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COASTAL PHOTOGRAPH BY MILES O. HAYES

The beach at Sitkagi Bluffs, located along the southern margin of the Malaspina Glacier, Alaska, the largest piedmont glacier in the world. Gravel beaches are fairly common along the southern Alaska Coast, although this one is about as coarse-grained as they get. The gravel beaches are there because the numerous glaciers in the area deliver the gravel to the near vicinity of the coast. The Coastal Hero kneeling is Paul Hague and the one standing is Frank J. Raffaldi, Jr. Photograph taken in the summer of 1970.

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ABSTRACT

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Economic mining of heavy-mineral sands has a long history in the Atlantic Coastal Plain. From the early part of the 20th century to date, a total of 11 heavy-mineral ore bodies either have been or currently are being mined in Florida and Georgia. Additional deposits have been lost to mining, primarily due to cultural events, or are waiting future exploitation. These deposits have different origins, as has been seen during recent evaluations of the deposits, some in contrast to conventional depositional models. It has long been believed that deposits formed along shorelines at the height of major marine transgressions, but it is now postulated that some heavy-mineral-bearing sands accumulated on regressional beach ridge plains during periods of temporary stillstands or during slight transgressions that accompanied general marine regressions. Although many deposits might indeed have formed as conventional beach placers, others might have accumulated as deposits associated with fluvial–deltaic regimes or with vegetational baffles. These different origins are reflected in the chemical and physical characteristics of the deposits as well as grain size of the sediment. The relationship of the heavy-mineral mineral deposits (location) to the landforms in the Atlantic Coastal Plain provides insight into the ancient shorelines of the Atlantic Coastal Plain.

ADDITIONAL INDEX WORDS: *Coastal geomorphology, barrier island, shoreline ridge, heavy minerals, delta sedimentation.*

INTRODUCTION

Miles Hayes' work along modern shorelines has important economic implications with regard to accumulations of economic concentrations of heavy-mineral sands. Hayes, and many others, have worked on the depositional systems of shorelines for several decades (Snead, 1982), and the work done within modern coastal frameworks (*e.g.,* Sexton, Hayes, and Colquhoun, 1992; Willis, 2006) has been of considerable significance to our understanding of ancient depositional environments.

Ancient shorelines have been important in the development of the human landscape of the southeastern portion of the United States since the discovery of the Western Hemisphere continents by Christopher Columbus in 1492. Native people have occupied the American landscape for centuries and divided their own land-use habits on the basis of the elevations of local landscapes. Indeed, James Edward Oglethorpe founded his colonial city of Savannah on Yamacraw Bluff, above the Savannah River in 1733 because the presence of a village of Yamacraw people suggested that it was a wise site choice; the bluff's elevation above sea level indicated that it was a suitable location for a settlement. Oglethorpe observed that "The river here forms a half-moon, along the south side of which the banks are about forty foot high, and on the top flat, which they call a bluff. The plain high ground extends into the country five or six miles, and along the river-side about a mile." (Fraser, 2003; Historic Savannah Foundation, 1968). For the purposes of this publication "bluff" is interpreted to mean "a high bank or bold headland" (American Geological Institute, 1984 [now, the American Geosciences Institute]). Whether a particular sandy ridge was of coastal origin or not was of no interest to the settlers, but in subsequent years the practical and economic differences that are represented by the opposing characteristics of uplands (ridges) and marshy lowlands (swales) have come to be appreciated.

Positive landforms (*i.e.* beach or shoreline ridges) develop and exist under depositional conditions different from those of the intervening swales, referred to above. The ridges described in this paper are beach ridges, defined by Snead (1982) as "linear accumulations of coarse sand or shingle on a prograding upper beach. . .Beach ridges may occur singly or in series, the youngest being most shoreward; their heights vary up to 6 meters (20 feet) or so and the ridges commonly survive as a result of vegetational cover or of cementation if the sand is calcareous and the climate warm." The ridges we have worked on are of the former type. Kellam, Mallary, and Laney (1991) describe and illustrate the locations of the many ancient

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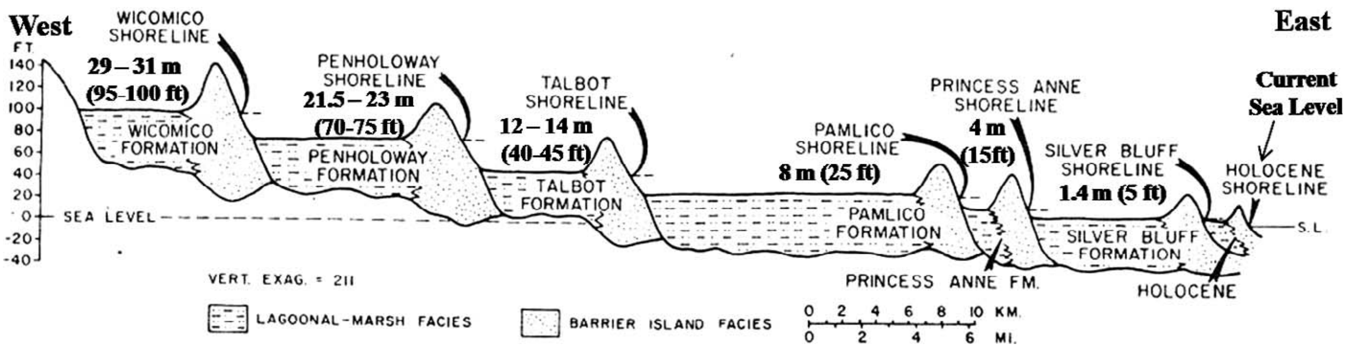

Figure 1. Seven shorelines recognized in southeastern Georgia that contain heavy-mineral deposits, the highest and oldest shorelines being in the west and progressively younger and lower shorelines occurring to the east. Modified from Hails and Hoyt (1969).

shorelines that dominate the Georgia coast, specifically, and they illustrate how those shorelines led to the accumulation of heavy-mineral sand deposits. Markewich, Hacke, and Huddlestun (1992) describe the ridge and swale topography of coastal Georgia, observing that "Each sequence is expressed as a broad trend in a 40- to 80-km wide (25–50 mi), low-altitude, low-relief, topographically "stepped" terrain that lies adjacent and subparallel to the present coast."

Willis (2006) presents a chronological interpretation of what are considered to be interglacial shorelines that lie between Charleston and the Santee River in South Carolina. His study area "…lies within the Lower Coastal Plain, which exhibits a stair-stepped topography consisting of various plains (termed terraces) of roughly similar elevation separated by scarps…." His use of the term terrace differs some from that used in this paper, in that the term in this paper refers to large-scale surfaces that lie east of the Wicomico Shoreline. Thus, terrace, in the context of this publication, conforms to the definition: "a relatively level bench or step-like surface breaking the continuity of a slope" (American Geological Institute, 1984). Snead (1982) defines a terrace as a "... bench more or less horizontal and parallel to the shore related to a higher-than-present stand of sea level...." This paper's focus is on heavy-mineral sand accumulations, as they relate to various shoreline features described here, that lie topographically east of Huddleston's (1988) Okefenokee Terrace. Bartholomew and Rich (2012) relate a complex association of beach ridges and ancient marine terraces to putative structural movements in the southeastern Coastal Plain of the United States, extending from Virginia to Florida.

Heavy minerals (those minerals whose specific gravity exceeds 2.9) are of economic value and, as sedimentary particles, they have particular environments of concentration. Heavy minerals that accumulate in beach, dune, river, and lake environments are of particular interest to sedimentologists who attempt to use heavy minerals to determine the sources of the sediments and the depositional environments (*e.g.,* beach, dune, *etc*., represented by particular deposits). The relationships among the occurrence, location, topographical expression, and depositional environments of heavy minerals and the presence of ancient shorelines along the Atlantic Coastal Plain of the southeastern United States in Florida and Georgia are discussed in this paper.

HEAVY-MINERAL MINING IN THE SOUTHEASTERN UNITED STATES

During the more than 90-year history of heavy-mineral mining from the Atlantic Coastal Plain of Georgia and Florida, ilmenite ($FeTiO_3$), rutile (TiO_2), and zircon ($ZrSiO_4$) have been the most economically important heavy minerals. The titanium minerals primarily are used to manufacture TiO_2 pigments, and zircon is used as specialty foundry sand as well as in the manufacture of refractories, ceramics, opacifiers, zirconium metal, and chemicals.

The deposits containing these minerals are found in beach, bar, dune, and stream sands throughout the region. Lynd and Lefond (1983) state that discrete, sand-size heavy-mineral particles are concentrated by gravity segregation of the chemically and physically resistant grains. Martens (1928) recognized that the higher-specific-gravity minerals were concentrated at the expense of those heavy minerals with lower specific gravity. The environments hosting the deposits can be grouped into fluvial-deltaic, barrier island, or beach ridge sequences consisting primarily of very fine-, fine-, and medium-size sands that were deposited in various relationships to ancient shorelines. Traditionally, the shorelines have been associated with different sea-level high stands that formed marine barrier island/beach ridge complexes, with the highest and oldest shorelines being in the west and progressively younger and lower shorelines occurring to the east (Figure 1). The barrier island/beach ridge complexes are separated by flat, lower-lying surfaces referred to as terraces, as previously described. The terraces are characterized by sediments deposited in a variety of environments including tidal marshes, tidal flats, lagoons, washover fans, intertidal and offshore bars, and lower-elevation stranded barrier islands. Beginning with the work of McGee (1887), most of the major former terrace investigations were reviewed by Hill (1966). Figure 2 shows the physiographic setting of the southeastern Georgia–northeastern Florida Atlantic Coastal Plain along with the locations of major heavy-mineral deposits.

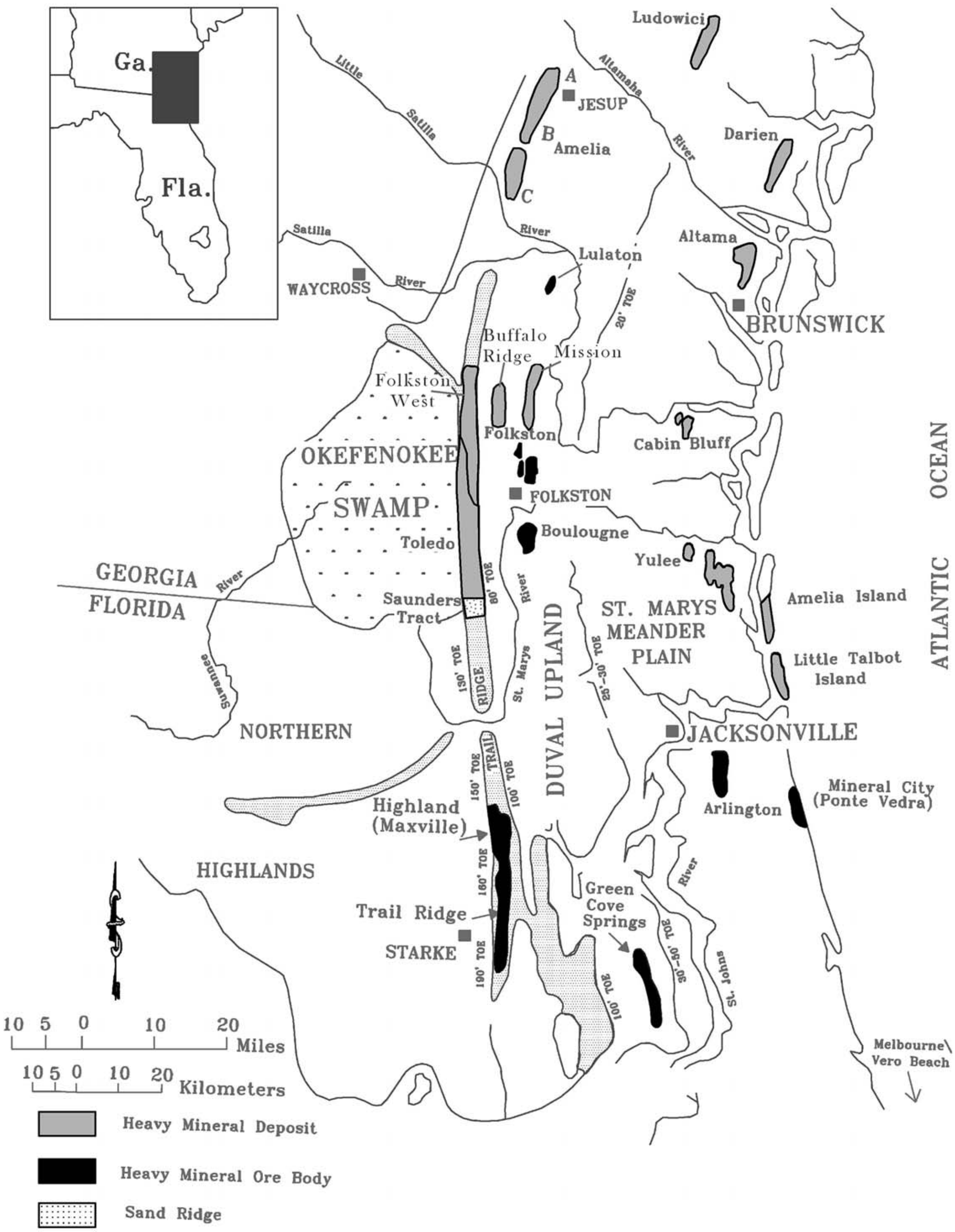

Figure 2. The physiographic setting of southeastern Georgia–northeastern Florida Atlantic Coastal Plain along with locations of major heavy-mineral deposits. Notice Trail Ridge truncates older ridges to the west. Modified from Pirkle, Pirkle, and Reynolds (1991).

In 1983, Lynd and Lefond provided guidelines for what constituted a commercial heavy-mineral deposit in the southeastern United States. At that time an economic heavy-mineral deposit had (1)sufficient reserves to support depreciation over a period of at least 10 to 20 years; (2) a minimum of 1 million tons of recoverable TiO_2; (3) an average heavy-mineral content of between 3% and 4% with a cutoff of 2%; (4) an average TiO_2 content of the raw ore of 1% or a little less and (5) an average ore depth of about 5 m for dredging, with a cutoff depth of 1.5 m. Today, in general terms, companies looking for a new commercial heavy-mineral deposit in the southeastern United States amenable to low-cost (dredge) mining methods desire at least a 10-year mine life and a total reserve of about 150 million metric tons (MMt) of ore at about 2.5% valuable heavy minerals. For higher-cost operations (such as truck and shovel) a total reserve of 22 MMt of ore at 8% valuable heavy mineral is desired. However, David Sleigh (*personal communication*, November 2012) believes that today's description of a commercial mineral-sands deposit must encompass a wide variability in deposit sizes, mineral types, and differing end uses and must take into account many factors including the mining method, depth, slimes, mineral assemblage, and distance from infrastructure (transport and power).

Deposits Exploited, or Lost to Mining, and Potential Future Operational Sites

Over the decades of heavy-mineral mining from Florida to Virginia approximately a dozen heavy-mineral deposits have been or are being exploited (Figure 3). The principal minerals produced at all of the deposits (with one exception) have been titanium and zirconium minerals. The one exception is the production that occurred along Horse Creek in Aiken County, South Carolina, where the principal mineral produced was monazite, a mineral useful in the extraction of rare earth elements (Figure 3).

During the last few decades numerous heavy-mineral deposits have been lost to mining due to cultural or environmental concerns. The mining of heavy minerals competes with a variety of other land uses such as forestry, residential development, and resort development. In the Coastal Plain of the southeastern United States, the competition is particularly strong because of the "Sea Islands" off the Atlantic Coast. The barrier islands from the mouth of the St. Johns River in Florida to the Santee River in South Carolina are generally referred to as the Sea Islands (Fillman-Richards, 1982; White, 1970). Heavy-mineral deposits have been evaluated on Little Talbot and Amelia islands off the Florida coast; Cumberland, Jekyll, St. Catherines, Ossabaw, Skidaway, St. Simons, and Sapelo islands of the Georgia coast; and Hilton Head, St. Helena, St. Phillips, Hunting, Wadmalaw, Johns, Capers, Bull, Edisto, Dewees, Pawleys Island, and Isle of Palms of the South Carolina coast. All of these deposits are lost to mining because islands such as Tybee and St. Simons are largely residential, whereas others such as Cumberland, St. Catherines, and Ossabaw are parks or preserves. Other deposits and properties such as Yulee in northeastern Florida, Cabin Bluff and Altama in southeastern Georgia, and Oak Level near Savannah, Georgia, have also most likely been lost to residential and resort development.

Further inland, the Folkston West deposit was lost to exploitation due to environmental concerns, and the Toledo and Saunders deposits may be lost for the same reasons. These deposits are located on Trail Ridge near the eastern edge of the Okefenokee Swamp National Wildlife Refuge and extend from near Race Pond, Georgia, on the north to state road 94 on the south (Figures 4 and 5).

There are other deposits in northern Florida and southeastern Georgia that might be exploited in the future. In Florida, these include areas along Trail Ridge from DuPont's Trail Ridge and Maxville operations north to Interstate 10, plus an extensive area of the Boulougne deposit not mined earlier by the Humphreys Mining Company. In southeastern Georgia, the potential deposits are known as the Mission, Buffalo Ridge, Darien, Amelia, and Ludowici deposits (Figures 2, 3, and 5). Pirkle, Pirkle, and Pirkle (2007) have described many of the deposits mentioned in this section in more detail.

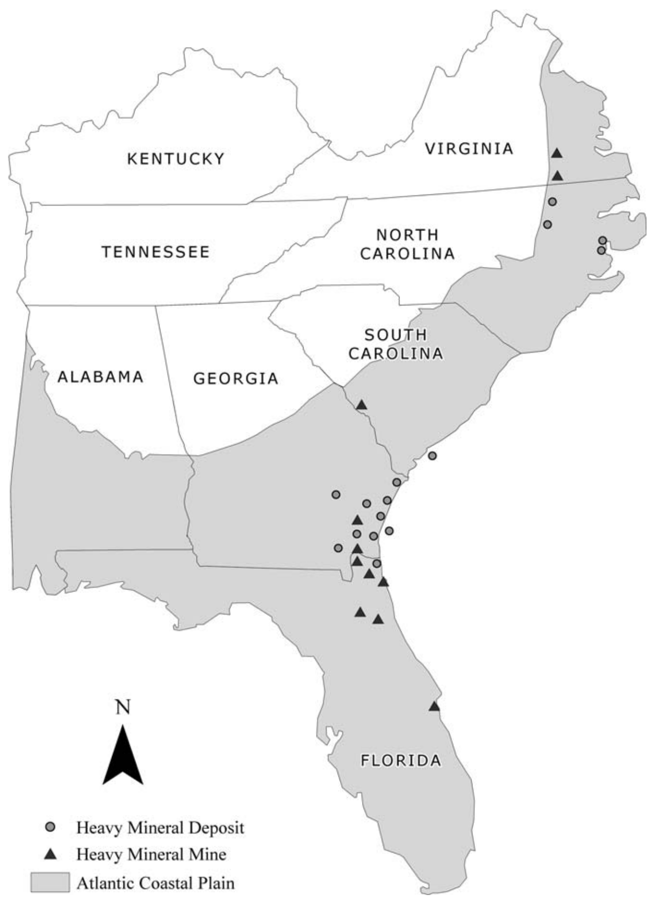

Figure 3. Location of heavy-mineral deposits within the Atlantic Coastal Plain from Virginia to Florida. Modified from Pirkle *et al*. (2007b).

SHORELINES OF THE ATLANTIC COASTAL PLAIN IN THE SOUTHEASTERN UNITED STATES

The manifestation of ancient shorelines, as commonly deduced from the presence of fossils, or anomalous landscape features, has been known among numerous observers for much more than a century. For example, ancient shoreline scarps in Georgia (*i.e*. an erosional feature due to wave action, *sensu* Snead, 1982; similar to beach scarp, *sensu* American Geological Institute, 1984) were recognized by Lyell (1845). Doar and Willoughby (2006) examined geomorphic boundaries of marine Pleistocene terraces (toes of scarps) for the Penholoway terrace in South Carolina and proposed new nomenclature for terraces and scarps of the lower coastal plain, whereas Doar (2012) discussed the Orangeburg and Parler scarps in South Carolina

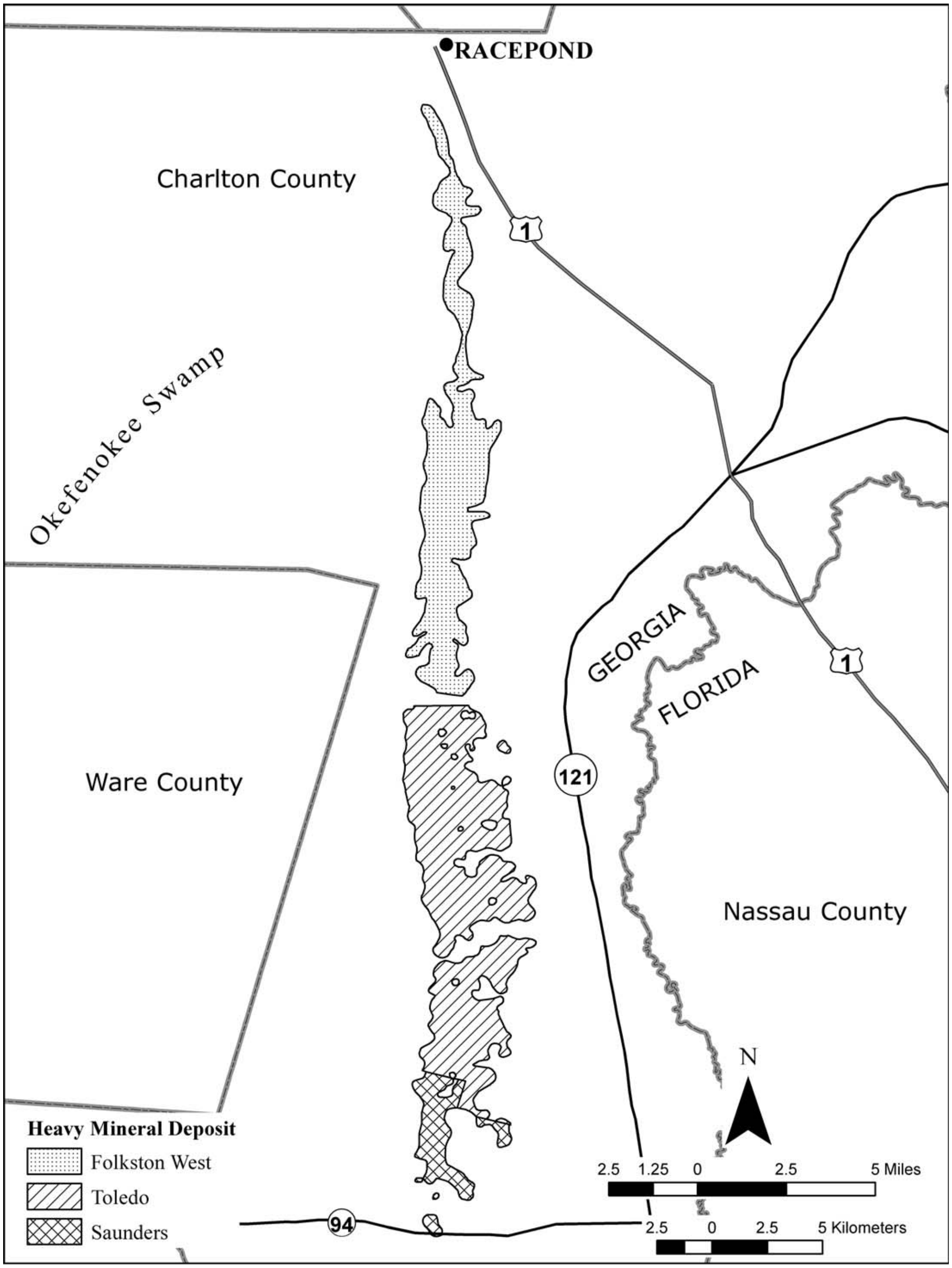

Figure 4. Location of select heavy-mineral deposits located along Trail Ridge in southeastern Georgia.

near the Savannah River. Much earlier investigations of the Chesapeake Bay region were conducted by McGee (1887); detailed studies of the terraces in Maryland were made by Shattuck (1901, 1906); the origins of terraces in North Carolina were investigated by Johnson (1907); the Coastal Plain terraces of Georgia were described by Veatch and Stephenson (1911); and the terraces of North Carolina were studied by Stephenson (1912). Later work includes contributions by Colquhoun (1969, 1974), Colquhoun and Pierce (1971), Cooke (1925, 1931, 1932, 1936, 1941, 1943, 1945, 1966), Doering

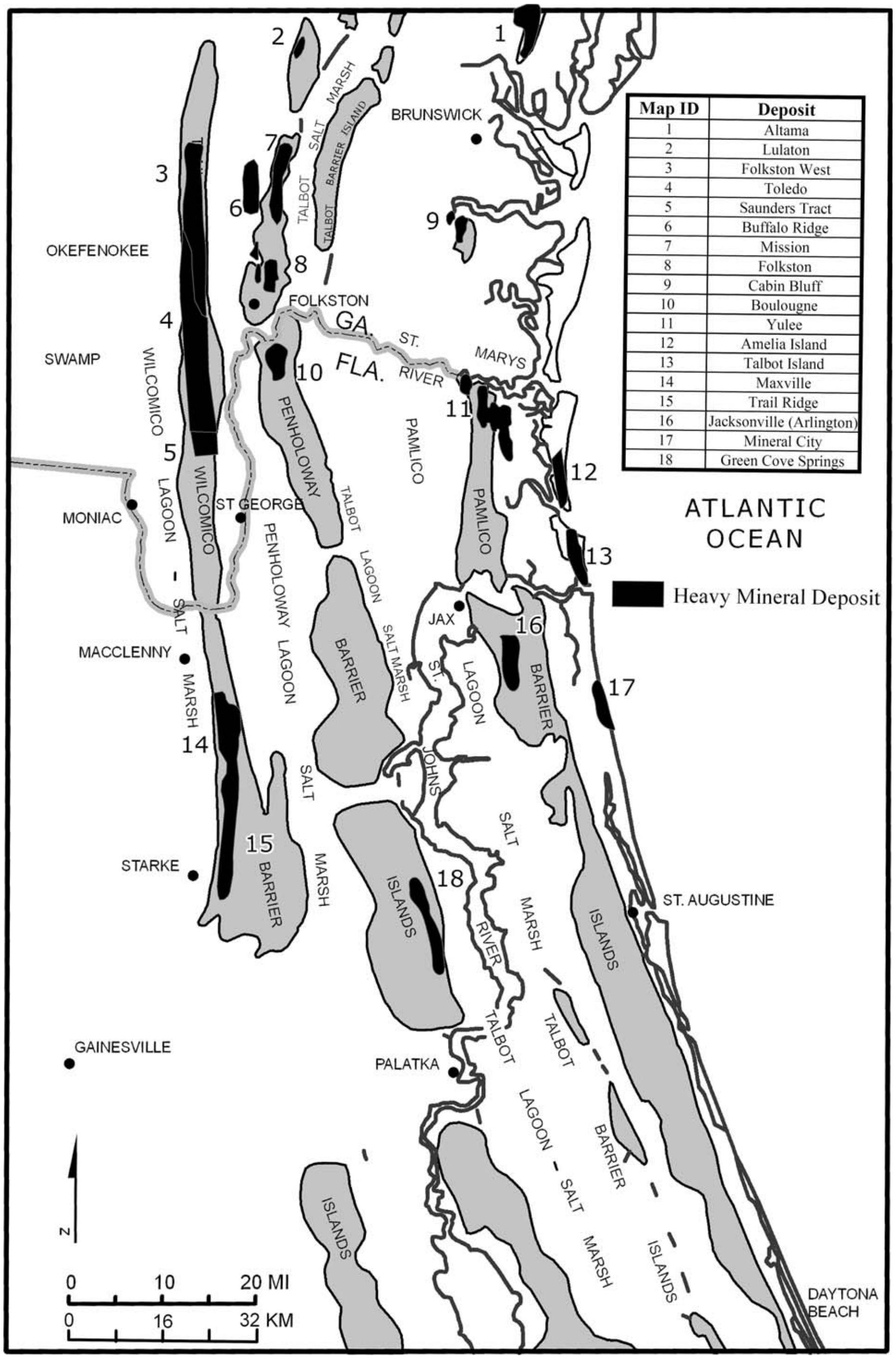

Figure 5. Shorelines along which heavy-mineral concentrations are found in southeastern Georgia and northern Florida. Modified from Hoyt (1969).

(1960), DuBar *et al*. (1974), Flint (1940, 1942, 1947), Herrick (1965), Howard and Scott (1983), Hoyt and Hails (1967, 1971, 1974), Huddleston (1988), Johnson and DuBar (1964), Kussel and Jones (1986), MacNeil (1950), Markewich (1987), Oaks and Coch (1973), Oaks and DuBar (1974), Prettyman and Cave (1923), Price (1951), Richards (1954), Thom (1967), and Winker and Howard (1977), among others. Markewich, Hacke, and Huddleston (1992) provide one of the most recent syntheses of this long-enduring series of investigations of deposition along the Georgia coastline. Clearly, the use of multiple terms such as scarp, shoreline, and erosional surface has confounded our understanding of landforms in this part of the Atlantic Coastal Plain.

Individual Shoreline Identities

As many as seven old shorelines have been recognized by workers such as Cooke (1941, 1945), Flint (1940, 1942, 1947), MacNeil (1950), and Parker and Cooke (1944) and are widely recognized today. The shorelines along which the heavy-mineral deposits are found in southeastern Georgia are, from west to east, the Wicomico (29–31 m above sea level), Penholoway (21–23 m), Talbot (12–14 m), Pamlico (8 m), Princess Anne (4 m), Silver Bluff (1.4 m), and Holocene (0 m) shorelines (Figures 1 and 5). The oldest of these shorelines, located farthest west, has been variously dated from middle Pliocene to early Pleistocene (Carpenter and Carpenter, 1991; Garnar and Stanaway, 1994; Pirkle and Czel, 1983; Pirkle *et al*., 1993; Pirkle and Pirkle, 1984; Pirkle and Yoho, 1970; Rich and Pirkle, 1993; Winker and Howard, 1977). In their study of a site in Springfield, Georgia, Markewich *et al*. (in press) determined that "...at this locality, the barrier/beach ridge has a minimum age of about 360 ka."

The Okefenokee Terrace, an upland feature that is not a single ridge but does lie immediately west of the Wicomico shoreline and is believed to be of marine origin, is one of a number of ancient terraces that lie well inland of the shorelines discussed in this paper. The Okefenokee Terrace is just the most easterly of several upper Coastal Plain terraces that were identified by Huddleston (1988). By contrast with terraces, the Wicomico, Penholoway, Talbot, Pamlico, and Princess Anne shorelines are the most recent additions to the Georgia outer coastal plain (Kellam, Mallary, and Laney, 1991). All are regarded as lines of farthest marine transgression during interglacial and postglacial periods, and most have produced commercial heavy-mineral deposits (Lynd and Lefond, 1975).

The shorelines associated with the traditional marine terraces of the Atlantic Coastal Plain of Georgia and Florida are not the same elevation along their length. The elevation of the shoreline associated with the Trail Ridge physiographic feature (Wicomico shoreline) is about 45 m in northern Florida, drops to about 30 m in the Southeast Georgia Embayment, then gradually rises through South Carolina into North Carolina and Virginia to an elevation of 60–75 m (Stanaway, 1996). Adams (2010), Adams, Opdyke, and Jaeger (2010), and Opdyke *et al*. (1984) attribute the variations in elevations to the dissolution of limestone with resultant isostatic uplift in Florida. Herrick and Vorhis (1963) and LeGrande (1961) attributed the elevation changes in Georgia, South Carolina, and North Carolina to structural deformation associated with the Southeast Georgia Embayment in the south and with the Cape Fear Arch toward the north.

Shoreline Sequences

Three major shoreline sequences and associated barrier island complexes between Florida and North Carolina were suggested by Winker and Howard (1977). The highest and most western was called the Trail Ridge sequence and is associated with the Wicomico sea level in southeastern Georgia. They argued that the sequence represents the line of maximum transgression in the Pliocene. The sand ridge named Trail Ridge, a major beach ridge complex, formed along this shoreline and hosts large heavy-mineral deposits including, from south to north, the Trail Ridge, Highland (Maxville), Saunders Tract, Toledo, Folkston West, and Amelia A, B, and C heavy-mineral deposits (Figures 2 and 5; Pirkle *et al*., 2005).

In 1996 two samples of organic-rich sediment were collected from beneath Trail Ridge in the Toledo deposit from two different exploratory drill sites. Only two samples were recovered simply because of the happenstantial nature of their occurrences, and because of the spacing of the exploratory drill sites. Both samples were unique in that they had the density and color of brown coal, as opposed to the more typical, friable characteristics of peat. One came from 42.5–45 feet ft (13 – 14 m) depth, the other from 52.5–55 ft (16 – 17 m). The samples were analyzed for their palynological contents to discern environments of deposition, though what they indicated concerning age was also of interest. More than 200 identifiable pollen/spores were counted in each sample.

Both samples contained typical continental taxa and, in fact, had to have accumulated under freshwater conditions. Pine and cypress were the dominant pollen genera in both samples, but they both contained abundant remains of the planktonic freshwater alga *Botryococcus*. The sample from 52.5 to 55 ft yielded 117 individuals during the point count, whereas the sample from 42.5 to 45 ft produced 18. Also of environmental significance is that the 52.5–55-ft sample contained 149 specimens of the alga *Pediastrum*, whereas the shallower sample yielded 11. Both algal types are indicative of standing freshwater environments.

The freshwater origin for these samples is borne out by the presence of plants such as *Alnus* (alder), *Nyssa* (black gum), and the floating fern *Azolla*. What is of interest from a geochronological point of view, however, is the fact that both samples contained pollen grains of the winged hickory, *Pterocarya*. *Pterocarya* was common in North America through the Pliocene, but it became extinct in the Western Hemisphere with the onset of the Quaternary. Each sample produced only one grain, but the genus cannot be confused with anything else, and the mere presence is indicative of a Pliocene age for the freshwater wetland strata lying immediately beneath Trail Ridge at that locale.

The Trail Ridge shoreline can be traced northward from Florida through South Carolina, where it is called the Orangeburg escarpment, into North Carolina. Carpenter and Carpenter (1991), Garnar and Stanaway (1994), and Pirkle *et al*. (2007a, 2013) suggest that this shoreline may be associated with heavy-mineral deposits in the Fall Zone of southeastern Virginia and northeastern North Carolina (Figure 6). It is of interest to note that *Pterocarya* has been identified in the sediments immediately below the heavy-mineral-bearing sands of the Bailey heavy-mineral deposits (Pirkle *et al.,* 2013).

The Effingham shoreline sequence lies east of the Trail Ridge sequence and is associated with the Penholoway and Talbot sea levels (Figure 5). It is designated as Pleistocene in age (Winker and Howard, 1977). The beach-ridge crests along the Effingham sequence shoreline have elevations that vary from 37 m in northern Florida to 25 m in eastern Georgia to 33 m in southeastern North Carolina, where it is called the Surry Scarp (Winker and Howard, 1977; Figure 6). The Green Cove Springs

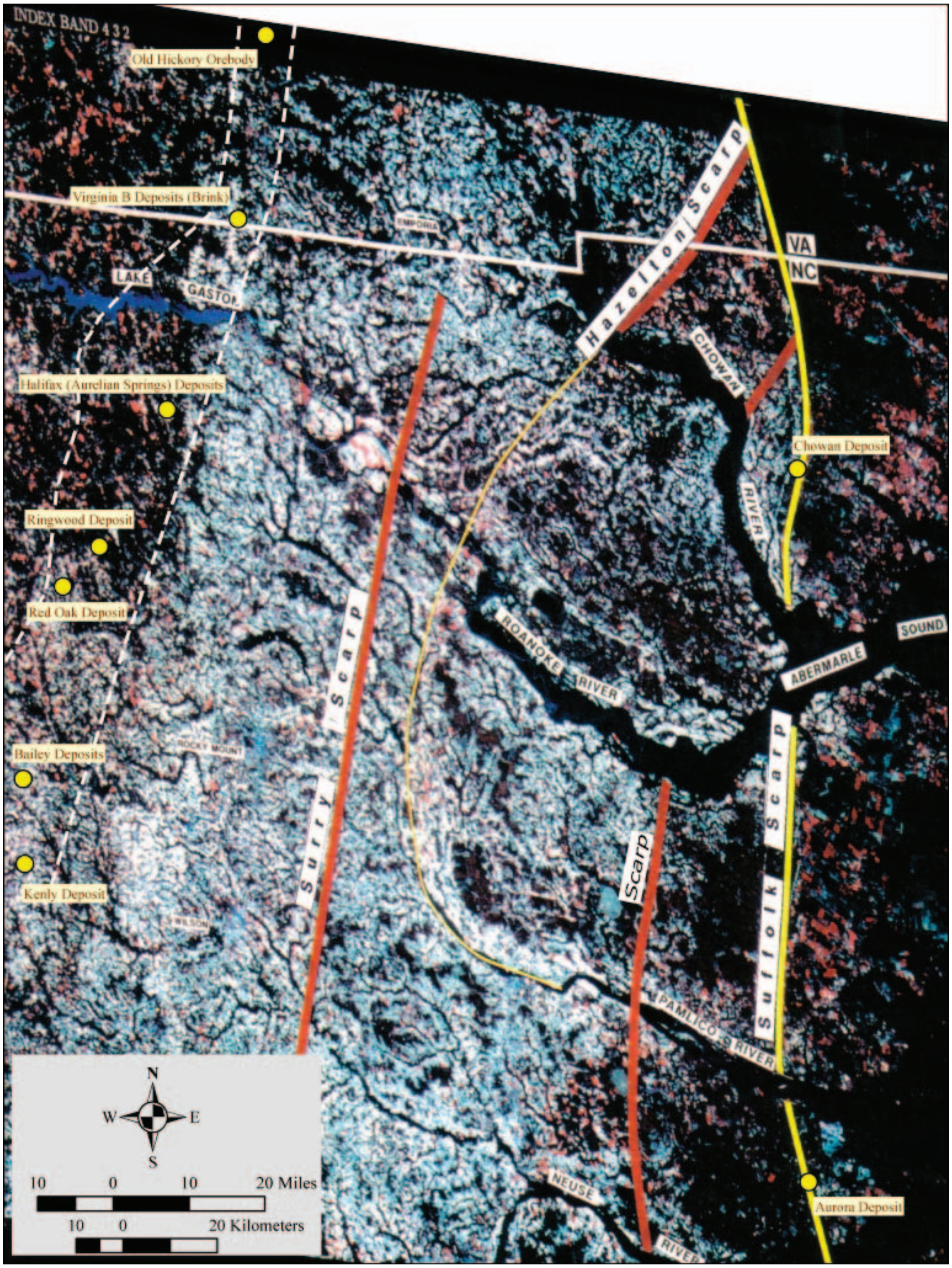

Figure 6. Satellite image of a portion of North Carolina and Virginia. Notice the Suffolk Scarp truncating older features such as the Hazelton Scarp. The Aurora and Chowan heavy-mineral deposits occur along the Suffolk Scarp. The dotted lines on the left side of the image demarcate the Fall Zone. Seven heavy-mineral deposits that occur within the Fall Zone are also shown. Modified from Pirkle *et al*. (1994).

and Boulougne heavy-mineral deposits of Florida and the Folkston heavy-mineral deposit, which lies at the Georgia–Florida state line (Pirkle, Pirkle, and Pirkle, 2007), are found along this shoreline. Also, the Mission, Lulaton, and Ludowici deposits in Georgia appear to lie on this shoreline (Figures 2 and 5).

The Chatham is the youngest, lowest, and most eastern shoreline sequence. The 8-m Pamlico shoreline forms its western margin and can be traced northward into North Carolina and Virginia where it is termed the Suffolk Scarp (Figure 6). The Princess Anne, Silver Bluff, and Holocene sea-level sequences were included by Winker and Howard (1977) in the eastern margin of the Chatham sequence. The elevation of the Chatham sequence is the most consistent of the three sequences, probably because it has had less time to undergo deformation because of its young age. The Jacksonville (Arlington), Yulee, Cabin Bluff, Altama, Darien, Aurora, and Chowan heavy-mineral deposits are located on its western border, and the Amelia Island, Talbot Island, and Mineral City (Ponte Vedra) heavy-mineral deposits occur along its eastern edge (Figures 2, 5, and 6). Table 1 summarizes the location of the Atlantic Coastal Plain heavy-mineral deposits from Florida to Virginia in relation to shoreline and shoreline sequences.

Heavy-Mineral Facies Associations

As can be seen, concentrations of heavy minerals in the coastal areas of the southeast clearly are related to both recent and ancient marine shorelines (Lynd and Lefond, 1975). However, the exact mechanism(s) of concentration of the heavy minerals has been a matter of debate. For example, seaward transport of sediments associated with a marine regression was the major concentrating mechanism according to Garnar and Stanaway (1994), resulting in major accumulations in the foreshore environment, but with accumulations also occurring in the upper shoreface or surf zone. Heavy minerals were concentrated during marine transgressions, according to Garnar and Stanaway (1994), only in conjunction with other factors such as aeolian winnowing by the wind and resultant heavy-mineral concentrations in aeolian dunes. Accordingly, some of the major heavy-mineral deposits are thought to have important aeolian contributions; examples are Trail Ridge and the western portion of the Green Cove Springs deposits (Force and Rich, 1989; Pirkle, 1984; Rose, 2005). Other concentration factors also can come into play. For example, heavy-mineral concentrations often occur a short distance downdrift from where a river now empties into the sea as illustrated by the Yulee deposits that are exposed at Reids Bluff and Bells Bluff on the Florida side of the St. Marys River and that are found just SE of the mouth of the ancestral St. Marys River (Figure 7). The Amelia Island deposits are a modern analog to the Yulee deposits and occur along the Holocene shoreline just SE (downdrift) of the current mouth of the St. Marys River (Figure 7).

Facies associated with the barrier island sequences include nearshore, foreshore, backshore, dune, freshwater swamp, backbarrier marsh and lagoon, and tidal channel. Of these facies, heavy-mineral concentrations most often are found in the foreshore or dune facies, but they sometimes occur in the nearshore facies, sands of the backbarrier facies, and in channel fill facies.

Analogs exist between modern sediments exposed along the St. Marys and Bells rivers at the Georgia–Florida border and the sediments of the heavy-mineral deposits of the Coastal Plain. For example, the beach ridge sands at Reids Bluff overlie stumps of a freshwater cypress swamp (Pirkle, Pirkle, and Reynolds, 1993; Figure 8) much as the beach-ridge sands of Trail Ridge overlie freshwater lignitic peat that contains stumps in upright positions (Force and Rich 1989; Rich, 1985; Rich and Pirkle, 1993). The outcrops at Roses, Reids, and Bells bluffs along the St. Marys River provide excellent examples of some of the major facies associated with heavy-mineral sand deposits of the Atlantic Coastal Plain, and will be discussed in later portions of this paper.

Heavy-mineral suites are similar in all the deposits except that the Trail Ridge deposits have little or no monazite, garnet, or epidote. Pirkle, Pirkle, and Yoho (1977) attribute this to an absence of monazite, garnet, and epidote in the sands of the western 45-m terrace, referred to as the Okefenokee Terrace by MacNeil (1950), or the Northern Highlands (White, 1970), and into which the Trail Ridge seas are believed to have eroded (Pirkle, 1975; Pirkle, Pirkle, and Yoho, 1977). These sands served as the source materials for the Trail Ridge deposits and as such they share compositional characteristics. The epidote and garnet of the much-lower-elevation deposits probably were brought in by longshore drift from northern sources. Table 2 shows the composition of the heavy-mineral suites from the various deposits of the region.

ORIGINS OF SHORELINE RIDGES

Some of the models developed by various workers for the origin of heavy-mineral deposits include the following: (1) height of marine transgressional beach-ridge model; (2) regressional beach-ridge plain model; and (3) fluvial–deltaic model.

Height of Marine Transgressional Model

Pirkle and Yoho (1970), Pirkle, Pirkle, and Yoho (1977), Pirkle *et al*. (1993), and Pirkle and Pirkle (1984) argue that the Trail Ridge heavy-mineral deposits (Trail Ridge, Highland [Maxville], Saunders Tract, Toledo, Folkston West, and Amelia A, B, and C) were formed at the height of a major marine transgression that eroded into the sands of the Northern Highlands of Florida (as described by White, 1970) and the 45-m Okefenokee Terrace of Georgia (as described by MacNeil, 1950) during the late Pliocene or early Pleistocene. Evidence cited to support this conclusion includes the fact that Trail Ridge is a prominent ridge, it truncates other ridges, and the area west of Trail Ridge is at a higher elevation than that east of Trail Ridge (Figures 2 and 9). According to this hypothesis, "...the sand blanket of the Northern Highlands was left as a plain when the ocean waters retreated from the present Coastal Plain areas of southern Georgia and northern Florida. This regressing sea was later followed by a major marine transgression. The transgressing sea eroded into sediments of the Northern Highlands. Trail Ridge with its ore bodies was built as a beach ridge at the crest of this eroding, transgressing sea. According to this concept the immediate source sediments for much of Trail Ridge were the sands of the high terraces of the Northern Highlands." (Pirkle, Pirkle, and Yoho, 1977, p. 11).

Regressional Model

Younger, lower-elevation, more easterly heavy-mineral deposits were formed during sea-level stillstands or minor transgressions during a general sea-level retreat from the Pliocene levels. This general sea-level retreat formed a beach-

Table 1. *Summary of transgressive events associated with heavy-mineral deposits.*

Deposit[a]	Location (State)	Sequence[b]	Shoreline	Age	Height Marine Transgression	Beach-Ridge Plain	Shoreline Elevation (m)
Trail Ridge, Highland, Maxville	Florida	Trail Ridge	Wicomico	Max. Pliocene	X		45
Saunders, Toledo, Folkston West	Georgia	Trail Ridge	Wicomico	Max. Pliocene	X		30
Amelia A,B,C	Georgia	Trail Ridge	Wicomico	Max. Pliocene	X		30
Kenly	North Carolina		Fall Zone (Orangeburg Scarp)	Max. Pliocene	X		60 −75
Bailey	North Carolina		Fall Zone (Orangeburg Scarp)	Max. Pliocene	X		60 −75
Red Oak	North Carolina		Fall Zone (Orangeburg Scarp)	Max. Pliocene	X		60 −75
Ringwood	North Carolina		Fall Zone (Orangeburg Scarp)	Max. Pliocene	X		60 −75
Halifax (Aurelian Springs)	North Carolina		Fall Zone (Orangeburg Scarp)	Max. Pliocene	X		60 −75
Virginia B (Brink)	Virginia		Fall Zone (Orangeburg Scarp)	Max. Pliocene	X		60 −75
Old Hickory	Virginia		Fall Zone (Orangeburg Scarp)	Max. Pliocene	X		60 −75
Green Cove Springs	Florida	Effingham	Duval Upland (Penholoway)	Pleistocene		X	37
Boulougne	Florida	Effingham	Duval Upland (Penholoway)	Pleistocene		X	37
Folkston	Georgia	Effingham	Duval Upland (Penholoway)	Pleistocene		X	25
Mission	Georgia	Effingham	Duval Upland (Penholoway)	Pleistocene		X	25
Buffalo ridge	Georgia	Trail ridge	East Flank Wicomico (Penholoway)	Pleistocene		X	25
Lulaton	Georgia	Effingham	Duval Upland (Penholoway)	Pleistocene		X	25
Ludowici	Georgia	Effingham	Duval Upland (Penholoway)	Pleistocene		X	25
Jacksonville (Arllington)	Florida	Chatham	Pamlico	Pleistocene	X		8
Yulee	Florida	Chatham	Pamlico	Pleistocene	X		8
Cabin Bluff	Georgia	Chatham	Pamlico	Pleistocene	X		8
Altama	Georgia	Chatham	Pamlico	Pleistocene	X		8
Darien	Georgia	Chatham	Pamlico	Pleistocene	X		8
Aurora	North Carollina	Chatham	Pamlico (Suffolk Scarp)	Pleistocene	X		8
Chowan	North Carolina	Chatham	Pamlico (Suffolk Scarp)	Pleistocene	X		8
Mineral City (Ponta Vedra)	Florida	Outer Chatham	Recent	Holocene		X	0
Talbot Island	Florida	Outer Chatham	Recent	Holocene		X	0
Amelia Island	Florida	Outer Chatham	Recent	Holocene		X	0

[a] Deposit locations are shown on Figures 2, 5, and 6.
[b] Sequence, defined by Winker and Howard (1977), is used here to include ridge systems as well as intervening swales. The swales are underlain by sediments deposited in tidal marshes, tidal flats, lagoons, washover fans, intertidal and offshore bars, and lower-elevation stranded barrier islands.

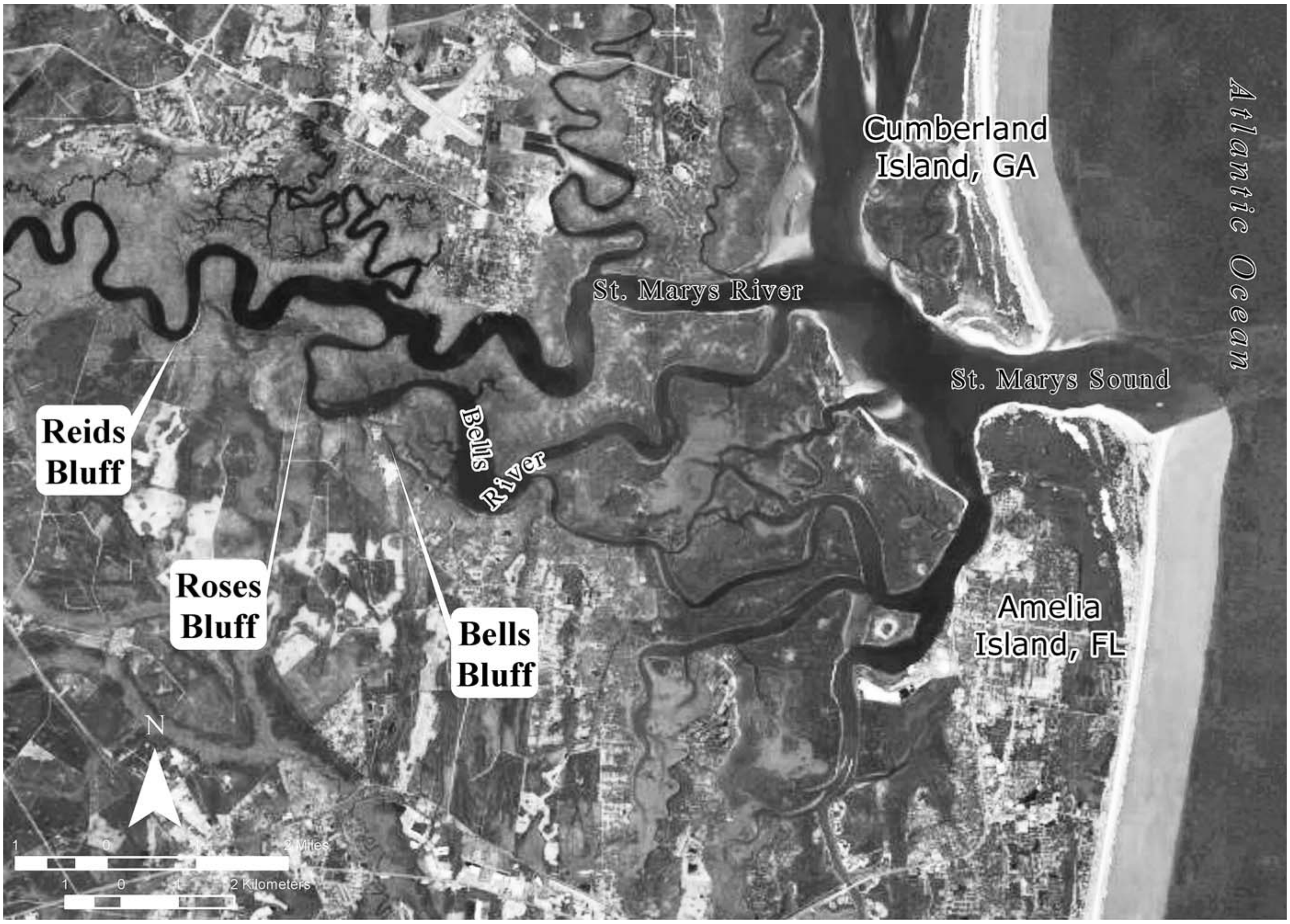

Figure 7. Surface areas east of the Yulee heavy-mineral deposits. Amelia Island, a present-day barrier island, occurs along the Atlantic Coast in the same general latitudes of the Yulee heavy-mineral concentrations. Salt marshes separate Amelia Island and the Yulee ridges. Photograph taken in 2005 and provided courtesy of the St. Johns River Water Management District. Modified from Pirkle *et al*. (2007b).

ridge plain upon which the deposits are located. Pirkle, Pirkle, and Yoho (1977, p. 12) state, "The Duval Upland east of Trail Ridge (Figure 1) is believed to be a regressional beach ridge plain. It is younger than Trail Ridge and is a remnant of a much larger plains area, much of which has been destroyed through subaerial erosion and later marine transgressions. While the regressional beach ridge plain was forming there were temporary halts in regression, and perhaps even slight transgressions. During these intervals more prominent beach ridges were built. Some of these ridges contain concentrations of heavy-mineral sands. Examples of these concentrations are the commercial Green Cove Springs and Boulougne deposits." See Figure 2 of this paper.

Heavy-mineral deposits along the Effingham shoreline (Green Cove Springs, Boulougne, Folkston, Mission, Lulaton, and Ludowici) are generally thought to represent a transgressive period within the general regression as described above (Pirkle, Pirkle, and Pirkle, 2007; Pirkle, Pirkle, and Yoho, 1974; Pirkle *et al*., 2005). An argument, however, could be made that the Green Cove Springs ore body formed in a ridge or ridges on the landward side of a shoreline at the height of a marine transgression because it occurs just to the west of the escarpment that marks the eastern edge of the Duval Upland (Figure 10). However, Pirkle, Pirkle, and Yoho (1974) present several lines of evidence that argue against such an origin. The ridges containing the Green Cove Springs deposits are not distinct, as would be expected if they formed at the height of a transgression. Also, the Boulougne deposit, which has physical and mineralogical characteristics very similar to the Green Cove Springs, lies near the center of the Duval Upland well away from the escarpment that forms the Duval Upland eastern boundary. This central location is a strong argument that the ridge or ridges of the Boulougne deposit, as well as the similar deposits of Green Cove Springs, did not form on the landward side of the shoreline that created the eastern boundary of the Duval Upland. A west-to-east profile across the Boulougne ore body shows that the land surface to the west of the deposits is the same elevation as the surface to the east of

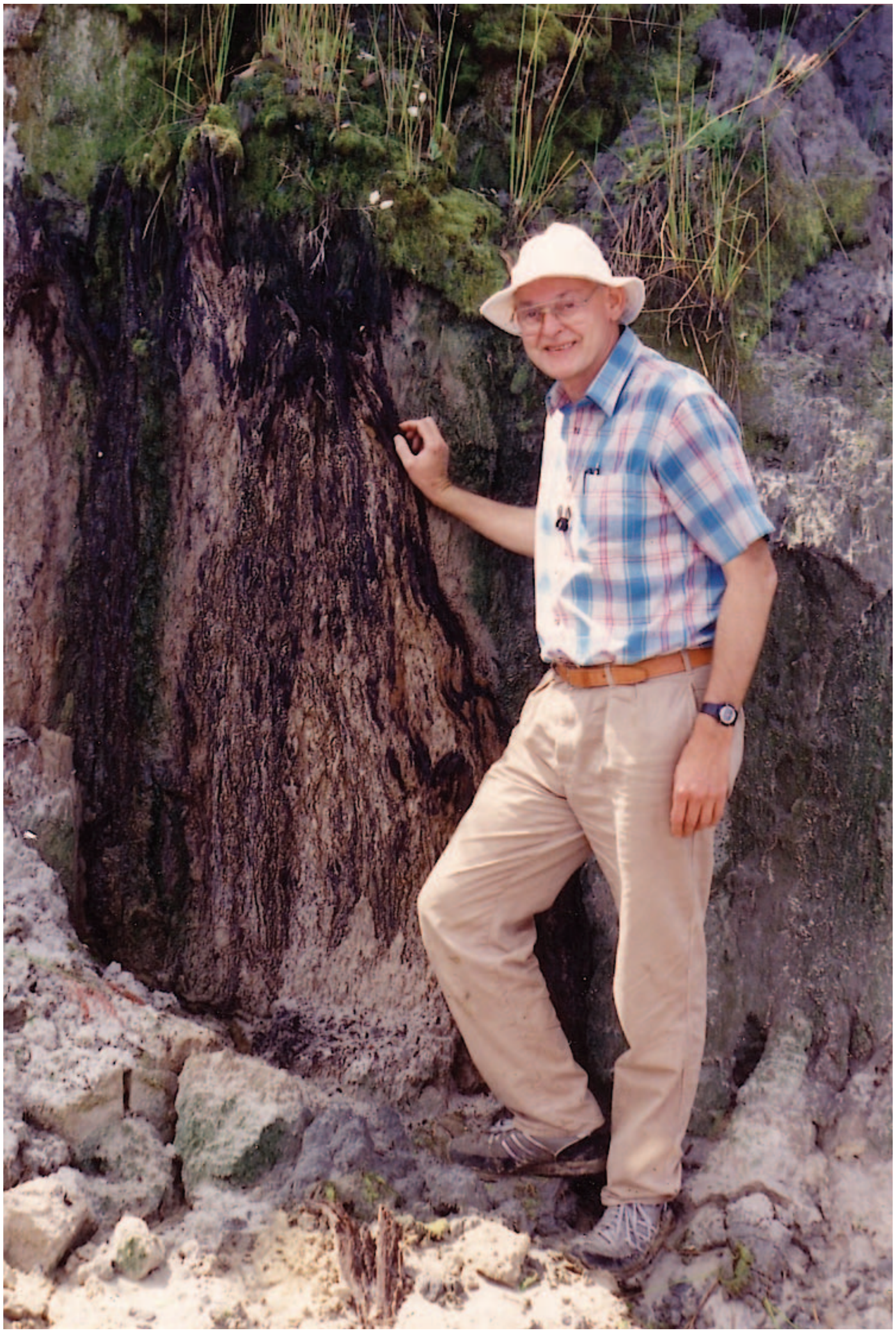

Figure 8. Paleobotanist David Dilcher next to an upright cypress stump. The presence of these stumps provides evidence that these trees are in place. From Pirkle *et al*. (2007b).

the deposits (Figure 11). Also, Rose (2005) states "The deposits are a series of regressive barrier island sequences deposited during interglacial periods of Pleistocene time." He believes the initial transgression of the ocean went as far as the western extent of the Henry ore body (Figure 12) and that the ore body thickness is evidence of an extensive sea-level stillstand.

The Folkston ore body (Figure 2) also suggests that the Effingham shoreline deposits were not formed at the height of a

Table 2. *Average heavy-mineral suite for the known heavy-mineral trends of the northern Florida and southeastern Georgia Atlantic Coastal Plain.*[a]

Heavy-Mineral Trend	Weight Percent Heavy-Mineral Species					
	Titanium Minerals	Zircon	Monazite	Staurolite	Epidote and Garnet	Hornblende
Holocene	56	12	1	5	16	0.6
Crestal Pamlico	58	14	0.7	5	5	0.4
Duval Upland	61	14	0.7	10	3	0.4
Trail Ridge	53	15	0.2	14	0.2	0.02

[a] From Pirkle *et al*., 2005.

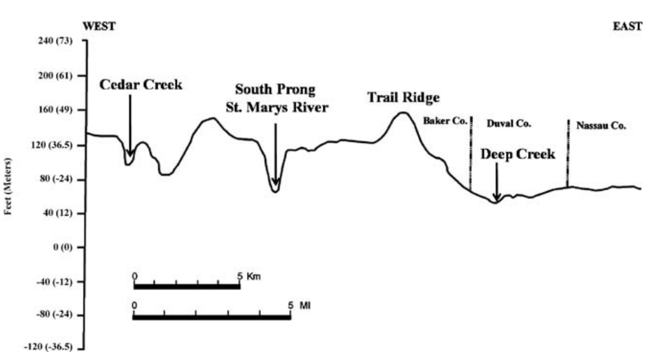

Figure 9. West-to-east profile across Trail Ridge. Note the land surface east of Trail Ridge (seaward) is lower than the land surface to the west of Trail ridge. This land surface relationship is evidence that the ridge is built in the crestal area of an eroding transgressing sea. See Figure 2 for ore body location. Modified from Force (1991), Pirkle (1972), and Pirkle *et al*. (1994).

marine transgression. Regarding the Folkston deposit Gillson (1955) states "...the deposit at Folkston is such a wide bar and has such a flat top that it is better described as a marine terrace and is not a true sand bar or old shore line. It lacks the ridge shape of a bar, typical of Trail Ridge, the Jacksonville deposit worked by the National Lead Company, and other ridge-like features found in the Carolinas and on the Florida coast and in Brazil. The area is remarkably flat over many square miles...a little north of Folkston the terrace is 4 miles wide and is at least 20 miles long." Figure 13 illustrates Gillson's comments and provides further evidence that the Green Cove Springs and Boulougne heavy-mineral ore bodies did not form on the landward side of the shoreline that created the eastern boundary of the Duval Upland.

Deposits along the Chatham shorelines in Florida and Georgia (Jacksonville [Arlington], Yulee, Cabin Bluff, Altama, Amelia Island, Talbot Island, Mineral City [Ponte Vedra]) and in North Carolina (Aurora and Chowan) are thought to have formed both during times of major marine transgression as well as times of sea-level stasis with only minor transgressive events. The ridges containing the Jacksonville (Arlington), Yulee, Cabin Bluff, Altama, Aurora, and Chowan heavy-mineral deposits, on the western border of the Chatham sequence, can be correlated with the crestal area of a major transgression (the Pamlico shoreline), whereas deposits on the Chatham eastern outer edge, such as the Amelia Island, Talbot Island, and Mineral City (Ponte Vedra) deposits, are thought to have formed during times of sea-level stasis with minor transgressive events (Pirkle and Pirkle, 1984; Pirkle *et al*., 2005; Pirkle, Pirkle, and Pirkle, 2007). Pirkle, Pirkle, and Reynolds (1991, 1993) and Pirkle *et al*. (1991) discuss the origins of the heavy-mineral deposits along the Pamlico barrier islands. They believe the heavy-mineral sand deposits located along this shoreline were formed at the height of an eroding, transgressing sea. White (1970) discusses the Pamlico shore-

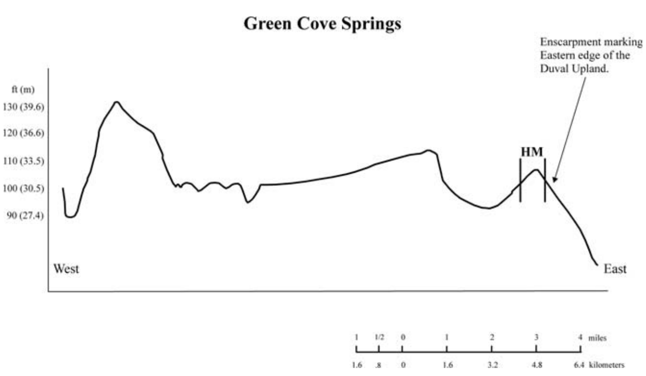

Figure 10. West-to-east profile across the Green Cove Springs ore body. An argument might be made that this ore body formed in a ridge or ridges on the landward side of a shoreline at the height of a marine transgression because it occurs just to the west of the escarpment that marks the eastern edge of the Duval Upland. However, the ridge or ridges that contain the heavy-mineral concentrations are not distinct as would be expected if they formed at the height of transgression. See Figures 2 and 5 for the ore body location.

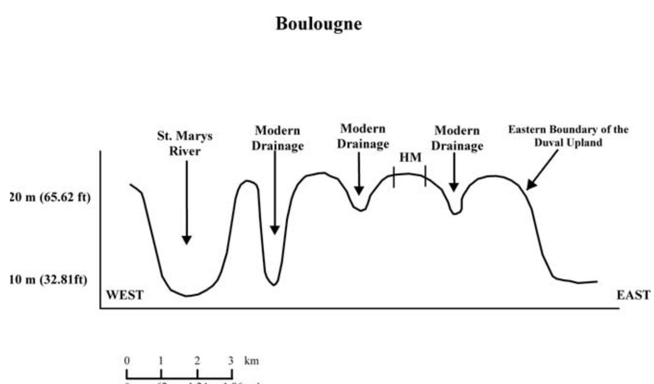

Figure 11. A west-to-east profile across the Boulougne heavy-mineral deposits. Note the land surfaces to the west of the heavy-mineral concentrations are the same elevation as the surfaces to the east of the heavy-mineral concentrations. This is evidence that the Boulougne deposits did not form on the landward side of the shoreline that created the eastern boundary of the Duval Upland. See Figures 2 and 5 for the orebody location.

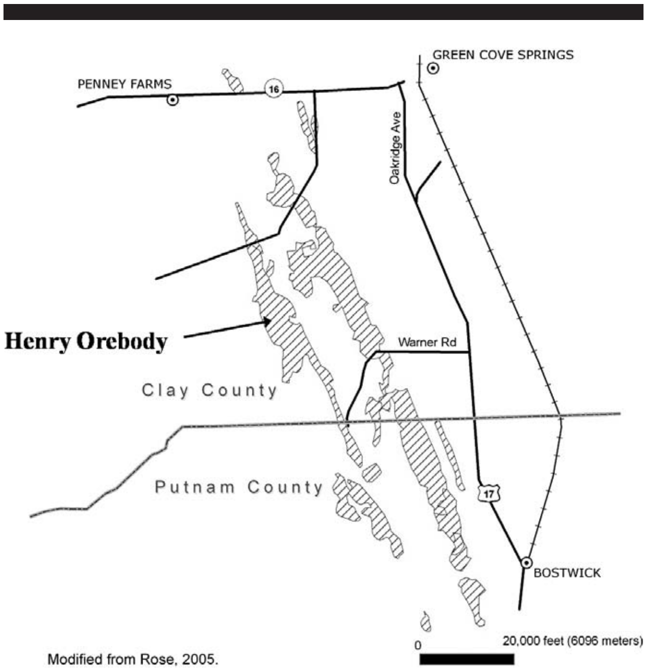

Figure 12. Location of the Green Cove Springs heavy-mineral ore body. Modified from Rose (2005).

line truncating older ridges in Florida and Figure 6 illustrates the Suffolk Scarp truncating older ridges in North Carolina and Virginia, thus indicating that the ridges associated with the Pamlico shoreline were formed at the height of an eroding, transgressing sea.

Sands of the heavy-mineral deposits are coarsest in the Trail Ridge shoreline sequence and finest in the Effingham shoreline sequence. Grain size is intermediate in the Chatham shoreline sequence (Figure 14). The commercial heavy-mineral suite consists primarily of ilmenite, leucoxene, rutile, and zircon. Kyanite, sillimanite, and staurolite have been produced commercially from some of the deposits. The TiO_2 content of the ilmenite is highest in the oldest, more westerly Trail Ridge deposits and becomes progressively lower in the younger, lower, more easterly deposits. Thus, TiO_2 content increases with age and weathering (Table 3). TiO_2 content does not vary in a N-S direction (Pirkle *et al.*, 2005).

Reids, Roses, and Bells Bluffs—Cases In Point

Reids Bluff, Roses Bluff, and Bells Bluff lie, from west to east, along the St. Marys and Bells rivers in northeastern Florida (Figures 7 and 15). The bluffs rise from 15 to 19 m above the river and are believed to have formed in association with former sea-level stands of the Pamlico shoreline. Stratified sediments, including cypress-stump-bearing sands, oyster- and clam shell beds, blue-gray clays, and aeolian sands are present (Figure 16). The stratigraphic relationships illustrate a classic transgressive/regressive sequence (Rich and Pirkle, 1994). A shell of *Anadara*, collected from river level at Bells Bluff mean sea level (MSL) in June, 1990, delivered a radiocarbon date of 37,395 ± 2155 YBP (as determined at the University of Georgia Center for Applied Isotope Studies, UGA-6056, uncorrected for radiocarbon pool; YBP is used throughout the text for consistency). The *Anadara* shell and associated molluscs such as *Dinocardium* were collected as articulated specimens and intact. They are, thus, believed to represent the original biological components of the sediment (*i.e.* not reworked from older strata), and represent a normal marine shoreline assemblage for this latitude, 31–32° N . Above this normal marine shoreline assemblage on Bells Bluff is a clay layer that contains diatoms and other biotic remains that suggest a slightly brackish to brackish water environment (Burckle, *personal communication*).

Several other radiocarbon dates were derived from wood collected from *in situ* tree stumps standing at river level [Reids Bluff 1, *Taxodium*, >38,130 YBP, as determined by BETA Analytic, Inc. (BETA-number lost due to Hurricane Andrew), processed in 1988], and from shells collected from a sequence of clay-rich, shell-bearing strata that lie above the stumps (Figure 16). Shells included *Ostrea virginica* (three articulated individuals, dated at >47,100 YBP [BETA-67069], >46,500 YBP [BETA-67470], and >47,100 YBP [BETA-67071, uncorrected values). Two valves were collected and dated from articulated individuals of the surf clam *Mercenaria mercenaria*. Both samples were collected from unit B shown in Figure 16. The first valve was collected in 1988 from about 2 m above the river. The age date was reported as 36,030 ± 610 YBP (BETA-26343). The second valve was collected in 1993. The age date for this sample was reported as 36,270 ± 1670 YBP (BETA-number lost due to Hurricane Andrew). In July of 2011 the *Taxodium* sample earlier identified as Reids Bluff 1, noted above, was dated again after having been stored in refrigeration for the intervening years. The earlier date was derived by scintillometer technology, and the more recently derived date was the product of atomic mass spectrometry. The latter date came in at >43,500 YBP (BETA-301,590) and validates the much earlier scintillometer date; both were discerned to be indeterminable and beyond the scope of radiocarbon technology. Trees

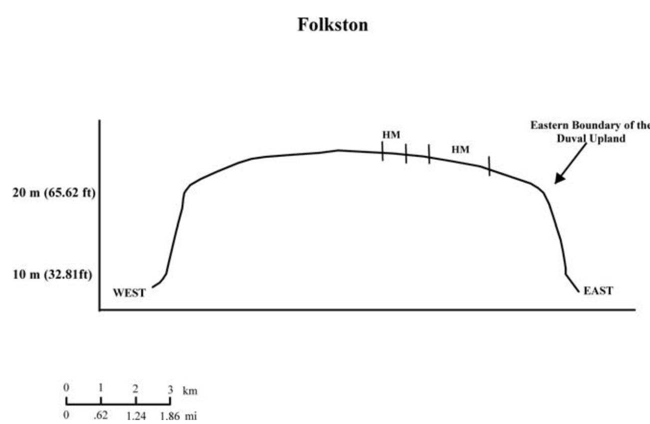

Figure 13. West-to-east profile across the Folkston heavy-mineral ore body. See Figures 2 and 5 for the ore body location.

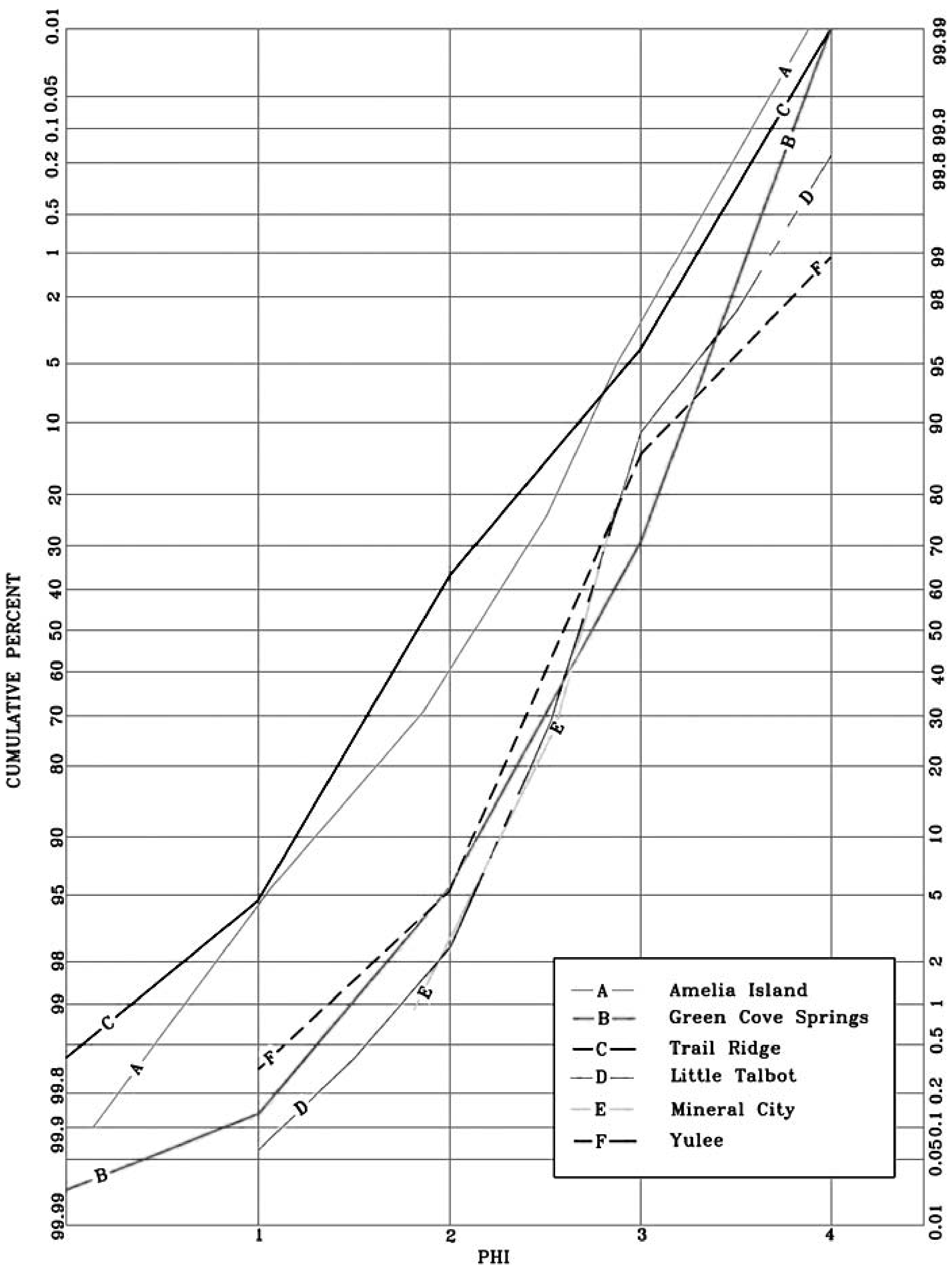

Figure 14. Cumulative size distribution of various heavy-mineral deposits found in the Atlantic Coastal Plain of Florida and Georgia. See Figure 2 for deposit locations. Amelia Island, Little Talbot, Mineral City, and Yule are in the Chatham shoreline sequence; Green Cove Springs is in the Effingham shoreline sequence; and Trail Ridge is in the Trail Ridge shoreline sequence. Modified from Pirkle *et al*. (2005).

at the base of the bluff are clearly very old, and the shells in the overlying and truncating bed of clay are similarly very old.

The Reids Bluff dates indicate a likely Late Pleistocene age for all but the uppermost charcoal unit, which is Recent in age. Charcoal recovered from 3–3.6 m below the surface of the bluff produced a date of 405 ± 55 YBP (UGA-5739, uncorrected). The lowest and oldest tree stumps have no discernible age, as previously stated, though they probably accumulated during

Table 3. *Average TiO_2 values for ilmenites found along various trends in the Atlantic Coastal Plain of Florida and Georgia*.[a]

Heavy-Mineral Trend	Average Percent TiO_2 in Ilmenite
Holocene	56
Crestal Pamlico	61
Duval Upland	64
Trail Ridge	65

[a] From Pirkle *et al.,* 2005.

the Quaternary. Portions of Roses and Bells bluffs clearly represent open-water marine conditions, whereas other parts of Reids–Roses–Bells bluffs, although not necessarily correlative, represent estuarine and lagoonal conditions.

In May 2003 four samples were collected by Steve Forman from Reids Bluff for optically stimulated luminescence dating (OSL) at the University of Illinois at Chicago. The results indicate that the sediments sampled may not have been fully bleached before burial, thus rendering the sediments as unsuitable for dating by OSL (J. Bartholomew, *personal communication*). In October, 2003 Tracy Zayac of Gannett Fleming, Inc. collected two samples from Reids Bluff and one from Bells Bluff for OSL dating. Ronald Goble at the University of Nebraska-Lincoln processed and analyzed the three samples and provided a discussion of the sample results and their implications. The results were similarly inconclusive (Pirkle *et al.,* 2007b).

Palynological data, *i.e*. those derived from the analysis of fossil spore and pollen contents of sediments, provide further insight into the probable timing and environments of deposition of the Reids–Roses–Bells bluffs complex of shorelines. Most of the palynological data have been presented by Rich and Pirkle (1994), but not all of the Reids–Roses–Bells bluffs samples were described in that paper because the results of particular analyses were not especially important for the purposes of that contribution. In view of the fact that we seek to define environmental constraints to the current argument for depositional systems, and because global environmental and depositional systems are of primary significance in the current discussion, more detailed analyses of palynological data are presented here. These include the observation that *Tsuga* (hemlock) pollen was present in several of the Reids–Roses–Bells bluffs samples. *Tsuga* is the Northern hemlock and is typical of wetland forests of northern latitudes. Although it is wind-pollinated, the presence of its pollen south of its current natural biological range is rare outside of the Blue Ridge.

Figure 15. Reids Bluff as seen from the St. Marys River. The bluff faces north and at its highest point rises to a little more than 19 m above the river level.

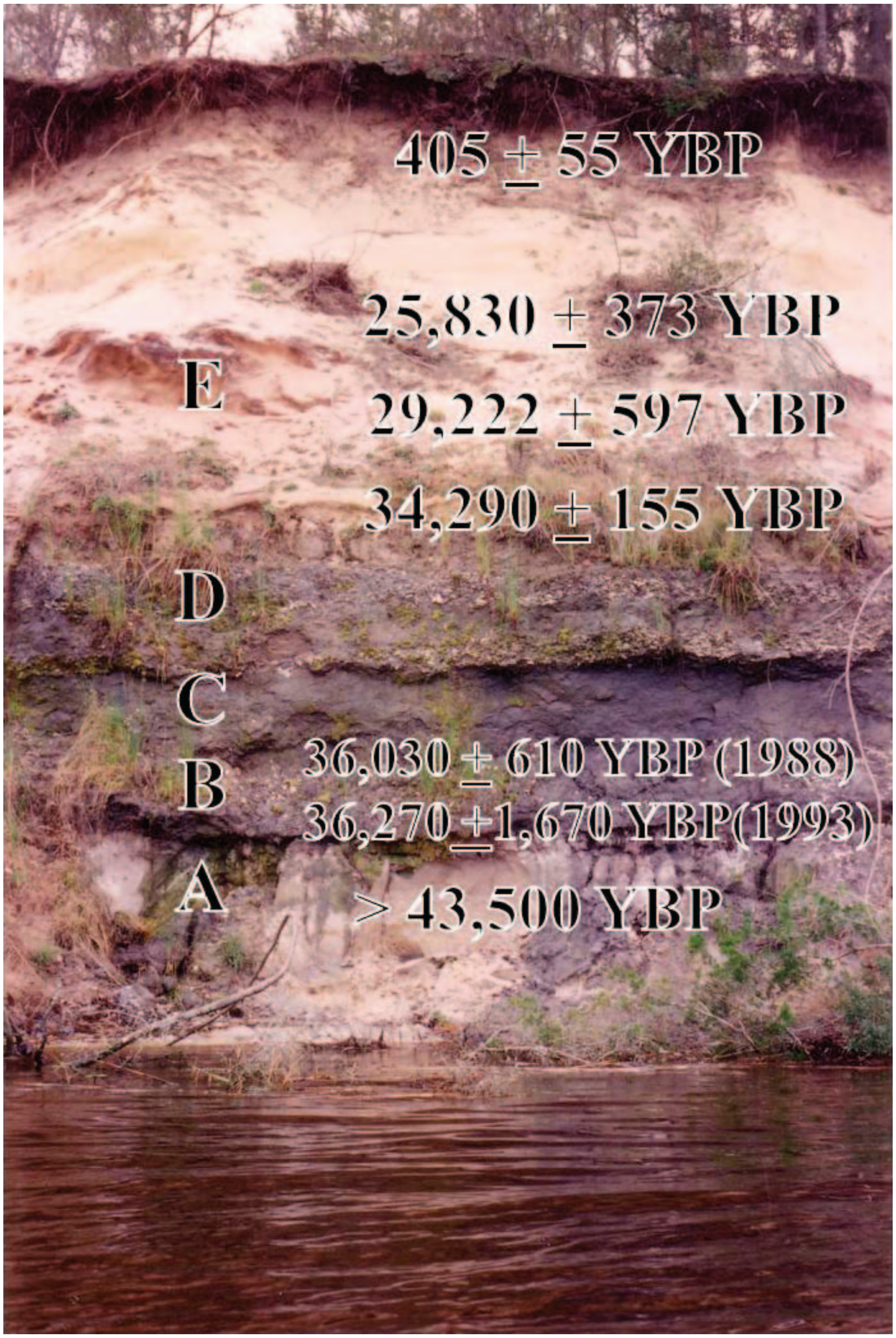

Figure 16. Sediments from the river level upward are loose quartz sand containing cypress tree stumps and *Ophiomorphia* burrows (A), a lower oyster lens (B), blue-gray clayey sediments (C), an upper oyster lens (D), and loose quartz sand that extends to the surface (E). A thin zone of blue-gray clayey sediments underlies the lower oyster lens and overlies unit A and a thin zone of blue-gray clayey sediments overlies the upper oyster lens and underlies Unit E. Cypress tree stumps are found not only in unit A but also are found in several sand layers (E). Also shown are radiocarbon dates from samples collected from Reids Bluff. Photograph taken in Spring 1989. Modified from Pirkle, Pirkle, and Reynolds (1991) and Pirkle *et al*. (2007b).

Hemlock pollen was found in 7 of the 11 samples collected and analyzed from the Reids–Roses–Bells bluffs complex in the late 1980s. The points of accumulation included a ghost shrimp burrow (form genus *Ophiomorpha*), so the regional presence of *Tsuga* is considered to have been significant. Supportive evidence derived from the presence of such taxa as *Fagus* (beech) and basswood (*Tilia*) and possibly *Acer saccharum* (sugar maple) provide microfossil evidence that the ridge complex did, indeed, accumulate during a climatically cooler period of time.

Equivalent landforms located to the south of the Reids–Roses–Bells bluff complex coalesce with the ridges that contain the Yulee heavy-mineral sand deposits. A plains region with summit elevations generally ranging from 5 to 7 m above sea level extends westward from the three bluffs to the eastern edge of the Duval Upland. Surface elevations east of the bluffs are generally lower than 7.6 m. This eastern surface passes into expansive, low salt marshes with elevations less than 1.5 m above sea level (Figure 17). These marshlands extend eastward to Amelia Island on the Atlantic Coast (Figure 7).

Dunes that occur along bluffs of the St. Marys River and are above or associated with the youngest charcoal-dated horizons seem to have been constructed by winds carrying sands up the front of the bluff. These dunes overlie older sands that also may be dunes. The older dunes may be associated with sea-level regression rather than the presence of the river.

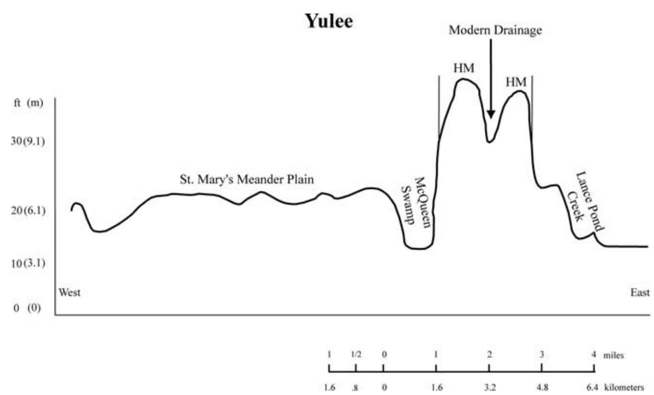

Figure 17. West-to-east profile across Yulee heavy-mineral deposits. A plain region with surface elevations from 7.6 to 10.7 m above sea level extends westward from the heavy-mineral deposits to the eastern edge of the Duval Upland (approximately 24–32 km).Surface elevations to the east of the heavy-mineral deposits are generally lower than 7.6 m above sea level. A short distance from the deposits, this eastern surface passes into expansive, low salt marshes with elevations less than 1.5 m above sea level. These marshlands, cut by meandering streams and winding tidal channels, extend eastward to Amelia Island on the Atlantic Coast.

Fluvial–Deltaic Model

Carpenter and Carpenter (1991) and Pirkle, Pirkle, and Pirkle (2007) described a series of heavy-mineral deposits along the Fall Zone in Virginia and North Carolina (Figures 6 and 18). Carpenter and Carpenter (1991) proposed that the sediments containing the heavy-mineral deposits are updip equivalents of the Lower Pliocene Yorktown Formation and were laid down between 3.5 and 3.0 Ma during a worldwide, Pliocene transgressive–regressive event. They believe the heavy-mineral concentrations formed in beach or dune sands during the regressive phase of this event over an elevation range of 96 m to 53 m. They relate the Trail Ridge deposits in Florida and Georgia to this same transgressive–regressive event. Workers such as Mallard (1992), Shafer (2000), and Berquist and Bailey (1999) postulated that the deposits were concentrated by "typical" nearshore or beach processes. Berquist and Bailey (1999) believed that the heavy-mineral concentrations were a result of nearshore processes interacting with promontories and embayments along a rocky coastline. Also, they believe faulting may have influenced hydrodynamic conditions responsible for the deposition of the heavy minerals.

Other investigators contend that fluvial processes played an important role in forming the deposits. Newton and Romeo (2006) argued that marine processes reworked deltas where paleorivers entered the sea during multiple transgressive–regressive sequences. They thought the reworking and concentrating process may have started in the Cretaceous and continued through Tertiary time. Newton and Romeo (2006) also thought that faulting may have played a role, creating topographic ridges and troughs that acted as barriers and traps to concentrate the heavy minerals.

Pirkle, Pirkle, and Pirkle (2007) and Pirkle *et al*. (2007a, 2013) suggested that the concentrating mechanism was a combination of fluvial processes allied with basement highs and lows. A transgressive sea (Pliocene) reworked Cretaceous deltas and basement material and, as sea level fell, existing rivers were forced to change their channels and pursue new courses to avoid erosion-resistant areas such as plutons and resistant beds with high clay content. Thus, paleorivers, fluvial processes, influenced by basement highs and lows, and tides rising and falling within existing deltas and salt marshes served, respectively, as the transportation mechanisms, depositional environments, and concentrating mechanisms that formed these Fall Zone heavy-mineral deposits. Longshore current and wave action were relatively inconsequential. All of the researchers are in general agreement that the Pliocene (?) maximum high sea-level stand associated with the westernmost of these deposits has not been reached again since the regression began.

CONCLUSIONS

Several conclusions can be drawn from the work presented here. Among them are the following: (1) Shoreline ridges, such as are displayed on the Atlantic Coastal Plain of Georgia and adjacent states, probably have multiple origins, each ridge having its own, and, perhaps peculiar, genesis; (2) Heavy-mineral accumulations have developed along shoreline ridges according to different depositional dynamics, as follows: (a) a marine transgressional model accounts for the deposition of sand ridges that have been identified for a number of years (the most well-known deposit probably is Trail Ridge); (b) a regressional beach-ridge plain model accounts for other ridges, including the lesser known but important Green Cove Springs, Boulougne, and Folkston deposits, among others; (c) a deltaic/

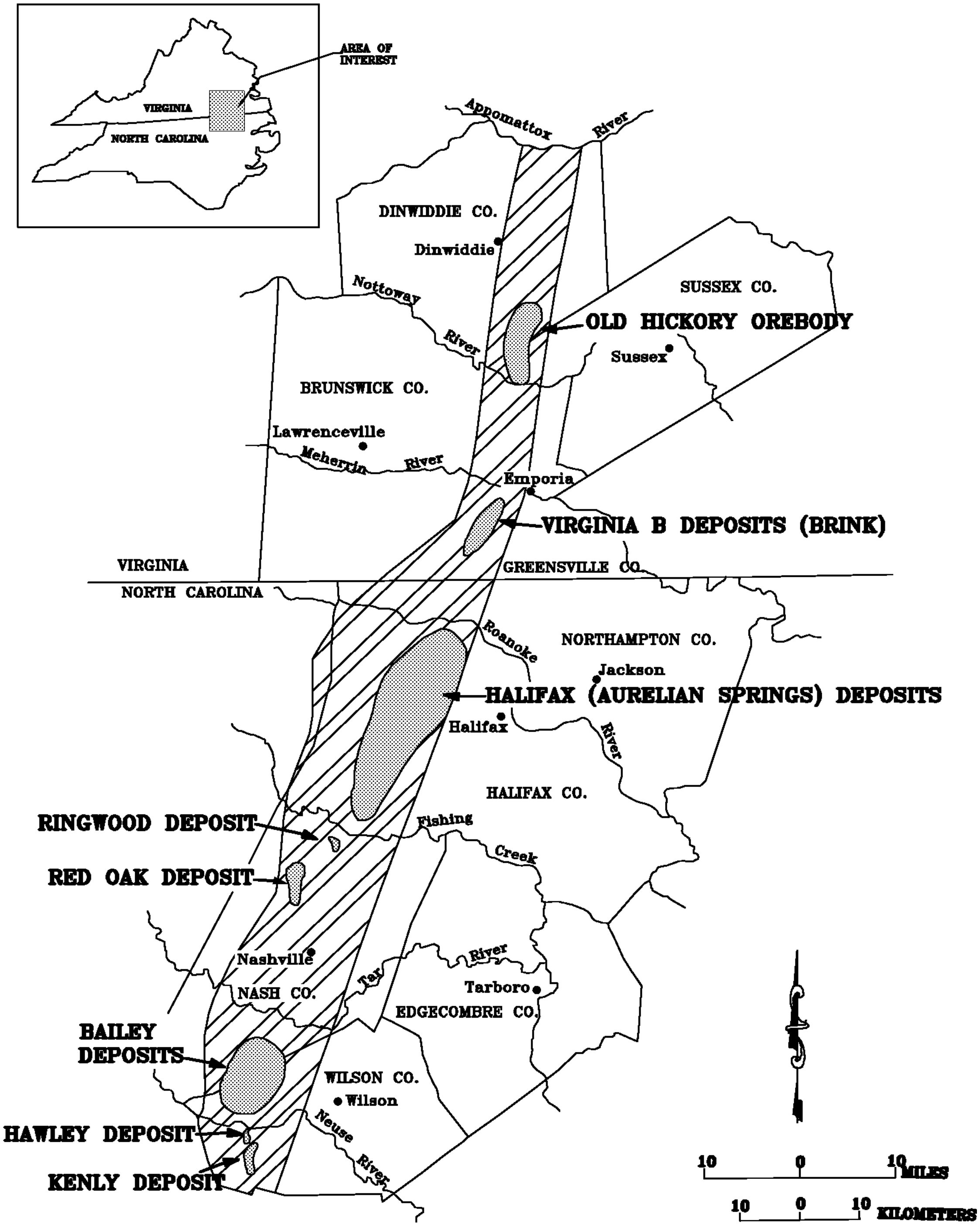

Figure 18. Areas along the Virginia and North Carolina Fall Zone in which heavy-mineral concentrations are present. The Old Hickory and Virginia B (Brink) deposits have been or are being exploited. Modified from Carpenter and Carpenter (1991) and Pirkle *et al*. (1991).

fluvial model accounts for other heavy sand accumulations, including the Old Hickory and associated deposits of North Carolina, that present a new depositional model for heavy-mineral accumulation—the tidal–marsh–baffle mechanism of heavy-mineral accumulation in a tide-dominated environment of deposition.

It should be clear that no single model works every time as we seek models of deposition for heavy-mineral sands; this observation is probably true of economic mineral deposits generally—one must keep an eye on multiple working hypotheses.

ACKNOWLEDGMENTS

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