6/6 in color. Some vI sand in the gray clay.
Silty clay, clay is light gray N7; silty areas are dark yellowish orange (10YR 6/4).

Clay.

Clay, mostly light gray N7 with blobs of silty clay (moderate yellowish brown 10YR 5/4).

Clay, mostly light gray N7 with blobs of silty clay 10YR 5/4 moderate yellowish brown 10 YR 5/4 clayey fine sand, fine mica, feldspar, and silty opaque grains. Sampled for XRD analysis at 115.0 feet.

Silty clay.

Alternating laminations of clay (yellowish gray 5Y 5/1) and silty clay to very fine sand with 1% mica (grayish orange 10YR 6/4).

Clay with some silt and very fine sand. Alternating laminations of yellowish gray 5Y 5/1 and pale red 10R 6/2.

Silty clay with some very fine sand, 1% mica.

Silty clay, very light gray N6.

Silty sandy clay, feldspar, 1% mica, 1% opaque.

Silty sandy clay, very fine sand.

Sandy silty clay, very fine sand. Increase in sand compared to unit above.
100% m quartz sand, rare silt, rare mica, well sorted.
Disrupted laminations of sandy clay and silt quartz sand (100%) with rare mica. Lighter colors contain more clay and reddish colors are more sand rich. Polish gray 5YR 8/1, pale red 10R 6/2, moderate red 5R 4/6.
Clayey sand (vf).
100% f to vf quartz sand.
Clayey sand (f to vf), well sorted.

Sandy silty clay, sand is f to vf. Sampled for XRD analysis at 122.6 feet.

99% c to m quartz sand, 1% c to m mica, moderately sorted, no obvious sedimentary structures.

99% c to m quartz sand, 1% c to m mica, moderate to poorly sorted, no obvious sedimentary structures, kaolin matrix present.

Clayey sand, 100% c to m quartz sand, moderate to poorly sorted, dark yellowish orange 10YR 6/4 with cm thick blocks of light gray N7.

100% c to m quartz sand with kaolin matrix, moderate to poor sorting.

No Recovery
Description

100% c to m quartz sand, with kaolin matrix present, moderate sorting, no obvious sedimentary structures.

99% c to m quartz sand, 1% f to v opaque grains, rare mica, moderate sorting, no obvious sedimentary structures, kaolin matrix present.

Silty clay, 1% m to f mica. (Upper) 0.4m contains pale red streaks SR G2 and (lower) 0.2m contains grayish orange streaks 10YR 7/4.

98% m to f quartz sand, 1% f to v opaque grains, 1% mica, subangular to subrounded, cm thick horizontal beds, well sorted.

Clayey sand, 99% f sand, 1% mica, well sorted.

98% m to f quartz sand, 1% f to v opaque grains, 1% mica, well sorted.

99% m to f quartz sand, 1% f to v opaque grains, rare mica, well sorted, some kaolin matrix.

99% m to f quartz sand, 1% f to v opaque grains, rare mica, well sorted, increase in kaolin matrix, cm thick lenses and blobs of matrix throughout.

Clay to silty clay, maybe some f quartz sand.

99% f quartz sand, 1% f to v opaque grains, rare mica, well sorted, kaolin matrix present.

98% f quartz sand, 1% f to v opaque grains, 1% m to f mica, well sorted.

99% m to f quartz sand, 1% f to v opaque grains, rare mica, well sorted.

99% m to f quartz sand, 1% opaque grains, rare mica, moderately sorted, occasional bands of grayish orange 10YR 7/4.

95% v to m quartz sand, 5% f to v opaque grains, poorly sorted.
163

Description
99% m to f quartz sand, 1% f to vf opaque grains, 0.5 cm bands of grayish orange 10YR 7/4, moderate sorting.

99% m to f quartz sand, 1% f to vf opaque grains, well sorted.

100% m to f (mostly f) quartz sand, well sorted.

Silty clay.

99% m to f (mostly f) quartz sand, 1% opaque grains, well sorted

No Recovery

Silty clay with 1% mica.

100% c to m quartz sand, rare opaque grains, moderately sorted.

No Recovery
99% c to m quartz sand, 1% fl of opaque grains, patches of pale red purple SFP 4/2, moderate sorting.
Clayey sand, 99% f to vl quartz sand well sorted, patches of pale red purple SFP 4/2.
99% vc to f quartz sand, 1% f to v opaque grains, poorly sorted.

No Recovery
Clayey sand. 100% f to yf quartz sand, rare opaque grains, rare mica, well sorted, no obvious sedimentary structures.
Silty clay, rare mica.

160% c to m quartz sand, rare opaque moderate to well sorted.

No Recovery.

98-99% c to m quartz sand, 1-2% f to v f opaque grains, moderately sorted, moderate reddish brown 10R 4/6.
98% c to m quartz sand, 2% f to v opaque grains, moderately sorted.

99% c to m quartz sand, 1% f to v opaque grains, moderately sorted.

Silty clay.

Silty clay w v f sand and rare mica, streaks of pale red purple S6P 6/2.
Silty clay.
No Recovery.
Silty clay.

Sandy silty clay, 99% v f quartz sand, 1% mica, 1% opaque grains, well sorted, possible horizontal laminations, few streaks of pale red purple S6P 6/2, a few streaks of moderate yellowish brown 10YR 5/4.

Sandy silty clay, 100% v f quartz sand.

160% m to f mostly q quartz sand, rare mica, possible 0.5 cm horizontal laminations, well sorted.

160% f to v quartz sand and clayey sand, alternating laminations present.

Silty clay with laminations.

160% f quartz sand, well sorted, clay laminations present.

No Recovery.
**Diagram Notes and Descriptions:**

- **210 Feet:**
  - **Clay Shale:** Greyish pink 5G 4/2
  - **Sand:** 100% vc to m quartz sand, rare mica, moderately sorted, subangular to subrounded (mostly subangular).

- **211 Feet:**
  - **Clay:** Clay matrix
  - **Sand:** 100% vc to m quartz sand, rare vc to c mica, moderately sorted.

- **212 Feet:**
  - **Clay:** Clay matrix
  - **Sand:** 100% vc to m quartz sand, rare mica, moderately sorted.

- **213 Feet:**
  - **Clay:** Clay matrix
  - **Sand:** Sandy gravel with kaolinite matrix, 100% vc to c quartz sand, poorly sorted.

- **214 Feet:**
  - **Clay:** Clay matrix
  - **Sand:** 100% vc to m quartz sand, rare vc to c mica.

- **215 Feet:**
  - **Clay:** Clay matrix
  - **Sand:** 100% vc to m quartz sand, rarely mica, moderate sorting.

- **216 Feet:**
  - **Clay:** Clay matrix
  - **Sand:** 100% vc to m quartz sand, rare vc to c mica, moderately sorted.

- **217 Feet:**
  - **Clay:** Clay matrix
  - **Sand:** 100% vc to m quartz sand, rarely vc to c mica, moderately sorted.

- **218 Feet:**
  - **Clay:** Clay matrix
  - **Sand:** 100% vc to m quartz sand, rare vc to c mica, moderately sorted.

- **219 Feet:**
  - **Clay:** Clay matrix
  - **Sand:** Very fine gravel

- **220 Feet:**
  - **Clay:** Clay matrix
  - **Sand:** No recovery
Silty clay, with 2-5 mm thick bands of pinkish gray 5YR 8/1 to dusky red 5R 3/4. Bed contains a few scattered grains of vf to c quartz sand.

Clayey silt with vf sand.

95% m to f quartz sand, 5% f to vf opaque grains, rare mica, moderate sorting.

95-99% vc to c quartz sand with rare pebbles, 1-2% f to vf opaque grains, moderate sorting, some accumulations of opaque grains along laminations and 2-6 cm cross-beds, some coarser than others. Darker colors are bolded cross beds.

Cross-beds of predominantly quartz sand, 2-6 cm thick cross beds. Some cross beds are vc to c, others are c to m sand. Quartz grains are subangular to subrounded.

65-99% vc to m quartz sand, 2-10% f to vf opaque grains, 1-3% mica. Opaque grains follow cross beds in some places, white N9 mm thick laminations of clay follow cross beds, cross beds are faint in places, moderate sorting, rare rose quartz.

Pebbly sand, scattered rounded to subrounded quartz pebbles (0.5 cm long), and (1-3 cm in diameter) very light gray N8 clay clasts (trip-up clasts), 100% vc to c sand, moderate to poor sorting.

No Recovery
172

99% c to m quartz sand, 1-2% f to v of opaque grains, rare mica; moderate sorting.

Increase in grain size vc to m.

100% vc to m quartz sand, into fine mica, f to v of rare opaque; moderate sorting. Send with laminations with mud around sand grains (above).

100% c to m quartz sand, vc to m fine mica, f to v of rare opaque; moderate sorting.

99% c to m quartz sand, 1% f to v of opaque grains rare as f to m, moderately sorted, grains are subrounded to rounded; rare rose quartz.

100% c to m quartz sand, rare f to v of opaque grains, vc to m fine mica, moderately sorted; low angle 0.5 to 1.0 cm color bands with possible laminations.

Sandy silty clay: c to f quartz sand, some red iron nodules (0.5 cm) very light gray N3 and dark reddish brown 10R 3/4.

Silty clay

Sandy silty clay: quartz sand is c to f; mostly dark yellowish orange 10YR 6/6, and some patches of very light gray N3 and dark reddish brown 10R 3/4. Sampled for XRD analysis at 239 ft.
173

**Description**

- Pebby sandy clay (pebbles up to 7 mm in diameter), 2-5% mica, rare opaques, rare rose quartz and smoky quartz.

- Pebby clay, lots of floating rounded pebbles (up to 1 cm in diameter).

- Pebby sandy clay. Same description as interval from 240.6 to 241.3 depths.

- 95% vc to m quartz sand with a few scattered pebbles (smoky quartz) up to 0.5 cm, 5% vc to m mica, few to sand sized clasts of clay, poorly sorted, possible horizontal bedding, up to 1 cm thick in places, subangular to subrounded.

- Rare fto v opaque grains.

- 94-97% vc to m quartz sand, 2-3% vc to m mica, 1% m to v opaque grains, moderate to poor sorting.

- 96% vc to m quartz sand, 2% m to f mica, 2% f to v opaque grains, possible low angle cross bedding, moderately sorted.

- 79-89% vc to m quartz sand, 5-15% f to v opaque grains, 1% clay clasts, poorly sorted, very light gray NB m places.

- 96% vc to m quartz sand with a few scattered (smoky and clear quartz) pebbles, 3% f to v opaque grains, 3% vc to m mica, moderate to poorly sorted.

- 96-98% vc to m quartz sand; 1-3% mica, and 1% opaque grains outside of laminations.

- Clay, possible laminations (wavy bedding). No obvious bioturbation, rare floating grains of m to v quartz sand. Sampled for XRD analysis at 248.6 feet.

- No Recovery.
**Feet**

250

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<tr>
<td>Silty clay, 100% silt to m sand, moderate to poor sorting, rare ophiomorpha.</td>
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<tr>
<td>Pale pinkish purple 10R 8/2</td>
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<tr>
<td>Silty clay with rare grains of c to f sand floating in clay.</td>
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<tbody>
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<td>Very light gray 10YR 6/6</td>
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<tr>
<td>Sandy (f to vf) clay, wispy laminations.</td>
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<td>Very light gray 10YR 6/6</td>
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<tr>
<td>89-90% vc to m sand, 1-2% mica, rare ophiomorpha, fining upwards, possible horizontal laminations, some smoky quartz, moderate to well sorted.</td>
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<tr>
<td>Very light gray 10YR 6/6</td>
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<tr>
<td>Sandy clay, sand is f to vf, with laminations. Rake 2.5 mm long black area iron (III)/organic (I).</td>
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<tr>
<td>95-99% vc to f quartz sand, 1-3% opaque grains, rare c to f mica; moderate to well sorted.</td>
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<tr>
<td>100% vc to m quartz sand, rare ophiomorpha, rare mica, moderate sorting, rounded to subrounded.</td>
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<tr>
<td>Possible 1 cm thick low angle bedding, less than 1 cm laminations, rare mica.</td>
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<tbody>
<tr>
<td>Dark yellowish orange 10YR 6/6</td>
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<tr>
<td>Silty clay with rare m to vf quartz grains, wispy laminations.</td>
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260
Silty day, 1% f to v f mica, with max thick horizontal and vertical pockets of dark yellowish orange 10YR 6/6. Sampled for XRD analysis at 260.5 feet.

Silty day, 1 cm sized horizontal and vertical pockets with c to f quartz sand dark yellowish orange 10YR 6/6. Sand pockets may be possible root structures (photographed).

99% c to f quartz sand, 1% c to m mica, moderate sorting, possible horizontal laminations.

Silty day, 1% f to v f mica. Possible root structure (2) dark yellowish orange 10YR 6/6 filled with v to f grains located in lower half of bed.

96-99% c to f quartz sand, 1-3% c to f mica, 1% f to v opaque grains, possible horizontal laminations, moderate to well sorted, subrounded to subangular.

Alternating 1-2 cm thick v to m and c to f quartz sand, rare md to v f mica, moderate to poor sorting.

Pebbles (muddy and clear quartz) 1 cm in diameter, v to md quartz sand, rare mica, rare opaques, poorly sorted.

No Recovery.

Disrupted laminations of light gray N7, f to v f quartz sand and areas of medium light gray N6 of c to f quartz sand. Possible pedestal (7), vertical tapering structure, disrupted strata c to f sand, poor sorting, rare mica.

Disrupted beds of c to f quartz sand, moderate sorting, areas of medium light gray.

99% c to f quartz sand, 1% opaque grains, rare mica, moderate sorting, no obvious bedding.
Same description as previous page 269.2-270.0:

Silty clay, possible horizontal laminations, 1% mica (vf sand - silt).
Pebble sand. Pebbles are subangular to subrounded and up to 1 cm in diameter, 60% vc to m quartz sand, 1% m to f mica, 1% f to vf opaque grains, moderate to poor sorting, 1% rose quartz pebble.
99% m to f quartz sand, 1% f to vf opaque grains, well sorted.

99% c to f quartz sand, 1% c to m mica, 1% f to vf opaque grains, 1% pebble; moderate sorting, subangular to subrounded.

100% c to f quartz sand, mostly m to f; rare opaques, moderate sorting, subangular to subrounded.
100% c to m quartz sand, rare opaques, moderate sorting.
98-99% m to f quartz sand with scattered vc quartz grains, 1-2% f to vf opaque grains, rare mica.

Clay. Sampled for XRD analysis at 274.1 feet.

100% m to f quartz sand, rare m to f mica, well sorted, 3 mm diameter smoky quartz pebble present.

100% m to f quartz sand, rare f to vf mica, rare vc sand and pebbles up to 3 mm in diameter, moderate to poor sorting. Subvertical, light olive 10Y 5/4 sandy clay; sand is c to f sand is 2 cm in width.
Upper: Clay bed, rare fossiliferous f to vf quartz grains, horizontal laminations); spots of light gray N7 2.5 mm in diameter some have horizontal orientation. Lower: Clay bed, wisps and blobs of medium light gray N6.

Sandy clay to clayey sand, quartz sand grains are f to vf, 1% f to vf opaque grains, rare mica.

100% f quartz sand, rare mica, well sorted.

99-99% f quartz sand, 1-2% f to vf mica, well sorted.

Irregular beds of 99% f to f sand, 1% f to vf opaque grains, 1% mica, light gray N7 and 99% f to quartz sand, 1% mica, very light gray N8; all beds are well sorted.
APPENDIX D

ADDITIONAL PINEHURST, TERRACE, AND FLOODPLAIN DEPOSIT DESCRIPTIONS
Lower Terrace Deposits (< 4.6 m off current floodplain)

(0-12 cm) 10YR 2/2 very dark brown, loose, coarse-to-medium sand, modern plant roots and woody debris, dry, a few subangular-to-angular quartz grains (up to 4 mm)

(12-18 cm) 10YR 6/8 brownish yellow, sandy loam, single grain, a few fine, weak, granules, very friable, dry, coarse-to-medium sand grains, sparse modern plant roots.

(18-107 cm) 10YR 6/6 yellow, sandy clay (mostly silt and clay with a few coarse to medium sand grains), dry, firm, modern roots penetrate down to 61 cm, sand grains are coated with clay and bridged together by a clay matrix, coarse, moderate, subangular blocky structure.

(107-122 cm) 10YR 6/8 yellowish brown, sandy loam, dry, subangular to angular quartz sand, up to 3 mm, single grain, very friable, a few fine, weak, granules, few clay chips up to 4 mm.

(122-134 cm) 10YR 7/4 very pale brown, sandy clay loam, friable, dry, single grain, a few fine, weak, granules.

(134-140 cm) 10YR 6/8 brownish yellow, sandy loam, very friable, dry, mostly single grain, a few fine weak, granules.

(140-168 cm) 10YR 7/6 yellow, sandy clay loam, mica present, dry, single grain, friable, a few fine, weak, granules.

(168-236 cm) 5YR 7/1 light gray, silty clay, massive, moist.

(236-335 cm) 5YR 7/1 light gray, sandy loam, well sorted fine sands with mica present, wet.

(0-23 cm) 10YR 3/2 very dark grayish brown, loose, coarse-to-medium sand, modern roots present, sparse sand grains up to 1 mm, single grain, dry.

(23-76 cm) 10YR 7/4 very pale brown, loose, single grain, very coarse-to-medium (mostly coarse-to-medium) sand, modern roots present, dry, sparse subrounded-to-angular pebbles up to 3 mm.

(76-137 cm) 10YR 7/6 yellow, loose, very coarse-to-medium sand, single grain, dry, subrounded-to-angular pebble us to 5 mm.

(137-168 cm) 10YR 7/6 yellow, loose, single grain, dry, very coarse-to-medium sand (mostly medium-to-coarse), small clay clasts up to 2 mm, subrounded-to-angular pebble us to 3 mm.

(168-183 cm) 10YR 7/6 yellow, loose, single grain, dry, very coarse-to-medium sand, small clay clasts up to 2 mm, subrounded-to-angular pebble us to 1 cm, dry.

Scale 1:27

Legend:
- = Sand
- = Sandy clay loam
- = Sandy Loam
- = Silt and clay
- = Pebble sand
- = Mica
- = Modern roots
- = Small change in grain size or color

Lower terrace deposits collected 1.2 m off of the modern floodplain. The terrace deposit on the left is from 0-168 cm while the deposit on the right extends the length of the profile.
Mid-Level Terrace Deposits (4.6 < x > 9.1 m above the modern floodplain)

(0-41 cm) 10YR 3/1 strong brown, loose, single grain, a few fine, weak, granules, very friable, medium-to-fine sand, modern roots and plant debris present, (1-2%) very coarse-to-coarse, subangular-to-angular quartz sand

(41-81 cm) 10YR 5/4 yellowish brown, loose, single grain, medium-to-fine quartz sand, tiny bits of organic material, (1-2%) very coarse-to-coarse, subangular-to-subrounded sand grains, dry.

(81-152 cm) 10YR 5/8 strong brown, sandy clay loam, fine, weak, subangular blocky, firm, very coarse-to-coarse sand grains make up roughly (1-2%), sand grains are covered in clay and subrounded-to-angular.

(152-183 cm) 10YR 5/6 yellowish brown, sandy loam, friable, sparse subrounded pebbles up to 5mm, fine-to-medium sand with (~1%) very coarse-to-coarse quartz grains, subangular-to-angular, fine, weak, subangular blocky peds.

The soil profile (above) was sampled 7.6 m (white star) off the modern floodplain. The profile was collected on a bench (yellow lines) that spans roughly 1.9 km (1.2 miles) in length. This surface does not contain sands associated with the Pinehurst formation.
Present Day Floodplain Deposits

(0-15cm) 10YR 4/2 dark grayish brown, silty loam, modern roots present, soft, single grain, a few moderate, medium granules, dry.

(15-31cm) 10YR 5/2 grayish brown, sandy loam, single grain, soft, dry, very coarse-to-medium sand grains, subangular-to-rounded, sparse modern plant roots.

(31-46cm) 10YR 2/1 black, sandy clay loam, organic rich, modern roots present, moderate, medium granules, friable, moist.

(46-91cm) 10YR 2/1 black, sandy clay loam, organic rich, modern roots present, massive, wet.

(91-175cm) 10YR 2/1 black and 10YR 5/1 gray, loamy sand, medium-to-fine, with sparse coarse grains, moderate sorting, wet, increase in coarse sand towards the base.

(0-12cm) 10YR 3/3 dark brown, sandy loam, very coarse-to-medium sand mostly coarse to medium, modern roots present, very friable, single grain, a few weak, fine granules, moist.

(12-46cm) 10YR 4/2 dark grayish brown, sandy loam, very coarse-to-medium sand, very friable, mostly single grain, a few weak, fine granules, modern roots present, sparse subrounded-to-angular pebbles (2mm).

(46-69cm) 10YR 5/8 yellowish brown, sand, very coarse-to-medium sand, single grain, very friable, subrounded-to-angular grains up to 3mm, moist.

(69-168cm) 10YR 7/2 light gray, sand, very coarse-to-medium, with clay matrix in between sand grains, massive, single grain, subrounded-to-angular and clear quartz pebbles up to 1cm, mica present, wet.

Scale 1:27

Legend:
- Sand
- Sandy clay loam
- Loamy sand
- Silt and clay
- Sandy loam
- Pebbly sand
- Modern roots

Present day floodplain deposits associated with Juniper (left) and Mill Creek (right).
High Terrace Deposits (x > 9.1 m above the modern floodplain)

Surface Elevation
62.5 m ASL

(0-198 cm) 10YR 5/6 yellowish brown, loose, single grain, coarse-to-fine sand, modern roots, subrounded-to-angular quartz sand grains, minor amounts of mica and heavy minerals, a few fine, weak granules, very friable, dry.

(198-259 cm) 10YR 5/8 strong brown, sandy loam, loose, single grained, medium-to-fine quartz sand, subrounded-to-angular, a few sparse very coarse-to-coarse grains that are subangular-to-angular, medium, moderate granules present, dry.

(259-351 cm) 7.5 YR reddish yellow sandy clay, strong, medium subangular blocky, firm, mottling present from 326-351 cm.

(351-412 cm) 7.5YR 5/8 strong brown, sandy loam, very coarse-to-medium, subrounded-to-subangular quartz pebbles (up to 1.5cm), pebbles are clear and milky quartz, 7.5YR 7/1 light gray clay rip up clasts (up to 2 cm).

(412-472 cm) 7YR 7/4 pink, sandy clay loam, coarse-to-medium sand, mica present, fine, weak granules.

(472-488 cm) 7.5YR pinkish white, loamy sand, very friable, mica, fine-to-coarse (mostly medium)

56.1 m ASL

(0-12 cm) 10YR 5/3 brown, medium-to-fine sand, with a few subangular-to-angular coarse sand grains, loose, single grain, plant debris and roots present, dry.

(12-38 cm) 10YR 5/3 brown, medium-to-fine sand, with a few subangular-to-angular coarse sand grains, loose, single grain, dry.

(38-114 cm) 10YR 5/8 yellowish brown sandy clay loam, fine, weak subangular blocky, dry, very coarse-to-medium, subangular-to-angular sand (mostly coarse-to-medium), very sparse angular pebbles (up to 0.7cm).

(114-137 cm) 10YR 6/3 pale brown, pebbly, sandy clay loam, rounded clear and milky quartz pebbles (up to 1.9 cm), subangular-to-angular very coarse-to-medium, fine, weak subangular blocky, dry.

(137-183 cm) 7YR 7/1 light gray silty clay, with 7YR 5/6 yellowish red mottles, fine, weak subangular blocky.

Scale 1:27

Legend:
- Sand w/roots
- Sandy loam
- Sandy clay loam
- Sandy clay loam
- Pebbly sand

High level terrace remnants > 9.1 m above Juniper Creek. High level terraces contain gravel at the base of the deposit. The deposit on the left goes from 259-412 cm, is overlain by thick Quaternary sands, and sits on the Middendorf Formation. The deposit on the right spans from 0-137 cm, and sits on a silty clay associated with the Middendorf Formation.
APPENDIX E

SETUP PARAMETERS AND POST-PROCESSING FILTER CONSTRAINTS (RADAN 7 SOFTWARE)
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APPENDIX F
GEOLOGIC AND MINERAL RESOURCES OF THE PATRICK QUADRANGLE,
SOUTH CAROLINA
LiDAR Derived Bare Earth Model of the Patrick Quadrangle
by Christopher Garrity (USGS)
VITA

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