GEOLOGY AND NATURAL HISTORY OF THE OKEFENOKEE SWAMP AND TRAIL RIDGE, SOUTHEASTERN GEORGIA-NORTHERN FLORIDA

EDITED BY FREDRICK J. RICH & GALE A. BISHOP

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GEOLOGY AND NATURAL HISTORY OF THE OKEFENOKEE SWAMP AND TRAIL RIDGE, SOUTHEASTERN GEORGIA-NORTHERN FLORIDA

Introduction

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The proposed mining of heavy mineral sands on Trail Ridge by E. I. DuPont de Nemours and Company has provided us with the framework to develop an assessment of the status of our knowledge of the origin and geological history of the Okefenokee Swamp and the origin, accumulation, distribution, and mining of heavy mineral deposits in Georgia.

We will use this trip to focus our attention on the accumulation of heavy mineral sands on the Atlantic Coastal Plain. We will follow heavy minerals through the rock cycle in a series of contributions detailing the provenance of heavy minerals (Contribution 2; Vance) from their initial source in the Piedmont of the Appalachian Mountains to their deposition on Georgia beaches presented as a model of deposition and accumulation on St. Catherines Island (Contribution 3; Bishop and Marsh). Then, this model is applied to the geologic history of the Okefenokee Swamp (Contribution 4; Rich) and a review of the origins of tree islands, called "houses," (Contribution 5; Rich) is then expanded to an overview of the Quaternary evolution of the Georgia Coastal Plain (Contribution 6; Booth and Rich). The mining of the Trail Ridge deposit is brought into the classroom by modeling the use of emerging electronic teaching technologies to engage students in the learning process through role playing over the Internet (Contribution 7; Marsh and Bishop). This information is be applied to ancient Coastal Plain sediments in the Trail Ridge deposit, and its potential exploitation by wet dredge mining techniques and its beneficiation by the DuPont Starke, Florida, milling process (Contribution 8; Renner, Samborski, Reynolds, and Mogillo).

These contributions are offered as a starting point for discussion on our fieldtrip which will take us first to Dupont’s Starke, Florida, heavy mineral sand mine to observe wet dredge mining and beneficiation processes first hand. The second day will take us into the Okefenokee Swamp where we will observe paludal processes first hand. The fieldtrip will place us squarely between the habitat potentially threatened by mining and the mining process itself.

The question of whether to mine or not to mine is being determined even as we explore the question ourselves on this trip. The process involves discussion of issues in a consensus-based, conflict mitigation process being managed by RESOLVE.

Recent developments in this conflict resolution process have led to the realization that we have but one Okefenokee Swamp. The uncertainties involved in mining on Trail Ridge in direct proximity to this unique habitat and the possible detrimental effects of unforeseen problems in mining seem to be leading to reevaluation of mining options, and the possible withdrawal of Trail Ridge from future mining consideration if the land is incorporated into the Okefenokee National Wildlife Refuge.
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Field Trip Itinerary

Friday, October 9  
   8:00 P.M. - Social Hour 
   9:00 P.M.- Orientation Talk 
   Jacksonville Airport Holiday Inn

Saturday, October 10  
   8:00 A.M.  Load Busses and Vans for 
   DuPont Mine and Wet and Dry Mill Tour 
   Lunch courtesy of DuPont

Sunday, October 11  
   7:00 A.M.  Load Busses and Vans for 
   Okefenokee Swamp Tour from Camp Cornelia 
   Lunch Ordered on Fieldtrip Form 
   Return to Camp Cornelia by 2:00 P.M.
ORIGIN AND CONCENTRATION
OF Ti IN HEAVY MINERAL SANDS

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INTRODUCTION
Heavy mineral sands with economic concentrations of titanium minerals are dominantly beach placers. These placers are mined primarily for the Ti ores ilmenite and rutile but also contain valuable concentrations of zircon and monazite. Ilmenite (FeTiO3) is the primary source of titanium dioxide pigment with U.S. production valued at approximately $2.73 billion in 1997. Although ninety percent of rutile (TiO2) is also consumed as pigment, it provides Ti for metals, with demand reaching record levels in 1977 (Gambogi, 1996, 1998). Zircon (ZrSiO4) is used as a refractory for foundry molds and furnaces and as a source for the zirconium cladding of nuclear fuel rods and for the hafnium used in superalloys and reactor control rods. Monazite (Ce,La,Y,Th)PO4 is the primary source of thorium as well as providing a supplemental source of yttrium and Rare Earth Elements (REE). Thorium is used in ceramics, alloys and welding electrodes; however, the greatest potential for increasing demand may depend on assessment as a nuclear fuel that may generate more energy than uranium with production of less waste. Application of yttrium and REE include phosphors, oxygen sensors, laser crystals, permanent magnets, catalytic convertors and petroleum refining catalysts (Hedrick, 1996, 1997, 1998).

MINERALOGY
Mechanical concentration of ore minerals to form placer deposits requires minerals with a high specific gravity (SG) and resistance to both abrasion and chemical weathering. The Ti minerals rutile and ilmenite (Table 1.) have a SG exceeding 4.1 providing a sufficient contrast with quartz (SG=2.65) and feldspar (SG=2.54-2.76) to promote mechanical concentration. Hardness in excess of 5.5 or malleable behavior (e.g., Au) favors survival under prolonged initial transport and re-working of sediments. One of the most important characteristics of placers which form in temperate to tropical climates is chemical stability. Many common rock forming minerals and some accessories (ex. olivine, pyroxene, pyrite) have sufficient hardness and SG to form placers but alter rapidly when exposed to hot, humid climates and an oxygen-rich atmosphere. Consequently, the mineralogy of placer deposits is influenced by climate as well as source area rock types and depositional environments.

The minerals known to occur in placer deposits are listed in Table 1 and are ranked by specific gravity. Placer titanium ore deposits of the
Table 1  
Placer minerals (rank by SG)

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Formula</th>
<th>Specific Gravity</th>
<th>Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gold</td>
<td>Au</td>
<td>15.0 - 19.3</td>
<td>2.5 - 3.0</td>
</tr>
<tr>
<td>Platinum</td>
<td>Pt</td>
<td>14.0 - 19.0</td>
<td>4.5</td>
</tr>
<tr>
<td>Cassiterite</td>
<td>SnO₂</td>
<td>6.8 - 7.1</td>
<td>6.0 - 7.0</td>
</tr>
<tr>
<td>Magnetite</td>
<td>Fe₃O₄</td>
<td>5.18</td>
<td>6.0</td>
</tr>
<tr>
<td>Monazite</td>
<td>(Ce,La,Y,Th)PO₄</td>
<td>4.6 - 5.4</td>
<td>5.0 - 5.5</td>
</tr>
<tr>
<td>Ilmenite</td>
<td>FeTiO₃</td>
<td>4.7</td>
<td>5.5 - 6.0</td>
</tr>
<tr>
<td>Zircon</td>
<td>ZrSiO₄</td>
<td>4.68</td>
<td>7.5</td>
</tr>
<tr>
<td>Xenotime</td>
<td>YPO₄</td>
<td>4.5</td>
<td>4.5</td>
</tr>
<tr>
<td>Garnet</td>
<td>Fe₃Al₂Si₃O₁₂</td>
<td>4.32</td>
<td>6.5 - 7.5</td>
</tr>
<tr>
<td>Rutile</td>
<td>TiO₂</td>
<td>4.18 - 4.25</td>
<td>6.0 - 6.5</td>
</tr>
<tr>
<td>Corundum</td>
<td>Al₂O₃</td>
<td>4.02</td>
<td>9.0</td>
</tr>
<tr>
<td>Spinel</td>
<td>MgAl₂O₄</td>
<td>3.5 - 4.1</td>
<td>8.0</td>
</tr>
<tr>
<td>Staurolite</td>
<td>Fe₂Al₉O₆(SiO₄)₄(O,OH)₂</td>
<td>3.65 - 3.75</td>
<td>7.0 - 7.5</td>
</tr>
<tr>
<td>Kyanite</td>
<td>Al₂SiO₅</td>
<td>3.55 - 3.66</td>
<td>5.0 - 7.0</td>
</tr>
<tr>
<td>Diamond</td>
<td>C</td>
<td>3.52</td>
<td>10.0</td>
</tr>
<tr>
<td>Epidote</td>
<td>Ca₂(Al,Fe)Al₂O₆(SiO₄)(Si₂O₇)(OH)</td>
<td>3.25 - 3.45</td>
<td>6.0 - 7.0</td>
</tr>
<tr>
<td>Sillimanite</td>
<td>Al₂SiO₅</td>
<td>3.23</td>
<td>6.0 - 7.0</td>
</tr>
<tr>
<td>Tourmaline</td>
<td>(Na,Ca)(Li,Mg,Al)₃(Al,Fe,Mn)₆(BO₃)₃(Si₆O₁₈)(OH)₄</td>
<td>3.0 - 3.25</td>
<td>7.0 - 7.5</td>
</tr>
</tbody>
</table>

Atlantic coast of North America, the east and west coasts of Australia, southern India, Sri Lanka and Brazil are dominated by ilmenite and the alteration product leucoxene; however, rutile also contributes to the total Ti grade and may locally exceed ilmenite (ex. East Coast of Australia, Sierra Leone). The U.S. Atlantic Coast beach placer ore bodies are characterized by the following minerals: ilmenite/leucoxene (43-65%), rutile (2.5-7.4%), zircon (11-18%), staurolite (4-15%), kyanite/sillimanite (4-15%), tourmaline (1-6%), monazite (<2%), epidote (0-7%) and traces of garnet and hornblende (Harben and Bates, 1984; Pirkle, Pirkle and Reynolds, 1989; Carpenter and Carpenter, 1991).

**PRIMARY SOURCES OF TITANIUM MINERALS**

The dominance of ilmenite over rutile in the beach placers of the U.S. Atlantic coast suggests either a greater abundance of ilmenite in the highlands feeding sediment to the coast, greater resistance to chemical or mechanical weathering or transport conditions which favor ilmenite over rutile. Although rutile has a slightly lower SG than ilmenite (Table 1), the abundance of staurolite, kyanite and sillimanite indicates rutile should also be concentrated if available. Titanium oxides are extremely resistant to chemical weathering (Force, 1976) and the abundance of rutile in some placers of Australia and Africa indicate chemical weathering does not explain the dominance of ilmenite in most placers. Consequently, the higher percentage of ilmenite relative to rutile may reflect difference in the availability of the two minerals in the primary source rock or a primary grain size (Gillson, 1959) that limits rutile concentration. Force (1976) provides a description and summary of the distribution of Ti between silicate and oxide phases in igneous and metamorphic rocks. Although substantial amounts of Ti are incorporated into silicates such as hornblende, titanaugite and biotite; chemical weathering decomposes these minerals leaving much of the Ti as part of the insoluble residue (Dennen and Norton, 1977; Sastri and Sastry, 1982). The presence of ilmenite, leucoxene and rutile in bauxites of Australia and Brazil (Grubb, 1971, 1979) and as discrete clasts in kaolinite deposits of Georgia confirms the resistance of Ti oxides to chemical weathering. Consequently, igneous or metamorphic rocks must carry an oxide phase to qualify as primary Ti source from which to derive placers.

The igneous rocks which contain the most Ti oxides are mafic to intermediate in composition. Among these rocks ilmenite and titanomagnetite are most abundant in basalts and diabases, particularly the alkalic versions. Ilmenite occurs in high-Ti diabase and titanomagnetite occurs in olivine diabase in the Mesozoic mafic rocks of South Carolina (Warner and Wasilowski, 1985). Pyroxenites, kimberlites and syenites are also potential sources of ilmenite (Force, 1976). Anorthosite bodies contain concentrations of ilmenite and titanomagnetite as magmatic segregation deposits (Herz, 1976) and provide a strong point source of ilmenite in drainage basins; however, igneous or metamorphic rocks which have lower Ti oxide contents but greater distribution throughout the drainage basin may contribute the greatest volume of ilmenite or rutile to the sediment load (Minard et al., 1976). Consideration of relative abundance of potential igneous source rocks for ilmenite favors basalt and associated diabase dikes and sills. Such rocks were produced in abundance in the Late Proterozoic (e.g., Catoctin Formation of Virginia and Maryland) and again in the Mesozoic (e.g., Watchung Basalts, New Jer-
sey; Talbotton dikes, Georgia) during continental rifting (Ratliffe, 1987, 1987; Puffer and Student, 1992; Milla and Ragland, 1992). Although Mesozoic rift basalts are not preserved in surface exposures of Georgia, Mesozoic basalt and sediments (Newark Supergroup) are preserved in thirty rift basins from Nova Scotia to South Carolina (Weems and Olsen, 1997) and the presence of numerous Mesozoic diabase dikes favors the former presence of flood basalts over Georgia (McHone, 1996). The Mesozoic flood basalts represent a very large former source area for Ti oxides - one that could have donated heavy minerals to Cretaceous sands.

Metamorphic rocks may be the most important source of Ti oxides (Force, 1976). The mineral assemblages of metamorphic rocks are determined by: [a] the bulk chemical composition of the protolith, [b] any modification of original bulk chemistry and [c] the temperature-pressure (T-P) environment of metamorphism. Consequently, the presence and stability of Ti oxides varies with bulk composition as well as the T-P conditions. Raymond (1995) summarizes metamorphic facies of the Southern Appalachians as an example of a Barrovian Facies Series. The eastern portion of the Southern Appalachian Blue Ridge and Piedmont province is dominated by Amphibolite Facies rock with the exception of Greenschist Facies rocks of the Carolina Slate Belt and restricted parts of the Blue Ridge. The metamorphosed mafic rocks (greenschists and amphibolites) are a potential source for Ti oxides. Review of mineral assemblages indicates sphene is the prevalent Ti phase in metabasites (mafic rocks) of the Greenschist Facies, but ilmenite is the stable Ti phase under Amphibolite and Granulite Facies conditions (Raymond, 1995; Force, 1976). The abundance of kyanite (4-15% including sillimanite) and staurolite (4-15%) in the beach placers (Pirkle et al., 1989; Carpenter and Carpenter, 1991) indicate the importance of contributions from Amphibolite Facies rocks. Both ilmenite and rutile are recognized in quartzofeldspathic rocks of the Amphibolite and Granulite facies (Force, 1976, Raymond, 1995). Extreme compositions may stabilize Ti oxides at lower grades and provide additional source rocks. Graves Mountain in the Carolina Slate Belt of Georgia is a kyanite granofel interpreted as the metamorphic product of argillic and advanced argillic hydrothermal alteration (Hartley, 1976, Allard and Carpenter, 1982). The locality is known for large museum quality specimens of rutile, but the granofel is also characterized by fine disseminated rutile. Espenshade and Potter (1960) describe fourteen deposits of aluminosilicates in a belt extending from Georgia to Virginia. Rutile is also known in pelitic rocks with high Al and/or low Ca contents at lower grades (Force, 1976).

The northern New England Appalachians also contain metamorphic Ti oxide source rock, but these rocks are more representative of Buchan Facies Series metamorphism. Sporadic occurrence of ilmenite and rutile are reported for aluminous protoliths (metapelites) of the Greenschist and Amphibolite Facies (Raymond, 1995). Sporadic occurrence of ilmenite is also noted for mafic protoliths and carbonates of the Greenschist Facies.

Force (1976) emphasizes high grade metamorphic rocks as an important source of ilmenite and rutile linking the high grade rocks of the Blue Ridge and Piedmont to Atlantic coastal placers. The occurrence of alluvial placers (Minard et al., 1976) in streams draining such regions supports this link. Puffer and Cousminer (1982) used microtextures to link the Ti-Fe oxide sands of the Cohanseay Formation,
New Jersey to Precambrian gneisses. Similar links between high grade metamorphic rocks and Ti beach placers are described (Force, 1976) for the eastern and western deposits of Australia, for southern India and Sri Lanka and for the eastern and western deposits of Africa. The zircon concentrates associated with Ti oxide sands can also be derived from high grade metamorphic rocks (Fraser et al., 1997).

In summary, the more important candidates for contribution of ilmenite and rutile to beach placers of the Atlantic coast include:

[a] Igneous sources -
- anorthosite and associated segregation deposits (ilmenite, Ti-magn.); syenite (ilmenite);
- Mesozoic diabase dikes and flood basalts (ilmenite & Ti-magnetite source)

[b] Metamorphic sources -
- aluminosilicate deposits & metapelite (rutile source); Amphibolite to Granulite Facies schist and gneiss (ilmenite & rutile);
- Metapelite (rutile)

[c] Sedimentary sources -
- An intermediate host which may include Cretaceous or Tertiary sedimentary rocks (heavy mineral suite of ilmenite, rutile, zircon, etc.)

CONCENTRATION OF TI OXIDES

For temperate to tropical climates, initial concentration of Ti oxides begins with chemical weathering of igneous or metamorphic rocks. Titanium is residually enriched during chemical weathering by decomposition of Ti bearing silicates (biotite, hornblende, titanaugite) and Ti bearing magnetite to form an insoluble residue of clays, iron oxides and fine-grained dispersed Ti oxides (Force, 1976; Dennen and Norton, 1977; Cawsey and Mellon, 1983). Ilmenite and rutile resist chemical weathering resulting in relative enrichment as the soluble components are leached away (Hartman, 1959; Grubb, 1971; Patterson, 1971; Sastri and Sastry, 1982). The extensive chemical weathering of the southern Appalachians has produced saprolite above much of the igneous and metamorphic rock of the Piedmont and lower elevations of the Blue Ridge. Studies of saprolite mineralogy in the Appalachians and elsewhere show preservation of ilmenite and loss of magnetite during weathering (Overstreet et al., 1963; White, 1972). Mesozoic diabase and flood basalts of the southern Appalachians would have been converted rapidly to saprolite. Ilmenite has been recognized (Hosterman; 1969; Patterson, 1971) in saprolite developed over basalt in other areas; therefore, ilmenite probably survived chemical alteration in the Mesozoic mafic rocks of the southeast United States. The ilmenite in the weathered basalts and the ilmenite and rutile of weathered metamorphic rocks of the southern Appalachians was liberated from its saprolite prison by erosion and carried into streams.

Sedimentary concentration of Ti oxides began with fluvial systems and continued with deposition/concentration of ilmenite and rutile in intermediate host (Cretaceous to Miocene?) beach sands of the Coastal Plain (Carpenter and Carpenter, 1991). Zircon morphology in the Trail Ridge ore body favors reworking of older beach deposits (Pirkle and Podmeyer, 1993). Periods of regression exposed these preliminary concentrations of heavy mineral sands to stream erosion and a new period of beach concentration through long shore currents, waves and wind. Reworking of intermediate host rocks is also in-
dicated for Ti sands of Australia and India (Force, 1976). A final episode of concentration is *in situ* alteration of ilmenite to leucoxene. This process increases the Ti content by removing Fe (Force, 1976; Force and Rich, 1989). In summary, evolution of Ti oxide ore bodies of the southeastern U. S. Atlantic coast is:

[1] weathering of ilmenite and rutile-bearing rocks to saprolite
[2] erosion and stream transport/concentration of Ti oxides
[3] deposition in Cretaceous to Tertiary coastal plain sand deposits
[4] erosion and reworking of older coastal plain sands during regression
[5] concentration/deposition of heavy mineral sands by longshore currents, waves and wind
[6] upgrade of heavy mineral sands by removal of Fe oxides during leucoxene formation

REFERENCES


ACCUMULATION, DISTRIBUTION, AND RADIOACTIVITY OF HEAVY MINERAL SANDS ON ST. CATHERINES ISLAND, GEORGIA: A Model for Ancient Heavy Mineral Deposits

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ABSTRACT

Research performed on St. Catherine’s Island (Fig. 1) during 1987-1998 has led to a model of heavy mineral accumulation and distribution. Heavy mineral samples taken on North and South Beach demonstrate there are significant deposits of heavy minerals entrained in sediments in the Holocene portion of Georgia barrier islands. These coastal heavy minerals originated from deeply weathered crystalline rocks of the Piedmont and have been transported onto the prograding coast through fluvial systems. Entrained heavy minerals in ancient sediments of the Coastal Plain provide a secondary source for heavy minerals. Heavy minerals entering the coastal systems are primarily sorted by wave action and accumulate primarily as shoestring sands in the back beach facies. Reworking of back beach sands during storms by washover and wind processes redeposits considerable heavy minerals in washover fan and dune facies. Concentrations of heavy minerals on St. Catherines vary along strike of the strand and are generally lower on North Beach than South Beach. Distribution of heavy minerals on North Beach have accumulated as a deposit near an outcrop of Silver Bluff Pleistocene Core, substantiating the importance of the Pleistocene core as a significant immediate source of heavy minerals and provides significant clues for future exploration for heavy minerals on the Georgia Coastal Plain.

The distribution of Ghost Shrimp burrows along 20 km of beach demonstrates their distribution as strand-parallel structures (hence, also back beach-parallel); confirming their utility as potential exploration tools for heavy mineral deposits in the ancient sedimentary rocks. A radiometric survey of the south half of North Beach demonstrates the utility of ground-based radiometric analysis in delineating distribution of heavy minerals. These techniques may be transferable to ancient heavy mineral deposits in the Coastal Plain or other areas.

The geologic history of St. Catherine’s Island has been deciphered to a point where significant questions of barrier island formation and evolution are now being addressed. Answering these questions should lead to an understanding of the results of rising sea levels on coastal Georgia as global warming continues to drive the present transgression.

INTRODUCTION

The presence and abundance of heavy minerals in sands on the Georgia coast and in Coastal Plain sediments have been the subject of numerous studies (McCuley, 1960; Neiheisel, 1962; Pilkey, 1963; Pirkle and Yoho, 1970; Hails and Hoyt, 1972; Pirkle et al. 1974;...
Fig. 1 - Index Map to Southeastern Coast, Georgia Barrier Islands, and St. Catherines Island. (From Shadroui 1990 with permission of the author.)
Grosz and Escowitz, 1983; Schmitter and Freeman-Lynde, 1988; F. L. Pirkle et al., 1991; Pirkle et al., 1989). Heavy mineral suites consisting of varying proportions of ilmenite, epidote, hornblende, zircon, rutile, sillimanite, staurolite, leucoxene, kyanite, tourmaline, monazite, garnet, magnetite, hypersthene, and sphene are indicative of an initial origin in the metamorphic rocks of the Piedmont Province of the Appalachian Mountains. Because of the complex geologic history of the Georgia Coastal Plain the immediate source of heavy minerals entrained in coastal sands could include sands being delivered by 1) rivers directly from the Piedmont, 2) from storage in older Coastal Plain sediments, 3) from sands being moved along the beach by longshore currents or circulating within sediment cells (Oertel, 1979), 4) from sands being delivered onto the beach from relict Pleistocene sands stranded on the continental shelf, or 5) from sands being derived from temporary storage in nearby eroding barrier island sand bodies.

LOCATION AND ACCUMULATION OF HEAVY MINERAL SANDS

Regardless of their initial or immediate origin, heavy mineral suites on the Georgia coast undergo a relatively predictable history. They are moved onto the beaches by various currents as part of the sand-sized sediment load and along the shoreface generally from north to south by longshore currents. Because of their high density, these minerals tend to be concentrated in higher energy areas such as on the open beaches (Fig. 2) as larger grained, less dense minerals (primarily quartz) are winnowed out by wave processes (Houston and Murphy, 1962, 1977; Force, 1991). This results in the concentration of heavy minerals in beach sands, particularly in sands deposited on the back beach (Fig. 3), and their subsequent transport into nearby facies such as washover fans, spits, and in intertidal sediments derived from beach areas.

Wind winnowing is an active process concentrating suites of heavy minerals in back shore dunes. Neiheisel (1962:371-372) recognized the zones of heavy mineral accumulation, 1) in a thin, narrow band in the upper littoral zone (back beach), 2) in thin black sands extending shoreward beneath dunes, 3) as cross bed laminations in the dunes, and 4) as disseminated particles in beach and dune sediments. Woolsey, Henry, and Hunt (1973) reported on the concentration of heavy minerals from dune systems and beach sediments into the backbeach of Sapelo Island during waning stages of Nor'easters.

What appeared to be significant concentrations of heavy minerals on the back beach on North Beach at St. Catherines Island were noticed in 1987 during early fieldwork on the Carolinian ghost shrimp Callirhirus major Say (Bishop and Bishop, 1992; Bishop and Brannen, 1993). The parallelism of the Carolinian Ghost Shrimp burrow strand on the lower beach and the robust accumulations of heavy
minerals on the back beach suggested that ancient Ghost Shrimp burrows might be useful in searching for such accumulations in the nearshore marine sediments of the Coastal Plain Province.

Fig. 3. Heavy mineral sands eroded and sorted by Nor'easter during Spring high tide, South Beach, St. Catherine's Island.

The beaches of Georgia characteristically are comprised mostly of sand-sized quartz grains. However, heavy mineral sands occur on many island back beaches as placer deposits concentrated primarily by wave action during storms. These deposits are often buried within the active beach, the upper 10-50 cm of quartz sand and occur as discrete layers interlaminated with the quartz sand (Darrell et al. 1993) (Fig. 4). Occasionally these black sands are exposed at the surface by concentrating or eroding mechanisms and are often seen to color the back beach area a rich black color. These sands are rich in many minerals (including rutile, ilmenite, leucoxene, garnet, hornblende, zircon, monazite, apatite, and staurolite). At least two of these minerals, monazite and zircon, are radioactive.

Radioactivity in Heavy Mineral Sands

The radioactivity of heavy mineral placers has been previously reported and investigated (Houston and Murphy, 1962; Groz, 1983; Force et al., 1982). Much of this work has involved aerial radiometric surveying techniques as a potential exploration tool for heavy mineral deposits and resulted in guarded conclusions.

Initial measurements of three sand samples collected along a transect on South Beach, St. Catherine's Island, Georgia demonstrated that equivalent dose gamma radiation of heavy mineral sands varied across the beach. Each sample was comprised of sand-sized minerals sorted by natural processes on the Georgia coast. Samples, air dried in plastic quart-sized Ziploc bags, and counted by repetitive automatic recycling using a PKCB-104 Geiger counter fitted flush to the surface of each bag. Background was measured by standing the Geiger counter on end so the Geiger tube was exposed to free air and subtracted from raw measurements taken in the Crab Lab located in the basement of the Herty Building, Georgia Southern University. The samples that were documented (Fig. 5) included a dune sand, a quartz beach sand from midway across the beach, and a heavy mineral sand from the surface of the back beach; they had counts of 2.6, 3.0, and 399 counts per cycle, respectively. A second series of measurements were subsequently made by measuring gamma radiation in a vertical exposure of a scarped dune being eroded by the sea for comparison with the horizontal transect (Fig. 6). Both techniques resulted in what appeared to be significant results and were subsequently followed by an attempt to systematically delineate a heavy mineral deposit by using a series of regularly spaced transects.

The concentration of heavy mineral sands in the back beach facies places them in a prime position to host nests of Loggerhead sea turtles (Brannen and Bishop, 1993), leading to the possibility of radiation induced mutation in de
Fig. 4. Block diagram of Georgia beach habitat showing dominant sedimentary structures in each beach zone (after Darrell, Brannen, and Bishop., 1993)

Radioactivity Transect:
So. Beach, St. Catherines Is., Ga.

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<th>Activity</th>
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<th>Dune</th>
<th>HM Placer</th>
<th>Beach</th>
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<td>22.8</td>
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Fig. 5. Radiometric Transect of sand from Georgia beach zones, St. Catherines Island.

Fig. 6. Radiometric Profile of sand dune South Beach, St. Catherines Island.
veloping embryos of clutches deposited in these sands with elevated radioactive levels. No data have been collected to test this possibility, but anecdotal observation has indicated deformed hatchlings often occur in these clutches. For example, Nest 93-039 was deposited July 1, 1993, at grid location 3.971 and emerged (after being swashed twice by high tides) on August 20. It was dug and assessed on August 25, proving to have 44 unhatched, undeveloped eggs, 86 hatched eggs, and 6 pipping eggs, giving a nest success of 67.6% (92 of 136 eggs hatched). Taken from the clutch were 3 corpses and 9 hatchlings (representing 9.8% of all hatchling produced from the nest); all deformed. To reinforce this possibility of radiogenic mutation, we illustrate (Fig. 7) a Loggerhead sea turtle nest (97-072) which had its egg chamber deposited in a 33 cm thick heavy mineral layer underlyng 33 cm of quartz sand on South Beach at 1.800 km. Had this nest not been relocated, the clutch of eggs, completely surrounded by black sand would have received a gamma radiation dose of ~0.3 milliRoentgens/hr. Three questions concerning radioactivity of Georgia's black sands have arisen in our work;

1) Is radioactivity intense enough to affect development of sea turtle eggs deposited on the back beach?,

2) Would a ground-based radiometric survey be useful in delineating heavy mineral placers, and

3) How would such surface data be integrated into ancient deposits via Walther's Law?

**METHODOLOGY**

The initial accumulation of data began when ghost shrimp transects were used to census Ghost shrimp burrow openings in 1989-90 for North and South Beach. We established a 100 m beach grid\(^1\) from the south end of the Island to its north end. Transects were surveyed with a 30 m tape perpendicular to the beach strike at each grid station and burrow openings were counted at transect stations from the highest burrow on the beach to low water level using a 7.5 m spacing. Burrows were counted by averaging 16 random tosses of a 1 m\(^2\) hoop around each station. These data were entered on a grid and contoured by hand.

**Heavy Mineral Distribution.--**Observations made while studying shrimp distribution on North Beach indicated that heavy minerals were concentrated on the back beach. Transects of heavy mineral samples were taken at Lines 0, 10 N, Line 5 S, Line 10 S, and Line 15 S to establish lateral variation of heavy mineral concentrations across the beach. Samples

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\(^1\) The grids established for this study had their origins at midpoints of each beach. On North Beach the origin was arbitrarily set at an iron marker near Picnic Bluff and stations were established by tapping every 100 m north and south of this "0" point. On South Beach the grid origin was set at the entrance of South Beach Road onto the beach and stations established by tapping every 100 m north and south of this "0" point.
were then taken near high tide line where the deposits reach their maximum values. Each line to the north of the initial station was sampled by taking a piston core and splitting it in half in the field. Initial sampling was taken to 15 cm. depth Subsequent samples were taken on each line to the south of the initial station and retaken on Lines 2, 4, 6, 8, and 10 N by trenching and channel sampling through the upper 50 to 60 cm of active beach to a depth where obvious stratification terminated. Each line south was sampled by digging a trench and taking a channel sample. Stratigraphy and sedimentary structures were recorded in all trenches and each trench summarized in a stratigraphic diagram and documented by photography. Heavy mineral layers were sampled as a discrete sample when encountered as thick deposits. Heavy mineral separations were done by GSU student Pam Pless using bromoform and a separatory funnel apparatus. Each heavy mineral sample was washed with fresh water, dried, and split to approximately a 50 g sample before separation. Some 56 heavy mineral samples were taken and analyzed. This protocol was then applied to South Beach in a subsequent project. Three of the samples were submitted to E. I. DuPont for mineralogic analysis by point counting techniques and validation of GSU techniques. This sampling technique was then applied to South Beach.

Radiometric Surveys- Radiometric readings of nearly all turtle egg chambers were systematically taken during the 1998 Loggerhead sea turtle nesting season upon removal of eggs for relocation. Furthermore, radiometric transects were run on 100 m spacings across Sea Side Spit from 20 m behind the spit to 20 m onto the foreshore, with slightly longer lines at whole and half kilometers. These were run during the interval from 7/22/98 to 8/29/98, most during and after a moderate Nor'easter of 7/9/98-7/11/98, 1998. Equivalent dose gamma radiation was measured with a PKCB-104 Geiger counter fitted flush to the surface at stations along each transect at (from west to east) -20 m, -10 m, -5 m, -4 m, -3 m, -2 m, -1 m, 0 m, 1 m, 2 m, 3 m, 4 m, 5 m, 10 m, and 20 m: 0 m was selected at the highest wrack line (marking high spring tide levels). These data were entered on a spreadsheet and labeled by patterning their respective cells to attain a first order analysis of the gamma radiation pattern.

RESULTS

Ghost Shrimp Distribution—The distribution of the burrow mouth openings of burrows of the Carolinian Ghost Shrimp on South Beach confirms the basic pattern mapped on North Beach (see Bishop and Bishop, 1992, Figure 2). Specifically the pattern of burrow mouth distribution is strike-oriented forming a narrow burrow strand parallel to the shoreline and situated from above mid-tide level onto the subtidal portion of the shoreface (Fig. 8b). Maximum densities are found immediately seaward of the mid-tide line with significant variation in density along the burrow strand ranging from 0 burrows per square meter (bpm) to one of the highest burrow densities ever observed for this species (40 burrows per square meter).

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5 The grid used for this radiometric sampling was a continuous beach grid established for sea turtle nest monitoring in 1992, modeled after that done for heavy mineral sampling, but having its origin at the mouth of Beach Creek on the south end of South Beach. The older grid ties into the newer at 5.0 km on the new grid at South Beach Entrance ("0" on the older South Beach grid) and the origin of the North Beach grid falling at 15.975 km on the new grid. The grid can be viewed on the WWW at <http://www2.gasou.edu/cturtle/072bchgr.html>.
The burrow density variation (see Bishop and Bishop, 1992; Figs. 9-11) appears on the contour maps as hill-like high density areas separated by saddle-like lower density areas. On the northern part of South Beach the burrow form a rather consistent burrow strand from Line 00 to Line 8 N, reaching their maximum density of 40.3 bpsm on Line 2 N. From Line 8 N to 17 N the burrow density is highly variable, declining generally toward the north, until it reaches a remarkably high burrow density of 25 bpsm at Line 17 and rapidly declines to less than 2 bpsm along a sharply defined line of demarcation running obliquely across the beach. North of Line 17 N are two more-or-less isolated burrows density highs at Lines 19 N and 23 N, with the latter gradually declining northward to Line 29 N. Burrow densities remain remarkably low from Line 29 N to 44 N, picking up in density again on McQueen's Ebb Delta. On the southern 5 kilometers of South Beach the pattern is remarkably constant from Line 00 to Line 30 S but generally decreasing in abundance southward until very low densities are reached at Line 36 S. Burrow densities remain very low from that point to the south tip of the island and these burrowing shrimp are often excluded from the beach by the presence of relict marsh muds on the beach, particularly from Line 44 to 50 S. Thus the burrow strand of the Carolinian Ghost Shrimp on South Beach is virtually continuous for 8.8 km along the beach and is significant (i.e. contoured densities > 5 bpsm) for 6.4 km. The highest known densities of this animal thus far observed on St. Catherines Island occur near the middle of South Beach.

**Heavy Mineral Distribution**—The distribution of heavy minerals on St. Catherines Beaches is closely associated with the back beach and adjacent facies (Fig. 8b). Transects across North Beach confirm the concentration of heavy minerals in the upper 50 cm of sediment in the active beach ranging from a few percent in the foreshore up to 80% in the back beach, then decreasing in concentration behind the beach. The pattern (Fig. 8a; Table 1) shows a decreasing concentration of heavy minerals on either side of Yellow Banks, a bluff on the modern North Beach shoreline developed by erosion of the Pleistocene Silver Bluff Island Core.

Transects along both beaches confirm the general pattern of concentration of heavy minerals along the back beach above the average spring high tide line. The consistency of the back beach concentration along North Beach is phenomenal; that of South Beach is continuous but with several concentration nodes. Most of this concentration of heavy minerals occurs in the upper 50-60 cm of active beach sediment as 2-3 distinct stratigraphic units. There is commonly one discrete basal layer of heavy minerals present of considerable thickness (4-13 cm) containing appreciable concentrations, 80% to 90%, of heavy minerals. The origin of these basal layers is thought to be due to massive sorting events triggered by storms. Observations made on South Beach March 27, 1990 during a Nor'easter, indicate that the back beach basal beds are formed during such storm events particularly when they occur during spring high tides, eroding both the back beach and foredunes, reworking the already concentrated heavy minerals into a basal bed formed as lag deposits as the lighter minerals are winnowed out by wave action. The back shore commonly contains multiple discrete stratigraphic zones of heavy minerals, each marking a discrete sedimentologic event (storm, sorting event, erosion, etc.).

The concentration of heavy minerals on the backshore places these concentrations into a po
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Table 1. Heavy Mineral percentage by Line and position relative to average Spring High Tide Line (htl) (Values to left are above htl, right are below htl; all values are in % of active beach layer).
Figure 8 - Distribution of Heavy Minerals and Ghost Shrimp Burrows, North Beach, St. Catherine's Island.
sition where other normal marine processes can redistribute them into nearby environments. Normal and storm-induced wave swash carries some of the heavy minerals back onto the beach and foreshore, accounting for moderate concentrations there. As indicated by Force and Rich, 1989), wind was observed blowing across this zone and selectively sorting the quartz out of the backshore concentrates as well as moving heavy mineral sands. The presence of heavy mineral laminations in festoon cross beds of dune sands has been previously documented (Neiheisel, 1962; Force and Rich, 1989) and is commonly observed in eroding dunes at St. Catherines Island. Black sands have been observed in active dunes on numerous occasions with wind-blown heavy minerals accumulations reaching significant concentrations (samples as high as 12.9 to 21.7%) in dunes on North Beach. Ancient dunes on South Beach were sampled by channel sampling techniques and found to contain 4% heavy minerals.

On the grass-covered high tidal flats of Sea Side Marsh on the back (shore ward) side of Sea Side Spit deposits of heavy minerals reach concentrations of 10.5-18.1%. These accumulations are concentrated by deposition of washover fans associated with storms coincident with spring high tides. On or about March 23 some 32 more or less discrete washover (or wash-on) fans formed on Sea Side Spit along a distance of 300 m during a coincidence of spring tide and a Nor'easter. Some of these washover fans attained sediment thicknesses of 15 cm a distance 5 m behind the beach with the upper 6.5 cm being a heavy mineral layer (77% heavy minerals) which extended 27 m into the marsh.

A series of Nor'easters (Davis and Dolan, 1993) during the Winter and Spring of 1990, particularly a series of storms in March, severely eroded South Beach, forming a continuous 40 to 50 cm scarp along the back beach and exposing the back beach heavy mineral deposit for hundreds of meters along strike. These exposures were investigated in detail by measuring stratigraphic sections every 20 m between Lines 8N and 9N, and by sampling and analysis of the concentration of heavy minerals. Major basal beds of heavy minerals were found to be correlatable and continuous over significant stretches of the strand (which was previously assumed to be the case), but is now established as fact. Minor deposits of heavy minerals within the exposed beach sediment were not continuous, varying in presence and concentration along the 100 m investigated in detail. The storms of March which exposed the back beach sediments, reworked the heavy mineral suite and redeposited it into a surficial back beach basal bed, clearly establishing this as the primary mechanism for formation of the significant basal beds found on St. Catherines Island.

Radiometric Beach Transects-- Radiometric transects of Sea Side Spit and the back beach deposit along Yellow Banks (Figs. 9-10) demonstrate a close correspondence of ground-based radioactivity with heavy mineral deposits. Deposits of several types are delimited, including back beach shoestring sands, washover fan deposits, and dune deposits. The provenance of the heavy minerals not only includes their initial source in the Piedmont, but also an immediate local source, storage in Pleistocene Silvert Bluff facies, freed by continuing erosion of the bluff at Yellow Banks (which has a heavy mineral content of 3.6% (Fig.9)). The sand from the bluff is rapidly being sorted as the bluff retreats by erosion and is reworked into the backbeach immediately in front of the bluff and then by longshore currents northward and
Figure 9. Portion of St. Catherines Sound Orthophotomap (left) showing Sea Side Spit and our radiometric survey of approximately the same area showing increasing radioactivity with increasing tone (note the scales are not quite the same). The radiometric data are repeated on Figure 10 with an enlarged scale enabling the reading of radiometric values for each station.
Figure 10. - Enlargement of radiometric survey across Sea Side Spit shown on previous figure.

[Note that this diagram is not drawn to scale, but depicts radiometric values in their relative positions.]
southward from the bluff. The heavy minerals are also being blown off the beach into dune fields or carried over the berm by washover, forming washover fans.

The resulting deposits are a shoestring deposit of heavy minerals on the back beach, thick low grade deposits of dune sands with heavy mineral festoons, and thin sheets of washover sand deposits with reversed stratigraphy, i.e. with dense heavy minerals overlying quartz sand in layers approximately 15-20 cm thick.

Data from the regularly spaced surface radiometric beach transects are reinforced by intermittent radiometric readings made along the back beach and egg chambers dug by Loggerhead sea turtles after clutches of eggs were relocated. These readings tend to be higher than surface readings because the Geiger counter not only was surrounded by radioactive sand, but also rested directly on the heavy mineral rich back beach laminations. In this case, sea turtle nests would have been useful exploration tools for radioactive Georgia black sands!

CONCLUSIONS

Heavy minerals are concentrated by storm events in the beach zone, particularly as a thin band on the back beach along the spring high tide line. Heavy mineral accumulations are found in environments near beaches, including sediment on spits, in back beach dunes, and in washover fans. Sources of heavy minerals on St. Catherines Island include fluvial sediment from the Piedmont Province, erosion of stored heavy minerals in Coastal Plain sediments, perhaps from relict sands on the continental shelf, and locally from an eroding, high-standing Pleistocene bluff (Yellow Bank) developed on the Pleistocene Silver Bluff island core. Parallelism of burrow strands of Carolinean Ghost Shrimp and back beach accumulations of heavy minerals indicate such burrows ought to be useful exploration tools for ancient heavy mineral deposits. Heavy mineral deposits seen on St. Catherines Island are small scale features associated with beaches which might be easily overlooked by conventional exploration methods.

The research thus far accomplished on the distribution and accumulation of heavy minerals on St. Catherines Island has allowed a heavy mineral accumulation model to be constructed (Fig. 11) for processes active on St. Catherine’s Island. This model, although preliminary, confirms that the coastal environment is not only a complex and dynamic geological and biological system which has yielded significant understanding of those systems, but also a highly variable environment with many subtleties and complexities.

ACKNOWLEDGMENTS

This study was directly supported by awards from the Chancellor’s Special Funding Initiative for Research in 1989 and 1990. Direct and indirect support for the research was provided by the St. Catherines Island Foundation, Inc. through various grants from the Edward John Noble Foundation administered through the American Museum of Natural History. Special thanks are extended to St. Catherines Island Superintendent Royce Hayes, and his staff, who enabled much of this study through their maintenance of the Island infrastructure. Eric Bishop assisted with fieldwork, especially in digging trenches along the back beach. The encouragement from many colleagues, especially Fred Pirkle and Fred Rich, expedited our studies of heavy minerals on St. Catherines Island.
Fig. 11 - Heavy Mineral Depositional Model for Georgia Coast
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A BRIEF GEOLOGICAL HISTORY
OF THE
OKEFENOKEE SWAMP

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INTRODUCTION
The Okefenokee Swamp is an exclusively freshwater paludal system which covers approximately 660 square miles [1703 sq km] of Ware, Clinch, and Charlton Counties, Georgia, and Baker County, Florida. It is of interest to many researchers because, 1) it is very large, 2) it is essentially self-contained hydrologically, 3) human disturbance over the last thirty years has not greatly altered many portions of it, 4) it is floristically very similar to the Tertiary lignite and brown coal swamps of North America and Europe, and 5) the swamp is reasonably accessible and is almost wholly publicly owned; it is administered by the U.S. Fish and Wildlife Service as the Okefenokee Swamp National Wildlife Refuge and the Okefenokee National Wilderness Area. Another reason for the current interest among geologists is, of course, the relationship that the Okefenokee Basin has with Trail Ridge. The fieldtrip for which this paper was prepared is a two day excursion; the first day we visit sites located on or near Trail Ridge, and the second day we take boats up the Suwannee Canal to visit the marshes and forests of the eastern Okefenokee Swamp.

The Okefenokee Swamp is a remarkable geological phenomenon as well as a complex and dynamic ecosystem; one cannot discuss one of these aspects of the swamp’s natural history without at least addressing the other. The surface of the Okefenokee Swamp as we see it at any point in time appears as it does because of a multitude of recurring interactions among living things and geological processes. In short, each day we see the swamp as it appears at a point along a continuum of development that extends as far back into Earth’s history as, perhaps, the Cretaceous. On this fieldtrip we will examine some of the geological and biological features of the eastern Okefenokee Swamp which make the swamp what it is, for the time being. The forests and marshes of the Okefenokee Swamp lie, literally, at the top of a sequence of sediments which record the geologic and climatic events which have affected southeastern Georgia for at least the last 70 million years. The record of events has not always been a positive one, i.e., it is not a record of continuous deposition because erosion and removal of materials have been just as important as the deposition and preservation of them; abundant charcoal layers within the peat itself make that plain.
PHYSIOGRAPHY

Clark and Zisa’s (1976) Physiographic Map of Georgia places the Okefenokee Swamp within the Okefenokee Basin District of the Sea Island Sector of Georgia’s Coastal Plain Province (Figure 1). Those authors characterize the Okefenokee Basin District as follows:

“Low relief, decreasing to the southeast, and numerous swamps are characteristic of the Okefenokee Basin District. Relief varies from approximately 50 feet [15 m] to less than 5 feet [1.5 m]. Elevations in the district range from 240 feet [73 m] in the northwest on Pliocene-Pleistocene deposits to 75 feet [23 m] in the southeast on Pleistocene deposits. The swamps range in size from a few hundred square feet to the 660 square miles [1703 sq km] of the Okefenokee Swamp. The northwestern portion of the Okefenokee Swamp, like the northern and western portions of the district, is drained by the southeast-flowing tributaries of the southwest-flowing Suwannee River. The southeastern portion of the swamp is drained by the south-flowing St. Marys River. At the extreme southern end of the district the St.Marys River turns east and flows through a gap in Trail Ridge. The northern and western boundaries of the district coincide with the northern and western drainage divides of the Suwannee River. The eastern boundary is the western base of Trail Ridge.”

Humans have a long history of contact with the Okefenokee Swamp, and Twentieth Century scientists are certainly not the first people to wonder about the place. A long Pre-Columbian history of human occupation of the swamp basin and its many islands is well documented, as described by Trowell (1984).

The first American explorer to document his observations of the swamp was probably William Bartram, a well-known natural scientist and ethnographer who travelled the Atlantic and Gulf Coastal Plains of the southeastern United States between 1773 and 1778. While travelling in the vicinity of the swamp he made the following observations:

“The river St. Mary has its source from a vast lake, or marsh, called Ouaquaphenogaw, which lies between Flint and Oakmugue rivers, and occupies a space of near three hundred miles in circuit. This vast accumulation of waters, in the wet season, appears as a lake, and contains some large islands or knolls, of rich high land; one of which the present generation of the Creeks represent to be a most blissful spot of the earth...It is, however, certain that there is a vast lake, or drowned swamp, well known, and often visited both by white and Indian hunters, and on its environs the most valuable hunting grounds in Florida, well worth contending for, by those powers whose territories border upon it. From this great source of rivers, * St. Mary arises, and meanders through a vast plain and pine forest near an hundred and fifty miles to the ocean, with which it communicates, between the points of Amelia and Talbert islands; the waters flow deep and gently down from its source to the sea.

* Source of rivers. It is said, that St. Ille, St. Mary, and the beautiful river, Little St. Juan, which discharges its waters into the bay of Apalachi, at St. Mark’s, take their rise from this swamp.” (Van Doren, 1928)

Bartram had a remarkable ability to
Figure 1. Selected physiographic districts of the Georgia Coastal Plain (after Clark and Zisa, 1976).
relate the geological and biological attributes of a place. He furthermore speculated upon the influence these natural factors had on human occupation of the landscape. This holistic approach to understanding a landscape is one I choose to follow and it is, in my estimation, a grave mistake to discuss the present swamp processes without understanding at first why the Okefenokee Swamp is there at all. To that end, I have structured the following text so that the reader may understand how the swamp basin, its flora, and the swamp itself have come to be the way they are. We will then proceed to a discussion of plant community dynamics and how they have determined how and where peat has accumulated, particularly in the eastern Okefenokee Swamp.

REGIONAL GEOLOGY

General Characteristics

A number of papers are referred to in the following text because there have not been many regional syntheses of the geology of the area of the Okefenokee Swamp; geologists have focussed more on particular aspects of the geological history. That situation notwithstanding, a brief but informative review was written by Carver et al. (1986) in association with the Geological Society of America’s hundredth year celebration.

The Georgia Coastal Plain seems to be remarkably simple structurally. It is composed of Tertiary sediments which dip very gently seaward. The direction of dip rotates progressively from eastward to southward and then southwestward as one follows the Atlantic coast line south to the Florida state line, and then west to the Alabama state line.

Herrick and Vorhis (1963) outline four structural/depositional characteristics which typify the Georgia Coastal Plain. These are as follows:

1) In any cross section from the Piedmont to the east, south, or southwest, the sediments form a wedge-shaped body which thickens seaward and which overlies a basement that is of Triassic to Pre-Cambrian age.

2) Most of the coastal plain sediments are composed of two distinct lithofacies, a) clastic deposits which occur in updip areas that are most similar to western Gulf Coastal Plain deposits, and b) limestones which occur downdip and are lithologically and paleontologically similar to stratigraphically equivalent deposits in peninsular Florida.

3) There are “depcenters” on the Coastal Plain where maximum deposition of sediments has occurred. The depcenters were caused by “...major variations in locale or rate of sedimentary accumulations and regional warpings related to epeirogenic and isostatic adjustments...” (Herrick and Vorhis, 1963).

4) Formational overlap is known where, for example, Upper Eocene beds overlap Middle Eocene and Upper Cretaceous beds and finally come to rest upon the Pre-Cambrian rocks of the Piedmont.

The Southeast Georgia Embayment is one of the two depcenters which Herrick and Vorhis (1963) identify (Figure 2). The other depcenter is the Gulf Trough-Apalachicola Embayment, sensu Huddlestun (1988). Popoe et al. (1987) provide a review and discussion of the Gulf Trough, and while it’s history certainly affected the area of the Okefenokee Swamp, I will focus more particularly on the Southeast Georgia
Figure 2. Some structural features of the coastal plains of southern Georgia and Florida (after Sever et al., 1967).
Embayment because the Okefenokee Basin lies within it. The Southeast Georgia Embayment is centered in Brantley, Pierce, and Glynn Counties, Georgia, but it extends over a much broader area. It is the largest depositional feature on the Georgia Coastal Plain because it extends across the Coastal Plain to the Piedmont, north into South Carolina, and south into Florida (Sever et al., 1967; Huddleston, 1988).

LeGrande (1961) believed the Southeast Georgia Embayment formed as the result of sagging of sediments between the Cape Fear Arch in North Carolina and the Ocala Uplift in Florida. He describes the latter features as "...giant beams of great crustal strength..." which have held up most of the Atlantic seaboard despite the great load of sediments which it bears.

Although Cooke (1943) did not designate a name for it, he discussed a region of "...intermittent downwarp in the central and eastern parts of [Georgia which] permitted the ocean to advance farther and farther inland..." as time passed. The sagging of the east-central and southeastern portions of Georgia resulted in the progressive overlap of older formations by younger ones. This phenomenon was also noted by Herrick and Vorhis (1963).

Pressler's (1947) "Okefenokee Embayment" is a portion of the Southeast Georgia Embayment. It contains a maximum of 6,000 feet [1829 m] of sediments which are primarily Tertiary and Cretaceous age. The embayment that Pressler identified was important as a depocenter in middle Eocene time and continued collecting sediments intermittently through the Miocene (Herrick and Vorhis, 1963). Deposition was interrupted during the Late Eocene and Oligocene so that little or no strata of that range of ages are known from the Southeast Georgia Embayment (Figure 3). According to Popenoe et al. (1987) the nondeposition indicates that the area of southeast Georgia was a "...current-swept marine strait that was active in the high sea levels of the middle and late Eocene and the early Oligocene." It was not until the deposition of terrestrial/delatic units associated with the Miocene/Pliocene Hawthorne Group that terrestrial conditions might have existed in southern Georgia and northern Florida. James (1961) has shown that, even then, significant land areas were lacking in the region.

The actual relationship that exists between coastal plain tectonism and the accumulation and deformation of strata has been speculated upon (Opdyke et al., 1984; Carver and Waters, 1984), but the very nature of the coastal plain makes structural analysis difficult. The sagging, "intermittent downwarp", "regional warps related to epeirogenic and isostatic adjustments" and other types of crustal deformation alluded to above have, thus, remained largely unproven. Opdyke et al. (1984) suggest that uplift in northern Florida and southern Georgia occurred in the Pleistocene and Holocene as a result of isostatic rebound caused by the dissolution and removal of limestone. At least 36 m of uplift is believed to have taken place in north-central Florida, and extreme southern Georgia might well have been involved in that vertical movement. Carver and Waters (1984) explained unusual river terrace profiles along the Chattahoochee and Flint Rivers by suggesting that vertical displacement along faults took place in western Georgia. It is only recently that geologists have collected field
Figure 3. Geologic cross-section of Tertiary and Quaternary strata in southern Georgia (after Sever et al., 1967).
evidence of structural deformation on the Atlantic Coastal Plain of Georgia (Bartholomew et al., in progress). The results of work that Bartholomew, Rich, and others have in progress are still to be published, but a number of episodes of coastal plain deformation are clearly indicated by several pervasive, cross-cutting sets of joints. The fracture systems identified by Bartholomew et al. (1997) can be found in strata as old as the Cretaceous, and as young as the Silver Bluff shoreline (< 80,000 years BP, see Booth and Rich, this volume). It is likely that further work will show that the southern Atlantic Coastal Plain has been anything but quiet, tectonically. Multiple episodes of compressional and extensional deformation will probably be seen to have had a significant influence on the geomorphology of the Georgia Coastal Plain.

The Tertiary System

The Charlton Member. The presence of lithified strata in the vicinity of the Okefenokee Swamp is very limited. One unit does exist locally that can be seen at the surface on the north bank of the St. Marys River, however. Veatch and Stephenson (1911) identified this unit as the Charlton Formation and described it from outcrops along the St. Marys River between Stokes Ferry (now, Stokes Bridge) and Orange Bluff on the Florida bank of the stream. Fossils which were collected from St. Marys River locations were identified by T.W. Vaughn as probably of Pliocene age (Veatch and Stephenson, 1911).

Since that time the Charlton has been put in one or another formation or group on either side of the Miocene-Pliocene boundary. Bennison (1975) put the Charlton right on the Mio-Pliocene boundary and noted that it is in part correlative with various facies of the upper part of the Choctowhatchee Group in Florida (see also Puri and Vernon, 1964). The Charlton’s lithology and fauna are not very similar to other southeastern sediments of comparable age, but apparently represent litho- and biofacies of unique kinds. It thus seems to have accumulated within a minor, and unique estuary in the Southeast Georgia Embayment.

Huddlestun (1988) redefined the Charlton Formation as the Charlton Member of the Coosawhatchee Formation and described it as “...a minor subdivision of the Hawthorne Group.” It is not much more than 20 feet [6.1 m] thick (Cooke, 1943) and is known from only a few scattered outcrops where the St. Marys and Satilla Rivers have cut channels through the overlying Quaternary strata. The areal extent of the Charlton Member is not known with certainty, and Huddlestun’s (1988) map of its areal distribution (outcrop and subcrop) shows an “irregular distribution”, mostly within Charlton and Camden Counties, with the Charlton Member being surrounded by facies changes which lead to its being replaced laterally by other members of the Coosawhatchee Formation. Though no one can say with certainty what the extent of the Charlton Member is, its distinctive texture and its position as a limestone which lies immediately beneath the Pleistocene sands of the coastal plain make it recognizable in core holes. The Charlton lithology is variously clayey, argillaceous, and calcareous. It may be soft or hard, and usually contains laminations of drab, chalky, yellow-white, fossiliferous limestone (Veatch and Stephenson, 1911). Fossils may be so abundant that the rock is
coquina-like, a characteristic that Huddleston (1988) considers to be very unusual for a unit of the Hawthorne Group. The fossils are seldom well-preserved because groundwater has removed the original shell material. Removal of the shells has left many small internal casts of bivalves which are easily removed from the matrix by crushing the fossiliferous samples. Solution pitting of the matrix has accompanied shell solution and has left the shelly portions of the Charlton Member very porous. This porous nature seems to be a rather distinctive feature of the formation.

The type locality of the Charlton Member is on the St. Marys River, as previously mentioned. Its westward extent has not been determined, but there is good reason to believe that the formation extends westward under the Okefenokee Swamp at least as far as Jones Island (Figure 4). The Georgia Geological Survey has drilled a few wells in Charlton County, both east of the Okefenokee Swamp in the city of Folkston, and on the west side of the swamp on Jones Island. At a depth of 70 feet [21.2 m] below the surface in a Folkston well (GGS-1154) a limestone was found and described as brownish-grey to cream colored, saccharoidal, porous, and “...bearing fragments and molds, and impressions of molluscan shells...” (Georgia Geological Survey, personal communication). The Jones Island well (GGS-965) produced a “...brownish-grey to cream, saccharoidal, porous [limestone with] fragments and molds of molluscan shells...” at a depth of 80 feet [24 m] below the surface. In both cases, “porous” was defined as bearing “...pores, or openings, formerly occupied by molluscan shells...” (Georgia Geological Survey, personal communication, cited in Rich, 1979). There is little question but that the limestones encountered in these wells was the Charlton Member of the Coosawhatchie Formation.

Herrick (1970) noted a “...clay of Pliocene age at an approximate depth of 65 feet [19.8 m]...” in a test hole drilled in southern Charlton County. He contended that the impermeability of the clay has been “...chiefly responsible for the existence of the Okefenokee Swamp.” Although he does not assign a formational name to the clay, the implication is that it is from the Charlton Member, or a deposit of similar age. Georgia Geological Survey well logs record clays at comparable depths in well numbers 453, 965, and 1154, above the limestone beds which are here proposed to be the Charlton Member.

Another recent reference to the poorly defined carbonate strata underlying the swamp is the paper by Pirkle and Pirkle (1984). In a discussion of the physiographic features of the swamp basin, those authors identify carbonate rock which lies close to the surface beneath the swamp. They refer to a well log from a hole drilled in the central part of the swamp under the supervision of the U.S. Geological Survey (W-6885). A “...sandy, impure dolomitic calcilutite beginning at a depth of 7.6 meters beneath the swamp surface” was identified in the hole. Pirkle and Pirkle (1984) go on to state that the solution of soluble sedimentary rock has probably been so important in the development of the swamp basin as to make it “...mandatory to consider solution as a major factor in the origin of the swamp.”

The Quaternary System

Quaternary deposits of the southeastern
Figure 4. Locations of two Georgia Geologic Survey core holes on Jones Island and in Folkston, Georgia.
portion of the Coastal Plain are chiefly of Pleistocene age. They cover that portion of the Atlantic Coastal Plain which lies between the Tifton Upland on the west and the Atlantic Ocean on the east (Figure 1). This is the Coastal Terrace Province of Cooke (1925). The deposits form a thick wedge of sediments which are thickest at the coast but thin progressively inland. Their coastward dip is approximately 2 feet per mile [.38 m/km] and they are as much as 65 feet [19.8 m] thick (Herrick, 1965).

**Pleistocene deposits.** Most of the Pleistocene material consists either of very old terraced deposits whose histories are very poorly known, or younger nearly pure quartz sands and silty/clayey sands which may date to the last interglacial. The more pure sands are generally regarded as ancient barrier island deposits and their associated shore line sands, whereas the silty/clayey sands are thought to represent back-barrier lagoonal facies (Hoyt and Hails, 1969).

The different lithologic compositions of Pleistocene deposits on the Georgia Coastal Plain have long been recognized. Veatch and Stephenson (1911) noted that sediments consisted of grey sands, greenish and bluish marine clays, and red, argillaceous sands or pebbly and coarse gravels. They divided the deposits into two formations based upon geographic positions and degree of topographic relief. Their Satilla Formation consisted of shoreline deposits lying 20 to 30 miles [32-48 km] inland of the modern coastline and was differentiated into marine and fluvial portions. Their Okefenokee Formation was found inland from the Satilla Formation at an elevation of 60 to 125 feet [18.2-38.1 m] above sealevel. It too was differentiated into coastal terrace sands and fluvial deposits.

Since Veatch and Stephenson’s time, a number of workers have examined Georgia’s coastal sediments and have established several classification schemes to deal with them. Most authors agree that the deposits are terraced and occupy distinct topographic positions. The number of such terraces and the stratigraphic status given to the deposits have, however, been sources of disagreement. Flint (1940) recognized three shoreline/terrace complexes ranging from Sangamon to pre-Yarmouth age. Cooke (1943, 1945) identified seven terraces, with the possibility of an eighth. MacNeil (1950) defined four shorelines, ranging from post-Wisconsin to Yarmouth age. Hoyt and Hails (1969) identified six shorelines below 100 feet [30.4 m] elevation, all of Pleistocene age, and acknowledged the possibility of others at higher elevations. Huddleston (1988) identifies 12 marine terraces. The various authors have used a somewhat bewildering assortment of names to accompany the terrace deposits and the result has been a voluminous and confusing literature.

In spite of the confusion, one point remains rather constant, and that is that the various Pleistocene sands and clayey silts can be placed in two distinct geomorphological groups, the High Terraces and the Barrier Island Terraces.

The High Terraces lie above an elevation of 100 feet [30.4 m], that is, above the highest prominent member of the Barrier Island Terraces (also known as the Wicomico Terrace, or Trail Ridge). They are the oldest Pleistocene deposits and are the most poorly understood. Cooke (1925) identified three such terraces, the
Hazelhurst Terrace (215 to 260 feet [65.5-79.2 m] above sea level), the Claxton Terrace (160 to 215 feet [48.7-65.5 m] above sea level), and the Okefenokee Terrace (100 to 160 feet [30.4-48.7 m] above sea level). Later, Cooke (1943) changed the names of the terraces to the Brandywine, Coharie, and Sunderland, respectively. Huddleston (1988) recognizes five terraces that lie inland of the Wicomico Terrace; these include the Hazlehurst, Pearson, Claxton, Argyle, Waycross, and Okefenokee Terraces. The lowest of the High Terraces, whether called Okefenokee or Sunderland is correlative with the Northern Highlands of north-central Florida. Pirkle and Pirkle (1984) and Davis (1987, 1996) make reference to that terrace as a source of erosional material which was later reworked and incorporated into younger sand bodies, including Trail Ridge. Several lines of evidence, based upon sedimentological studies and land-form analysis make this a very logical conclusion.

During the course of the Pleistocene, and following the deposition of the Okefenokee Terrace, the Atlantic Ocean occupied various positions on the coastline depending on the position of eustatic sea level. Each still-stand of the sea was accompanied by the development of a shoreline terrace. The oldest shoreline lies furthest inland and each successively lower shoreline is younger, with the youngest shoreline being the present Atlantic shore. The most widely accepted terminology for the Barrier Island Terrace shorelines is still the set of terms that was employed by Hoyt and Hails (1969) and redefined by Huddleston (1988). These include the Wicomico Terrace (oldest, and equivalent to Trail Ridge), Penholoway Terrace, Talbot Terrace, Pamlico Terrace, Princess Anne Terrace (equivalent to the western half of Skidaway Island), Silver Bluff Terrace (equivalent to the eastern half of Skidaway Island, and the central island cores of St. Catherines and Cumberland Islands in Georgia), and the Holocene Terrace (youngest, and equivalent to Tybee Island in Georgia). Among these terraces, the Pamlico, Princess Anne, Silver Bluff, and Holocene are all included within Huddleston’s (1988) Satilla Formation, a term whose use he extended from Veatch and Stephenson’s (1911) much earlier work.

Okefenokee Terrace. Regardless of the name one applies to this high terrace, there is little doubt but that the time of its development was the most significant period of time during the formation of the Okefenokee Basin. During that 150 foot [45.7 m] highstand the swamp basin acquired the sub-peat topography that now exists, and Trail Ridge formed as older sediments were reworked.

A large embayment existed before Trail Ridge accumulated, and it was that embayment which has come to contain the Okefenokee Swamp. The swamp currently covers about 660 square miles [1703 sq km], but the original embayment may have been much more extensive, particularly if it covered a large portion of the surface of the 150 foot [45.7 m] terrace. Several factors seem to have operated during the geomorphic development of the region, however, which have lead to the formation of the Okefenokee Basin as a basin, while the remainder of the terrace has stayed higher and fairly level. The Okefenokee Basin lies at the “head” of a depositional trough which Herrick (1965) identified in his study of
subsurface Pleistocene deposits. The trough occupies the same position as the St. Marys River channel and extends from Fosterton to St. Marys, Georgia. Both the subsurface trough and Trail Ridge (which runs perpendicular to the trough) probably served to direct much of the drainage of the Southeast Georgia Embayment toward the Okefenokee Basin as sea level gradually rose and fell repeatedly during the Pleistocene. The enhancement of negative topography in the basin through karsting and dissolution of limestone (e.g., the Charlton Member) as suggested by Pirkle and Pirkle (1984) could only have enhanced the basinward flow of water as sea level fell.

**Okefenokee Basin.** The surface of the Okefenokee Terrace deposits must have become fairly irregular during development of the Okefenokee Basin. One would expect that to be the case simply as a result of the irregular removal of subsurface limestone. There are many large-scale topographic features on the sandy surface, however, including the arcuate islands and ridges which stand above the surface of the swamp today which probably developed independently of karsting. Their elevations above the surface of the basin (i.e., above the sand-peat contact) range from 7 to 18 feet [2.1-5.5 m], and some of them are several miles/km long (e.g., Billys’ Island, Blackjack Island). The islands tend to be concentric about a point which is almost midway on the western side of the swamp, and their shapes strongly suggest that the islands developed as spits or sand bars at a time when the basin was still occupied by the Atlantic Ocean.

Davis (1987, 1996) conducted an exhaustive and thought-provoking analysis of the arcuate sand ridges of the Okefenokee Swamp. He collected 31 cores from a variety of sites within and outside of the swamp. Five sand ridges were selected for detailed study, including The Pocket, Floyds Island, Pine Island, Chesser Island, and Cowhouse Island. Using sediment analysis, including descriptive stratigraphy and statistical analysis of sieve samples, and landform analysis, Davis came to some interesting conclusions. A piecemeal process of swamp-basin in-filling is envisioned which extends back into the Pleistocene, when the Atlantic coastline lay immediately west of the swamp basin. At that time, the Alapaha and Ocmulgee Rivers were proposed to have had a common channel that lay west of the swamp (Figure 5). Heavy mineral sand suites that were identified in samples from The Pocket, and Floyd’s and Pine Islands suggested to Davis that the terraces west of the swamp (including, potentially, everything from the Okefenokee Terrace to the Hazelhurst Terrace) were the sources of the sand in the Okefenokee Basin; the stream that entered the basin therefore had to have come from the west. After flowing across the High Terraces, the Alapaha-Ocmulgee River entered the Okefenokee Basin where a series of deltas developed in a fashion similar to what has been described for the Mississippi River delta (Frazier and Osanik, 1969). Davis further contends that the Suwannee River flowed into the basin rather than out of it, and it thereby contributed to the flow of water and sand entering the Okefenokee Basin. Deltaic channel fluctuations resulted in the following sequence of depositional events:

1. Floyd’s and Minnie’s Islands were built as subaqueous levees, while coarse channel sediments accumulated at Pine Island
Figure 5. Approximate locations of Alapaha-Ocmulgee river channels and Atlantic coastline in the vicinity of the Okefenokee Basin, Pliocene or Early Pleistocene (after Davis, 1987, 1996).
represent the period of time when peat deposition first became significant there. If these are indeed the oldest peats in the swamp, then a period of several tens of thousands of years may have passed between the time when the sea evacuated the basin, abandoning the subaqueous levees, and the time when peat accumulation began. Sea level was much lower during the Pleistocene glaciations than it is now, perhaps by as much as 200-300 feet [60.9-91.4 m; see for example Bloom, 1983]. The 200-300 foot [60.9-91.4 m] difference in elevation between the Okefenokee Basin and the sea would have left the basin in a relatively high and dry position. The comparatively high relief of the southeast Georgia coast probably was not conducive to the accumulation of water in the basin or the development of a peat deposit. There would have been a tendency for stream channels and drainage systems to develop instead. The formation of stream systems was probably inevitable, especially if, as has been suggested above, much of the drainage of the Southeast Georgia Embayment was directed toward and through the Okefenokee Basin.

The formation of karst depressions, and the subsurface trough identified by Herrick (1965).

Davis (1987, 1996) identifies one further modification of the swamp basin which occurred perhaps intermittently during the Pleistocene. Four large elliptical features can be seen in the swamp, two to the northwest of The Pocket, one between Billy’s and Floyd’s Islands, and one to the north of Floyd’s Island. Davis believes these were Carolina Bays (Figure 9) which formed after the final regression of the sea during the Pleistocene. Craven’s Island, Hickory Hammock, parts of
Figure 6. Appearance of Floyd's and Minnies's Islands as subaqueous levees; channel sediments accumulated where Pine Island now stands. The position of the coastline is speculative (after Davis, 1987, 1996).
Figure 7. Appearance of Pine Island and Mixon’s Hammock, following deposition of Floyd’s and Minnie’s Islands (after Davis, 1987, 1996).
Figure 8. Appearance of The Pocket, Chesser Island, Strange Island, Honey Island, and Blackjack Island as subaqueous levees derived from one, or possibly two distributaries of the Alapaha-Ocmulgee system. At this point most of the Okefenokee Swamp’s major islands have appeared (after Davis, 1987, 1996).
Figure 9. Appearance of Carolina Bay basins following elevation of the Okefenokee Swamp basin above sealevel. Circular water currents within the bays are indicated (after Davis, 1987, 1996).
Minnie's Island, and several other sub-peat ridges are proposed to be receding lake-margin dunes associated with the four bays. The bays and their associated dune ridges are apparently superimposed on the land-form pattern established during the deltaic phase of swamp basin formation.

**Trail Ridge.** In addition to the Okefenokee Swamp itself, Trail Ridge remains one of the most remarkable features of the southeast Georgia coastal plain. The genesis of the swamp basin and the ridge are inextricably linked. So much literature exists which pertains to the ridge that separate chapters are necessary here to cover all the information that is available. The numerous sedimentological works of E.C. Pirkle, W.A. Pirkle, and F.L. Pirkle provide an essentially complete history of the development of our knowledge of the ridge. More recent paleoecological studies by F.L. Pirkle and F.J. Rich have helped to clarify some of the earlier depositional models, while Davis' physiographic analysis fits Trail Ridge very nicely into the land-form puzzle which seems to make up the Okefenokee Swamp.

According to W.A. Pirkle and E.C. Pirkle (1984), Trail Ridge is unquestionably derived from the sands of the Northern Highlands and, by implication the Okefenokee Terrace. Heavy mineral suites, grain size distributions, and the similarity of heavy mineral grain sphericities all lead to that conclusion. Furthermore, Trail Ridge truncates the Waycross Ridge in Georgia, and the Lake City Ridge in Florida, subsidiary ridges which are part of the high terrace. In their summary remarks, Pirkle and Pirkle (1984) make the following observations:

"In summary, the high terraces of the Northern Highlands are believed to have been left as a plain when ocean waters retreated from the present areas of southern Georgia and northern Florida. At a later time transgressing seas eroded into these high terrace deposits. Trail Ridge with its heavy-mineral sand deposits was built as a beach ridge at the height of this transgression."

One remaining question relates to how much of the ridge was deposited under water, as a longshore sand spit, and how much was deposited subaerially as a beach ridge/dune complex. F.L. Pirkle (1984) performed factor analyses on several hundred sand samples from the southern end of Trail Ridge, where heavy mineral sands are currently being mined from Trail Ridge. In his conclusions, he makes the following remarks:

"Trail Ridge sands were deposited in a wind-wave environment. Thus, those hypotheses explaining Trail Ridge as a beach ridge deposited in a wind-wave dominated environment are more consistent with the features of Trail Ridge sediments than are those hypotheses that explain Trail Ridge as a spit developed in an environment dominated by current action."

Pirkle's (1984) conclusion that Trail Ridge sands are, to a significant extent, terrestrial deposits was born out by work performed by Force and Rich (1989). Their work was prompted by earlier work done by Rich (1985) which had proven the freshwater origin of brown-coal (very mature peat) which is known to commonly underlie Trail Ridge near its southern terminus in Clay County, near Starke, Florida. The timing of the accumulation of the brown-coal relative to the deposition of
the sands of Trail Ridge was a matter that Force and Rich wanted to investigate. Examination of sand-bearing samples of the brown-coal lead Force and Rich to conclude that the brown-coal accumulated originally within a freshwater wetland very near the coast. The sands themselves accumulated as coastal dunes, and the dunes migrated landward, eventually burying the wetland. More recent analysis of yet another brown-coal site in Clay County has substantiated the generally widespread nature of the coastal freshwater wetland (Rich, 1995a). Though data collected from sites nearer to the Okefenokee Swamp are not yet available to the public, it is safe to assume that the freshwater wetlands extended north into Georgia, and may even have occupied the Okefenokee Basin before, during, and after the transgression which produced Trail Ridge. The wetlands appear to have had a consistent composition, with freshwater genera such as *Cyrilla* (ti-ti), *Gordonia* (loblolly bay), *Taxodium* (cypress), *Nyssa* (black gum or tupelo), and *Sphagnum* being significant contributors to the flora. It was, for all intents and purposes, the same flora that one finds within the Okefenokee Swamp now. Vertical and lateral variations of pollen and spore components, and the thickness of the brown-coal itself (almost 5 feet [1.5 m] in some cases) suggest that the wetlands were mature, well-established complexes of plant communities which took up residence along the coast soon after the Okefenokee Basin was abandoned by the Atlantic Ocean. The swamps and marshes would probably have remained there until today, essentially unchanged, except that sea level rose and fell so many times during the Pleistocene. The initial transgression, during which Trail Ridge undoubtedly accumulated, resulted in the demise of the wetlands that stood nearest to the shore line. Even though they were gradually buried, other wetlands which stood further inland maintained the presence of cypress and hardwood swamps on the coastal plain, providing a source for the plants which would, at a much later date, completely occupy the Okefenokee Basin once again.

**Holocene deposits.** At present we have very limited information about what happened in the Okefenokee Basin between the time of deposition of Trail Ridge (whose actual age is unknown) and the time of deposition of the oldest dated peats, which accumulated about 6600 years ago (Cohen et al., 1984). As is usually the case in topics of geological debate, there have been opposing schools of thought regarding the characteristics of the early environment of the Okefenokee Basin. Parrish and Rykie (1979) provide a detailed account, with commentary, wherein they review the various hypotheses that had been advanced up to that time. They flatly reject any notion that the swamp itself could have originated in a saline lagoon (their "Harper-Cooke marine origin theory"), favoring instead the belief that "...the swamp itself originated and developed entirely in Holocene time" and entirely under the influence of fresh water. Assuming that Davis' (1987, 1996) interpretations accurately portray events within the basin, one must reconcile the presence of a deltaic/marine basin with the complete lack of paleontological evidence that marine water ever occupied the basin. As is oftentimes the case, the evidence of the Okefenokee's ancient marine history has probably been removed by the processes of
weathering and reworking of sediments. This seems to be born out by the pervasive charcoal-spicule-phytolith layer that lies at the peat-sand interface in the Okefenokee Swamp. This distinctive horizon suggests that long periods of exposure and oxidation of the basin sediments occurred during the Pleistocene. It was during that time that Davis (1987, 1996) believes Carolina Bays (which were filled with lakes) occupied the swamp basin in certain places (Figure 9), but there is no paleontological evidence to support that contention. The rising and falling sea had to have had a dramatic effect on groundwater, causing water tables throughout the southeastern United States to rise and fall. This has been amply demonstrated by Watts (1971), who first described depositional hiatuses in lake basins near the Okefenokee Swamp. More recently, Rich (1995b) has described a disconformity in the peat deposit in Ulmers Pond, near Valdosta, Georgia, which separates peats dated at 35,000 and 5500 years. The Ulmers Pond disconformity correlates very nicely with those identified by Watts elsewhere in the Southeast, and shows that normal wetland deposition was seriously interrupted at least once late in the Pleistocene. Earlier depositional breaks certainly must have taken place, producing the charcoal-spicule-phytolith layer, but until deposits of peat which accumulated in the Okefenokee Swamp during the time of the depositional hiatus are recovered, we can only guess at the nature of events which characterized the swamp basin. A paper by Booth and Rich (this volume) provides a synthesis of what we know about terrestrial plant communities on the Georgia Coastal Plain during these “missing years”.

Once sea level and water tables had risen again in the early Holocene, permitting the inundation of the sediment surface in the swamp basin, the record of the plant communities which lived in the area was firmly established. Several studies have been undertaken in order to describe the characteristics of those early communities, and they have yielded remarkably uniform results. Rich (1979) analyzed eleven cores of peat from the Okefenokee Swamp, and later presented the results of palynological investigations of 26 basal sediment samples (Rich, 1984). Fearn and Cohen (1984) presented the analytical results of a study of six cores of peat from the swamp, including data from basal samples of all six cores. Finally, Fair-Page and Cohen (1990) studied nine cores from the swamp, and analyzed the basal samples from them all. Rich’s samples came from Territory Prairie, Chase Prairie, Mizell Prairie, Chesser Prairie, and Grand Prairie. Fearn and Cohen’s came from Chase Prairie, Floyds Prairie, Territory Prairie, Sap Prairie, the Gannet Lake boat trail, and from between Billy’s Lake and Floyd’s Island Prairie. Fair-Page and Cohen’s cores came from a 4429 foot [1350 m] long transect across the upper reaches of the Suwannee River near Minnie’s Lake. Among them, these sample localities represent a fairly good sampling of basal peats from a broad area of the swamp.

Several genera, or families of plants are consistently represented in the basal peat samples. Some of them are abundant, and others are simply persistent, but they constitute a distinctive assemblage of plants, particularly in comparison to plant communities which occupy the swamp now. Among the most abundant basal pollen types are *Pinus* (pine),
Quercus (oak), Chenopodiaceae and Amaranthaceae (including a variety of usually weedy herbaceous plants that inhabit disturbed or otherwise marginal ground; common types include redstem pigweed and lamb’s quarters, or goosefoot), Compositae (a large family of plants including daiseys, asters, and similar types), Poaceae (formerly identified as the Gramineae, this includes grasses, in this case of a probable wide variety), Cyperaceae (sedges, herbaceous plants similar in habit to grasses), Nymphaea (the white water lily), and Sagittaria (arrowhead, a common wetland herb). Less common pollen, but genera which are sometimes quite abundant include Myriophyllum (water milfoil), Xyris (yellow-eyed grass in the northern states, or hardhead in southeast Georgia), Sparganium (burr reed, similar in appearance to grasses or sedges), and Brasenia (water shield, a floating leaved aquatic usually included among the “water lilies”).

The basal Okefenokee Swamp pollen flora certainly represents a mixture of plants derived from two distinctly different communities; marshlands of limited extent and freshwater origin which grew in low areas and were dominated by herbaceous plants (Nymphaea, Brasenia, Sparganium, Myriophyllum, Xyris, and probable Poaceae, Cyperaceae, and Compositae), and sand ridge vegetation which occupied sandy hills and which was dominated by woody vegetation (Quercus, Pinus), and herbaceous plants (probable Chenopodiaceae and Amaranthaceae, Compositae, Poaceae, and Cyperaceae). The swales, produced by streams which incised their channels following subaereal exposure of the swamp basin, logically became areas of ponding and so could sustain marshlands. The sand ridges, remnants of the subaqueous levees of the ancient Ocmulgee-Alapaha delta, would have been readily occupied by species of plants which still occupy edaphically dry sand ridges in the southeastern United States. The relationship that the original topography had on the pollen/spore compositions of basal sediments is suggested in Figure 10. Three cores of peat taken in the eastern Okefenokee Swamp [Tree Islands 1, 2, and 3 of Rich (1979)] had very different basal depths. For T11, the deepest sample came from 78 inches (1.98 m) depth. For T12 the deepest sample was retrieved from 72 inches (1.83 m), while T13 produced a basal sample from 162 inches (4.1 m). The T13 sample has more than twice as much herbaceous pollen in it (36%) as the other two samples, suggesting that a marsh grew in the swale that lies beneath the current position of T13. This is in contrast to the modest quantity of herbaceous pollen/spores found in the samples that I propose accumulated on ancient sand ridges.

One reason that it is so easy to visualize the kinds and distribution of the ancient Okefenokee communities is that they were probably identical to the communities that exist in the area today. The only thing that has measurably changed since the earliest days of the Okefenokee flora is that the water table has risen, and a great deal of peat has accumulated over the past 6,000 to 7,000 years. Figure 11 (taken from Rich, 1984) provides a diagrammatic illustration of how the accumulation of peat gradually lead to upland communities being supplanted by wetland communities. This interpretation is a variation on the theme established by Cohen (1973) and shared by Parrish and Rykiel (1979).
Figure 10. Generalized compositions of three basal Okefenokee Swamp samples from beneath Tree Islands 1, 2, and 3.
Figure 11. Reconstruction of the ancient Okefenokee plant communities which existed early in the development of the peat deposit (from Rich, 1984).
Habitats About 4000 B.P.

Modern Swamp Environment

Figure 11. continued.
Cohen et al. (1984) summarize the many years of work which Art Cohen, in particular, and many other workers have put into the study of the Okefenokee peat deposit. It is sufficient to say that, once peat began to accumulate in the Okefenokee Swamp it continued more or less unabated to the present. The Okefenokee peats are not homogeneous, but are, rather, derived from a wide variety of plant communities. These tend to be dominated by waterlily-filled marshlands, and cypress or hardwood-dominated swamps. The dynamics of these communities, and how they relate to the presence of fire particularly, are the topics of several papers which appear in the book edited by Cohen et al. (1984), entitled The Okefenokee Swamp: Its Natural History, Geology, and Geochemistry. The reader is encouraged to read the various papers in that book in order to get a detailed picture of the characteristics of the peat-forming environments of the swamp.

Throughout all the debate that is likely to continue relative to the origin of the Okefenokee Swamp, two bits of wisdom come from some of the workers whose research is referred to here:

"The modern landscape...is a palimpsest resulting from the superimposed impacts of...geomorphic systems." (Davis, 1996), and

"The origin of the Okefenokee Swamp is related to a constellation of interacting factors no one of which can be singled out as clearly the most important.” (Parrish and Rykiel, 1979)

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A REVIEW OF THE ORIGINS OF TREE ISLANDS (“HOUSES”) IN THE OKEFENOKEE SWAMP

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INTRODUCTION

According to Cypert (1972) about 15% of the Okefenokee Swamp surface is covered by “prairie”. Prairie is a local term used for extensive, fairly open, aquatic herb communities. They may be more properly termed marshes since they are wetlands dominated by herbaceous growth and are in no way similar to the edaphically dry or mesic grassland communities of the American West. Okefenokee prairies are, nonetheless, usually covered with a substantial amount of slowly flowing water which makes them easily accessible by boat during most years [water depth varies with the seasons and over a period of years it may show striking fluctuations (Rykiel, 1977)].

Areas such as Chase Prairie and Chesser Prairie are complex associations of two of the habitats which Wright and Wright (1932) identify in their detailed account of plant communities in the swamp: there is the open marsh which supports floating-leaved and emergent aquatic genera [e.g. *Nymphaea* (white waterlily), *Brasenia* (water shield), *Nymphoides* (floating heart), and *Xyris* (hardhead), *Panicum* (maidencane grass), *Lachnanthes* (paintroot), *Carex* (a sedge), respectively], and there are floating and attached islands of peat which are called “batteries”, and tree- or shrub-covered islands called “houses” or “bay heads”. The relationship of the islands to the surrounding marsh will be the focus of this paper.

The houses of the large prairies in the eastern portion of the Okefenokee Swamp have been discussed by Cypert (1972) and Duever and Riopelle (1984), and were illustrated by Spackman et al. (1974) and Rich (1979). They vary in size from a fraction of an acre to several acres [.5 to many hectares]. An arbitrary size limit of 20 acres [8 hectares] was mentioned by Cypert (1972) in his study of house origins. Any group of trees larger than 20 acres [8 hectares] is termed a bay. Larger houses may support groves of cypress and various hardwoods [*Ilex* (holly), *Gordonia* (loblolly bay), *Persea* (red bay), *Magnolia* (sweet bay)] or slash pine (*Pinus elliottii*).

In certain portions of the prairies, especially near the margin of prairie and swamp forest, there may be a very gradual gradation from house-filled prairie to closely spaced houses, and house-bearing swamp forest. This gradual change of habitats may be seen in Christie and Chase Prairies (U.S. Geological Survey 7.5 minute photomap, Chase Prairie Quadrangle, Georgia). It would appear that houses are important agents in initiating the development of swamp forest where prairie
now exists. Cypert (1972) states unequivocally that it "...is obvious that the Okefenokee prairies are reverting to swamp forest through the development of houses." That is an hypothesis which was tested by Rich (1979) and which has been proven true.

The most extensive investigations of Okefenokee houses and their development have been conducted by Rich (1979; 1984) and Duever and Riopelle (1984). Among them, those authors investigated 23 houses, though different means of inquiry were used. Rich collected cores of peat from beneath the islands of vegetation and analyzed the peat palynologically and petrographically. He was able to determine how the environments of deposition at each site had changed over time. Duever and Riopelle observed and recorded the composition of the living plant communities on the islands they selected, and used tree-ring analysis techniques to determine the ages of the three largest specimens of each woody species. In so doing they were able to tell when each species initially occupied the island, and were able to describe the succession of species on each island as well as to determine the minimum age of the plant community on each site. One site, a large cypress covered island in Chesser Prairie was studied by both techniques, so a synopsis of its history is included here, as well as the history of a smaller island in Chesser Prairie which was studied only by Rich (1979).

The larger island, identified by Rich (1979) as Chesser Narrows Tree Island, and the smaller one, identified as Tree Island #2, have not been described in readily available literature, so the data presented here are essentially new. A third site, Tree Island #3, has been described by Spackman et al. (1974) and Rich (1984); its history is briefly reviewed below.

**ORIGINS OF HOUSES**

Houses figure very prominently in the Okefenokee landscape. While they certainly must have been visited, and perhaps even speculated upon by the earliest inhabitants of the Okefenokee Swamp, "houses" did not enter the scientific literature until Eugene Cypert, a former Okefenokee Swamp National Wildlife Refuge worker, recorded his observations (Cypert, 1972). Cypert contended that houses each originated where marsh vegetation once grew. The houses formed following the appearance of a "battery", a floating mass of peat. Peat masses periodically rise to the surface in the prairies, and may be of three types: 1) floating mats which are completely detached from the substrate and which have thin, attenuated margins [these are very much like the floating bogs of the northern United States, and provide a springy, unstable surface which is treacherous to walk upon]; 2) large domal bulges of peat whose surfaces descend beneath the water and which remain attached to the substrate; and 3) mats composed of accumulated bits of peat which float almost like bubbles on the water’s surface [most similar, perhaps, to the flotant of the Mississippi Delta marshes, as described by Russell (1942)]. Figure 1 diagrammatically illustrates the three types of batteries.

While water lily plants which rise to the surface with batteries survive for a time, they eventually become stunted and die as they lie exposed to the air and the drying effects of the sun. The freshly exposed surfaces of batteries provide an excellent seedbed for seeds of other species which may have lain dormant in the peat, or new seeds which are carried to the peat surface by wind or animals. A new growth of sedges (Rhynchospora species) may cover a battery quickly, and is often accompanied by a
Figure 1. Types of floating peat masses (batteries) in the Okefenokee Swamp (after Spackman et al., 1974).
curious assortment of herbaceous plants including the green orchid *Habenaria repens*, Ladies'-tresses orchid (*Spiranthes* sp.), and insectivorous species such as the diminutive yellow bladderwort *Utricularia cornuta* and the sundew *Drosera intermedia*.

Cypert (1972) contended that the herbaceous species were eventually displaced by woody plants as a battery gradually became a house. He chronicled the appearance of several species on batteries, and determined that woody plants which commonly comprise house communities fairly rapidly occupy the surfaces of batteries. These include *Taxodium* (cypress), *Cyrilla* (ti-ti), *Cephalanthus* (button bush), *Itea* (Virginia willow), and *Leucothoe* (hurrahbush). A battery in Chesser Prairie which I observed for three years (1974-76) had *Taxodium, Leucothoe, Cephalanthus,* and *Lyonia* (fetterbush) growing on it after about a year of exposure above water. Reason suggests that, once these plants establish themselves, they spread steadily over the surface of a battery until they cover it. From the point beyond which a battery is covered with shrubs until it is occupied by trees, it experiences a succession of plant communities which may lead to the former prairie site being occupied by cypress trees which are several centuries old. Examination of the geologic record (i.e., the peat deposit beneath a house) shows that Cypert (1972) was correct, and what appears to happen now actually has happened many times in the past as the Okefenokee prairies gradually convert to swamp forest.

**A Prairie Without Houses**

Before looking at the actual sedimentological evidence for house origins, it might be useful to consider what an Okefenokee peat deposit looks like if there is no record of tree or shrub covered islands in the stratigraphic record. Common as houses are, they have not had a role in the deposition of the peat in certain “deep” prairie peat deposits. Cohen (in Spackman et al., 1974) illustrated and described peat cores from the eastern portion of Grand Prairie that show no evidence of tree or shrub peat. His core Grand Prairie #3 is illustrated here in Figure 2. Accompanying it is an abbreviated pollen diagram for another core from Grand Prairie, GP#2, that shows the nature of the palynological composition of that core.

Both GP2 and GP3 show that, as long as there is no serious disruption of the hydroperiod in the deep prairies, they remain sites of deposition of marsh peats. In the case of GP2 the marsh has been dominated by waterlilies ever since the peat column began to accumulate. Minor changes in water depth resulted in the appearance of grasses, sedges, and ferns (*Woodwardia*) but the dominant peat-forming community has been that of the waterlilies. GP2 shows a similar history. Shrub pollen such as *Ilex* and the Ericaceae are of minor significance, whereas *Nymphaea* pollen is present at every level. Where it diminishes it is replaced by grasses, *Woodwardia*, or *Sphagnum*. The algal zygospore *Ovoidites* is present in small amounts at most levels, a fact that suggests long, persistent periods of freshwater inundation (Rich et al., 1982). Any variation from that situation can be easily identified in the pollen and macrofossil record, as is nicely illustrated by the core from Tree Island #3.

**Analysis of Tree Island #3**

Spackman et al. (1974) and Rich (1984) provided a very detailed analysis of a tree island found in Grand Prairie, Tree Island #3 (TI3).
Figure 2. Comparison of the peat stratigraphy of Grand Prairie Core #3 (from Spackman et al., 1974) and the partial pollen stratigraphy of Grand Prairie Core #2. There is little evidence of tree or shrub contributions to the peat deposit in this area where houses never existed.
TI3 was cored in 1973; the peat and pollen stratigraphy are illustrated here in Figure 3. The compositional characteristics of the peat beneath TI3 illustrate an upward change from waterlily peat to peat produced by a small woody plant, _Decadon_ (swamp bend-down, a common battery inhabitant), and then shrub peat, which occupies the upper three feet (meter) or so of the peat column. The pollen stratigraphy shows a similar upward change from peat where waterlily pollen are common (both _Nymphaea_ and _Brasenia_), through a zone characterized by battery occupants (in this case _Xyris_ and _Lachnanthes_), and then up to peat dominated by _Cephalanthus_ and _Ilex_. Both peat and pollen characteristics clearly show a progression from open prairie to shrub-covered house. Radiocarbon dates published by Spackman et al. (1974) show that the battery rose about 700 years BP, and that shrubs occupied the surface of the island, producing nothing but shrub peat between 200 and 300 years ago. The fact that it seems to have taken several hundred years for the woody vegetation to establish itself is at odds with observed successional rates. Duever and Riopelle (1984) point out, however, that unknown factors, such as the frequency and effect of fires in the swamp several hundred years ago make it difficult to assess all the implications of the TI3 study. What is clear, though, is that TI3 formed just as Cypert had envisioned.

**Analysis of Tree Island #2**

Tree Island #2 is located in Chesser Prairie, nearly 2.5 miles [4 km] north of TI3. It is smaller than TI3, though its surface stands several inches/cm above water level. The peat at the surface was moist, but was not saturated at the time it was sampled, so small dry _Cyrilla_ leaves and fruits were abundant. At the time it was sampled (mid 1970's) it was covered mainly with _Cyrilla_, though various heaths and _Cephalanthus_ were present. The vine _Smilax laurifolia_ (bamboo vine) was present, and its roots appeared to be an important component of the peat mound.

A core 72 inches [183 cm] long was taken from TI2; Figure 4 shows some of the petrographic components of the peat core, including charcoal, fecal pellets, and sponge spicules. From bottom to top, the core consisted first of fibrous, sandy peat which was overlain by fibrous peat with a piece of _Taxodium_ wood. Above that, the peat was composed primarily of waterlily remains, with prominent layers of charcoal-rich peat at 50.5 to 48.5 inches [128-123 cm]. Highly degraded peat with _Lyonia_ and _Ilex_ wood and the roots of the fern _Woodwardia_ lay at the top.

The pollen/spore stratigraphy of TI2 is shown in Figures 5-7. The succession of pollen producing plants under TI2 began with a zone of aquatic plants between 72 and 54 inches [183-137 cm] depth. _Myriophyllum, Utricularia_, Cyperaceae, and _Nymphaea_ appear there, as well as pollen of arboreal species, including _Liquidambar_ (sweet gum), _Quercus, Pinus_, and _Taxodium_. Because _Utricularia_ and _Myriophyllum_ are most abundant at the base, and because _Taxodium_ rootlets and a large piece of _Taxodium_ wood were present very close to that level, it is probable that the site was occupied initially by a small grove of cypress with deep-water, shade-tolerant aquatic genera growing in the water under the trees. This relationship is common in the swamp today.

A fire and/or drought seems to have destroyed the forest. At 48 inches [122 cm] cypress pollen drops noticeably in abundance and is replaced by pollen of grasses and sedges.
Figure 3. Summary pollen and peat stratigraphy of Tree Island #3. Data were derived from Cohen, in Spackman et al. (1974) and Rich (1984).
Figure 4. Generalized peat stratigraphy of Tree Island 2 (from Rich, 1979).
Figure 5. Partial palynostratigraphy of Tree Island 2 (0-1% range; from Rich, 1979).

Figure 6. Partial palynostratigraphy of Tree Island 2 (0-5% range; from Rich, 1979).
Figure 7. Partial palynostratigraphy of Tree Island 2. (0-5, 0-10, 0-20, and 0-50% ranges and unknowns; from Rich, 1979).
[Poaceae (Gramineae) and Cyperaceae]. The sudden appearance of sedge and grass pollen at this level is consonant with Cypert’s (1972) observation that these plants rapidly occupy sites where swamp fires have burned an area. The post-burn pollen zone extends from 48-24 inches [122-61 cm], and contains pollen from Nymphaea marsh plants (Nymphaea, Compositae, Xyris, and Woodwardia).

The highly degraded peats from 18 inches [46 cm] to the top of the T12 core contain pollen of a rapidly passing battery phase. Degradation and bioturbation were the dominant processes, and there must have been a rapid change from the Nymphaea-sedge marsh to a peat island which was rapidly covered with Cephalanthus, Ilex, and the Ericaceae (including Lyonia and Leucothoe). Among the woody genera, Cyrilla, and the vine, Smilax occupied the house most recently.

To summarize, the succession of environments at the T12 site began with a small grove of cypress which grew in moderately deep water. Submerged and floating-leaved aquatic plants grew beneath the trees. A prolonged period of dryness and intermittent fires destroyed the cypress trees, and the site was occupied by waterlilies, grasses, sedges, and associated plants for a very long time. Eventually, a floating island of peat, or a floating mat of herbaceous vegetation occupied the site. The surface of that battery was covered rapidly with shrubs and woody vines as the tree island took over the site.

Analysis of Chesser Narrows Tree Island

Among all the tree islands which have been studied in the Okefenokee Swamp, this is the only one that has been analyzed stratigraphically (Rich, 1979) and by tree ring analysis (Duever and Riopelle, 1984). The following discussion contains a combination of interpretations based on both methods.

Four peat cores were taken in and near the Chesser Narrows tree island, a large stand of cypress lying at the constriction in the marshland which separates Chesser and Grand Prairies. The four cores constitute a transect of the island, and were taken to determine the subsurface extent and thickness of the forest peats of the island.

Core CN1 was taken in the prairie west of the island. The site produced 88 inches [223 cm] of sediment. Cypress wood with clayey sand filled the 88-82.5 inch [223-209 cm] segment; that was also the horizon with the most sponge spicules (Figure 8). Fine, dense, fibrous, woody, mottled peat, rich in charcoal lay between 82.5 and 69 inches [209-175 cm]. Between 69 and 0 inches [175-0 cm] the peat consisted primarily of light brown, compact, finely fibrous Nymphaea peat. Numerous charcoal bands were scattered through that section of the core, though charcoal was noticeably abundant between 84-66 inches [213-168 cm], and was concentrated at 36 inches [91 cm].

The palynological composition of CN1 is dominated by aquatic genera throughout the core (Figures 9-11). Nymphoides, Sagittaria, Utricularia, Woodwardia, Xyris, Cyperaceae, Poaceae (Gramineae), and Nymphaea are common. Arboreal genera are abundant and evenly distributed (e.g., Quercus, Pinus, Taxodium, Carya, Liquidambar) and shrub pollen, especially pollen of entomophilous (insect pollinated) plants is uncommon or absent (e.g., Ericaceae, Ilex, and Cyrilla).

The succession of habitats at CN1 was fairly simple. Early in the swamp’s development the site was near to or inhabited by
Figure 8. Peat stratigraphy of Chesser Narrows 1 (CN1; from Rich, 1979).
Figure 9. Partial palynostratigraphy of Chesser Narrows 1 (0-1% range; from Rich, 1979).

Figure 10. Partial palynostratigraphy of Chesser Narrows 1 (0-5% range; from Rich, 1979).
Figure 11. Partial pollen stratigraphy of Chesser Narrows 1 (0-5, 0-10, 0-20, 0-45, and 0-75% ranges; from Rich, 1979).
a cypress grove. The low abundance of pollen from floating-leaved and submerged aquatics in the lower 17 inches [43 cm] of the core, and the abundance of charcoal in that interval suggest that the site of the forest underwent a long period of intermittent dryness which, perhaps, was responsible for the destruction of the cypress forest. A marsh replaced the forest and has continued to be the principal peat-forming community at CN1.

Core CN2 was a shorter core taken adjacent to CN1. The coring could not be completed at that location because the core tube encountered a buried cypress log (?) or stump at 65 inches [165 cm]. The section which was retrieved was prepared and analyzed, however, and its stratigraphy was the same as that of CN1.

Core CN3 was taken in the shrub fringe on the west side of the tree island. The core was 72 inches [183 cm] long. From 72 - 49 inches [183-124 cm] the peat was poorly consolidated and coarsely fibrous. It was too sandy below 60 inches [152 cm] to prepare thin-sections, but a piece of Taxodium wood was found at 67 inches [170 cm]. From 60 - 18 inches [152-46 cm] the peat was composed almost entirely of waterlily rootlets and leaf debris, though Taxodium rootlets were present. The latter were, in all likelihood, intruded from trees growing on the island at the time coring took place. A piece of cypress wood lay at 44 - 42 inches [112-107 cm]. The upper 12 inches [30 cm] of peat contained Woodwardia remains, and, though highly degraded, had the characteristics of shrub peat.

Though the pollen stratigraphy of CN3 was not determined, the peat stratigraphy makes it clear that a grove of cypress trees first inhabited the site. Following its destruction by fire and/or drought, and subsequent flooding of the area, waterlilies occupied the site and remained the most important peat-forming plants for most of the time that deposition took place at CN3 (Figure 11). Some ferns (Woodwardia) began to invade the site when the 18 inch [46 cm] peat was deposited. The ferns probably grew near the edge of the tree island which was, at that time, slowly expanding outward from its point of origin nearby. Eventually the shrubby fringe of the Chesser Narrows house spread over site CN3, and has been the only peat-forming community in recent time.

Core CN4 completed the transect of the Chesser Narrows tree island, but, unfortunately, it was an incomplete core. We tried several times in 1975 and 1977 to obtain a complete core from within the island, but it proved very difficult to get an undisturbed peat profile from the upper 36 inches [91 cm]. That section of the peat deposit is, evidently, very highly degraded and filled with large cypress roots and fallen branches. Duever and Riopelle (1984) make mention of the fact that peat depth probing in this tree island “...revealed much wood at about 1 m within the forest and at 1.5 m in the shrub fringe.” In fact, it was the great size of the cypress trees on this tree island that prompted the latter authors to investigate the island. It appeared that the trees on the island were very old, and that the island would, therefore nicely represent the end member of a successional sequence. We shall return to the results of Duever and Riopelles’ study later in this discussion. The CN4 core did demonstrate several characteristics of the peat beneath the site below the 36 inch (1 m) level, as follows.

Sand from 100-90 inches [254-229 cm] depth and overlying peaty sands could not be observed petrographically, but they did contain some charcoal and woody fragments. Between
90 and 86 inches [229-218 cm] charcoal was prominent in a brown, fibrous peat/sand mixture. Between 86 and 80 inches [218-203 cm] the sediment was loosely consolidated, dark brown, fibrous peat with *Taxodium* wood at 86-83 inches [218-211 cm]. At 84 inches [213 cm] the peat contained a mixture of *Nymphaea* debris and *Taxodium* rootlets. That same general composition persisted up to the highest sample which could be thin-sectioned and observed. Another piece of *Taxodium* lay at 72-70 inches [183-178 cm], while a prominent charcoal band occurred at 66 inches [168 cm]. Charcoal at 66 inches [168 cm] comprised 16.6% of the particles seen in a point count. Sponge spicules were also common in the peat at that horizon, comprising 5.9% of the points counted at 66 inches [168 cm].

The CN4 core was incomplete, as noted, so only half of the history of the habitat successions could be determined by pollen analysis. The palynoflora of the two lowest CN4 samples is that of an open marsh, which is not particularly surprising (Figures 12 and 13). The Poaceae (Gramineae), *Woodwardia*, and *Nymphaea* are all abundant at 96 inches [244 cm], for example. Cattail (*Typha*) rises to sudden abundance at 90 and 84 inches [229-213 cm]. From 84 to 60 inches [213-152 cm] there is a zone where emergent aquatic genera become more pronounced [e.g., *Xyris*, Cyperaceae, *Sagittaria*, Poaceae (Gramineae), Compositae]. Following this interval, the 54-40 inch [137-102 cm] samples contained fewer of the emergent genera, and *Nymphaea* resumed a position of importance. Waterlily is accompanied by the aquatic genera *Brassenia* and *Utricularia* at the top of the sampled section.

*Arboreal* genera (e.g., *Carya*, *Liquidambar*, *Pinus*, *Quercus*, and *Taxodium*) maintain their abundance throughout the core. There is a steady rise in the percentage of *Taxodium*, which probably indicates that the forest near the Chesser Narrows house was growing in size and extent.

The pollen stratigraphy of CN1 and CN4 are remarkably alike, at least as far as they can be compared. Both cores show evidence of initial site occupation by herbaceous vegetation, though there seems to have been a cypress grove at or near the site at a depth of about 70 to 90 inches [178-229 cm] below the surface. Cypress pollen and/or wood at CN1, CN3, and CN4, and a cypress stump or log which is presumed to have been present at that depth at CN2 demonstrate the presence of the trees at that horizon. Charcoal concentrations just above the wood and pollen occurrences, and subsequent reduction in the amount of wood and pollen of cypress indicate destruction of the cypress forest, and its replacement by marsh vegetation. The marsh remained at the site until a tree island was established, perhaps near the center of the existing island, and since that time the cypress trees and their associated fringe of shrubs have steadily expanded outward, and stratigraphically upward.

As stated earlier, Duever and Riopelle (1984) selected the Chesser Narrows tree island for evaluation of the trees by tree ring analysis. The purpose of their study was to use tree ring analysis to determine the ages of the three largest specimens of each woody species on 16 houses. This would permit them to know when each species entered the sere, or successional sequence, and to tell the maximum age of each species on the islands in order to estimate the minimum age of the plant community on each house. What they learned from the Chesser Narrows house is that the oldest cypress tree is 576 years old; a second tree was dated at 373 years. Slash pines (*Pinus elliottii*) ranged in age
Figure 12. Partial palynostratigraphy of Chesser Narrows 4 (0-1, 0-5, and 0-10% ranges; from Rich, 1979).
Figure 13. Partial palynostratigraphy of Chesser Narrows 4 (0-20, 0-50, and 0-65% ranges; from Rich, 1979).
from 62 to 88 years, and a number of smaller trees and shrubs growing under the cypress trees were on the order of 50 years old. Several shrubs growing in the shrub fringe (in the approximate position of core CN3) were dated at between 35 and 48 years. Duever and Riopelle concluded that the interior hardwoods and plants of the shrub fringe probably began growing at about the same time, sometime about 50 years ago. The large cypress trees, however, constituted the oldest trees and the oldest continuously existing tree island plant community that they sampled in Chesser Prairie. The house has probably supported a forest at the Chesser Narrows site for a minimum of 600 years. The cypress grove stands on top of a thick layer of sediment which is filled with logs and stumps, but none of those have been radiocarbon dated, so we can only postulate the true age of the tree island. Tree Island #3, discussed previously, is a relatively modest shrub-covered island which was determined to be about 650 years old (using peat petrology to determine the level at which the island appeared and matching that with 25 radiocarbon-dated horizons). If the Chesser Narrows house actually developed from an earlier shrub-covered island, similar to TI3, and if that shrub-covered island developed along the same lines as TI3, then the house at Chesser Narrows could easily be 1000-1200 years old.

ACKNOWLEDGMENTS

In one way or another, many people helped either with fieldwork or with the synthesis of the information contained in this paper. Much of it came out of my doctoral dissertation, hence the many references to Rich (1979); it was a convenient source of data and the citations were required in order to hold to proper formatting. The GP2 data were gathered while I was a graduate student at Southern Illinois University, whose Geology Department is acknowledged. Other people who have helped over the years include Dr. Arthur Cohen, University of South Carolina, and Dr. Fredric Pirkle, formerly of E. I. DuPont de Nemours and Co. Georgia Southern University is acknowledged for material and financial support of my continuing work in the Okefenokee Swamp, and all the personnel of the Okefenokee Swamp National Wildlife Refuge deserve my special thanks for having always made work in the swamp a true pleasure.

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Top figure - Location of the Okefenokee Basin relative to the Pleistocene shoreline terraces discussed in the text.

Bottom figure - Location of Trail Ridge and the Orangeburg erosional escarpment relative to the Okefenokee Swamp and the Holocene coastline.

Both figures modified from Rich and Pirkle (1994)
QUATERNARY EVOLUTION OF
THE GEORGIA COASTAL PLAIN
AS INDICATED BY
PALYNOLOGY, STRATIGRAPHY, AND AGE OF SELECTED
COASTAL, INLAND, AND MARINE DEPOSITS

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30460-8149

INTRODUCTION
The modern topography and morphology of the Atlantic Coastal Plain of Georgia are to a significant extent the result of fluctuating eustatic sea level throughout the Pleistocene and Holocene. The diverse flora and fauna of the region are also products of the past geological and climatological events associated with these sea level changes. Intuitively it therefore makes sense to approach studies of the region from both biological and geological perspectives. The underlying formational process, i.e., sea level fluctuation, also suggests that the comparison of marine, coastal, and inland deposits is necessary to reach an understanding of the evolution of the region as a whole. The present study uses the applications of radiometric dating, palynology, and stratigraphy and sedimentology to assess Pleistocene and Holocene depositional and botanical changes in the region.

REGIONAL GEOLOGIC FRAMEWORK
Quaternary shoreline terrace deposits lie in bands that are parallel to the modern coastline on the Georgia coastal plain; these relict shorelines are the result of fluctuations in eustatic sea level (Hoyt and Hails, 1967, 1974; Winker and Howard, 1977). The shoreline terrace deposits become progressively younger from west to east, the youngest shoreline being the modern coast. An excellent map of these terrace deposits can be found on the 1976 Georgia Department of Natural Resources publication entitled “Georgia's Coast - Wetlands and Geologic Resources”. The discussion presented here is limited to the three youngest shoreline complexes; these include the Princess Anne shoreline, the Silver Bluff shoreline, and the modern, or Holocene shoreline.

The Princess Anne shoreline complex is considered to have formed during the early Wisconsinan, and these sediments presently have a maximum elevation of 4 meters above sea level (Hoyt and Hails, 1974). In central and southern portions of Georgia, Princess Anne sediments lie along the mainland shoreline just to the west of the prominent coastal marshes; this places them as much as twelve kilometers west of the modern beaches (Hoyt and Hails, 1974). Along the northern portion of the Georgia coastline, Princess Anne barrier sediments constitute the west side of Skidaway Island, where uranium-series dates from corals recovered from a shell bed underlying the southern end of the western half of the island show that the shells were deposited 80,000 years ago (Wehmiller et al., 1997). The

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maximum age of the entire Princess Anne shoreline complex, of which Skidaway Island is a part, can be inferred to be the same (Booth, 1998). Wilmington Island and Whitemarsh Island, both in Savannah, are also part of the Princess Anne shoreline. Some evidence suggests that large former Princess Anne islands may have eroded during more recent Silver Bluff and Holocene time (Hoyt and Hails, 1974).

If one follows the trend of the Princess Anne shoreline southward along the coast, it can be seen that it forms the broad terrace upon which the cities of Darien and Brunswick were built. Further south, St. Marys occupies the Princess Anne shoreline. In spite of the large size of Princess Anne deposits, there are comparatively few sites representing this shoreline that have been studied. One locality that was visited during the 1993 Georgia Geological Society fieldtrip is Reids Bluff, on the St. Marys River just across the river and upstream of the town; the bluff is mapped as part of the Princess Anne shoreline complex by Hoyt and Hails (1967) and the Georgia Geological Survey (1976). A number of radiocarbon dates from cypress wood, *Mercenaria* and *Anadara* shells show that Reids Bluff sediments accumulated at least 25,830 years ago, and date back to 37,395 years BP or greater (Rich and Pirkle, 1993). There is, thus, overlap in the ages of some of the strata from Reids Bluff and those from Skidaway Island (this paper), and it appears that the entire Princess Anne shoreline complex began to form 80,000 years ago and continued to accumulate sediments up into the time that the Silver Bluff Shoreline appeared.

The Silver Bluff shoreline complex probably began to form in the late Wisconsinan, some 40,000 years ago; it incorporates portions of most barrier islands along Georgia's coast (Hoyt and Hails, 1974) and formed at a time when sea level was probably about 1.4 meters higher than at present (Flint, 1971; Hoyt and Hails, 1974). The morphology of the modern coastline is largely a function of the morphology of the Silver Bluff Shoreline complex, and nowhere is this more evident than on St. Catherines Island, where the Silver Bluff and modern shorelines converge.

**STUDY AREAS**

Sediments from various sites were studied in order to determine the nature of plant communities during the Late Pleistocene. Two coastal localities, St. Catherines Island (Silver Bluff and Modern Shoreline) and Skidaway Island (Princess Anne and Silver Bluff), were investigated to determine the age of the sediments, the environments of deposition, and any relationships to other inland and coastal deposits. One off-shore site, Grays Reef, is being studied, and preliminary results are shown here. Grays Reef is located about 32km east of Sapelo Island. Inland sites that have been chosen for comparison with the barrier island localities include Ulmers Pond, in Loundes County, studied by Rich (1996) and the Okefenokee Swamp, also studied by Rich (1979) These localities, along with several other comparable inland localities in Florida, South Carolina, and Georgia are shown in Figure 1.

**PALYNOLOGICAL PROCESSING TECHNIQUES**

Each sample was processed using standard palynological techniques, as outlined by Traverse (1988), which included HF treatment, HCl treatment, and KOH treatment to remove silicates, carbonates, and soluble humic acids, respectively. Microscope slides were prepared
Figure 1. Geographic locations of study areas and selected, comparable localities in Florida, Georgia, and South Carolina.
using glycerine jelly as a mounting medium and were examined at 400x magnification with a Jena research microscope. A minimum of 500 palynomorphs were identified and counted in each sample, a number that is more than ample for a statistically valid count (Rull, 1987). The relative abundance of each taxon was calculated as a percent of the total palynomorphs counted. Dinoflagellates and microforams, the pseudochintinous inner test linings of foraminifera (Cohen and Gruber, 1968) were included in the palynomorph sum. Broken, folded, or badly decomposed palynomorphs were included as "unknowns".

SEDIMENTS OF ST. CATHARINES ISLAND

Selected results of the palynological and radiometric analysis of two sediment cores (CTB and CTH) from the mid-southern portion of St. Catherines Island (at what is known as the Cracker Tom Locality) are shown in Figure 2. A radiocarbon (AMS) date from a dense peat at a depth of over 5m in the CTB core suggests that the Pleistocene core (Silver Bluff) of St. Catherines Island is greater than 40,000 years old (Booth, 1998). Hoyt and Hails (1974) obtained similar infinite radiocarbon age dates for the Silver Bluff shoreline complex from Sapelo Island, although some of their dates were between 25,000 BP and 36,000 BP. The dense peat in the CTB core at the Cracker Tom Locality is palynologically dominated by fern spores, which are probably attributable to Woodwardia virginica (Virginia Chain Fern; Booth and Rich, in press); the abundance of these spores and the nature of other associated plant taxa suggest that the peat was derived from an inland, fresh-water influenced plant community.

An organic rich sand in the CTH core is correlative to the peat in the CTB core; like the peat, the sand is dominated by typical southeastern floral elements although it also contains trace amounts of characteristically northern taxa such as Picea (spruce), Tilia (basswood), Fagus (beech), and Tsuga (hemlock; see Table 1).

The peat and sand are both disconformably overlain by marine sediments, as evinced by marine shells; sediment trapped in these shells also contains a characteristic marine pollen signature (including abundant dinoflagellates) similar to those derived from other marine deposits in the southeast (Rich, 1995).

Table 1 - Plant taxa encountered in the St. Catherines Island CTH core organic-rich sand (559cm depth), excluding Pinus and Quercus.

<table>
<thead>
<tr>
<th>Plant Name</th>
<th>Family</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambrosia</td>
<td>Asteroideae</td>
</tr>
<tr>
<td>Carya</td>
<td>Cheno-Am type</td>
</tr>
<tr>
<td>Corylus</td>
<td>Cyperaceae</td>
</tr>
<tr>
<td>Cupressaceae</td>
<td>Ericaceae</td>
</tr>
<tr>
<td>Fagus</td>
<td>Fraxinus</td>
</tr>
<tr>
<td>Juglans</td>
<td>Liquidambar</td>
</tr>
<tr>
<td>Myrica</td>
<td>Nyssa</td>
</tr>
<tr>
<td>Osmunda</td>
<td>Picea</td>
</tr>
<tr>
<td>Plantago</td>
<td>Poaceae</td>
</tr>
<tr>
<td>Polygonum</td>
<td>Salix</td>
</tr>
<tr>
<td>Sphagnum</td>
<td>Tilia</td>
</tr>
<tr>
<td>Tsuga</td>
<td>Typha latifolia</td>
</tr>
<tr>
<td>Woodwardia-type</td>
<td></td>
</tr>
</tbody>
</table>

A radiocarbon date on an Americardia shell that came from directly above the disconformity in the CTB core indicates that at approximately 4,000 BP eustatic sea level rose high enough to isolate the core of St. Catherines Island from the mainland. The disconformity that is preserved in the two sediment cores therefore spans at least 36,000 years. Since the
Figure 2. Radiocarbon dates and relative abundances of selected pollen taxa encountered in two cores from the Cracker Tom Locality on St. Catherines Island.
mid-Holocene sea level rise, the island has extended southward through the accumulation of accretionary terrains (topographically distinct ridges of sand which have been welded onto the island progressively from north to south; Bishop, pers. com.). Radiocarbon dates from other more southerly localities on the island attest to this north to south progradation (Booth, 1998). A hammock-marsh plant community, dominated by Spartina (saltmarsh cordgrass), chenopods (saltworts), and Iva (marsh elder) in and adjacent to the marshes, and Quercus (oak) on the hammocks, presently occupies the Cracker Tom Locality. This plant community became established in the mosaic of swales and ridges created by the accumulation of accretionary terrains sometime after 3,000 years ago. The colonization of the area by the hammock-marsh plant community is indicated in Figure 2 by the rise in Quercus, Myrica (wax myrtle), Poaceae (grass family), and Cheno-Am type (probably saltwort) pollen.

SEDIMENTS FROM SKIDAWAY ISLAND

Sediments from two excavated ponds at what is known as the Jones Girls Site on Skidaway Island provide a record of past vegetation and geologic events on the island and in the region. As mentioned earlier, corals recovered from a shell-bearing unit indicate that near-shore marine strata on the southern end of the western half of the island were deposited 80,000 years ago (Wehmiller et al., 1997). The palynology of the shell layer and associated strata indicate the presence of a flora similar to that found in coastal Georgia today, i.e., one dominated by Pinus and Quercus (Figure 3), but containing a variety of lowland hardwood, and herbaceous species.

Peat clasts deposited 36,000 years ago were recovered from a channel lag deposit overlying the shell layer at the site. These are also dominated by plant taxa commonly found in the southeast today (Figure 3).

The deposition of the Jones Girls Site peat clasts and strata at Reids Bluff correspond to the time when deposition of strata at more inland sites on the Georgia coastal plain virtually ceased. Thus, there is special significance to these localities when reconstructing Late Pleistocene plant communities is concerned.

SEDIMENTS OF ULMERS POND

Selected palynological and radiometric results of a portion of a sediment core recovered from Ulmers Pond in Loundes County, Georgia, are presented in Figure 4. Peat older than 39,000 BP is characterized by floral elements that are common in the southeast today. This $>$39,000 year old peat is separated from 5700 year old peat by a thin clay and charcoal layer.

The $>$39,000 year peats accumulated in a water lily-dominated wetland. By contrast, the clay and charcoal layer is characterized by abundant Cheno-Am, Quercus, and composite pollen, with no indication of there being wetland conditions. The overlying 5,700 year old peat shows that a fresh water pond, characterized by a dinoflagellate spike in the pollen diagram, was followed by the re-establishment of the fresh water wetland plant community.

GRAY'S REEF SEDIMENT

The Gray's Reef sediment sample was taken from near the surface of a short, shallow sediment core. The sediment was dominated by Pinus and Quercus. High taxonomic diversity, including abundant Alnus (alder) and small amounts of Betula (birch), Fagus, Picea, and
Figure 3. Generalized stratigraphy and selected palynological and radiometric data from the Jones Girls Site on Skidaway Island.

Figure 4. Selected radiometric and palynological data from a portion of the Ulmers Pond sediment core.
Tsuga characterize the sample. Table 2 shows all the taxa encountered in the sample.

Table 2 - Taxa encountered in the Grays Reef sediment sample, excluding Pinus and Quercus.

<table>
<thead>
<tr>
<th>Taxon</th>
<th>Genus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alnus</td>
<td>Ambrosia</td>
</tr>
<tr>
<td>Asteroidae</td>
<td>Betula</td>
</tr>
<tr>
<td>Carya</td>
<td>Caryophyllaceae</td>
</tr>
<tr>
<td>Castanea</td>
<td>Cheno-Am type</td>
</tr>
<tr>
<td>Cupressaceae</td>
<td>Cyperaceae</td>
</tr>
<tr>
<td>Fagus</td>
<td>Fraxinus</td>
</tr>
<tr>
<td>Iva</td>
<td>Liquidambar</td>
</tr>
<tr>
<td>Myrica</td>
<td>Osmunda</td>
</tr>
<tr>
<td>Picea</td>
<td>Poaceae</td>
</tr>
<tr>
<td>Polygonum</td>
<td>Salix</td>
</tr>
<tr>
<td>Sphagnum</td>
<td>Tsuga</td>
</tr>
<tr>
<td>Ulmus</td>
<td>Woodwardiataype</td>
</tr>
</tbody>
</table>

The sediment seems to have been derived from an inland plant community, though some marine influence is evident. Palynologically, this sediment is very similar to the organic-rich sand which underlies the disconformity in the St. Catherines Island CTH core (Table 1).

REGIONAL SYNTHESIS

The disconformity that separates the fern peat from the overlying shell layer on St. Catherines Island represents a depositional hiatus of at least 36,000 years. During that time interval, eustatic sea level dropped to its lowest level in recent geological history, having been at least 80 m below present day sea level (Bloom, 1983). The coast of Georgia was at that time much further east than at present (probably near Grays Reef), and the areas of St. Catherines Island and Skidaway Island were part of the mainland.

The fact that sediments from St. Catherines Island apparently preserve the same disconformity as the one found in many inland lakes (Watts, 1969, 1971, 1988; Watts and Hansen, 1988), including Ulmers Pond means that we have a potentially powerful correlation tool that can be employed over a large geographic area. Furthermore, the disconformity separates strata that accumulated before the Late Pleistocene lowstand from those of the Holocene, so we have an opportunity to reconstruct the terrestrial floras on either side of a very important paleoclimatic time-line.

The presence of the disconformity further substantiates Watts’ (1971) contention that lakes in Georgia and Florida dried up due to a regional drop in the water table, which was brought about by a drop in eustatic sea level. Reduced precipitation may also have played a role in lowering the water table; pollen diagrams from two sites preserving coastal lacustrine sediments in South Carolina [White Pond (Watts, 1980) and Clear Pond (Hussey, 1993)] suggest that for a period of time those areas were indeed more arid than they are now. Between 12,000 BP and 9,000 BP there was a sharp decrease in pine pollen entering the sediments, and an accompanying increase in oak. This is interpreted to reflect increasing aridity. Sediments older that 12,000 years at White Pond and Clear Pond preserve a flora that is very similar to that which is preserved in the Jones Girls Site peat clasts and similar-aged paleosol samples from Reids Bluff (Rich and Pirkle, 1993). None of those samples show indications of a drier climate than now exists in the region.

At Ulmers Pond, the palynoflora of the disconformity itself indicates the presence of the oak-prairie herb plant community that Watts et al. (1992) believe characterized the cold, dry climate of the Late Wisconsin glaciation (Rich,
Typical plants included probable dry-land species (oak and pine) and herbaceous forms (grasses and chenopods or amaranths) that lived on the dried out pond sediments. Above the disconformity at Ulmers Pond, 5,700 year old sediments record a fresh water dinoflagellate bloom followed by the re-establishment of the fresh water pond plant community. The flooding of the Ulmers Pond basin, as well as that of other karst lakes (e.g. Watts, 1971; 1969) occurred as St. Catherines Island and, eventually, Skidaway Island were isolated from the mainland by rising eustatic sea level. A regional rise in water tables caused by rising base level is further indicated by basal peat dates from the Okefenokee Swamp, published by Spackman and others (1974) which indicate that peat accumulation began there about 6,500 years ago.

The position and morphology of Georgia's coastline during the maximum Late Wisconsin glaciation (at the time when inland lakes were drying up) is not completely clear. However, the Woodwardia-dominated peat from the Cracker Tom Bridge core, and the peat clasts from the Jones Girls Site show that organic sediments were being deposited at what were inland localities at that time. The sediment sample from Gray's Reef also apparently accumulated within an inland plant community. Palynologically the Gray's Reef sediment is very similar to the sand underlying the disconformity in the Cracker Tom Hammock core.

CONCLUSIONS

The results of our work show that regional and local plant communities responded to the dynamic climatic and geologic changes that characterized the Late Pleistocene and Holocene on the coastal plain of Georgia. On a regional level, before the maximum southerly extension of the North American continental ice sheet, the flora was quite similar to today's. This is demonstrated at the many sites that have produced samples from below the disconformity.

Spruce (Picea) macrofossils, including 21,300 year old cones have been reported from Andersonville, Georgia, (Cofer and Manker, 1983). Those fossils, as well as the pollen diagrams from Florida lakes (Watts, 1975; Watts et al., 1992; Watts and Hansen, 1994), and from the disconformity at Ulmers Pond (Rich, 1996a) all suggest that the current flora of coastal Georgia did change for several thousand years during the Wisconsin maximum. This would have been the time when alder and birch grew in the vicinity of Grays Reef. Whether taxa that are spatially separated today grew contemporaneously on the coastal plain, (i.e., Taxodium growing alongside Tsuga), is unclear. It is also unclear as to what extent the presently submerged regions of the coastal plain, east of the modern coastline, acted as a refugium for coastal plain plant species during the coldest periods of the Late Pleistocene.

By the time sea level returned to near its present level in the mid-Holocene a flora similar to today's, dominated by Pinus and Quercus on the uplands, and Taxodium, Nymphaea, and Nyssa in the lowlands was re-established on the coastal plain. The St. Catherines Island and Ulmers Pond sediment cores, as well as the numerous cores taken from the Okefenokee Swamp (Spackman et al., 1974) record the uniform regional presence of this flora since about 4,000 BP (the time of the Holocene transgression on St. Catherines Island).

The significance of the regional disconformity which characterizes the Late
Pleistocene-Holocene transition in coastal Georgia has yet to be fully appreciated. Unfortunately, there are essentially no palynologically analyzed sediments from inland portions of the Georgia coastal plain that represent the Wisconsin glacial maximum. The vast amount of lost record represented by the disconformity, which spans at least 36,000 years, is astounding and raises many tantalizing questions regarding the paleohydrology, paleoecology, and paleoclimate of the region during the Late Pleistocene lowstand.

ACKNOWLEDGMENTS

We wish to thank Dr. Gale Bishop, Department of Geology and Geography, Georgia Southern University, for his generous help in recovering cores from St. Catherines Island. Mr. Royce Hayes, Superintendent of St. Catherines Island is similarly recognized. Dr. Jim Henry, Director of the Applied Coastal Research Laboratory on Skidaway Island, and Dr. Reid Bohne, Director of the Grays Reef National Marine Sanctuary have our gratitude for providing samples from the reef. Mr. Sonny Jones, owner of the Jones Girls Site permitted us to collect from his property. Drs. Helaine Markewich and Jack McGeehin, U.S. Geological Survey generously provided support for some of the radiocarbon dates.

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WEB RESOURCES FOR HEAVY MINERAL SANDS:
A Model for Relevant Science Education

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Because of the regional significance of the potential mining of the Trail Ridge deposit by Dupont, we designed and used an Internet exercise based largely upon web resources, and implemented through the vehicle of role playing for our students in Physical Geology, Earth Science, and Geology of Georgia. That exercise is presented below and followed by an annotated list of web resource sites useful in completing exercises such as this. The exercise itself, although timely and now apparently obsolete, serves to show one technique for integration of locally relevant geological problems into traditional curricula using emerging electronic technologies (Bishop and Marsh, 1996).

GEORGIA QCC OBJECTIVES
The teaching of public K-12 school courses, including science, in Georgia is guided by a series of teaching objectives known as the Georgia QCC (Quality Core Curriculum) objectives, these are assembled into teaching strands (topical sequences of content) by grade level. As teachers move through their respective curricula, they are expected to have taught each of the QCC objectives for their content area and their grade level during the year, and where appropriate, to have reiterated and reinforced as many QCC Objectives as is feasible.

The exercise below allows the teacher to address multiple QCC Objectives in a student-centered activity which is based on a real-world problem of considerable significance utilizing a high-interest teaching mode, the Internet. We feel the result of exercises such as this models life-long self-learning techniques; the goal of many educators.

THE INTERNET EXERCISE
Geology 555/755: Earth Science
Internet Exercise 5
Name: Xxxxxxxxxxxxxx
Due Date: March 3, 1998

In Earth Science you have studied Earth Materials including Minerals and Rocks, Earth Processes, and Economic Products. In this exercise you will role play as a geological employee of Georgia Economic Minerals, Inc. Your assigned task is to write a short technical memo for your company on the "Origin, Dispersal, and Concentrating Mechanisms for Titanium oxide minerals in Coastal Plain Sediments of Georgia."

This short technical report should be no longer than five double-spaced pages, 12 point font, and margins of 1.0 inches on all sides.
Major sections we expect to see are:

**Abstract** (250 word linear summary of the content of your memo)

**Titanium** (What is it? Position on Periodic Chart? History? Use?)

**Common Titanium Minerals** (Relate to St. Catherines sand samples & DuPont Product samples)

**Origin of Titanium Minerals** (specifically in Georgia) Related to Origin of Granite and Saproilite Exercises

**Dispersal Mechanisms** (How are these minerals liberated and transported?)
Relate this to Physiographic Provinces, the Rock Cycle, and the Saproilite Exercise. Did you see the little black grains in the sand as you decanted your saprolite?

**Concentrating Mechanisms** (Processes sort and concentrate Ti minerals?)
Relate to Physiographic Province, Rock Cycle, “Geology of Georgia” The Backbeach

<http://www2.gasou.edu/geol/8.4FTBB.html>
and “Sand Activities”
<http://www2.gasou.edu/geol/8.8bFTA2.html>

**Probable Distribution** of Ti Deposits on the Georgia Coastal Plain.

**Bibliography** (Names and URLs of web sites; also cite any Books and Papers)

Access an Internet Browser and perform a search for “Titanium.”

How many sites have been identified? ______

Use the “Go To Location” function and look at these specific sites for information about titanium:

**Materials Home Pages**
http://me.mit.edu/2.01/Taxonomy/html/Materials.html

**Britannica On-Line “ilmenite”**
http://www.eb.com/cgi-bin/g?keywords=ilmenite

**Web Elements**
http://www.shef.ac.uk/~chem/web-elements/nofr-biol/Ti.html

**Mining the Okefenokee**

Cite all your sources of information see **Copyright** at ftp://ftp.loc.gov/pub/copyright/circs/circ01.html

Any copied material must be placed in quotation marks and cited as to its source.

All essays completing this exercise must be e-mailed from the student’s own e-mail account.

Please identify yourself by including a memo header, as below:

To: Dr. Gale A. Bishop
From: Your Name
Subject: Internet Exercise 5
Date: March 3, 1998

E-mail your essay to me at:
<gabishop@gsu.edu>
and copy to Nancy at:
<nmarsh@bulloch.com>

Print out a hard copy of supportive materials and the final report for insertion in your Class Notebook’s Internet Section

*************************************************************

Hint: Compose your essay on a word processing program. When finished, select all
the text in your essay, then copy your text into the body of the e-mail message.

CONCLUSIONS
The exercise presented above has been assigned to students in three classes with a wide spectrum of results. Natural history-based exercises, such as the one presented, are easy to generate for use in class. They provide an opportunity to capture the teachable moments provided by real-life situations. Unlike “canned” exercises from laboratory manuals, they provide the science educator with the opportunity to customize their curriculum with high interest, relevant exercises while integrating national, state, and local standards into the lessons. The integration through emerging technologies of library and Internet resources with science, mathematics, and language arts allows the leveraging of a holistic learning experience into the curriculum (Bishop and Marsh 1995a, 1995b, 1996, 1998a, 1998b; Marsh and Bishop, 1994).

ACKNOWLEDGMENTS
The equipment for generating this Internet exercises came from funding partners including: The Eisenhower Higher Education Program (50%), The St. Catherines Island Foundation, inc., The Georgia Department of Natural Resources, Georgia Southern University, the University System of Georgia Office of Information and Instructional Technology, The Turner Foundation, and the JST Foundation. Developmental work was done at Georgia Southern University’s “Crab Lab” and student exercises were piloted from computers in the Earth Science Computer Applications Laboratory (ESCAL) and the Portal Computerized Science Classroom.

SELECTED ANNOTATED WEB RESOURCES

Australia’s Mineral Industry
A general site with a description of occurrence, mining, and uses of heavy minerals linked to numerous other Australian sites.

British Columbia Mineral Deposits
Marine Placers
http://www.ei.gov.bc.ca/geosmin/metalmin/mdp/PROFILES/C03.htm
Technical site maintained by Bristish Columbia to summarize “Deposit Profiles” of various mineral deposits of the Province.

CSIRO Minerals
This Australian research organization has an extensive web site detailing many aspects of research and development.

Encyclopedia Britannica
http://www.eb.com/
A searchable commercial site which includes a wealth of encyclopedic topics linked by key words.

Georgia Environmental Protection
Georgia DNR
http://www.ganet.org/dnr/environ/

Georgia’s Quality Core Curriculum
http://admin.doe.k12.ga.us/gadoe/qcc.nsf
This Georgia Department of Education site allows Internet access to the teaching objectives in the Ga. Quality Core Curriculum. The site is searchable by various criteria.
Idaho State University
Radiation Information Network
http://www.physics.isu.edu/radinf/index.html
A site about radiation and radiation professions with lots of links.

Iscor Heavy Minerals Project
http://www.iscorltd.co.za/ihm/Welcome.html#Project information
A holistic South African site detailing the mining of heavy mineral sands with sections on background, scope, social issues, location, environmental issues, and communications sections.

Mineral Sands
A good content site that summarizes the occurrence, distribution, and mining of Australia’s mineral sands. The site has a nice time line summarizing history of heavy mineral sand development and information on chemical processing, statistics, and properties of titanium. A feed back form is provided. The site is a little frustrating because it lacks a linear forward mode, users have to return to the home page to access subsequent pages.

Mineral Sands
adapted from Nuclear Issues Briefing Paper 25
This site presents information on radioactivity of heavy mineral sands.

Mining the Okofenokee ©1998
Savannah Morning News
http://www.savanews.com/stories/122996/more info.html
A news site established to filter information about the Dupont proposal to mine Trail Ridge. This site has some clever animated diagrams which load and run as slide shows

National Uranium Resources Evaluation (NURE)
http://edcwww.cr.usgs.gov/glis/hyper/guide/nu re
Site with information on the National Uranium assessment and resulting products.

Radioactivity in Nature
http://www.sph.umich.edu/group/eih/UMSCH PS/natural.htm
An extensive site detailing natural sources of radiation, including mineral sands.

South Africa - Mineral Sands
http://mbendi.co.za/indy/mining/mingsa06.htm
A premier web site with a well organized structure and tremendous content covering African Mining Industry. Lots of statistics and detail of processes and mines.

St. Catherines Science Education Model
http://www2.gasou.edu/geog/webconf.html
A summary of the St. Catherines science education model presented as a web-based presentation. Details of our educational collaborative, the use of emerging instructional technology, and the Model.

Technologically Enhanced Normally Occurring Radioactive Material
http://www.normis.com/nindex.htm
An extensive site detailing naturally occurring radioactive materials.

USGS Eastern Mineral Resources
http://minerals.er.usgs.gov/emrst/offshore/grap h1.html
A site which illustrates a submarine heavy mineral deposit on the Georgia continental shelf in a graph of induced polarization.
USGS Terrestrial Gamma Radioactivity
A site with a gamma radioactivity map.

WebElements
http://www.shef.ac.uk/~chem/web-elements/
A chemistry site with a front end periodic table allowing access to details about each element. Click on Ti and receive key data, history, electronic information, and a wealth of other information.

Western Australia’s Titanium Industry
A very compact site with a summary of origin, concentration, and mining of mineral sands with several nice photographs which can be enlarged.

Selected References
DUPTON'S TITANIUM MINERAL MINING OPERATIONS IN FLORIDA

James F. Renner - Golder Associates Inc.,
3730 Chamblec Tucker Rd., Atlanta, Georgia 30341
Jon A. Samborski and John G. Reynolds - E.I. DuPont de Nemours & Co. (Inc.),
White Pigment and Mineral Products, Florida Plant, P.O. Box 753, Starke, Florida 32091
Ralph F. Mongillo, Jr. - Golder Associates Inc.,
8933 Western Way, Suite 12, Jacksonville, Florida 32256

1.0 INTRODUCTION
Since 1949 E.I. DuPont de Nemours & Company has mined and processed titanium mineral sands on Trail Ridge in northeast Florida. Three mine sites have operated, with two mines still active today (Figure 1, Figure 2). The titanium minerals are used by DuPont as a feedstock for the production of titanium dioxide pigment. DuPont has recently proposed to mine for titanium minerals in southeast Georgia on Trail Ridge near Folkston, Georgia.

1.1 Occurrence Of Titanium Minerals
Titanium occurs naturally in a variety of minerals, including ilmenite (FeTiO3), leucoxene (altered FeTiO3), and rutile (TiO2). Titanium minerals, along with several other minerals (zircon, staurolite, garnet, epidote, sphene, etc.), are commonly referred to as "heavy minerals" because they have a specific gravity greater than quartz. The heavy minerals often are concentrated through wind and wave action in beach sands eroded from igneous and metamorphic rocks. Beach sand deposits can occur inland from the coast where they represent ancient shore lines created and exposed through a series of sea level regressions and transgressions.

Potentially economic deposits of heavy minerals throughout the world typically contain 1 to 10 percent heavy minerals by volume. The Trail Ridge deposit being mined by DuPont in Florida ranges between 1.5 to 4 percent heavy minerals. Ilmenite is the dominant titanium mineral at Trail Ridge and in many other heavy mineral deposits. Ilmenite is the most common titanium mineral but has the lowest TiO2 content, typically ranging from 50 to 60 percent. However, in a few cases, the TiO2 content can be as high as 64 percent due to intense weathering, such as has occurred in the Trail Ridge deposit in northeast Florida and southeast Georgia. Trail Ridge is one of the few known deposits in the world containing economic concentrations of this high quality ilmenite.

Lower quality titanium minerals are mined in other locations throughout the world. Notable operations can be found in Australia and South Africa. Several other heavy mineral deposits are found in politically or economically unstable areas. In the United States, only DuPont and RGC, an Australian-owned company, are actively mining titanium minerals.

1.2 Uses For Titanium Minerals
The major use for titanium minerals is as a feedstock to produce titanium dioxide (TiO2). Titanium dioxide is a non-hazardous, chemically stable and weather resistant material used as a white, bright pigment in paint, paper, plastics, fibers and numerous other products. It is an opacifier, providing hiding power to these products, for example allowing paint to cover over a previous color in a "one-coat application". Prior to using titanium dioxide, lead was a widely used white pigment and opacifier. TiO2 replaced lead and provided substantial societal benefit by reducing the health hazards associated with

Figures 1, 2, 5, 6 & 7 are in map pocket in back of guidebook.
lead-based paints. Some TiO₂ is used in cosmetics, sunscreens (a major UV-blocking ingredient), and food products. None of the material mined by DuPont is used in the production of titanium metal alloys.

1.3 Uses For Other Mineral Products
In addition to ilmenite, commercially valuable minerals in the Trail Ridge deposit include zircon and staurolite. Zircon is a zirconium-silicate mineral used in the foundry, ceramic and refractory industries. In foundries, zircon is used to make the molds for high temperature castings. It is chemically inert and stable at high temperatures; and its well rounded grains make it ideal for precision metal castings such as aircraft turbine blades, pump shells, etc. In the ceramic industry, zircon is used as an opacifier in china and toiletry uses. In the refractory industry, zircon is used to make high temperature bricks and linings for furnaces and steel making.

Staurolite is an iron-aluminum-silicate mineral used in abrasive cleaning and cement. The grains of staurolite are hard and angular which makes it very effective as an abrasive agent in sand blasting. In fact, in many applications it is superior to using quartz (with its possible health hazards from respirable silica) since staurolite is low-dusting and recyclable. Staurolite is also an additive in the manufacture of cement.

1.4 History Of Titanium Mineral Mining In The Southeastern United States
The valuable black sands containing titanium and other heavy minerals were first noticed by Henry Buckman and George Pritchard along the beach near Mineral City, Florida in 1916 (Martens, 1928). Martens also examined heavy mineral concentrations at St. Simons Island, Georgia; and Kingsley Lake, Eau Gallie, Venice, Crooked Island, and Cape San Blas, Florida during his reconnaissance in 1927. Production from the Mineral City deposit began in 1916 (Calver, 1957). Ilmenite was first used in the manufacture of titanium tetrachloride which became important in the production of tracer bullets, smoke screens and spotting shells during World War I. Mineral City ilmenite production continued until 1929. The mined lands were developed residentially and sold in 1942 by the Ponte Vedra Company. The present day Ponte Vedra Country Club and golf course are located on the mined out portion of the Buckman and Pritchard property.

In 1940, the Riz Mineral Company of Florida started a mining operation on beach sands in Brevard and Indian River Counties, Florida (Elsner, 1997). In 1944, they began mining an older sand dune complex just north of Vero Beach, Florida. Hobart Brothers also operated a mine near Vero Beach during the 1956-1963 period (Garner, 1978). In 1943, the Rutile Mining Company of Florida, a subsidiary of Titanium Alloy Manufacturing Company, began mining a dune ridge complex in Duval County, Florida, midway between Atlantic Beach and Jacksonville. In 1944, Humphreys Gold Corporation made improvements to the mine and operated it until 1964. The Arlington mine is now the site of the Regency Square Mall in Jacksonville.

In 1947, Bob Spencer, a mining engineer with the U.S. Bureau of Mines working in cooperation with the Florida Geological Survey, launched a drilling program on a stabilized dune ridge in northeast Florida known as Trail Ridge (Spencer, 1948). Spencer outlined a potential deposit approximately 3000 to 8000 feet wide and 19 miles long in Clay County, Florida, extending from just north of Highland, south to Blue Pond on Camp Blanding Military Reservation. This deposit was later claimed by E.I. DuPont de Nemours & Company. Mining was begun at the Trail Ridge Site in 1949 by Humphreys Gold Corporation under contract with DuPont.
A second operation was started on the same deposit in 1955 and was named the Highland Site. Both sites were operated by Humphreys until 1958 when DuPont took over the mining operation. In 1993, DuPont began mining on a third portion of the Trail Ridge deposit near Maxville, FL. The Highland Site was shutdown in December 1992, just prior to the startup of the new Maxville Site. Presently, the original Trail Ridge Site and the Maxville Site are still operating.

In 1964, Humphreys Gold Corporation opened a mine just east of Folkston, Georgia and operated it under contract for DuPont until 1980 when the reserves were depleted. Presently, the reclaimed mine site is used as a commercial pine plantation, residential and recreational property, and the site of the new D. Ray James State Prison. Humphreys also mined a small deposit just south of the St. Marys River near Boulogne, Florida during this period.

In 1972, a mine was opened near Green Cove Springs, Florida, by a group known as Titanium Enterprises, a joint venture between Union Camp Corporation and American Cyanamid Corporation (Garnar, 1971). The mine stopped operating in 1978 and was later sold to an Australian company, Associated Minerals Consolidated, who began mining on the same deposit in 1980 (Samborski, 1983). Associated Minerals was later bought out by another Australian Company, Rennison Goldfields Consolidated (RGC). Presently, the RGC mine is still in operation.

2.0 GEOLOGY

2.1 Physiography And Geomorphic History
The landscape of the coastal region of southeast Georgia and northeast Florida is characterized by a series of relatively flat terraces, ridges and scarps, dissecting stream valleys, ancient and modern aeolian dunes, and karst areas. The step-like pattern of terraces and ridges descending from the interior to the coast is derived from a succession of ancient coastlines developed during stands between rising and falling sea level. The exact location and form of current landscape features reflect the primary deposition (e.g. barrier island vs. back marsh) and subsequent uplift, erosion, fluvial and aeolian deposition, and karstification.

2.1.1 Trail Ridge  DuPont's mines occupy a portion of Trail Ridge, a linear sand ridge that parallels the Atlantic coast, extending northwesterly from the Interlachen Karst Highland near Starke, Florida to the eastern edge of the Okefenokee Swamp and then north northeasterly to the Altamaha River near Jesup, Georgia. Trail Ridge is 130 miles long and one to two miles wide. There are two major breaks along its length: one on the Georgia-Florida border where the St. Mary's River forms a sharply incised valley as it cuts eastward through the ridge, and another north of the Okefenokee Swamp where Trail Ridge becomes relatively indistinct over a broad area where it is broken by the Satilla River.

Trail Ridge is generally the divide between the Atlantic and Gulf drainages, but because of the breaks in the ridge at the St. Marys River and the Satilla River the actual divide is often west of the Ridge. In fact, in Georgia the Atlantic-Gulf drainage divide occurs partly in the Okefenokee Swamp, since both the St. Marys River and the Suwannee head in the Okefenokee.

In general, Trail Ridge and the adjacent terraces lose elevation from south to north. Crest elevations fall faster than surrounding terrace elevations, so Trail Ridge becomes less pronounced from south to north. In Florida, crest elevations are around 240 to 250 ft. at the Trail Ridge Mine, with the terrace to the west averaging 160 to 175 ft., and the terrace to the east averaging 150 to 160 ft. At the Maxville
Mine crest elevations are around 200 ft., with the terrace to the west, the New River Swamp, averaging 140 to 150 ft., and the terrace to the east averaging 80 to 100 ft. East of Trail Ridge in Florida, North Fork Black Creek dissects the terrace down to elevations of 100 to 50 ft. On Trail Ridge near Folkston, Georgia, the crest elevation is fairly uniform, around 145 to 150 ft., but high and low crest elevations occur within 3.5 miles of each other on the southernmost portion of DuPont’s proposed Folkston project site (175 ft. and 137 ft.). The Okefenokee terrace west of Trail Ridge in Georgia, occupied by the Okefenokee Swamp, is at an elevation of approximately 110 to 120 ft., while the terrace to the east, the Duval Upland, is at an average elevation of approximately 70 ft. Spanish Creek and St. Marys River have eroded through this eastern terrace to elevations from 55 to 10 ft.

In general, Trail Ridge in Georgia has a higher water table than in Florida, as evidenced by more extensive and abundant wetlands. Additionally, Trail Ridge in Georgia is more highly dissected by intermittent drainageways on its west flank than it is in Florida.

Trail Ridge is an ancient shoreline feature, initially formed as a complex of barrier island, beach ridge, and inland dunes that have been reworked by wind as sea level receded (Elsner, 1997). Huddlestun (1988) assigns Trail Ridge in Georgia to the Waycross Terrace, although in Florida it has been described as part of the Hazlehurst or Coharie Terraces. The heavy mineral-bearing sands comprising the uppermost 50 feet of Trail Ridge are most likely reworked from the underlying Pliocene Cypresshead Formation. The reworking of these sands by currents around the north end of the Lake Wales Ridge and formation of the coastal feature that eventually became Trail Ridge occurred during the late Pliocene or early Pleistocene (Pirkle and Yoho, 1970). Some topographic, soil, and drainage characteristics of the west side of Trail Ridge in Georgia are similar to the Ohopee dunes, suggesting that aeolian deposition may have occurred as recently as the Wisconsin glacial episode of the Pleistocene epoch (30,000 to 10,000 years B.P.). Uplift of the southern end of Trail Ridge and adjacent terraces occurred during the Pleistocene and may be on-going. The uplift of 35 to 50 meters apparently is due to rebound as the sediment mass is reduced through karstification (Opdyke et al., 1984).

2.1.2 Okefenokee Swamp In Georgia, Trail Ridge is bounded on the west by the Okefenokee Swamp, an irregularly shaped basin covering approximately 425,000 acres. Most of the swamp is forested or dense scrub. Open water and prairie (marsh) are limited to approximately 60,000 acres (Hurt, 1967). Open water lakes are mostly less than one-quarter mile in diameter, and rarely exceed 6 feet in depth. A series of arcuate, low sand ridges in the interior of the swamp form small upland islands. The Suwannee River exits the west side of the swamp and flows to the Gulf of Mexico. The St. Marys River exits the southeastern corner of the swamp, cuts through Trail Ridge, and flows to the Atlantic Ocean.

On the north and east side of the Okefenokee Swamp, the land and water surface stand at approximately 123 ft. The elevation of the Okefenokee Swamp where the Suwannee River exits is approximately 112 ft. The elevation of the swamp where the St. Marys River exits is approximately 115 ft.

Peat has accumulated in the Okefenokee basin, and the elevations mentioned above refer to the land surface of exposed peat or the level of surface water. The peat ranges from 0 to 14 ft. thick, with variations in thickness due largely to the topography of the underlying sand that forms the floor of the swamp (Spackman et al., 1976).
Hoyt and Hails (1974) and others have proposed that the Okefenokee Swamp represents the back-barrier lagoon on the landward side of the Trail Ridge barrier island. However, peat has only accumulated in the Okefenokee Swamp for the past 7000 years and no salt water plant material is recognized in the peats, so clearly the Okefenokee basin has not been continuously inundated since its formation in the early Pleistocene (Parrish and Rykiel, 1979). More likely, the present day Okefenokee began forming within the last 10,000 years, as rising sea level and a change to a more humid climate took place after the last glaciation. These factors, combined with uplift of the land to the south (Cohen et al., 1984; Opdyke et al., 1984) raised the water table and caused more prolonged inundation, thereby allowing small swamps to enlarge and coalesce as peat accumulated, even further raising the water table. In this scenario, as originally proposed by Veatch and Stephenson (1911), Trail Ridge is only a minor influence on development of the Okefenokee Swamp. The geology underlying the Okefenokee Swamp is uncertain as investigations have focused on the surficial peat (Cohen, 1997).

2.2 Stratigraphy
Pliocene, Pleistocene, and/or Holocene clastic sediments of the Trail Ridge sequence are exposed at the surface on Trail Ridge (Figure 3, 4, 5, 6 and 7). Wells and boreholes commonly penetrate through the underlying Pliocene Cypresshead Formation and Miocene Hawthorn Group and are completed in carbonates of the Eocene Ocala Group or occasionally the Avon Park Formation. These units are exposed at the surface on terraces adjacent to Trail Ridge or in karst areas southwest of the Florida mining operations. In general, the stratigraphy at DuPont’s Florida mine sites is similar to that encountered on Trail Ridge in Georgia.

2.2.1 Avon Park Formation Five borings at DuPont’s Florida mine sites have penetrated the Eocene Avon Park Formation. The Avon Park Formation consists of a lower sequence of dark brown to black porous, firm to hard, fossiliferous dolomitic limestone and an upper sequence of grey to tan, hard to dense, very fine grained, microcrystalline, fossiliferous dolomitic limestone. The top of the Avon Park limestone was observed at a depth ranging between 530 feet bgs and 575 feet bgs. The Avon Park Formation contributes to some of DuPont’s wells accessing the Floridan Aquifer System.

2.2.2 Ocala Group The Eocene Ocala Group is penetrated by at least 11 wells or borings on or near DuPont’s Florida mine sites. The carbonate typically encountered was a white to light tan, very fine microcrystalline, soft to hard, fossiliferous (Lepidoscyclina), and porous limestone. The top of the Ocala Group was encountered at depths between 250 feet bgs at the St. Johns River Water Management District monitoring well station C-451, located southwest of Lake Magnolia, and 471 feet bgs at the DuPont Maxville production well. Therefore, the top of the Ocala Group apparently dips toward the northeast in the vicinity of the Florida mine sites. The thickness of the Ocala Group was approximately 220 feet at three boring locations on the Trail Ridge mine site.

Ocala Group sediments comprise the Floridan Aquifer, utilized by DuPont for water supply.

2.2.3 Hawthorn Group Miocene sediments underlying the Florida peninsula are collectively referred to as the Hawthorn Group. At least 21 borings have penetrated Hawthorn Group sediments at or near DuPont’s Florida mine sites. The early to middle Miocene Hawthorn Group sediments are typically olive-green to gray clay to clayey sand with intermittent lenses of phosphate and
<table>
<thead>
<tr>
<th>GEOLOGIC AGE</th>
<th>STRATIGRAPHY</th>
<th>APPROXIMATE THICKNESS (FT)</th>
<th>LITHOLGY</th>
<th>HYDROGEOLOGIC UNIT</th>
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<tr>
<td>QUATERNARY</td>
<td>PLEISTOCENE</td>
<td>50 TO 125</td>
<td>UNIDENTIFIED MARINE TERRACE AND FLUVIAL DEPOSITS - SAND, CLAY, AND SHELL BEDS</td>
<td>SURFICIAL AQUIFER SYSTEM</td>
<td>SAND AND SHELL DEPOSITS PROVIDE LOCALLY LIMITED WATER SUPPLIES</td>
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<td>PLIOCENE</td>
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<td>CYPRUSHEAD Fm (ORIONNELLE Fm)</td>
<td>20 TO 200</td>
<td>INTERBEDDED PHOSPHATIC SEDIMENT AND CARBONACEOUS SAND CLAY, MARL, LIMESTONE, AND DOLOMITE</td>
<td>INTERMEDIATE AQUIFER SYSTEM AND/OR UPPER CONFining UNIT FOR FLORIDIAN AQUIFER</td>
<td>LOW PERMEABILITY CLAYS SERVE AS THE PRINCIPAL CONFining BEDS FOR THE FLORIDIAN AQUIFER DISCONTINUOUS LAYERS OF SAND, SHELL, AND DOLOMITE DEPOSITS LOCALLY PROVIDE LIMITED WATER SUPPLIES, BOTH ARTESIAN, AND NON-ARTESIAN</td>
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<td>FLORIDIAN AQUIFER SYSTEM</td>
<td>HIGH PERMEABILITY WATER-BEARING LAYERS SEPARATED BY LOW PERMEABILITY LIMESTONE AND DOLOMITE</td>
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<td>700 TO 1,000</td>
<td>ALTERNATING BEDS OF MASSIVE GRANULAR AND CHALKY LIMESTONES AND DENSE DOLOMITES</td>
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<td>LOW PERMEABILITY LIMESTONE AND DOLOMITE</td>
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REFERENCE:
STATIGRAGPHIC COLUMN ADAPTED FROM FOLLOWING SOURCE:
gray sandy limestone. In general, the subdivisions of the Hawthorn Group were not investigated by DuPont. However, the Charlton member of the Coosawhatchie Formation of late Miocene age is described in some logs as an olive-green to cream colored clayey sand with fossiliferous sandy limestone and marl.

The top of the Hawthorn Group has been encountered at depths between 70 feet bgs at the SJRWMD monitoring well station C-451, located southwest of Lake Magnolia, and 143 feet bgs in a boring (TR1Z1FL) in the southern portion of the Trail Ridge mine. The thickness of the Hawthorn Group ranges from 371 feet at the Maxville production well site to 180 feet at well C-451, located southwest of Lake Magnolia.

Water-bearing carbonates of the Hawthorn Group are referred to as the intermediate aquifer by DuPont. Clay strata in the Hawthorn confine the underlying Floridan aquifer and the intermediate aquifer.

2.2.4 Cypresshead Formation Pliocene Cypresshead Formation sediments have been penetrated in numerous wells and boreholes at the DuPont mine sites. The sediments typically consist of fine to coarse sand, olive-green to gray sand to clayey sand with lenses of calcareous fossils and mica flakes.

The top of the Cypresshead Formation in eight borings at the Maxville mine occurred at depths from 70 feet bgs at Maxville FeCL2 Well No. 2 to 40 feet bgs at the Maxville intermediate well site No. 6. The variation in the depth below ground surface at which the top of the Cypresshead was encountered is largely related to the location of the borehole on the crest or the flanks of Trail Ridge. The thickness of the Pliocene sediments ranges from 68 feet at the Maxville Site No. 5 intermediate well location to 30 feet at the Maxville site No. 13 intermediate well.

Clay strata in the Cypresshead Formation are referred to as semi-confining units, since they act as aquitards, restricting vertical groundwater movement and partly confining ground water in the more permeable sand and gravel strata.

2.2.5 Trail Ridge Sequence Undifferentiated Pleistocene to Holocene sediments are exposed on the surface of Trail Ridge. These sediments are not formally defined as stratigraphic units, but DuPont informally refers to them as the Trail Ridge sequence, consisting of an upper sand unit and a lower sand unit. The upper unit of the Trail Ridge sequence is mined by DuPont. The upper unit of the Trail Ridge sequence consists of tan to brown fine to medium grained sand interstratified with organic stained and cemented zones (hardpan). Woody debris is often encountered in the lower reaches of the upper unit of the Trail Ridge sequence. The lower unit of the Trail Ridge sequence is typically described as tan to white very fine to fine grained sand and silt with interstitial clay and clay stringers. Woody debris and peat may occur near the top of the lower unit of the Trail Ridge sequence or underlying it.

On Trail Ridge, the upper unit of the Trail Ridge sequence ranges from 0 to 65 feet thick, with greater thickness at higher elevations along the crest. The average thickness of the upper unit of the Trail Ridge sequence is 35 feet (Pirkle and Yoho, 1970). The contact between the upper and lower Trail Ridge sequence has been observed by DuPont in numerous boreholes on Trail Ridge. On the Maxville site, the contact occurs at depths ranging between 9 feet bgs and 49 feet bgs, depending on the location of the borehole relative to the ridge crest.

The upper unit of the Trail Ridge sequence is
the surficial aquifer at the Florida mine sites. The lower unit interacts with the surficial aquifer, but is referred to as a semi-confining unit since clay strata act as aquitards to more permeable sand strata within the lower unit and the Cypresshead Formation.

3.0 MINE DESCRIPTION
DuPont actively mines at two sites, referred to as Trail Ridge and Maxville. Mining methods are generally similar at both locations, although improvements in dredge operation, mineral processing, reclamation, and water management have been continually incorporated.

3.1 Mining Summary
DuPont mines titanium-bearing sands using wet dredging techniques similar to those employed by other companies throughout the world. DuPont's mining methods generally include the following steps.
- Exploration defines the ore body and a mine plan is developed utilizing environmental and economic constraints.
- The initial dredge pond is constructed and the dredge and wet mill are installed in the pond.
- Water treatment ponds and other support facilities are constructed.
- The area to be mined is prepared by harvesting the timber, removing stumps, stripping and stockpiling topsoil, and constructing temporary stormwater detention berms and ponds.
- The dredge advances into the pond wall, the sand/water slurry is pumped to the wet mill (floating in the pond), the heavy minerals are separated by gravity during repeated passes through spiral separators, and the tailings (quartz sand) are replaced onto the backside of the pond.
- The heavy mineral concentrate is pumped to a stockpile, washed, loaded into trucks, and transported to the dry mill.
- The tailings are contoured, topsoil is replaced, and the mined area is fertilized and seeded with a groundcover.
- Pine seedlings are planted in upland areas and wetland areas are planted with hydrophytic species.
- The temporary berms and ponds are removed.

The mines operate 24 hours per day, 365 days per year. The typical rate of advance is 100-500 acres per year. The pond advances throughout the mine site as the dredge continually removes sand from one wall and the tailings are replaced onto the opposite wall, so except for initial construction, each mining step may be occurring simultaneously on different parts of the mine.

Methods to access areas which are not accessible by the dredge and wet mill, or which present unique topographic or environmental constraints are currently being evaluated. These areas may be excavated with a trackhoe and the sand transported to the dredge/wet mill with trucks or as a slurry.

3.2 Site Preparation
Operation of the mine begins with preparation of the land in the path of the dredge and wet mill. Trees are harvested by the timber owner or lessee. DuPont then removes tree stumps using a trackhoe and bulldozer. The stumps may be sold, used in reclamation, or piled and burned. After the stumps are removed, the upper one foot of topsoil is stripped using pan scrapers. The topsoil is frequently spread onto adjacent mined areas or stockpiled for later application on a reclamation site or may be used to construct temporary stormwater containment berms. If the dredge will be advancing through a wetland area, the wetland is ditched and drained prior to topsoil stripping. If the dredge is advancing into an area not previously flanked by a perimeter containment berm, an additional berm is constructed.
3.3 Dredge And Wet Mill
An electrically powered suction cutter dredge removes sand from the advancing wall of the dredge pond with a rotating cutterhead. The face is either undercut, allowing it to collapse, or bench cut. The loosened sand slurry is captured by a suction pipe nested within the cutterhead and pumped through a floating pipeline to the wet mill. The Maxville and Trail Ridge dredges can pump approximately 2000 and 1100 tons of sand per hour, respectively. The cutterhead is on a boom assembly which swings back and forth in an arc across the face of the advancing wall. Typical arcs are 150-200 feet. Several arcs are made across the advancing face so that the total width of the dredge pond is 800-1000 feet. Swingline cables attached on the port and starboard side at the front of the dredge are reeled in and out to create the swinging action. The swinglines are secured at the sides of the dredge pond using anchors, and the swingline anchors are repositioned as the dredge advances. The dredge is anchored in the pond by one of two long cylinders at the rear called spuds. The main spud is lowered and serves as the pivot point and to push the dredge into the advancing wall. The auxiliary spud is only lowered to secure the dredge when the main spud must be repositioned.

The floating wet mill receives the sand slurry from the dredge and separates the heavy minerals from quartz sand and other material. The wet mill is electrically powered. Rotating screens remove large debris (wood and hardpan) and reject it to the rear of the dredge pond which has already been mined. The slurry is then pumped to the top of the wet mill where it is distributed to spiral gravity separators. As the sand and water flow down the spirals, the heavier minerals migrate to the inside of the spiral. The concentrated heavy minerals are collected through cutters or ports located at the bottom or along the path of the spiral. The collected heavy minerals are sent through several stages of spiral separators to maximize recovery and product quality. The final concentrate is then collected and pumped from the wet mill to the concentrate stacker area. The rejected sand is placed on the back side of the dredge pond with either stackers or a pipeline. The distance from the advancing face to the back side of the dredge pond is typically 800-1200 feet.

The wet mill is anchored in the dredge pond by cables which extend from the corners to the bank. The cables are secured to four anchors along the sides of the pond. Winches on the corners of the wet mill allow the wet mill to move to the port and starboard sides of the pond, and forward as the dredge advances. The wet mill anchors are repositioned as mining advances.

As the dredge advances through the sand, it may also encounter humate-stained zones and organically cemented sands called hardpan. Some of these organics are resuspended as the cutterhead churns the sand so that the dredge pond becomes quite turbid. Organic content can affect the viscosity of the dredge pond water, decreasing the effectiveness of the gravity separation by coating the spirals and plugging pipes. Frequent washing of the spirals with fresh water is required to maintain efficiency. A surfactant (such as NaOH) may also be used to keep the organic material from settling.

Eventually, the dredge and wet mill reach the end of a mining block (typically one mile). At this point the dredge begins a 180 degree turn into the adjacent mine cut, creating a new 800-1000 foot wide mine path parallel to the previous cut. A narrow strip of unmined ground is left between the adjacent cuts to insure that the dredge accesses unmined material and provides space for on-shore equipment and reclamation activities.
Some portions of the deposit may be inaccessible due to their location in an area where the dredge cannot advance or turn around. Also, shallow areas where insufficient water depth exists to float the dredge and wet mill may also be inaccessible. In these areas, heavy equipment such as dozers or trackhoes may be used to excavate the ore, which would then be trucked or pumped to the dredge or wet mill. Temporary pumping of the surficial aquifer may be required in these cases.

The quartz sand and other light material passing through the spirals is collected in the bottom of the wet mill and discharged onto the back wall of the dredge pond. These tailings are discharged aerially through one or two elevated tail stacker booms, or they may be discharged through a land laid pipeline. The tailings slope back toward the pond so that they drain into the pond as they dewater. As the mill advances, heavy equipment traverses the recently deposited tailings to aid in compaction and dewatering. Elevations and drainage patterns are generally restored to approximate pre-mining conditions. DuPont is developing an active Global Positioning System to guide tailings placement and assist in reclamation activities.

The heavy mineral concentrate is pumped from the wet mill through a small diameter flexible pipeline lying on the ground to the stockpile and loading area. An elevated boom discharges the concentrate into a series of stockpiles where the concentrate is allowed to dewater and air dry. Front end loaders access the driest concentrate stockpile to load 20-25 ton trucks, which transport the concentrate to the existing dry mill near Starke or Highland, Florida.

If the concentrate grains are heavily coated with humate (which reduces their response to electromagnetic separation at the dry mill) the concentrate will be washed with a 25 per cent solution of sodium hydroxide (NaOH). This step may be performed at the mine prior to discharge into the concentrate stockpile or at the dry mill. If performed on site, the wash water is recycled in the scrubber, and excess water is returned to the dredge pond.

3.4 Dry Mill
Trucks transport 20-25 tons of concentrate from the concentrate stockpiles at the Trail Ridge and Maxville mines to the dry mills at the Trail Ridge or Highland plant. The dry mills employ a series of electrical and magnetic processes to separate the various minerals in the heavy mineral concentrate. Products include a bulk titanium mineral concentrate (mixed ilmenite, rutile, and leucoxene) and various grades of zircon and staurolite sand. The titanium mineral concentrate is transported by rail to DuPont TiO2 pigment plants throughout the United States. The zircon and staurolite are transported by truck and rail as bagged or bulk products.

3.5 Water Use And Management
The dredge and wet mill float in a 20-25 acre pond. The water in the pond is the natural expression of the water table contained in the surficial sands. It is very similar to a recreation or agricultural pond where water fills the excavated area and reaches equilibrium with the surrounding water table. A very small and localized depression of the water table may occur in the immediate vicinity of the dredge pond as mining advances.

Although the water in the dredge pond is used in the mining process, its recycle maintains the water level in the dredge pond. The dredge and wet mill use and recycle approximately 30-40,000 gallons per minute of dredge pond water to transport and separate the heavy minerals from the lighter weight quartz sand. Most of this water is returned directly to the
pond from wet mill overflows or flows back into the pond from the tailings replacement. Approximately 250-500 gallons per minute of dredge pond water is withdrawn from the pond to transport the heavy mineral concentrate to the stockpile area. This water is usually recycled to the dredge pond although it may also be sent to settling ponds before returning to the dredge pond. Water is also lost from the dredge pond by evaporation, or retention in the tailings. Water is added to the pond from direct rainfall and surface runoff. A small quantity of water (approximately 250 gallons per minute) is brought onto the wet mill for housekeeping and domestic purposes. The source of this water may be treated water recycled from the water treatment system, groundwater from wells in the intermediate or Floridan aquifer, or surface water from natural or excavated systems. Overall, the water balance around the dredge pond allows for a relatively stable water level in the dredge pond.

In areas disturbed by mining, naturally occurring humates and other organics, originally present as stained zones or hardpans in the sediments, may be resuspended. Stormwater on the mine site is retained by berms around the mining and reclamation areas to prevent humate-laden water from leaving the site. Stormwater can be released by permit when it meets stormwater quality criteria established by the regulatory agencies. During dry periods, the stormwater may seep into the ground or evaporate. During wet periods, excess stormwater may accumulate and require pumping to temporary settling basins constructed in previously mined areas. Water from the concentrate stacker area or the dredge pond may be pumped to the temporary settling ponds also. The temporary settling ponds allow suspended humate to settle out in the mining area so that chemical treatment and discharge from the water treatment system may not be required. After several feet of humate has accumulated, the temporary ponds are allowed to dry and compact. Dried humate will not resuspend if the pond is reflooded. The temporary ponds may be utilized for several years and then reclaimed.

Occasionally, too much water may accumulate for the stormwater berms and temporary settling ponds to allow for adequate settling. In these cases, water is pumped to the water treatment system to promote rapid humate settling and discharge of good quality water into local streams. A standard water treatment flocculant, such as 30 per cent ferric chloride or ferric sulfate, is added to the humate-laden water to lower the pH slightly from 4.0-5.0 to approximately 3.8-3.9. The humate rapidly settles and is collected in ponds. The humate may require occasional removal by returning it to mined areas, drying, and incorporating it into the soil. The water from the top of the ponds is decanted and lime is added to raise the pH to 6.0-8.5. Typically, the pH is adjusted to a neutral 7.0. Several small polishing ponds receive the lime-treated water and allow any additional sediments to settle out. Finally, the high-quality treated water is recycled for use in the mining process or released to small streams.

3.6 Reclamation
Much of DuPont’s mined land is owned by commercial timber producers, and the post-mine use is commercial pine production. Exceptions to this land use include wetlands established to satisfy permit requirements or areas maintained for National Guard training or other minor uses. This goal requires that DuPont re-establish a stable land surface suitable to allow the timber companies to plant pine seedlings. In general, timber companies have not encouraged re-vegetation of understory species as these plants compete with pines for limited nutrients. In a small portion of the Maxville Mine, the Florida Game and Freshwater Fish Commission has
suggested that DuPont introduce native plant species that can provide food to bears that may attempt to cross Trail Ridge.

As heavy minerals are separated from the Trail Ridge sand on the wet mill, the unwanted quartz sand is returned to the back wall of the dredge pond by elevated tail stackers or land-laid pipeline. Crawler tractors and pan scrapers contour the tailings to approximate the pre-mine topography and drainage patterns. Also, compaction and dewatering of the tailings is accelerated by the heavy equipment movement. The general ridge profile and drainage basins are re-established although the exact elevation or contour may be slightly different at any single location. DuPont is experimenting with a Global Positioning System (GPS) which will allow more accurate elevation and contour control.

Once the tailings are graded to the desired topography and drainage patterns, approximately one foot of topsoil is spread onto the tailings. The preferred method is to strip topsoil from an adjacent area being prepared for mining, and immediately reuse it in a post-mined area. This helps to promote rapid re-establishment of native grasses and shrubs. Stockpiled topsoil from dikes or other areas may also be used. The topsoil is typically fertilized with 300 pounds per acre of 15-15-15 fertilizer.

Depressions and swales in the graded tailings surface become ponds and wetlands due to the high water table on Trail Ridge. On older portions of the Trail Ridge and Highland Mines ponds are abundant, some of which are more than ten feet deep. Current methods for replacing and grading tailings do not leave behind such deep depressions, and smaller wetlands and shallow ponds develop rather than large deeper water ponds.

Wet depressions on the reclaimed land surface are managed to promote wetland establishment. If topsoil is available from a wetland that is being cleared in front of the mine, the topsoil is placed into the wet depression. Otherwise, these areas receive upland topsoil. Even if wetland topsoil is introduced into a wet depression, the surficial muck and peat will likely have been mixed with mineral soil from other areas so that the soil profile of a reclaimed wetland is unlikely to have a well defined organic stratum (muck or peat layer or an umbric epipedon). If woody debris (stumps and roots) is available from an area being cleared, it may be placed into the wetland in order to promote structural habitat diversity. Native herbaceous hydrophytes voluntarily colonize the depressions, and DuPont typically plants native tree species around the perimeter of the larger wetlands.

Many wetlands that have voluntarily developed in older areas of the mines have a diverse native plant assemblage and appear to be succeeding toward a plant community and hydrologic regime similar to natural conditions. Three areas on the Highland Mine and Trail Ridge Mine were intensively planted in the 1980's to determine the feasibility of wetland re-establishment: Highland North (HLN), Highland 1 (HL1), and State Road 16 (SR16). Subsequent monitoring of water levels, water quality, plant growth, invertebrate and fish populations, etc. indicates
that wetlands have been successfully established. The plant and animal communities contain many elements typical of natural wetlands, but community structure is different as would be expected in an early successional system.

There are two obvious characteristics of wetlands on reclaimed land that are different from natural wetlands: reclaimed wetlands usually have more open water than natural wetlands, and significant organic strata in the soil are absent. Both of these conditions are expected to change over time as emergent and floating leaved aquatic vegetation colonize the sites and contribute to accumulation of a peat layer on the floor of the depression.

4.0 SUMMARY OF DUPONT'S PROPOSAL FOR THE FOLKSTON PROJECT SITE

In the 1970s DuPont began exploring for titanium mineral deposits on Trail Ridge in Charlton County, Georgia. In 1991 DuPont purchased approximately 15,000 acres from Union Camp Corporation, and in 1996 DuPont leased mineral rights on approximately 23,000 acres from Toledo Manufacturing Corporation. The two tracts are managed for commercial pine production and are dominated by slash pine plantation. These two tracts, referred to as the Folkston Site, are contiguous with the eastern edge of the Okefenokee National Wildlife Refuge. However, mining would not occur in the Refuge or in any portion of the Okefenokee Swamp. DuPont estimates that perhaps only one half of the Folkston Site could be mined economically, considering the extent of mineralization and logistical and environmental constraints.

In 1995, DuPont and Golder Associates began an environmental assessment of the Folkston Site, in anticipation of applying for permits from state and Federal agencies. Investigations focused on ground water and surface water hydrology, wetlands, endangered species, archaeology, and air quality. In April 1997, DuPont suspended technical work on the project and entered into collaborative discussions with various stakeholder groups. The purpose of these discussions is to develop a consensus about mining at the Folkston site. As a participant, DuPont is committed to abiding by the consensus decision of the stakeholder group. Options being considered by the group include mining and no-mining scenarios. In September 1998 the stakeholder group agreed to delay investigation of technical issues associated with mining options in favor of vigorously pursuing the no-mining option. DuPont expects that in the near future, collaborative work will focus on developing components of the no-mining option that benefit Charlton County, DuPont, private landowners, the Okefenokee National Wildlife Refuge, and other stakeholders.

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