H. Mississippi Coast: Stratigraphy and Quaternary Evolution in the Northern Gulf Coastal Plain Framework

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Stratigraphic and Paleontologic Studies of the Neogene and Quaternary Sediments in Southern Jackson County, Mississippi

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ABSTRACT

A thick 1,600- to 5,000-ft-thick (about 500 to 1,500 m) marine and paralic-alluvial interval of early to late Miocene age, and a similarly thick 650- to 1,000-ft (about 200 to 300 m) Pliocene sequence, underlie a thin Pleistocene interval seaward of the late Pliocene (Citronelle) uplands in the Quaternary Coastal Plain under the Mississippi coast and adjacent areas. Geomorphic features created by tectonic lineaments mimic landforms that were previously misinterpreted as relict late Neogene and pre-Sangamonian shorelines. However, field work and drill data indicate that only a single Pleistocene marine-parlic complex of Sangamonian Interglacial age survived intensive Coastal Plain erosion associated with prolonged Quaternary uplift. This complex is identifiable along the entire northeastern Gulf of Mexico Coastal Plain. In sharp contrast, thick Pleistocene sequences underlie the northwestern Gulf Coastal Plain with numerous pre-Sangamonian sediment cycles. A wide belt of marine terraces with well-preserved barrier morphology and fossil content also characterize the middle and southern Atlantic Coastal Plain.

Floral assemblages from the Citronelle Formation, and pre-Sangamonian (“Montgomery”-equivalent) Pleistocene logjam-bearing, organic-rich pond sediments behind the Big Ridge fault-line scarp on the central Mississippi coast, suggest climatic conditions that closely resemble the present. Fluvial deposits of that older Pleistocene terrace recently provided luminescence dates of 224 to 202 ka B.P. (Oxygen Isotope Stage, OIS, 7).

Pollen spectra of Sangamonian and recent deposits show great similarity. The Sangamonian cycle consists of three well-defined laterally correlative units: the alluvial Prairie Formation, the discontinuous Gulfport Formation (barrier), and the nearshore-marine to inshore (estuarine) Biloxi Formation. Evidence based on these formations does not support a Sangamonian sea level higher than +20 ft (+6 m) . Post-Pliocene regional uplift of the mainland coast is responsible for the +295 to +360 ft (+90 to +110 m)

maximum elevations of the Citronelle upland surface and +30 to +60 ft (+9 to +18 m) maximum elevations of the Prairie surface.

Of the three Gulfport mainland barrier sectors in Mississippi, the western one is largely buried by Prairie alluvium. Amino acid D/L ratios from Biloxi Formation *Chione* bivalves at different Gulf-wide locations correlate with each other and appear to be consistent with a Sangamonian (OIS 5) age. Luminescence dates from coastal Mississippi and northwestern Florida place the peak-Sangamonian (OIS 5e) Gulfport and Prairie deposits in the 124-90 ka B.P. age range. Locally, correlatives of these units were mistakenly assigned in the past to a Wisconsinan interstade marine highstand.

The late Holocene shoreline may have coincided briefly with the present mainland shore. Thus, the late Holocene Belle Fontaine spit complex, as well as Hancock County's Magnolia Ridge, formed along an open, not lagoonal shore. Intensive barrier growth has narrowed bay entrances (for example, Mobile and Pensacola Bays). The Mississippi barrier island chain has emerged as the islands grew by lateral progradation, thereby initiating Mississippi Sound by separating it from the Gulf of Mexico. Growth of the Mississippi River's St. Bernard subdelta induced the seaward extension of the south Hancock County marshland. The marshland's decay, due to continued Mississippi delta subsidence coupled with slow eustatic sea level rise, has resulted in continuing heavy shore erosion. Recent shoreline retreat degraded the abandoned Escatawpa River delta on the Mississippi-Alabama border.

INTRODUCTION AND STUDY METHODS

A large body of subsurface data, generated at the Gulf Coast Research Laboratory (GCRL) between 1970 and 1995 provides the context for interpreting three continuous USGS coreholes drilled in southwestern Jackson County, Mississippi. Most GCRL drillholes were less than 30 m deep. GCRL has obtained samples from more than twenty southern Jackson County rotary coreholes. These drillholes were located on the late Pleistocene Coastal Plain, adjacent to earlier GCRL coreholes that penetrated the entire Pleistocene interval and the uppermost Neogene. Detailed microfossil studies in these and other cores were undertaken at GCRL. Sample cuttings from deep coastal and offshore gas exploration wells in Mississippi and Alabama have been used to reconstruct the Neogene depositional history (Otvos, 1988a, 1994).

Drill samples were subjected to granulometric and microfossil studies. Where closely sampled and abundant, microfossil assemblages or their absence provide a tool for distinguishing among alluvial, brackish, and marine facies within late Pleistocene and Holocene sedimentary cycles. The assemblages define four facies groups on the basis of depositional salinity (Table 1; Otvos, 1988b). David M. Price (University of Wollongong, NSW, Australia) provided thermoluminescence (TL) dates, and Edward J. Rhodes (University of Oxford, UK) supplied optically stimulated luminescence (OSL) dates.

Table 1. Salinity-range categories (parts per thousand) based on foraminifer assemblages (after Otvos, 1988b).

(1.) Oligohaline - lower mesohaline (about 2-16 ppt)

Dominant (Typical percent of assemblages)
Ammotium salsum (0-100%)
Ammonia beccarii parkinsoniana (0-100%)

Secondary and minor
(Each species usually less than 10-50 percent; several are common in salt marshes)
Ammobaculites exiguus
A. exilis
Ammonia beccarii tepida
Trochammina sp.
Miliammina fusca
Jadammina polystoma
Arenoparella mexicana
Haplophragmoides subinvolutum
H. canariense
Ammoastuta inepta
Thecamoebians

Very few species (1 to 3) dominate each sample.

(2.) Mesohaline - lower polyhaline (about 10 to 26 ppt)

Dominant (Typical percent of assemblages)
Ammonia beccarii parkinsoniana (10-60%)
Ammonia beccarii tepida (10-80%)
Elphidum galvestonense (10-50%)

Secondary
Ammotium salsum (0-20%)
Nonion depressulum matagordanum (0-15%)

Minor (usually less than 5% of total)
Cribroelphidium poeyanum
Palmerinella gardenislandensis
Elphidium latispatium pontium
E. incertum mexicanum

Altogether 15 or less species

(3) Polyhaline - lower euhaline (about 20 to 30 ppt)

Dominant (40-60%)
Ammonia beccarii tepida (10-35%)
Nonion depressulum matagordanum (5-30%)
Elphidium galvestonense (10-30%)

Secondary (30-40%)
(a) Lower salinity subgroup
Cribroelphidium poeyanum (0-10%)

Ammonia beccarii parkinsoniana (0-10%)
Buliminella elegantissima (0-15%)
(significant organic content in sediments also favors this species)
Hanzawaia strattoni (0-5%)

(b) Higher salinity subgroup
Hanzawaia strattoni (0-10%)
Nonionella opima (0-15%)
Elphidium incertum mexicanum (0-5%)

Minor (About 5-10% of total. Each species less than 1%.)
Fursenkoina sp.
Elphidium latispatium pontium
E. advenum
E. sp.
Brizalina lowmani
Quinqueloculina sp.
Triloculina sp.
Guttulina sp.
Cibicides sp.
Nonionella atlantica
Globigerinoides sp.
Globigerina sp.

Very high species diversity.

(4.) Euhaline (about 25 to 32 ppt)

Dominant
Hanzawaia strattoni (15-50%)

Secondary
Elphidium galvestonense (5-20%)
Ammonia beccarii tepida (10-15%)
Nonion depressulum matagordanum (10-15%)

Minor (Each species about 5 to 10%.)
Quinqueloculina lamarckiana
Q. seminulum
Buliminella sp.
Rosalina columbiensis
Nonionella opima
Elphidium incertum mexicanum
Cribroelphidium poeyanum
milliolids

(Each species about 0 to 5%)
Bigenerina irregularis
Textularia mayori
T. agglutinans
T. candeiana
Cibicides floridanus
Cassidulina subglobosa
C. crassa
Reussella atlantica

Elphidium discoidale
Buccella hannai
Trifarina bella
Sagrina pulchella primitiva
Globigerina sp.
Globigerinoides sp.

Highest species diversity

Drill data from more than fifty Mississippi Sound, barrier island, and nearshore Gulf of Mexico coreholes in or near Jackson County supplement the onshore information (Otvos, 1981). GCRL shares Mississippi Coastal Plain and offshore Core Data Inventory (CDI) with the Mississippi Office of Geology computerized database. In addition, drill and field data from five Gulf states provide a broad regional framework for interpreting Pleistocene stratigraphy and Coastal Plain evolution.

GEOGRAPHIC SETTING:

MISSISSIPPI and SOUTHWESTERN ALABAMA COAST

The Mississippi Coastal Plain consists of three coast-parallel terrace units (Fig. 1). Erosional and, at least in part, fault-scarp-related slopes separate the terrace surfaces. A strongly dissected highest surface at +60 to +100 ft (about +18 to +30 m) near the present shore is typically cut by headward-eroding steep gullies and underlain by the Citronelle Formation. The Citronelle surface gradually rises inland to +360 ft (+110 m) elevation in the six-county Mississippi coastal area. Discontinuous, pre-Sangamonian Pleistocene, intermediate terrace sectors adjoin the Citronelle on the south (Fig. 1).

Bounded by Mississippi Sound and its estuarine embayments (St. Louis Bay, Back Bay of Biloxi, Pascagoula Bay, Grand Bay), the lowest coastwise (Prairie) terrace reaches +20 to +25 ft (about +6 to +8 m). Its width, about 0.6 mi (1 km) at the narrowest, ranges up to 30 mi (50 km) along the Pearl River, near Louisiana. Also affected by continuing late Quaternary regional uplift, elevations of the Pleistocene Prairie surface reach +40 to +60 ft (about +12 to +18 m) inland. Cutting across the Pleistocene Coastal Plain, the lowest Quaternary surface is formed by late Holocene floodplains and marshlands. Holocene floodplains and estuarine marshlands are widest along the Mobile, Pearl, and Pascagoula rivers. Fragmented remains of the probably early Wisconsinan ("Deweyville") river terraces, associated with falling sea levels and intermediate in elevation between the Prairie surface and the present valley floor, occur in a few localities in a number of major stream valleys (Otvos, 1985).

The 80-mi-long (130 km) and 5-mi- to 14-mi-wide (8 to 22 km) Mississippi Sound, which is 10 ft (3 m) deep on the average, separates the mainland from an offshore barrier island chain. Late Holocene growth of Louisiana's St. Bernard subdelta resulted in addition of the western Sound basin. While the distances to the offshore islands do not change, the lengths and widths of their intervening passes have undergone dramatic fluctuations in historic times.

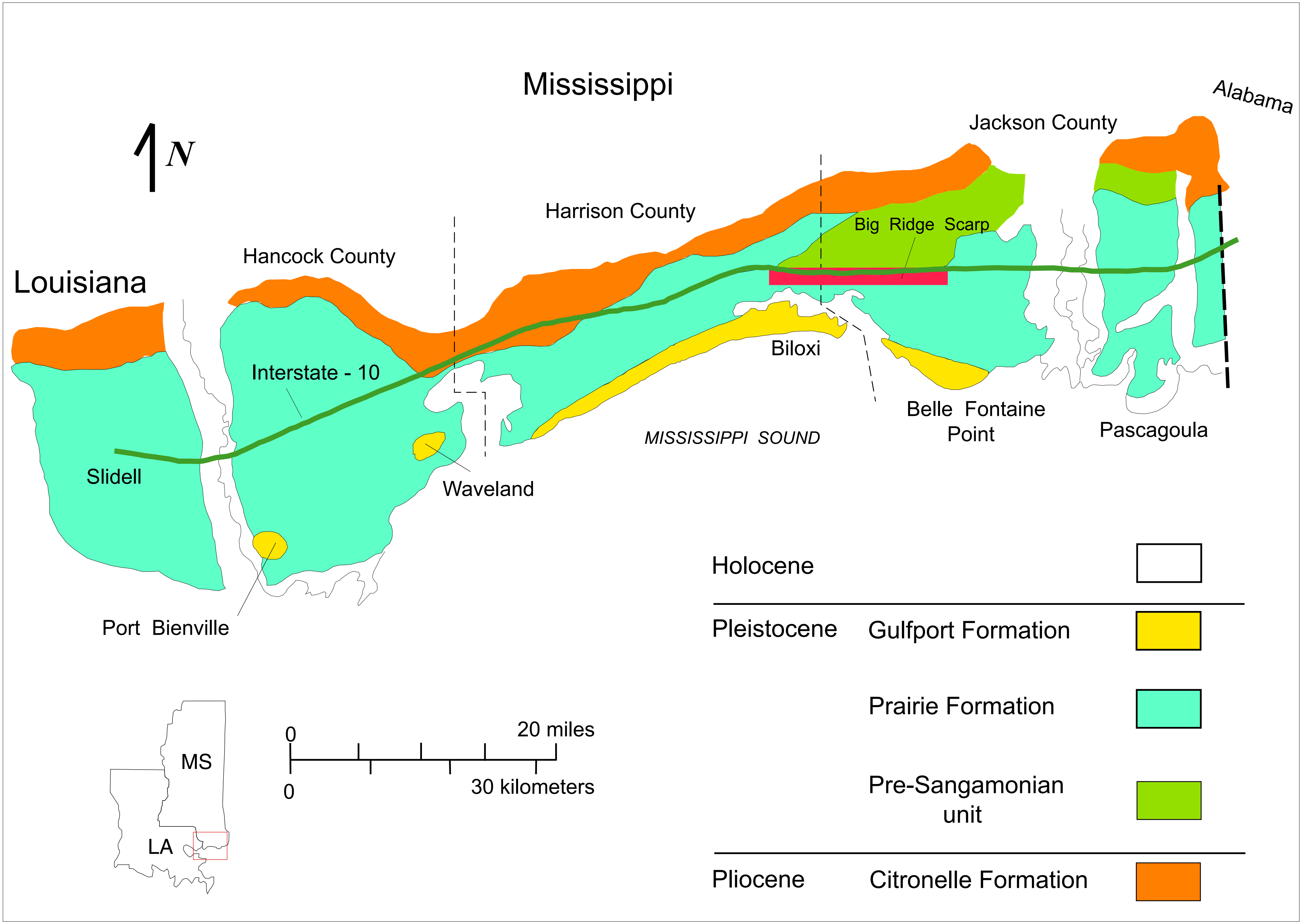


Figure 1. General distribution of Pleistocene units, Mississippi coast.

COASTAL EVOLUTION

Miocene

A maximum 5,000-ft-thick (about 1,500 m) Miocene sequence underlies younger sandy and clayey alluvial-paralic Coastal Plain deposits in Mississippi. Identifiable contacts between nonfossiliferous Miocene units (such as between the Catahoula, Hattiesburg, and overlying Pensacola) in Mississippi are problematic even inland (Li and Meylan, 1994; Meylan and Li, 1995). In the absence of clearly definable and correlatable lithostratigraphic horizons to define and bracket units, the formation names previously assigned to the paralic-alluvial intervals in the coastal area (for example, the Miocene Hattiesburg and Pascagoula and the Pliocene Graham Ferry; Brown and others, 1944) do not appear to be acceptable in Mississippi. Whenever applicable, designation of a Pascagoula Member and a Graham Ferry Member is recommended (Fig. 2). Intervals for which a Miocene or Pliocene age can not be established are designated as "undifferentiated Neogene clastics" (Otvos, 1988a, 1991a, 1994, 1995b).

Until recently, the limey and shaley *Heterostegina* horizon was considered to be the youngest regionally correlatable Neogene unit. With the exception of the thin *Amphistegina* Zone (Gravell and Hanna, 1938), no other Miocene marine units are known from the southern Mississippi mainland area. Thick, inner neritic-to-upper slope siliciclastic sections with local, thin limestone horizons having limited carbonate content recently have been identified in mainland and offshore drillholes. Planktonic foraminifer species played the key role during the past 15 years in identifying their lower to early upper Miocene ages. These sections are associated with two major transgressive cycles in the middle Miocene and the lower upper Miocene (Otvos, 1992, 1994, 1995b) (Fig. 2).

Foraminifer assemblages from well cuttings obtained from the Mississippi Office of Geology archives and elsewhere now indicate that the middle Miocene transgression extended as far as northern Pearl River and George Counties. While marine carbonates had been dominant on the Miocene-Pliocene inner shelf in the eastern and central Florida Panhandle, the upper Neogene deposits gradually become more brackish and overwhelmingly siliciclastic westward under the Coastal Plain.

The siliciclastic Miocene deposits consist of alluvial-terrestrial, nonfossiliferous, stiff to medium stiff, generally greenish-gray, light-olive-gray, dark-greenish-gray, or moderately yellowish-gray muds, sandy muds, clays, and muddy very fine sands. Brackish-water sediment horizons are common. They contain reduced-salinity benthic foraminifer assemblages. *Rangia cuneata* bivalve concentrates and scattered molluscan molds are not uncommon in this interval, which has been redesignated as the Pascagoula member of the Pensacola Formation (Otvos, 1994) (Fig. 2). Appearing first probably in the late middle Miocene, *Rangia johnsoni*-dominated, estuary-influenced nearshore shelf and inshore (bay, lagoon) zones are present in the northern Gulf through late Miocene times. With possible exceptions (Campbell and Otvos, 1992), this small bivalve lived in low-salinity facies and may have survived into earliest Pliocene times.

EPOCH/ AGE		GEOLOGIC UNITS
HOLOCENE		Coastal wetlands, lagoonal, inlet, and delta deposits. Mainland and island strandplains,beach complexes, alluvium. Transgressive and regressive hemicycles preserved in certain estuaries.
LATE PLEISTOCENE	WISCONSINAN	AL and FL: dunes over Gulfport Fm. barrier sectors; LA: Florida Parishes dune clusters. Valley fill alluvium.
	SANGAMONIAN INTERGLACIAL	Prairie Fm. (alluvial) Gulfport Fm. (barier complex) Biloxi Fm. (neritic-to-estuarine deposits)
	GLACIAL	Undifferentiated early and pre-Sangamonian alluvial deposits
PLIOCENE	UPPER	Citronelle Fm. (in uplands only)
	MIDDLE	Perdido Key Fm. (AL-FL border area) Undifferentiated alluvial and marine siliciclastic sediment
	LOWER	Pensacola Fm. Graham Ferry Mbr. Jackson Bluff Fm.
LATE MIOCENE	UPPER	Pensacola Fm. Pascagoula Mbr. Choctawhatchee Fm./Stage (=? part of Intracoastal Fm.)

Figure 2. Quaternary coastal stratigraphy, Mississippi-Alabama (modified from Otvos, 1994).

Intercalated sand and granular sand beds are common in the dominantly clayey and silty siliciclastic sequence that includes numerous oxidized unconformity surfaces that separate sedimentary cycles. Frequent shifts may have taken place in the sediment-supplying drainage network during this time interval. Thick alluvial and shoreline sand units represent the most important artesian aquifers on the Mississippi-Alabama coast.

Pliocene

Paralic-alluvial sequence

The upper part of the Neogene alluvial-paralic section of thick clay and intercalated sand units (Graham Ferry Member of the Pensacola Formation; Otvos, 1994) is underlain by the *Rangia johnsoni*-bearing interval and overlain across a pronounced erosional unconformity by the Citronelle Formation (Fig. 2). In terms of overall lithology, the alluvial-paralic Miocene depositional facies are indistinguishable from the lower Pliocene facies. Unlike Florida, where sharp breaks separate thin marine units, the Miocene-Pliocene unconformity has not yet been located precisely in the thick paralic sequence.

The consistent absence of *Rangia johnsoni* from the uppermost 590 to 650 ft (about 180 to 200 m) of section in Mississippi and Alabama points to the interval's post-Miocene age. The three USGS coreholes on Mississippi's mainland (Gohn and Reinhardt, this volume) and a USGS core on Horn Island bottomed in Pliocene alluvial-paralic sediments. Our foraminifer data reveal that, in addition to the dominant fluvial units, the Horn Island corehole contained several brackish intervals but no open-marine horizons. Greenish-gray and gray, sandy mud beds in the Pascagoula River bluffs and other outcrops contain scattered bivalve molds that provided no age definition (Brown and others, 1944; Otvos, 1985).

Brackish inshore-estuarine beds alternate with fossil-free fluvial deposits. Unpublished seismic profiles from central Mississippi Sound that utilized a 300-3000 kHz frequency range (USGS, 1991-1992) revealed three to four sets of erosional unconformities. These include incised channels in the top 115- to 180-ft (35 to 55 m) interval. Sets of 15- to 50-ft-thick (about 5 to15 m) clinoform sequences filled 790- to 1,575-ft-wide (about 240 to 480 m) stream(?) channels. Comparable foreset beds originally were regarded in part as prograded coastal barrier segments (Otvos, 1985, fig. 20; Oivanki and Otvos, unpublished Mississippi Office of Geology-USGS progress report, 1995).

Pterocarya pollen and and the dinocyst *Impagidinium fenestroseptatum* (Willard and Edwards, this volume) confirm the Pliocene age of at least the uppermost part of the paralic sequence. These fossils occur in the upper Neogene intervals of USGS drillholes BelF No. 1 and OSPD No. 1 (drillholes 16 and 21, Fig . 3). Willard and Edwards' pollen association II at 132 ft (40.3 m) contains 0.33% spruce (*Picea*) pollen in corehole BelF No. 1. Contrary to a tentative Pleistocene age assignment by Willard and Edwards for this *Picea*-bearing interval, its typical stiff, dark-greenish-gray clay lithology indicates a Neogene age. The presence of that cold-climate indicator (*Picea*) in Neogene sediments may be puzzling. However, several Pliocene glacial intervals are known worldwide from the North Atlantic, Alaska, and elsewhere in the far north. As far west as the Mississippi bluffs at Tunica in southeast Louisiana, this unit exclusively contained an East Gulf Province heavy mineral assemblage, without indicators of Mississippi River provenance (Otvos, 1994).

The lower Pliocene Perdido Key Formation of southern Alabama and westernmost Florida, an apparent correlative of the Graham Ferry Member, is the nearest datable marine Pliocene unit on the coast. It correlates with late Neogene southern Mississippi and Alabama intervals (Otvos, 1988a).

Citronelle Formation

Lithology

The northeastern Gulf coastal uplands between Louisiana and coastal Georgia are capped by the regionally very extensive but only 30- to 80-ft-thick (about 10 to 25 m), locally 130- to 200-ft-thick (about 40 to 60 m) Citronelle deposits (Fig. 2). They consist dominantly of bright-orange-red and brownish-yellow muddy sands. Thin, gray and bluish-purple clay and sandy silt beds, very rarely with muddy and sandy layers containing carbonized plant fragments, occur in minor amounts throughout the formation. Numerous papers (among them, Li and Meylan, 1994, p. 390) reported kaolinite as the dominant clay mineral in the Citronelle. Our data (analysis by Dr. D. Darby) from adjacent Alabama and northwest Florida indicate the predominance (74 to nearly 100 %) of kaolinite, with illite (11 to 20%) as the secondary clay minernal. Halloysite, considered a highly disordered form of kaolinite, occured in one Baldwin County, AL clay sample (83%). In sharp contrast with underlying "Hattiesburg" beds, little or no smectite has been encountered in Mississippi's Citronelle sediments.

Citronelle deposits that contain significant bodies of finer grained, laminated lithofacies in northwestern Florida and southern Georgia east of the Apalachicola River have been referred to, without sufficient justification, as a separate (originally upper Miocene) "Miccosukee Formation" (Hendry and Yon,1967). A rather widespread lake sequence of the "Miccosukee" is represented by thousands of alternating, intercalated laminae composed of dark-yellowish-orange fine sand and pale-yellowish-orange clay. In addition, the "Miccosukee" generally includes typical coarse- and fine-clastic lithofacies of the Citronelle. To emphasize the artificiality of the division; the Apalachicola River is used to separate "Miccosukee" deposits on the east from those mapped as Citronelle by the Florida Geological Survey.

Utilizing a vertebrate fauna questionably associated with this lithosome, the "Miccosukee" was first assigned to the Miocene. Based on regional stratigraphy, a Pliocene age for the "Miccosukee" sequence was later applied by Huddlestun (1984, 1988).

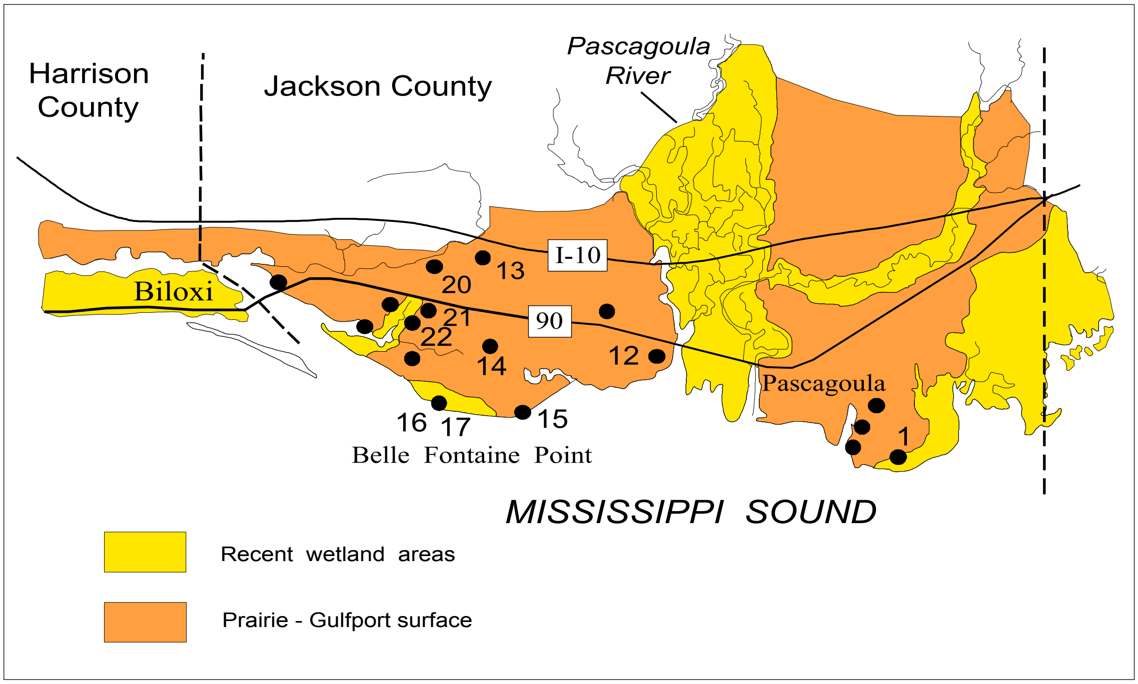


Figure 3. Southern Jackson County drill-core locations (Jackson County CDI serial numbers; exact locations in Otvos, 1991. GCRL cores, unless marked USGS). Coreholes noted in text: 1-Pt. aux Chenes; 12-Shepard State park, Gautier (USGS, 1990); 13-Sunplex Industrial Park; 14-Applewhite; 15-Belle Fontaine Beach East (J. Germany property); 16-Belle Fontaine Beach, west end; 17-Belle Fontaine Beach, west end (USGS, 1990); 20-Toche; 21-Ocean Springs Police Firing Range (USGS, 1990); 22-Palmetto and 6th Street, Gulf Park Estates, Ocean Springs.

Chert, quartzite, tripoli, flint, and jasper pebbles are typical of the Citronelle gravels, which locally display silicified Devonian-Mississippian fossils (Smith and Meylan, 1983). These fossils had originally been part of limestones deposited in the general southern Appalachian region. The Appalachian area was also the source of the eastern Gulf heavy mineral assemblage, which has undergone repeated recycling. Thick Citronelle hardpan ledges, including limonite-cemented, typically granular to gravelly sandstone beds, are quite common in the northeastern Gulf Coastal Plain. Silica- and limonite-cemented sandstone ledges crop out in the nearshore areas of Mobile Bay south of the Weeks Bay entrance and just above mid-tide level in the Perdido Bay bluffs (Marsh, 1966). Similar ledges were encountered in the Dees Pit at Vancleave, Mississippi. Large numbers of eroded Citronelle flagstones were retrieved from Mobile Bay near Fairhope for construction purposes (Otvos, 1995b). The thickest (3 to 5 ft; 1 to 1.5 m), strongly cemented Citronelle sandstone beds occur at the foot of Red Bluff, in the southwest corner of Perdido Bay, Alabama.

A minute hematite content, representing only 5% of the clay-silt film that coats sand grains in the Citronelle, causes the strong diagenetic pigmentation (Otvos, unpublished data). X-ray data by Dr. D. Darby revealed 29.5% kaolinite and 13.3% gibbsite in the film. These findings indicate kaolinitic sediment sources and prolonged exposure to intensive weathering before and during Citronelle deposition.

Citronelle upland elevations reach +245 ft to +360 ft (about +75 to 110 m) only 20 to 37 mi (about 32 to 60 km) inland from the modern shore. The great rise of Citronelle summits and fossiliferous nearshore lithosomes from near present sea level to considerable heights, and the narrowness of the Pleistocene plain (minimum less than 0.6 mi (1 km)) that separates the Citronelle from the shore, indicate steady uplift and seaward tilting of interior areas in post-Citronelle times. Several authors suggest a somewhat similar history for the much wider Pleistocene Atlantic Coastal Plain. Discrete separate Citronelle upland surfaces (Vernon, 1942) may be primarily explained by post-depositional tectonic events (faulting?), rather than subsequent development of aggraded river terraces.

A mottled, leached and iron-enriched ancient oxisoil zone that generally forms the top several feet in Citronelle outcrops includes yellowish-brown root traces, peds, and other paleosol features that resulted from prolonged pedogenic activity. Orange-red pigmentation is typical in the massive near-surface intervals that lack recognizable sedimentary structures. A thick paleopedogenic horizon commonly appears near the land surface. Due to possible groundwater related reduction of pigmentation and intensive coastal erosion, remnants of Citronelle deposits are unrecognizable or absent seaward in the subsurface.

Locally strongly dissected, seaward-sloping upland surfaces form the Citronelle surface at +65 ft to +360 ft (+20 to +110 m) elevations in coastal Mississippi and adjacent areas (Otvos, 1985, 1991a). Occasionally a spectacular erosional unconformity surface (for example,. fig. 1 in Isphording, 1976) is found marking the contact toward underlying Pliocene alluvial-paralic deposits.

Fluvial facies group. The Citronelle consists predominantly of fluvial deposits. Vertical sequences of planar- and trough-cross-stratified, micro- and mesoscale sets of gravelly sands, separated by unconformity surfaces dominate in the scores of outcrops that have been investigated in three coastal states, including Mississippi. Common mottled, gray and red mudclasts, derived through river bank erosion of thin pond and lake muds and clays, typically are finely laminated and have a wet plastic consistency. These intraformational clasts range in size from a few tenths of inches to 1.5 ft (millimeters to 0.5 m).

Sediment textures and structures may help to decide whether braided or meandering streams played the dominant role in the deposition of fluvial Citronelle deposits. Two characteristics appear to argue against meandering streams. First, the Citronelle deposits generally lack readily recognizable lateral accretion features and upward-fining vertical sequences that would readily identify them as point bars. Although point bars are not unique to meandering rivers, they are much more typical of meandering channels than of braided drainage patterns (Davis, 1992). Second, despite the abundance of intraformational clasts in the Citronelle, the general scarcity of silty and clayey overbank deposits indicates braided conditions that did not allow significant vertical accumulation and preservation of lacustrine and swampy floodplain sequences. Instead, thick gravel-rich-sand and coarse-sand beds, alternating with coarse-to-medium sand units that include scattered gravels, commonly occur in the Citronelle lithofacies. Even though pebble size tends to diminish close to the present shoreline, gravel clasts of 3 to 4 in. (7.5 to 10 cm) length do occur even in sand and gravel pits at Perkinston, Mississippi and Flomaton, Alabama, only 25 to 40 mi (about 40 to 60 km) inland from the present seaward limit of the formation. The gravelly sands may have been deposited in shifting and, at low-water levels, sediment-choked multiple channels with an abundance of migrating transverse and longitudinal channel bars.

Estuarine facies. A shallow estuarine and/or nearshore-marine Citronelle facies, interspersed locally with granular-pebbly fluvial deposits, includes typical white-clay-lined burrows and *Ophiomorpha* generally with knobby surfaces. While known earlier east of the Apalachicola River, these burrows were first described by Marsh (1963; 1966, p. 80, 85-86). Marsh reported kaolinitic tubes of callianassid shrimp from Escambia and Santa Rosa Counties of westernmost Florida. Huddlestun (1988) reported fossil burrows from Georgia's Cypresshead Formation, the eastern correlative of the Citronelle. Burrows were described from the "Miccosukee" of southern Georgia and adjacent northwestern Florida as well (Huddlestun *in* Otvos, 1985 and 1988; Johnson, 1989).

Ophiomorpha-rich lithofacies underlie the coarse-to-medium sandy, locally muddy-sandy alluvial Citronelle sequence at Magnolia Bluff on Escambia Bay. Outcrops that display a few burrows of ghost shrimp and polychaete worms are located close to Mobile Bay's eastern shore in Alabama (Otvos, 1997b). Several densely tunneled, spectacular ichnofossil sites recently have been encountered in Walton, Washington, and Escambia Counties of the central Florida panhandle (Otvos, 1997b). A very rare, well-sorted, subtidal sandy shoreface or bar lithosome is associated with the burrows in the Rolling Hills Road landfill pit, western Pensacola, Florida.

Small diameter (0.5 in. (1 cm) and smaller) circular burrows of unknown origin also occur in southwestern Alabama and southern Mississippi, whereas *Ophiomorpha*, both kaolinite-lined and unlined, and other ichnofossils of demonstrably marine or brackish origin are absent from that region.

In addition to a variety of internal molds of veneride and other shallow-marine bivalves, the slightly granular, kaolinitic, medium-sand unit at Mossy Head, Walton County, also contains a great abundance of *Ophiomorpha* and smaller diameter polychaete tubes. These tube-bearing white sands are several feet (meters) thick at the base of the Diamond Sand Company pit (SW 1/4, sec. 21, T3N, R21W), Mossy Head, Florida (J. Bryan, pers. comm. and author's field data, 1995-1996). Prolonged weathering eliminated all remnants of calcareous and other body fossils from the trace-fossil-bearing interval. The typical medium sands and fine pebbly sands of these tube-bearing estuarine deposits suggest that these estuaries were located in the proximity of river mouths that conveyed coarse detrital sediments to muddy bays and lagoons.

Preliminary data indicate that, between Perdido Bay and De Funiak Springs, Florida, the fluctuating early late Pliocene Citronelle estuarine belt and the mainland shoreline extended landward of the location of Interstate Highway 10. East of the Apalachicola river, the estuaries reached well into Georgia.

At Pensacola, Marsh (1966, p. 85) misinterpreted a shallow, fossil-rich, nearshore interval in the shallow subsurface as marine Citronelle. That unit belongs to the late Pleistocene Biloxi Formation instead.

<u>Vegetation and climate</u>. Initial pollen data (Marsh, 1966, p. 82) and other plant-fossil and molluscan data (Marsh, 1966, p. 85) have been advanced inconclusively to support an early ("pre-glacial") Pleistocene age for the Citronelle. Two new pollen samples have been analyzed from this unit.

Berry (1916) described pine, oak, birch, ash, and water gum from Citronelle deposits. Three of eighteen plant species from north of Mobile, Alabama and near Perdido Bay suggested to him the Pliocene age of the Citronelle flora. A review of Berry's work, however, casts doubt on the validity of his identifications (D.L. Dilcher, written comm., 1994).

The Citronelle also contains carbonized plant lenses and silicified tree logs, deposited originally as logjams in ponds and backswamps of coalescing floodplains. Diagenetic silica replacement of woody tissues petrified the logs. A comprehensive study of available petrified logs eroded out of the Citronelle, and pollen analysis of additional organic-rich sediment samples, remain a task for the future. Evaluation of macroflora elements, petrified tree logs, and pollen in the Citronelle Formation would contribute to a much better understanding of the climate and age issues.

Marsh (1966, p. 82-83) reported predominant pine and grass plus additional aquatic *Eriocaulon*, sundew, and bog moss, as well as sweet gum, holly, hemlock, walnut and other pollen from carbonaceous clay beds in the Citronelle of northwestern Florida. In addition to the dominant pine and oak, a fairly varied bottomland pollen assemblage, including the fresh-water marsh form *Sagittaria,* in a Citronelle backswamp peat lens in the Vancleave pit of southern Mississippi (Table 2, sample 1) represents a flora similar to the present (Otvos. 1995).

On a regional basis, the early Pliocene was characterized by the warmest temperatures of the last 7 m.y. (Kennett, 1995). Globally, the mid-Pliocene was also a warm period (Leg 151 Shipboard Party, 1995). During Yorktown deposition, which correlates at least in part to the Citronelle time interval, temperatures in coastal Virgina were 2 to 2.5 degrees Centigrade warmer than today (Cronin and others, 1993). Willard and others (1993) have shown that between about 3.5 and 1.0 Ma following a cooler interval, the land and ocean water temperatures in the west-central Florida panhandle periodically were comparable with those of present south Florida.

<u>Age problem: Vertebrate and pollen dating</u>. The generally finer grained, laminated "Miccosukee" of northwest Florida and south Georgia, mapped earlier as Citronelle, was miscorrelated and described by Hendry and Yon (1967) as a separate upper Miocene formation. However, this age designation was based on a Barstovian vertebrate assemblage (Olsen, 1963), the Ashville local fauna, which apparently is derived from a bed that underlies and predates the Citronelle-"Miccosukee" interval (Huddlestun, 1988, p. 128-129). More recent vertebrate work that places the fauna in the middle Miocene, at about 12-13 Ma (Tedford and Hunter, 1984; Hulbert, written comm., 1996), confirms this assumption.

"Miccosukee" beds, here considered as consisting of partly finer grained deposits within the Citronelle Formation, are correlative with and in part overlie age-dated lower upper Pliocene deposits, the nearshore-marine Jackson Bluff Formation in the eastern panhandle region (Tedford and Hunter, fig. 4, 1984; Huddlestun, 1984, 1988, p. 116 and 128). The Jackson Bluff consists of fossil-rich, calcareous, sandy clays deposited on the inner shelf. Its relationship toward the overlying Citronelle ("Miccosukee") beds may be locally gradational or unconformable. East Georgia's littoral-paralic Cypresshead Formation, another Citronelle-"Miccosukee"-Jackson Bluff correlative has been dated at 2.2 to 2.5 Ma (Huddlestun, 1988). A more precise dating of the Citronelle time interval by vertebrate finds is not yet feasible. The Hemphillian Mobile-Mauvilla Local Fauna came from muddy upper Neogene, pre-Citronelle deposits in southwestern Alabama (Isphording and Lamb, 1971). Tedford and Hunter (1984, p. 140) and Hulbert and Whitmore (1997) place these fossils in the early Hemphillian interval, at about 6 to 7.5 Ma. This date corresponds to a late Miocene age (Berggren et al., 1995).

The Tunica Hills vertebrate fauna of southeastern Louisiana collected from creek-bed alluvium (Manning and MacFadden, 1989) is assumed to have been reworked either from upper Neogene muddy paralic-alluvial beds or the overlying Citronelle. Because of

Table 2. Pollen spectra of Pliocene and Quaternary alluvial units, Mississippi Gulf Coast. Sample designations - Pliocene: 1-Backswamp peat, Dees Pit, sec. 21, T6S-R7W, Vancleave, Jackson County. Pleistocene: 2-Pre-Sangamonian peaty and clayey backswamp deposits, Lamey Pit, NW 1/4 sec. 34, T6S-R9W, Jackson County; 3-Backswamp peat in Prairie Formation, Gravel Pit Road, landfill excavation, Stennis Space Laboratories, Hancock County; 4- Lignitic backswamp alluvium, SE 1/4 R17W-T7S, Stennis Space Laboratories, Hancock County; 5- Backswamp peat, Big Creek Road Pit, east of Wolf River, NW 1/4 sec. 28, R28W-T7S, Harrison County. Holocene (marsh surface sediments, comparison samples): 6-Clermont Harbor, Hancock county; 7-Halstead Bayou, Jackson County; 8-Heron Bayou, Jackson County. Analyzed by D.A. Willard (USGS) (1, 2), Linda E. Heusser (3, 4), and A. Lee Meyerson (5-8).

Group Names	Common Name	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8
Pinus	pine	44.86	54.23	51.00	42.00	67.30	16.90	32.40	46.00
TCT	cypress/cedar	4.67	10.95	2.00	3.00	6.30	0.00	0.00	0.00
Quercus	oak	20.56	12.44	11.00	11.00	8.20	18.20	32.40	24.00
Sciadopitys	Japanese umbrella pine	0.93	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Betula	birch	2.80	0.50	0.00	0.00	3.00	0.00	6.90	12.00
Salix	willow	1.87	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fraxinus	ash	1.87	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Castanea	chestnut	0.93	0.00	0.00	0.00	0.60	0.00	0.00	0.00
Corylus	hazelnut	1.87	0.50	0.00	0.00	0.00	0.00	0.00	0.00
Liquidambar	sweet gum	0.00	2.49	2.00	3.00	0.00	0.00	0.00	0.00
Nyssa	water gum	0.00	3.98	3.00	2.00	3.10	1.30	2.00	0.00
Alnus	alder	0.93	0.50	0.00	1.00	0.60	1.30	0.00	0.00
Cheno-Ams	salt worts	1.87	0.00	4.00	3.00	0.00	2.60	1.00	0.00
Poaceae	grasses	10.28	4.48	0.00	0.00	0.00	0.00	0.00	0.00
Ambrosia	ragweed	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
Fagus	beech	0.00	0.00	2.00	1.00	0.00	0.00	0.00	0.00
Ulmus	elm	0.00	0.00	0.00	2.00	0.00	0.00	0.00	0.00
Ostrya	hophornbeam	0.00	0.00	1.00	3.00	0.00	0.00	0.00	0.00
Gramineae	--	0.00	0.00	13.00	19.00	5.00	39.00	10.80	7.30
Compositae (Asteraceae)	composites	2.80	0.50	0.00	0.00	0.60	19.50	6.90	6.00
Ericaceae	heaths	0.00	0.50	8.00	4.00	0.00	0.00	0.00	0.00
Cyperaceae	sedges	3.74	2.49	0.00	0.00	1.30	1.30	2.00	0.70
Labiatae	mints	0.00	0.50	1.00	5.00	0.00	0.00	0.00	0.00
Ilex	holly	0.00	4.98	1.00	0.00	0.60	0.00	2.90	3.30
Carya	hickory	0.00	0.00	0.00	0.00	0.60	0.00	2.00	0.70
Plantago	plantain	0.00	0.00	0.00	0.00	2.50	0.00	0.00	0.00
Umbelliferae	parsley family	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00
Total Pollen Grains		**107**	**201**	**250**	**250**	**159**	**77**	**102**	**150**

the assigned 7 to 4.5 m.y. age (R.C. Julbert, written comm., 1996), the vertebrate matter must have originated in upper Miocene beds. Northwestern Florida and Georgia correlations and core work, based on late Pliocene pelagic microfossil zones refute the Citronelle's early Pliocene age (Huddlestun, 1984, 1988).

Thus far the very rare *Sciadopitys* (Japanese umbrella pine) pollen, found in a peat lens of the Russel Lane pit at Vancleave, Mississippi (one grain; Table 2, sample 1) and in the cited Mossy Head pit, Florida, are the only Citronelle fossils to prove the Pliocene age. Another Vancleave lignite sample of a lower total pollen count did not include this taxon. The *Sciadopitys* pollen (three grains, without signs of reworking) in the Florida panhandle were identified by D.A. Willard (USGS) from a thin organic-rich clay layer in the lower mid-Citronelle interval of the Diamond Sand Company pit, Mossy Head, Walton County. This temperate-climate genus, known on this continent since the Miocene and present in the correlative Yorktown Formation of southeastern Virginia (Cronin and others, 1993), became extinct in North America by the end of the Pliocene (deVernal and Mudie, 1989; Groot, 1991; D.A. Willard, USGS, written commun., 1994, 1996).

Significant uplift of Citronelle surfaces and the formation's intensive diagenetic alteration, that requires a warmer climate, also favor a late Pliocene age.

<u>Enclosed surface depressions</u>. Citronelle uplands are peppered by a multitude of 150- to 2,800-ft-long (about 45 to 850 m), usually circular to elliptical closed depressions (Otvos, 1976, 1985). Their distribution extends from southern Alabama, across coastal Mississippi and into southeastern Louisiana (Figs. 4a, b). Even if most of these depressions rarely hold standing water, the terms "Grady soil" or "pond" have long been in use by pedologists (e.g., Moon and Bacon, 1932). This name, used for depressions probably of a somewhat different genesis, originated in Grady County, southwestern Georgia. That county is located along the fringe zone of the Carolina bays region (Prouty, 1952), adjacent to the Citronelle-covered karst belt (Fig. 4). Wind, as well as pond waves were most likely responsible for these oval "bays", formed primarily on Pleistocene Atlantic Coastal Plain surfaces.

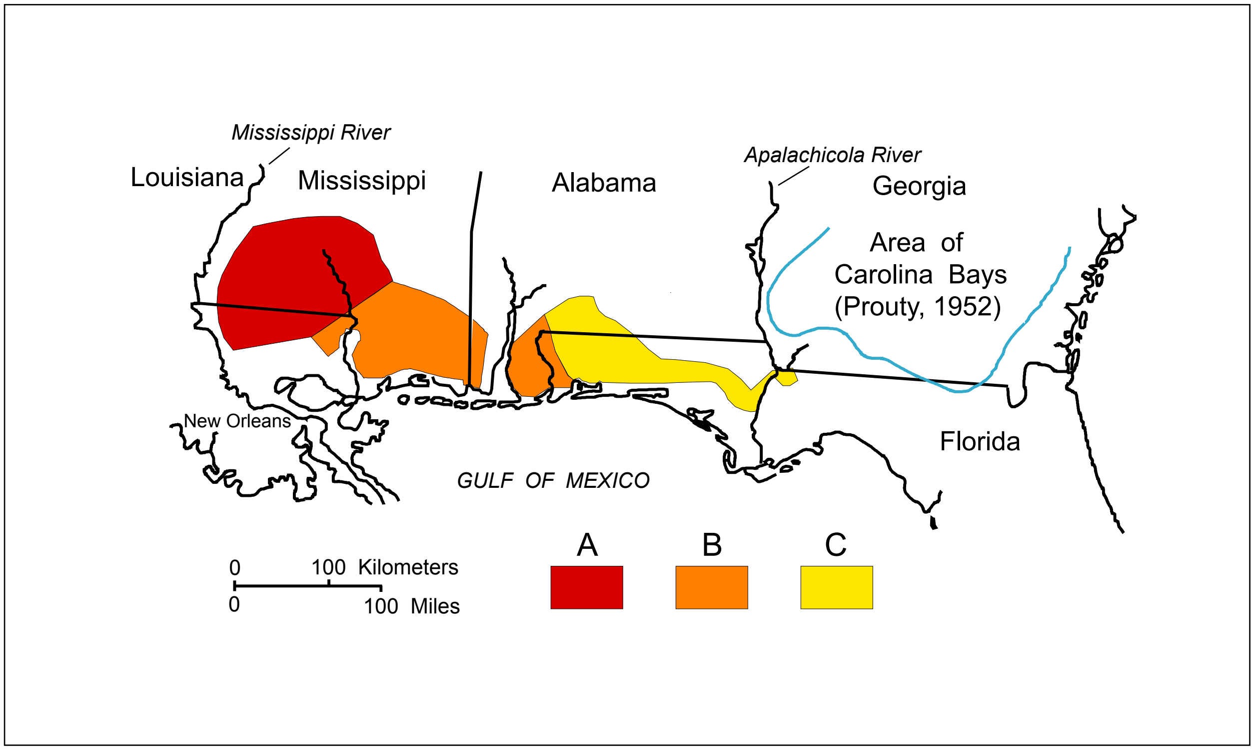


Figure 4. (a.) Distribution of enclosed eolian and other surface depressions on the Citronelle surface, northeastern Gulf Coast (modified from Otvos, 1976). (A) Citronelle surfaces without depressions. (B) Citronelle surfaces with eolian depressions. (C) Surface depressions over covered karst.

(b.) Eolian depressions between Daphne and Belforest, Baldwin County, southeastern Alabama, secs. 15, 16, 21, and 22, T5S-R2E. USDA aerial photograph, October, 1966.

The much larger and less rounded depressions in the eastern Citronelle area of northwestern Florida appear to be mostly of covered-karst origin (Otvos, 1976). However, the well-defined basin orientation in south Mississippi, Alabama and the adjacent Florida panhandle indicate deflation origins associated with a drier late Pliocene or early Pleistocene climate phase.

Following record warmth during earlier Pliocene times, temperatures and sea level dropped significantly during the last several hundred thousand years of the Epoch (Cronin and others, 1993; Wilson, 1994; Nelson and Carter, 1994). In addition to Alaska, late Pliocene glaciation also occurred in Iceland (Geirsdottir and Eiriksson, 1994). As in the Pleistocene, the colder intervals at lower latitudes may have translated into dry climate episodes with pronounced wind activity. Paleoclimatologically, it is signficant that, except in the coastal Wisconsinan dune fields of northwest Florida, closed depressions are absent from northeastern Gulf coastal surfaces of Quaternary age.

Pleistocene

Early and new stratigraphic concepts: Problems of coastal terrace correlation

The antiquated concept of four glacial periods and three interglacial periods that orginated in the Alps early in this century, survives to this day in Gulf Coast literature (for example, Wornardt and Vail, 1991). Advances in deep-ocean stratigraphy and refinements in continental glacial subdivisions have rendered that notion obsolete. The number of recognized interglacial stages has increased and certain old subdivision terms (for example, Nebraskan, Kansan, Yarmouthian, etc.) were long purged from the literature of glaciated areas (Fig. 5; Richmond and Fullerton, 1986).

In an attempt to trace Atlantic terraces to the Gulf coastal Plain, Cooke (1939) and his followers mistakenly correlated south Atlantic coastal barrier-lagoonal terrace sequences with topographic-tectonic features (level alluvial terrace surfaces, fault and rectilinear joint lineaments, erosional interfluve ridges) in alluvial Neogene and Quaternary deposits of northwestern Florida, Alabama, and Mississippi (Otvos, 1972, 1991a, 1992, 1995a). Cooke and others thus inferred multiple Pleistocene shoreline trends as far west as the Mississippi embayment.

Compared with the thick Louisiana-Texas Pleistocene marine-paralic sequences, and extensive Atlantic coastal barrier complexes, only fragments of presumably alluvial (and eolian?) pre-Sangamonian Pleistocene lithosomes remain on the northeastern Gulf Coast. These occur at several localities between the Mississippi River and the Apalachicola Delta region. Light-colored sandy deposits of different and often limited extent and thickness, without recognizable evidence for their depositional environments, occur at several northeastern Gulf Coastal Plain locations, including the Apalachicola Delta region. These deposits also overlie Citronelle, Citronelle-"Miccosukee", and Pleistocene deposits (Otvos, 1985; P.F. Huddlestun, Georgia Geologic Survey, pers. comm.).

In sharp contrast with the extensive, very well developed, barrier-strandplain-lagoon terraces of the southern Atlantic Coastal Plain, the Gulf coastal terrace fragments also reflect the effects of steady post-Pliocene uplift. Accompanied by intensive erosion of Coastal Plain units, the uplift has long eliminated even vestiges of identifiable old marine lithosomes. Pre-Sangamonian Pleistocene "marine terrace" designations therefore are without merit (Otvos, 1991a; 1995a).

Pre-Sangamonian Pleistocene deposits of coastal Mississippi

Elevated pre-Sangamonian deposits locally form fragmented coastal surfaces that are intermediate in elevation between the Sangamonian Coastal Plain and the Citronelle surface. Brackish-inshore and marine deposits are absent here. The deposits are correlative with Fisk's intermediate Montgomery ("Irene") terrace of coastal Louisiana – southeast Texas (Otvos and Howat, 1992). At Black Creek Reservoir and in Big Ridge Terrace (Lamey Pit), Jackson County, Mississippi, sands in this terrace were luminescence dated at 224 to 202 ka B.P. (Otvos and others, 200).

The largest intermediate terraces occur northwest of Belle Fontaine Beach in southern Jackson and Harrison Counties. They extend parallel to the modern shore for 12.5 mi. (20 km) (Fig. 1). Their level surface at +40 to +50 ft (+12 to +15 m) elevation,

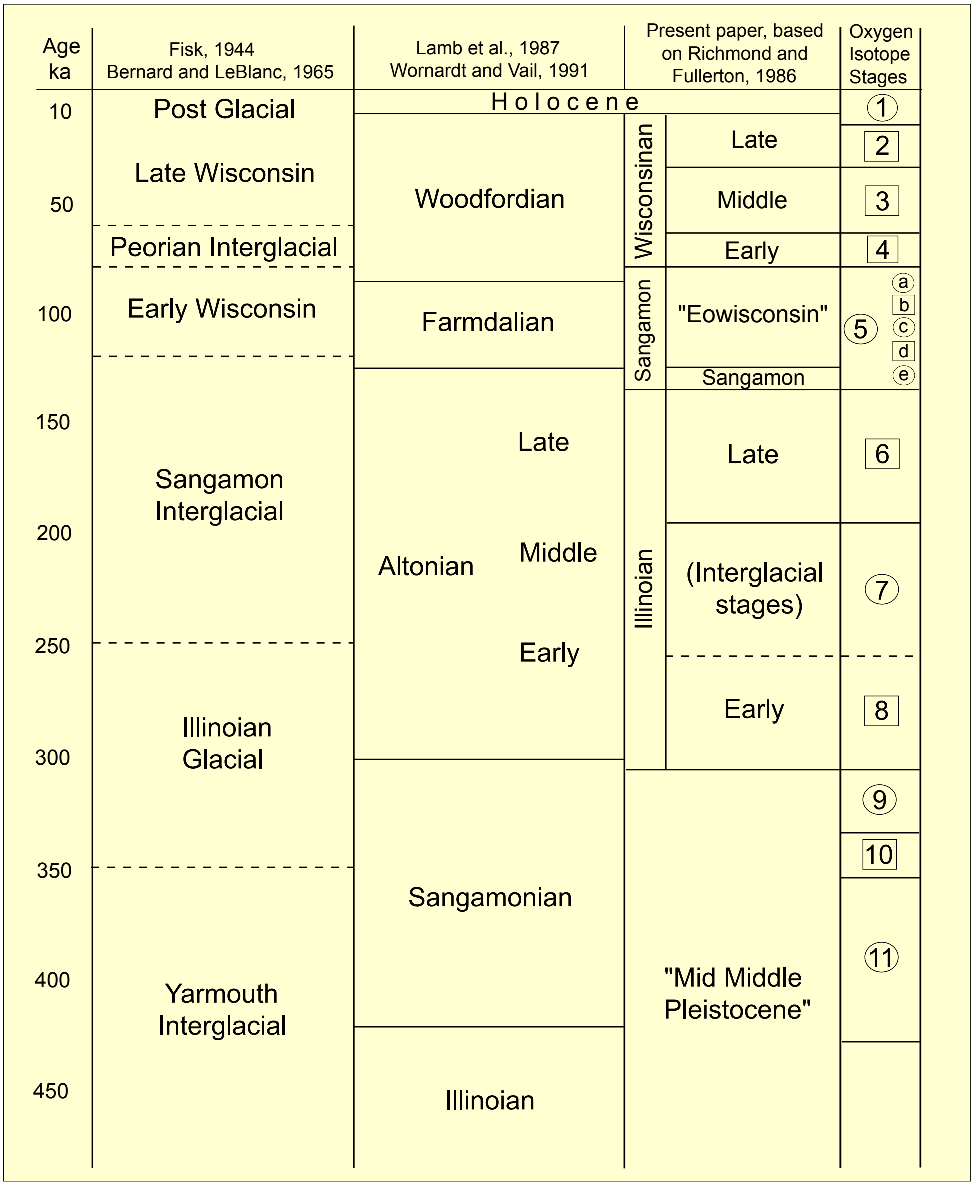
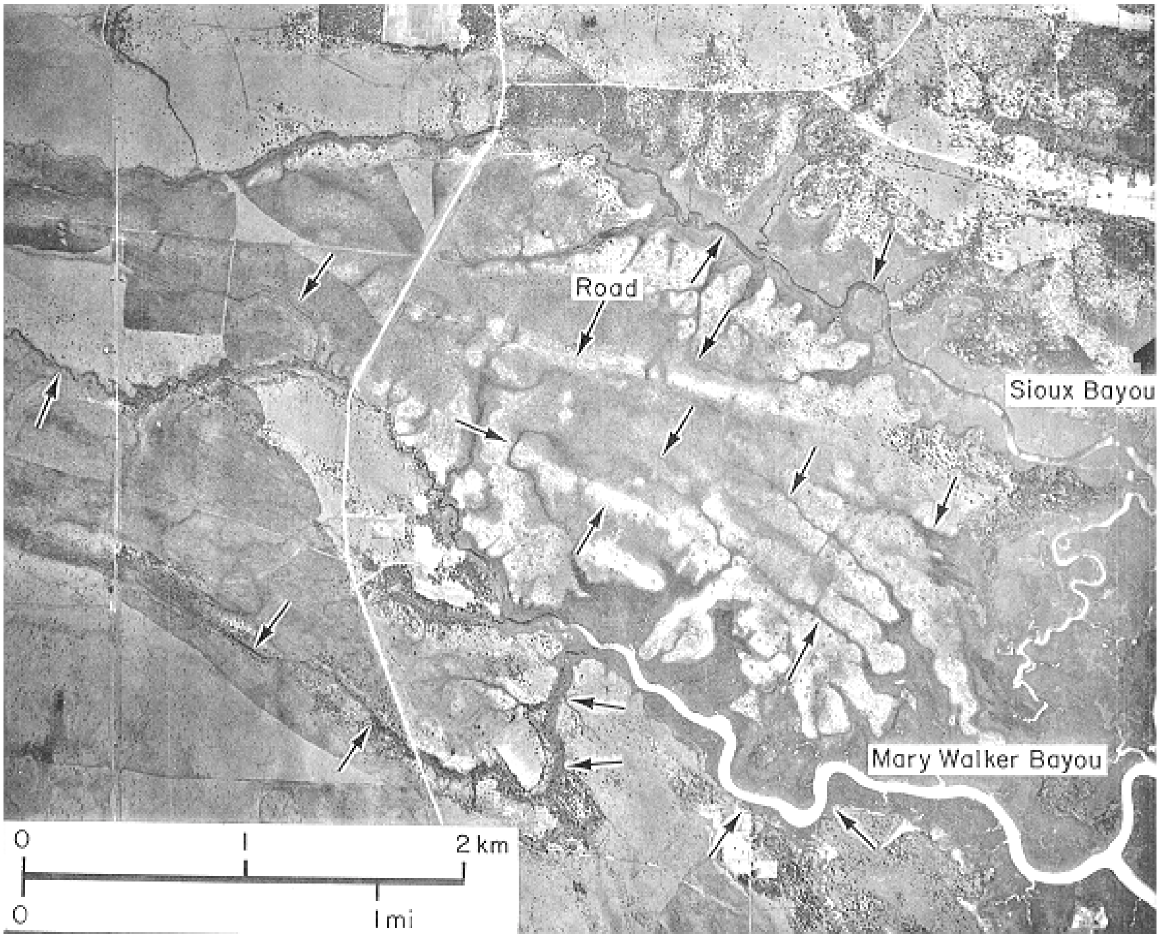


Figure 5. Changes in late Pleistocene chronostratigraphy, 1965-1991. Oxygen isotope stages and substages: circle = warm, square = cold. Columns for present paper and oxygen isotope stages based on Richmond and Fullerton (1986)

rises 23 to 26 ft (7 to 8 m) above the younger Prairie surface, which is adjacent on the south. A prominent, gently arcuate, 15- to 20 ft-high (4.5 to 6 m), eroded faultline(?) scarp (thought by earlier authors to be a "wave-cut bluff") bounds this alluvial unit at its seaward margin. This elevated terrace rim is known as the "Big Ridge" (Figs. 1, 6a,b). The inactive Lamey borrow pit (NW 1/4, section 34, T6S-R9W; Jackson County) exposed 20 to 23 ft (6 to 7 m) of parallel- and cross-laminated, poorly sorted, silty and muddy fine sands with few laminated clay beds and peaty clay lenses. These are partly carbonized, yellow-pine logjam deposits (fig. 6). The clay beds, including finely disseminated, dark organic matter, formed in lacustrine-backswamp floodplain environments (Otvos, 1985).

Figure 6. (a.) West end of Big Ridge Scarp, Harrison County. Landward view from Prairie surface.



(b.) East end of Big Ridge Scarp (hachured line). Arrows point fo fine-textured, rectangular drainage lineament pattern incised in the older Pleistocene (north of scarp, northwest of Old Fort Bayou) and to the Prairie surface (elsewhere). USDA aerial photgraph, 1942.

Floral elements, primarily pollen, suggest that the climate during depositon of the intermediate-terrace deposits strongly resembled that of the Sangamonian Interglacial and the present. In addition to predominant pine and oak, water gum and sweet gum occured in significant percentages (Table 2). A semiquantitative review of a few samples by Dr. Kam-biu Liu confirmed the predominance of yellow pine, lesser concentrations of oak and several other extant arboreal taxa, including *Carya*, *Ilex*, *Liquidambar*, Castanaea, and *Myrica*. Numerous carbonized, in part flattened cones from the clayey backswamp facies were assigned to *Pinus elliottii* (slash pine; an alternate assignment to *Pinus serotina*, pond pine, is less likely), and *Pinus glabra* (spruce pine), which is presently less frequent in the general area. (The pine cones were identified by Dr. Tom Wendt and Robert Kral). The specimens have been deposited in Louisiana State University's Herbaria, Baton Rouge, under accession numbers 87,743 through 87,755.

Except for floodplains, hard pine species overwhelmingly dominate present Gulf Coast forests. *Pinus elliottii* often occurs with live oak, and *P. glabra* currently grows scattered and intermixed with hardwoods on more elevated floodplain forests and upland slopes.

Sangamonian Units

Sangamonian barrier sands and associated deposits represent the only proven Pleistocene marine-estuarine deposits, and the sole coastal-marine sediment cycle, in this region (Otvos, 1972, 1985). In recent decades, abundant and consistent radiometric dates, and to some extent amino-acid-ratio-zones (Toscano and York, 1992) established the age range of the Sangamonian Interglacial on the global scale (Fig. 5). Sangamonian coastal deposits are widely recognized on the Atlantic and Pacific coasts as well. At the start of the Sangamonian transgression, the Gulf sea level on Florida's Apalachicola coast stood at -120 ft (about -37 m) and possibly even as low as -157 ft (-48 m) (Otvos, 1992). Deposition of muddy and sandy, marine and estuarine sediments of the Biloxi Formation (Otvos, 1972, 1985) accompanied subsequent sea-level rise. Coalescing floodplains constructed the Prairie Formation before, during, and after barrier progradation (Fig. 1).

According to recently acquired luminescence dates, Wisconsin-age aggradation of the Prairie Formation and Prairie coastal plain did continue or resume between ca. 50 and 30 ka B.P. along certain coastal streams in Louisiana (Otvos and Price, 2001). The dimensions and exact extent of this floodplain aggradation are not yet known.

The Prairie Formation was re-designated in southwestern Louisiana (Otvos, 1991b) as the lowest shore-parallel Pleistocene unit. It underlies the coastwise Prairie terrace surface described by Fisk (1938) in Louisiana. Fisk and his followers defined the Prairie and older terrace "formations" only by their respective overlying land surfaces. Prairie alluvium continued to be deposited during both the transgressive and regressive stages. Overlying the Biloxi in Hancock County, Mississippi (Fig. 1), the Prairie alluvium also overlies the Gulfport Formation (coastal barriers). Mississippi-River province heavy mineral spectra of the Gulfport in south Hancock County indicate (Otvos, 1985) that, although westward sediment movement by littoral drift dominated, limited transport in the opposite direction had also taken place from Louisiana.

The Gulf sea level reached about +20 ft (+6 m) between 125 to 122 ka. During this highstand and the early stages of the subsequent regression, barrier strandplains prograded seaward from the edge of the Prairie Coastal Plain (Otvos, 1972, 1991a). Named the Live Oak (later Ingleside) barrier in Texas (Price, 1933; Otvos and Howat, 1996), the barrier sands are less extensive and generally not as well sorted as on the northeastern Gulf coast. Strandplain morphology on the Apalachicola coast suggests distinct erosional truncation surfaces between barrier sets of slightly different ages (Otvos, 1992).

It has been suggested informally that because of their close inter-relationship, the three Sangamonian formations (Prairie, Gulfport, Biloxi) should be treated as members of a single formation. However, each unit, compatible with formation rank, is a discrete entity and mappable on the scale of 1:25,000. There are striking contrasts in sediment characteristics, and fossil content or lack of it, among these formations. At most, only two of them, usually the Biloxi and either the Gulfport or the Prairie (Figs. 7a,b), appear in vertical combination at a given location. In certain onshore and offshore drillholes, the Prairie and the Biloxi occur alone. Combination of the three Sangamonian formations into one thus would create an artificial and impractical stratigraphic entity.

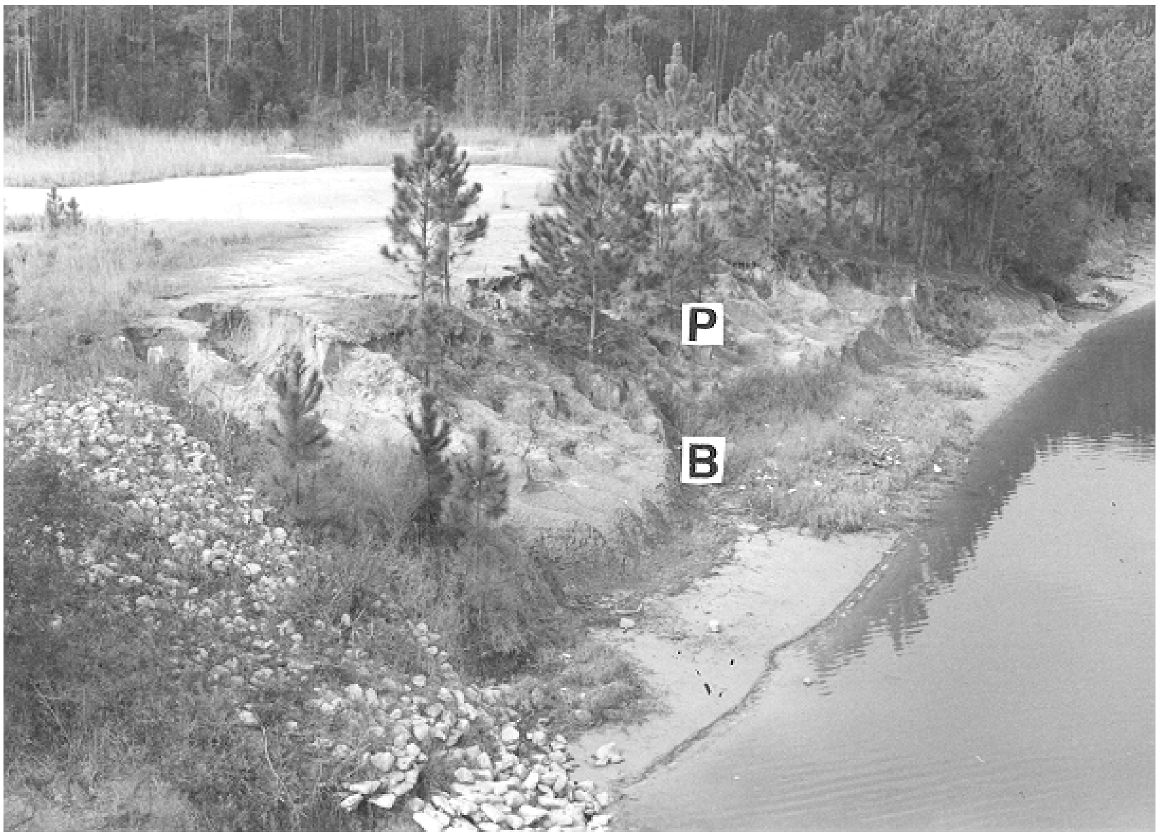
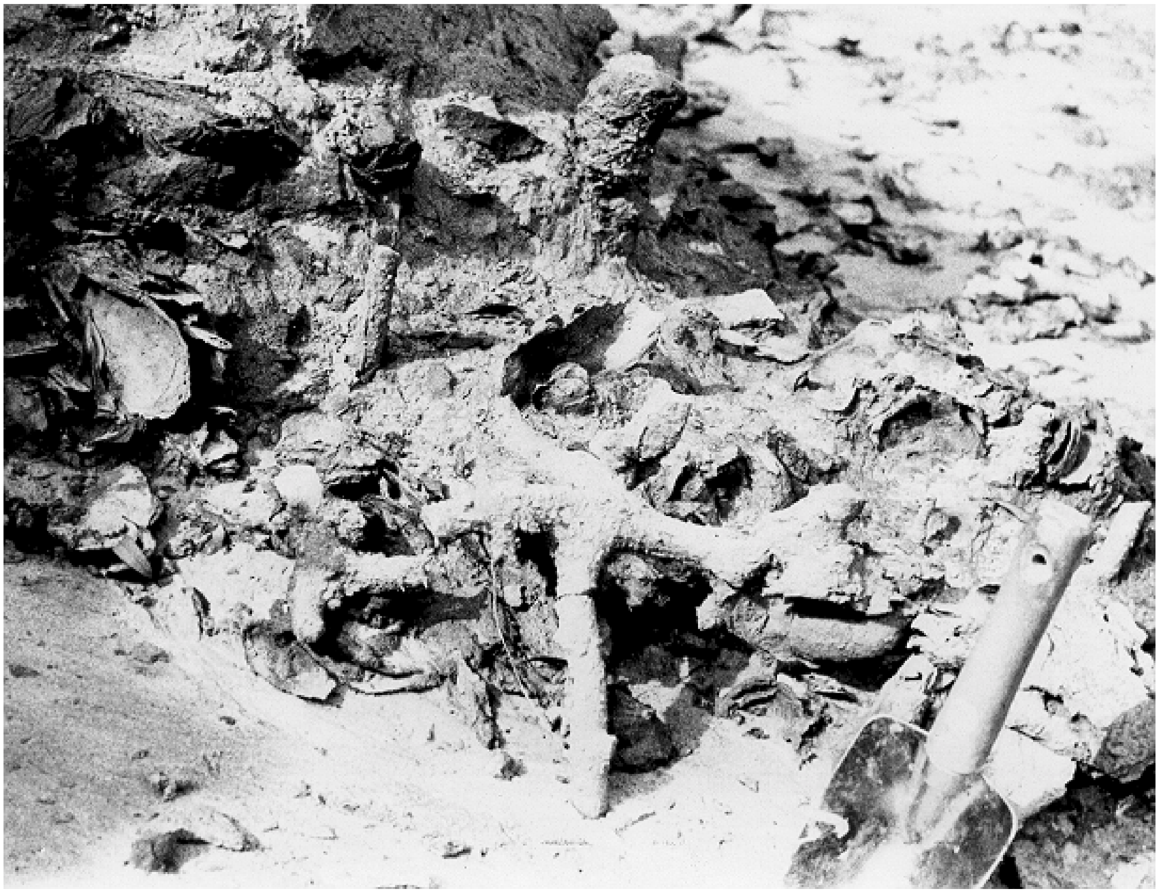


Figure 7. Biloxi Formation and Prairie Formation outcrops in south bank, Industrial Seaway at Lorraine Road bridge, Gulfport, Mississippi. (a.) Dark-gray Biloxi clay (B) overlain by Prairie silty sand (P).

(b.) Sandy and pebbly Prairie Formation river-channel deposits, Gulfport, Mississippi. Channel cut into gray, estuarine Biloxi clays. Biloxi-Prairie relationship is in part erosional and in part conformable.



(c.) ***Upogebia*** **shrimp burrow casts in limonitized** ***Crassostrea virginica*** **oyster reef, bank bottom (hand shovel for scale).**

Biloxi Formation and Fauna

Described first in Mississippi (Otvos, 1972, 1991a, 1997a) and subsequently correlated from southwestern Texas to northwest Florida coastal areas, the sandy and muddy Biloxi Formation represents transgressive and regressive marine and brackish-inland phases of the last interglacial sedimentary cycle (Figs. 2, 5, 8, 9a,b). Several chapters in this publication deal with various groups of Biloxi biota encountered in corehole USGS-Belf No. 1 on Belle Fontaine Point.

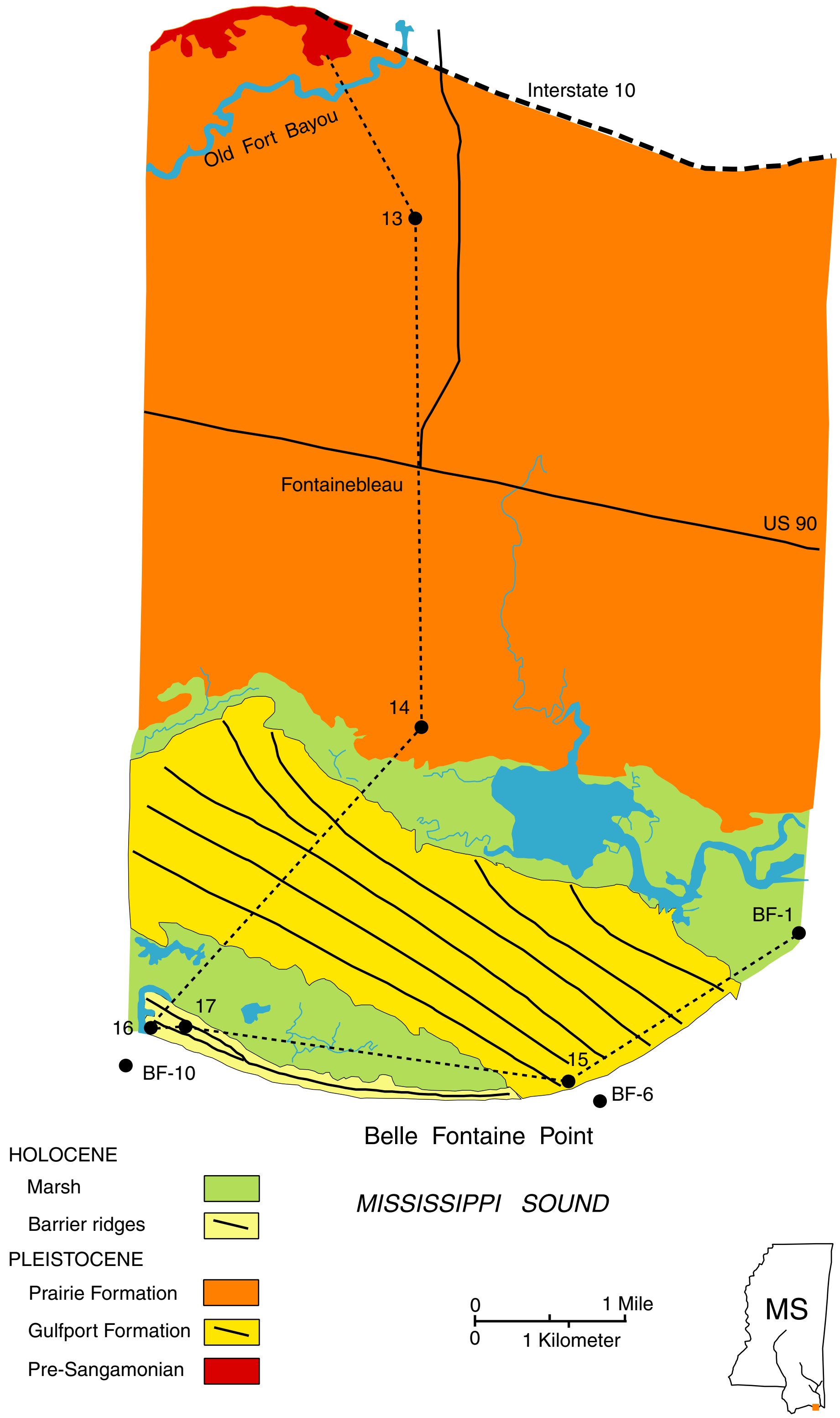


Figure 8. Southwestern Jackson County surface geology and locations of coreholes and cross-section lines. BF = Mississippi Office of Geology vibracore locations.

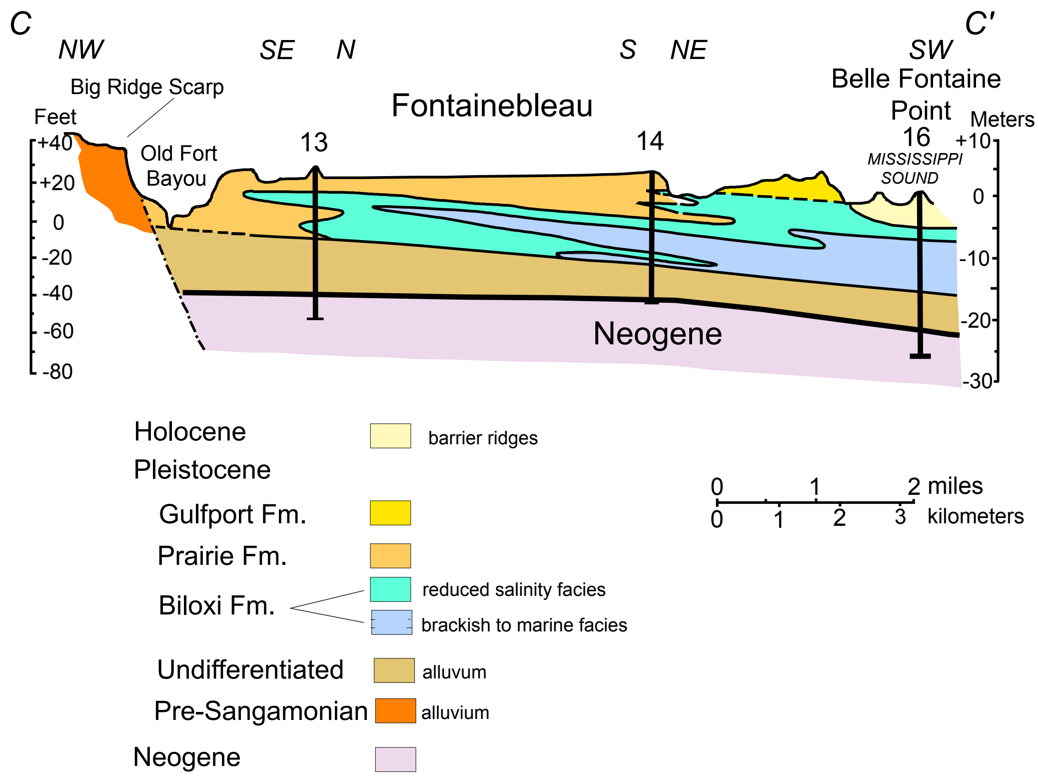
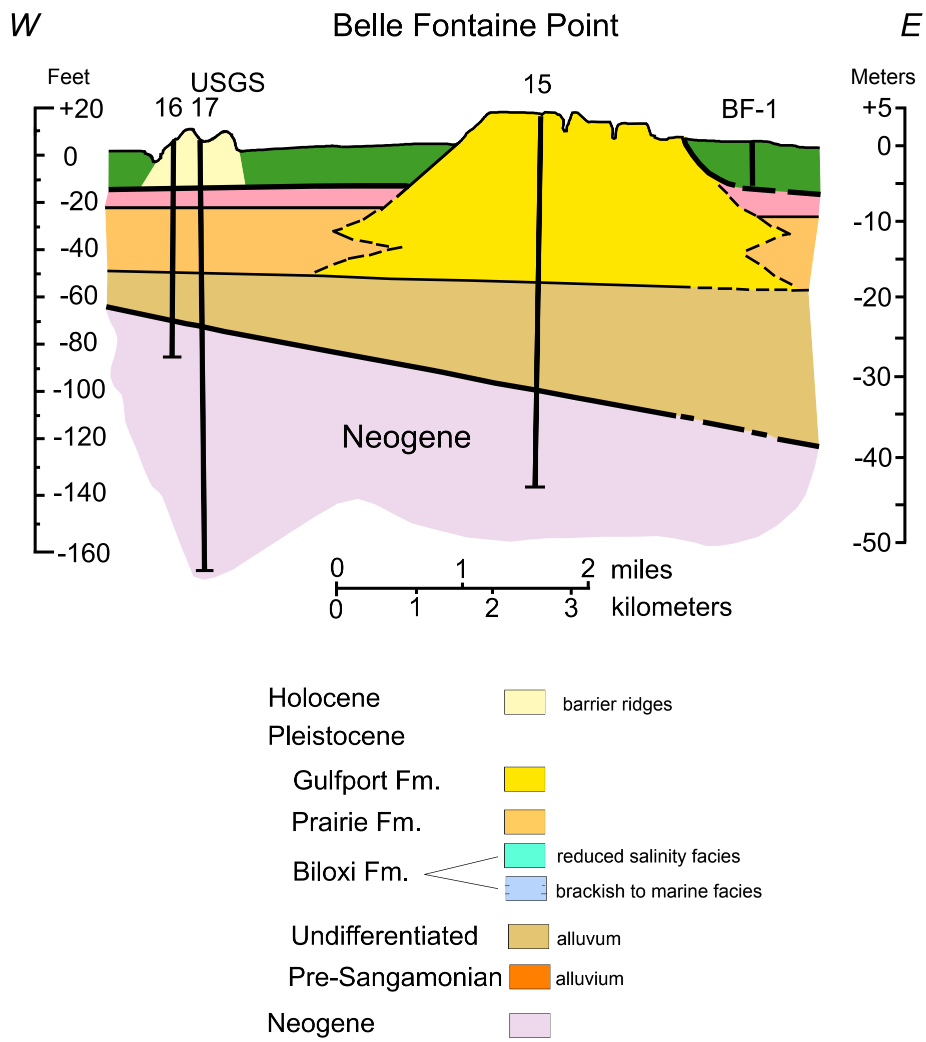


Figure 9. Southwestern Jackson County cross sections; locations shown on figure 8. Holocene units include underlying brackish, sandy and muddy deposits that are not shown separately. (a). Dip section.



(b.) Strike section.

Benthic foraminifers are sensitive salinity indicators in coastal Quaternary units. Paralic inshore Biloxi facies that include agglutinated benthic taxa and calcareous species at the landward "feather edge" of the estuarine Biloxi, locally interlayer with the Prairie alluvium. Only a few foraminifer species represented by large numbers of individuals occured in such Biloxi samples. Presumably due to local intercalation with Prairie alluvium and later erosion, the Biloxi displays variable thicknesses that seldom exceed 26 to 33 ft (8 to 10 m). The formation is absent from corehole #12 (USGS Shepard State Park test hole) and core #20 (Fig. 3).

In addition to the agglutinated species, *Ammonia beccarii*, *Elphidium galvestonense*, and *E. incertum mexicanum* dominate the very brackish inshore facies, frequently with the typical estuarine bivalves *Rangia cuneata* and *Crassostrea virginica*. While erosion locally eliminated both bottom and topmost units in the estuarine-marine sediment cycle, they clearly are present and clearly recognizable from their foraminifer faunas. These faunas include agglutinated taxa at the landward end of the Jackson County dip section (Figs. 8, 9). Contrary to an alternative interpretation (T.G. Gibson, USGS, written commun.), late Holocene brackish inland sediment intervals in the subject area could not be mistaken for Pleistocene units, which are characterized by lighter colors and more compact sediments. Inland, as at the updip end of the Jackson county section (Fig. 9a), Holocene deposits are absent.

A brackish Biloxi unit, with large miliolid tests typical of a somewhat higher salinity facies, is less than 6 ft (about 2 m) thick in corehole #21 (USGS Ocean Springs Police Range; Fig. 3). Approximately 1,300 ft (400 m) to the southwest, corehole #22 includes two Biloxi intervals; the lower interval is 13.8 ft (4.2 m) thick. These two intervals correlate with the Biloxi interval in corehole #21. The 257-ft-deep (78.3 m) Point aux Chenes corehole #1 (Fig. 3), revealed the thickest Biloxi interval (93.5 ft; 28.5 m). Several neritic assemblages in Jackson County holes reflected open-marine environments, occasionally impacted by fresh-water influx.

Inner-to-middle neritic Biloxi facies often contain as many as 40 to 50 species. *Hanzawaia strattoni*, *Rosalina columbiensis, Bigenerina irregularis*, and *Quinqueloculina* miliolids dominate. Flushed from estuaries and influenced by variable fresh-water influx from streams, "estuarine" species do also occur in inner neritic settings (Table 1). Occasional agglutinated foraminifers, typical of very low salinity inshore facies occur also. Inner-shelf species, along with taxa most common in estuarine-inshore environments, were found in the lower and middle intervals of the 59-ft-deep (18 m) GCRL Belle Fontaine corehole (#16). Located 1,080 ft (330 m) to the east, the USGS BelF #1 corehole (#17; Figs. 8, 9b) postdated corehole #16 by several years. Dark-gray (N5), dark-greenish-gray (5G4/1), and moderate-greenish-gray (5G 5/1), fine sandy and very fine sandy muds and muddy medium sand form the Biloxi sequence in GCRL corehole #16. Thin, moderately well sorted, dark-greenish-gray and white sand layers also are present. Biloxi thicknesses were nearly identical in these holes.

USGS BelF #1 (core #17) contains varied Biloxi molluscan fauna elements, but no low-salinity taxa such as *Crassostrea* and *Rangia* (Wingard, this volume). These taxa, however, were the most abundant forms in drainage ditches at the Sunplex Industrial Park (near core #13, Fig. 3). There, the fauna includes *Crassostrea virginica*, *Rangia cuneata*, *Sinum perspectivum*, *Littorina irrorata*, *Anadara transversa*, *Noetia ponderosa*, *Nassarius acutus*, *Anomia simplex*, *Isocardium recurvum*, and *Blanus* sp. Another fauna in core #15 resembles Wingard's and our own Apalachicola coast Biloxi assemblages (Otvos, 1992). It came from fresh-water-influenced, inner-shelf Biloxi deposits on the central Harrison County shore. That fauna includes *Abra aequalis*, *Anachis* cf. *A. obesa*, *Anadara transversa*, *A. ovalis*, *Chione grus*, *Corbula contracta*, *Crassinella lunulata*, *Nassarius acutus*, *Nuculana concentrica*, *Noetia* sp., *Polinices duplicatus*, *Strigilla mirabilis*, *Tellina versicolor*, *Tectonatica pusilla*, and *Urosalpinx cinerea*.

Conclusons on temperature and salinity that characterized depositional conditions of four bioecozones of the Biloxi Formation in the USGS Belle Fontaine drillhole (Poag, this volume) are in agreement with earlier cited deductions on paleosalinities.

Poag's (this volume) interpretation of Bioecozone 4 as representing an interval of relatively low paleosalinity may be reconsidered in the light of our additional data. In a corehole (#16, Fig. 3) immediately adjacent to that studied by Poag, the 44- to 49-ft (13.2 to 14.7 m) interval of this bioecozone is represented by a fauna of more than fifty species. A few relatively lower salinity taxa (*Nonion*, *Elphidium*, *Ammonia*) predominate over the quite abundant open-neritic *Rosalina* and *Hanzawaia* species that are predominant immediately above and below that interval. This suggests an episode of fresh or brackish water influx into open-shelf settings. T.G. Gibson's data for USGS-BelF No. 1 (T.G. Gibson, USGS, written commun.) does not register these salinity fluctuations.

Ostracodes assemblages from USGS-Belf #1 (Cronin, this volume) include several species also described from the Holocene of coastal Mississippi. These ostracode assemblages represent rather broad paleosalinity ranges, definable more narrowly and with greater precision by foraminifers spectra (Otvos, 1988b).

<u>Age</u>. The calcareous nannofossils *Gephyrocapsa oceanica* and *G. caribbeanica* in Mississippi Sound core S-2, drillhole #25 (Otvos, 1981), confirm the Biloxi's late Pleistocene age. Amino acid D/L ratios from the bivalves *Chione* and *Anadara* in Mississippi, Texas, and northwest Florida were used for correlation (J. Wehmiller, Univ. of Delaware, written comm.). Although this work is yet incomplete, and major problems of data interpretation remain (J. Wehmiller, Univ. of Delaware, pers. comm., 1996), the *Chione* D-alloisoleucine/L-isoleucine ratios (0.61 to 0.78), plotted against current mean temperatures, appear to fit the regional trend for a Stage 5 isochron that corresponds to the Sangamonian interval. Such ratios obtained from *Rangia* and *Crassostrea* valves (brackish interval at base of Biloxi in the Mississippi Sound S-2 hole; #25, at -56 ft (-17.1 m) depth) were remarkably similar.

Prairie Formation

The Prairie Formation is a 14.7- to 39-ft-thick (4.5- to 12-m) blanket of alluvial deposits that wedges out landward against older units. It interfingers with the Biloxi Formation (Fig. 9a). At several landward locations, Prairie sediments directly overlie the

Biloxi at varying distances inland from the present shoreline. In the absence of Biloxi deposits, the lower Prairie boundary locally is undefinable toward the underlying nonfossiliferous earlier Pleistocene or Neogene fluvial siliciclastic sediments.

C.W. Cooke's Atlantic coast term, "Pamlico", derived from a distant North Carolina location, is still being used for a Gulf terrace surface. However, the "Prairie" designation from southern Louisiana (Fisk, 1944) is more pertinent and applicable to Gulf coastal morphostratigraphy. While the "Pamlico" unit in its original definition consists of marine deposits, the Prairie is alluvial in origin. The coast-parallel Prairie surface forms the upper bounding surface of the Prairie Formation, redefined as a valid lithostratigraphic unit in areas where it directly overlies the Biloxi (Otvos, 1991b; 1997b).

Absolute (luminescence) dates recently reconfirmed the Sangamon age of the Prairie coastal plain surface and directly underlying deposits in several Texas, Louisiana, and Mississippi coastal plain locations. However, while sea level positions remained too low throughout the Wisconsin glacial stage to induce sediment aggradation in the coastal plain, abundant sediment supply to streams during this dry climate phase apparently did induce aggradation of the Mississippi, Pearl, Amite, and other valley terraces and certain parts of the adjacent Prairie coastal plain in southeastern and southwestern Louisiana in early and mid-Wisconsin times (Otvos and Price, 2001).

Muddy and clayey fine sands and moderately silty, fine and very fine sands dominate this alluvial complex. Cross-bedded, sandy and gravelly fluvial channel sediments and clayey and silty backswamp peat deposits also occur locally. The sorting and median size values of certain channel lithosomes in a borrow pit northeast of the intersection between highways 90 and 57 near Gautier are compatible with beach-foreshore sands and were recently used to renourish central Belle Fontaine Beach. Unlike on the Texas Coastal Plain, vertebrate finds are extremely rare. At depth, the sediments are yellowish-gray, greenish-gray and gray. Very pale orange, pale-yellowish-orange, and medium-yellowish-orange oxidation colors predominate near the surface. Locally, incised remnant meander bends mark the latest Prairie aggradation stage on the Prairie surface. Along the eastward continuation of the Big Ridge Scarp at Gautier, the low, level Prairie alluvial surface (Fig. 1) is scored by lightly impressed parallel drainage lineaments (Otvos, 1981b). The Scarp had been mistaken for an "old beach promontory", and the faint lineaments (fig. 5b) were incorrectly characterized as fossil beach ridges (Brown and others, 1944; p. 24-25).

In contrast with our three Prairie peat samples (Table 2; samples 3-5) and two USGS Biloxi samples (#4424 AA AB), a USGS pollen sample from the Prairie Formation (#R4331A; Willard and Edwards, this volume) displayed relatively low *Pinus* counts. Localized environmental (edaphic or selective depositional) effects may account for the difference. With the exception of floodplains, hard pine species predominate in present coastal forests. Three Recent marsh reference samples (Table 2, #6-8) provided even lower pine and higher oak pollen counts. In summary, none of the pollen samples depict major contrasts with current climate conditions.

Higher (maximum +59 ft; +18 m) Prairie surface elevations at the landward margin in southwestern Mississippi and adjacent Louisiana may be attributable to the slow post-Citronelle uplift that impacted the Citronelle and the older Pleistocene units even more intensively. Discontinuous remnants of the Prairie extend seaward beneath Mississippi Sound.

Gulfport Formation

Gulfport lithofacies display a pattern of aggradation. The formation grades upward from muddy, poorly sorted sandy, relatively low-energy, nearshore neritic deposits to subtidal shoal sands to higher intertidal and finally eolian sands. Laterally, Biloxi sandy muds grade upward into Gulfport shoal sands under Belle Fontaine Beach, Jackson County (Fig. 9b).

The Gulfport Formation (Otvos, 1972; Otvos and Howat, 1992) has dates centering in the 124-116 ka B.P. range in coastal Mississippi and northwestern Florida (peak Sangamon marine highstand, OIS 5e). The Gulfport forms a discontinuous barrier trend on the northeastern Gulf shore (Fig. 10a). Between Mobile and Apalachee bays, most of the formation is buried at shallow depths by Wisconsin and early Holocene dunes of various dimensions, as well as by a gently rolling eolian sandplain. These deposits were luminescence-dated in the 64 to 5 ka B.P. range (Otvos and others, 2000).

In Mississippi, Brown and others (1944, p. 26) were the first to describe these dune or beach ridges and inter-ridge swales. Members of the Live Oak-Ingleside trend, identifiable as barriers in Texas (Fig. 10b) and first described by Price (1933), correlate with the Gulfport barrier chain (Otvos and Howat, 1996, 1997). Price (written commun., 1978) stated that he recognized the Pleistocene barrier at Gulfport, Mississippi during his 1936 visit. Doering (1956, p. 1957) noted that the ridges, subsequently included in the Gulfport barrier trend at Apalachicola (Fig. 10a and Otvos, 1992), "are probably barrier chains, similar to the Live Oak bar".

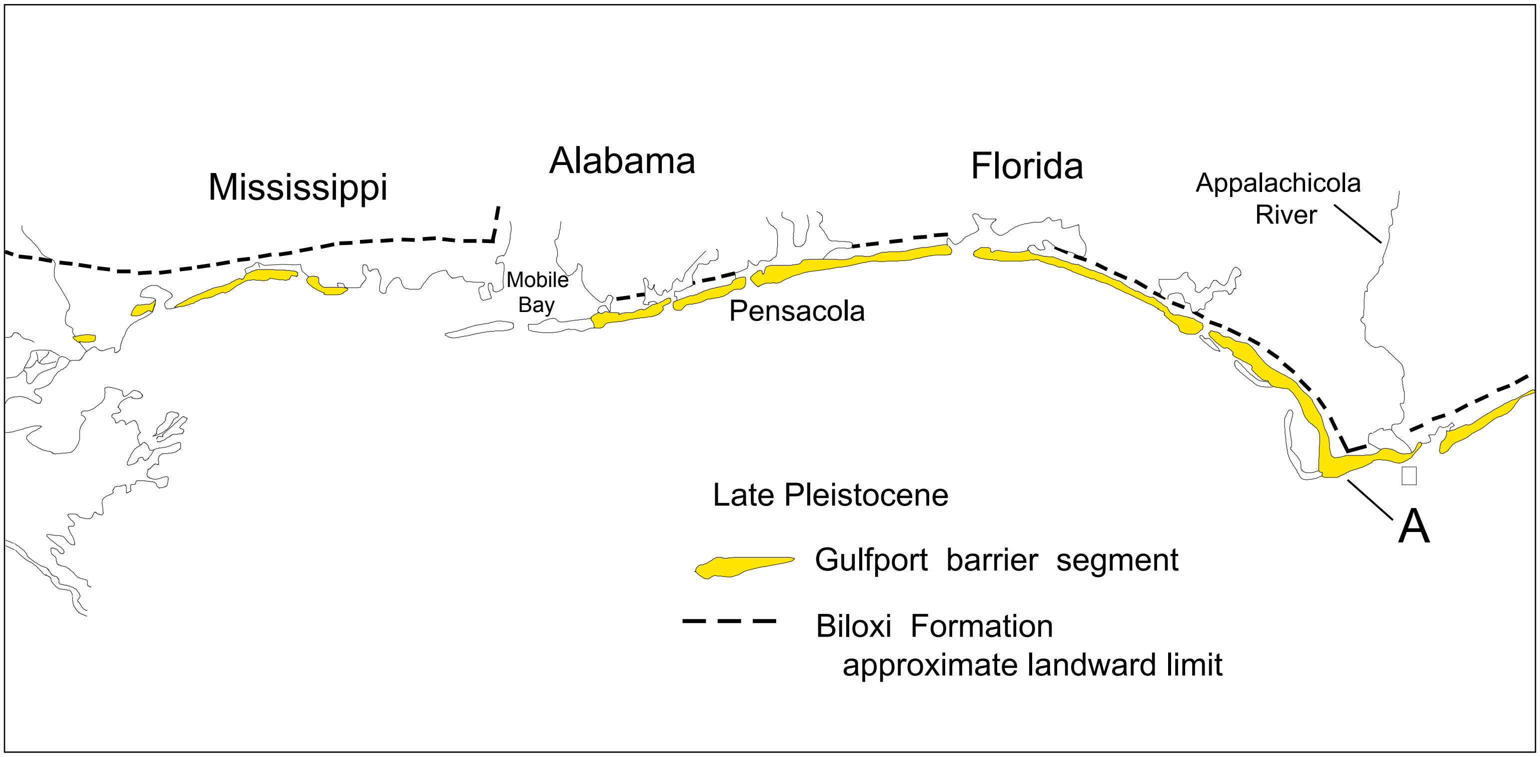
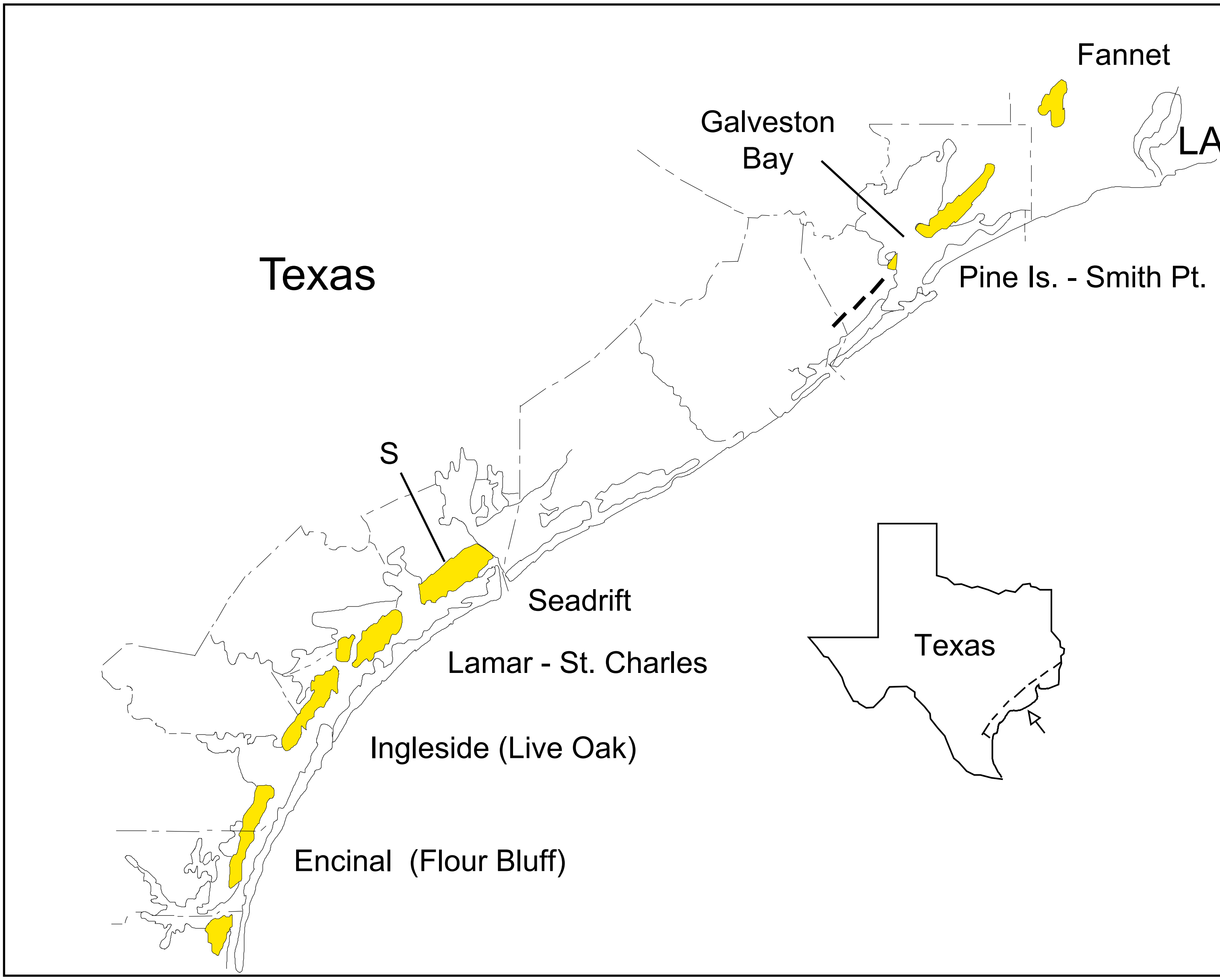


Figure 10. Late Pleistocene (Sangamonian Interglacial) coastal barrier sectors (from Otvos and Howat, 1992). (a.) Northeastern Gulf Coast.



(b.) Texas "Ingleside" barrier ridges.

Estuarine and fluvial gaps separate the members of the barrier trend. These barrier ridge sectors are at a maximum only 1.2 mi wide (2 km) in Harrison and Jackson Counties. A maximum width is 7.5 mi (12 km) on the western Apalachicola coast. A truncation interface there indicates two stages of barrier progradation separated by an erosional episode (Otvos, 1992).

Contrary to earlier opinions, it is now clear that only the Fannett sector represents a clear-cut Ingleside barrier on the upper Texas coast. Despite unsubstantiated claims to the contrary, with the exception of the Fannett sector, no Pleistocene barrier sectors are identifiable in the central and eastern Texas Coastal Plain. None occur in coastal Louisiana (Fig. 10; Otvos, 1991b; Otvos and Howat, 1992, 1997). Only subtidal Sangamonian sand and muddy sand lithosomes occur west of the Fannett barrier in the shallow subsurface and perhaps in the land surface (Otvos and Howat, 1997).

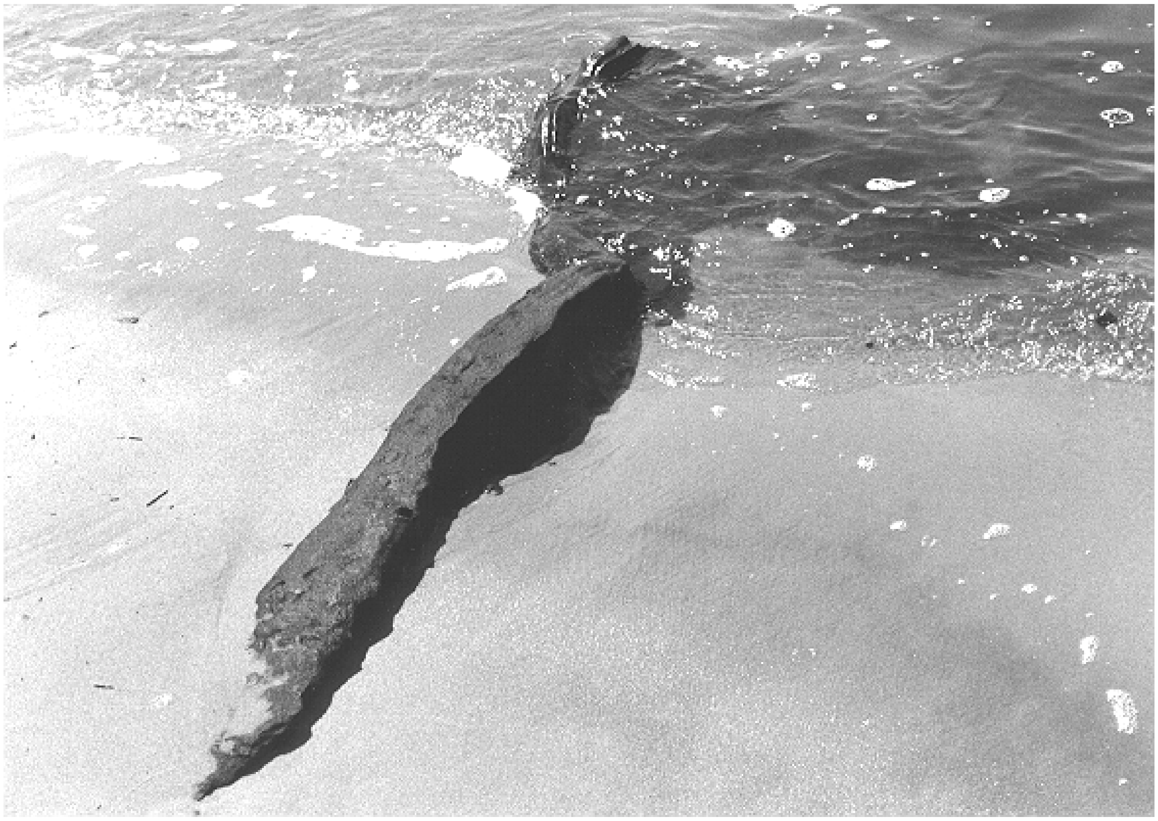
Barrier progradation started on the seaward front of the Prairie plain during the Sangamonian highstand and may have continued through the early regressive phase. Ridge-and-swale strandplain topography characterized several Texas and northeast Gulf barrier segments. Wisconsinan wind erosion and sand accumulation in inter-ridge swales in most areas reduced or completely eliminated the ridge-plain topography in most areas. Influenced by tectonic subsidence and following shore retreat in southern Hancock County (Otvos and Howat, 1992; Fig. 1), the barrier area was mostly buried by regressive Prairie alluvium.

Ingleside barriers and several northeastern Gulfport barrier sectors often are refered to as relict barrier islands. In the absence of correlative lagoonal deposits in the subsurface in the rear of the barriers in the northern Gulf, this view is not supportable (Otvos and Howat, 1996). Deposits that directly underlie alleged relict lagoon plains landward of the barriers are fossil-free and apparently of alluvial origin. Brackish deposits beneath this alluvium belong either to interfingered estuarine Biloxi intervals or, as at certain Texas localities, to pre-Biloxi fossiliferous paralic and nearshore-marine units formed during earlier Pleistocene transgressive-regressive cycles (Otvos and Howat, 1996).

Belle Fontaine barrier strandplain and its erosion history

A record 69-ft-thick (21 m) Gulfport sand interval at East Belle Fontaine Beach marks a period of extended shoal aggradation. The interval extends from 54 ft (16.5 m) below sea level to above sea level. Core 15 includes moderately to very well sorted, white and grayish-olive, fine (locally medium) sands. Thin lenses of pine debris occur locally in the sands. White, light-yellowish-brown, yellowish-orange, and light-yellow sands occur at the surface. Westward, the shoal sands interfinger with greenish-gray and dark-greenish-gray, nearshore-marine Biloxi muds and sandy muds (Fig. 9b). East Belle Fontaine bluffs expose humate-impregnated, semiconsolidated sandstone lenses and layers of various thickness. Eroding humate sandstone ledges in and slightly above the intertidal zone contain abundant *Ophiomorpha* (burrow tubes) of shallow-subtidal *Callianassa*-type shrimp (Figs. 11a, b, c). A limonitized, oxidized, positive mold of the bivalve *Raeta plicatella* was found here.

Figure 11. Gulfport humate sandstone, East Belle Fontaine Beach. (a.) *Ophiomorpha* (*Callianassa* sp.) shrimp burrow tube from humate-impregnated, dark-brown Gulfport sandstone; scale = 6 in. (15 cm).



(b.) Eroding dark-brown sandstone ledges with erosion-resistant Ophiomorpha from foreshore.

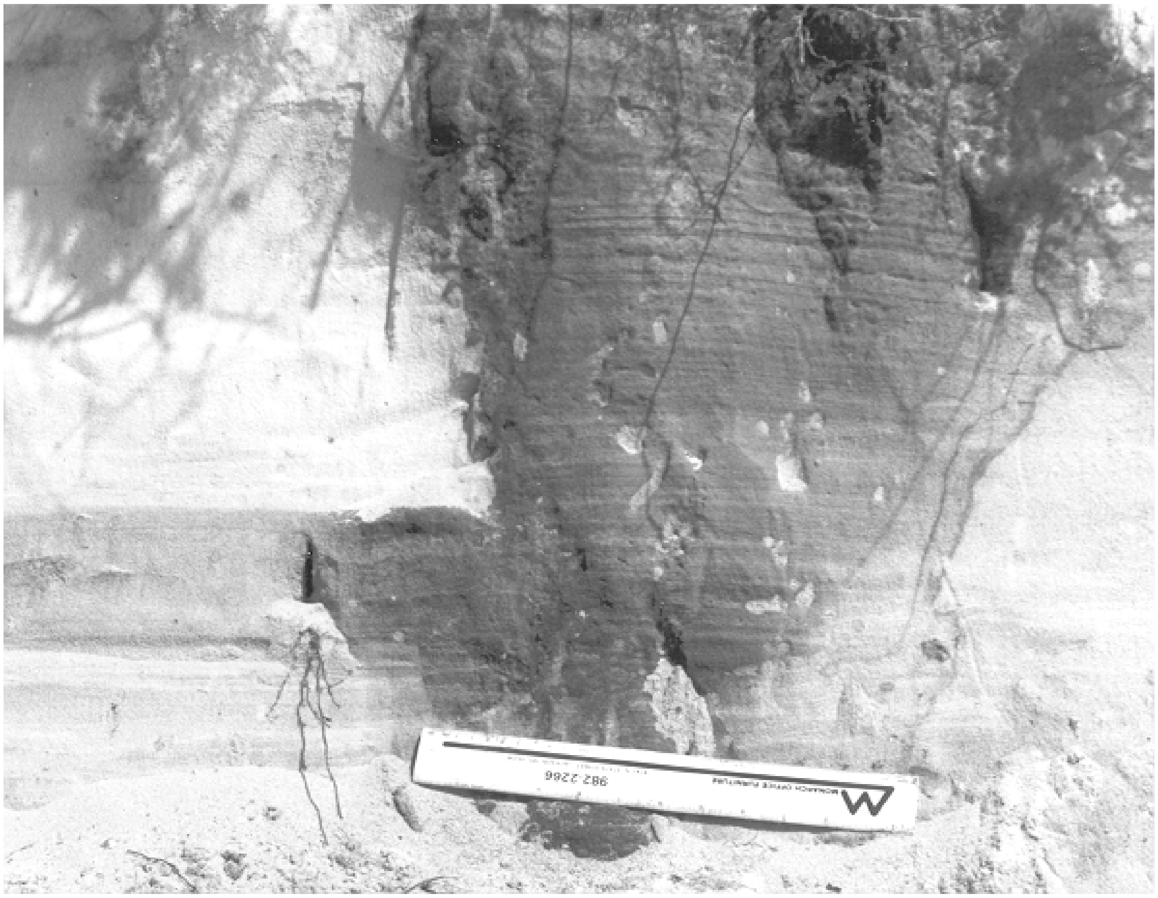
(c.) Dark-brown, ripple-laminated humate sandstone bed between white sand layers in bluff face; camera case for scale.

Bayou and Lake Graveline separate the Gulfport strandplain on the south from the Prairie alluvial plain to the north. More than a dozen northwest-to-southeast-striking strandplain ridges alternate with broad swales (Fig. 8). This topography is even more subdued than in Harrison County. Ridge-crest elevations range from +10 to +20 ft (about +3 to +6 m); swale elevations also are lower than in the Harrison sector. Barrier progradation may have accompanied sea-level drop during a regressive phase of late Oxygen Isotope Substage 5e.

Belle Fontaine sectors experienced 82 to 545 ft (25.2 to 166.3 m) of shore retreat between 1850 and 1986 (Suhayda and Oivanki, 1993). One property owner (J. Germany) noted 85 ft (26 m) of bluff recession between 1969 and 1990 on East Belle Fontaine. Heavy rains produce numerous ephemeral springs from the bluff's toe above humate-cemented aquiclude beds, thereby providing the French name for this shore area. Belle Fontaine currently is undergoing intensive real estate development in combination with "hard" and "soft" types of shore protection measures (Otvos, 1997).

Six-and-one-half to thirteen-ft-high (2 to 4 m) Gulfport scarps face Mississippi Sound at East Belle Fontaine Beach (Fig. 12). Wave erosion of the scarp toe during high spring tides and occasional tropical storms is a major cause of shore retreat. Sand slump and grain flow, as well as rain-derived sheetwash, surface channel erosion, and spring sapping by fresh ground water represent usually minor, occasionally significant contributing factors to erosion (Otvos, 1997).

Figure 12. (a.) Retreating East Belle Fontaine bluff, Jackson County. Note eroded masonry in foreground.



(b.) Laminated Gulfport barrier sand; scale = 6 in. (15 cm).

(c.) Gulfport Formation humate-sandstone pebble concentrate at bluff toe. High water level due to onshore winds. May, 1993.

(d.) Close-up view of bluff in figure 12c.

High interglacial sea level: Evidence from Sangamonian barriers

Marine and estuarine fossils, humate cementation of barrier sands, and sedimentary structures associated with subtidal environments mark the lowest possible sea-levels inferable for the Sangamonian. Limonite- and humate-cemented molluscan molds at Belle Fontaine Beach and a shell bed under the Ingleside ridges at San Antonio Bay, Texas (Otvos and Howat, 1996) occur only slightly above present sea level. Chemical reaction between invading brackish ground waters and downward-percolating soil acids formed widespread humate cementation in Gulf beach sands (Swanson and Palacas, 1965). Post-depositional humate precipitation is known from inland locations far from salt water. However, humate sandstone ledges and lenses at +8.5 ft (+2.6 m) elevation in East Belle Fontaine bluffs indicate higher sea levels associated with a high brackish-water table during strandplain formation.

Parallel-laminated and current-ripple cross-stratified Gulfport sands occur at + 8.8 ft (+2.7 m) in the bank of the Gulf County Canal near Port St. Joe, northwest Florida. The shallow subtidal cross sets provide another elevation constraint for the interglacial sea levels (Otvos, 1982).

Sea-level position and ridge crest/swale elevations

Reconstruction of ancient sea level positions from strandplain ridge and (or) swale elevations is a challenging possibility (Otvos, 2000). Recent to subrecent strandplain ridges on islands and mainland strandplains tend to be narrow. Relatively steep slopes bound the ridges both landward and seaward. In contrast, the gentle slopes of broad, rounded Pleistocene ridges, and their generally slight (2.0 to 5.0 ft; 0.6 to 1.5 m) vertical relief, point to a long history of erosion and beach ridge degradation. Gradual accumulation of wind-eroded, slopewash, and peaty wetland deposits in inter-ridge lows have raised inter-ridge swale floor elevations considerably.

The foredune base on a given Gulf beach is slightly (about 1.6 to 3.3 ft; 0.5 to 1.0 m) above high-tide level; often at some distance inland from the foreshore. This elevation corresponds to that of the highest foreshore berm. Depending on local wind, vegetation, and edaphic conditions, the original foredune heights may vary significantly and essentially are unrelated to the sea-level elevation at the time of their formation (Otvos, 1995a). Inter-ridge swale-floor elevations within a strandplain provide the best approximation for establishing maximum relative elevation of the associated sea level. In contrast, the 30 to 33 ft (+9 to 10 m) ridge summit elevations in Gulfport, Mississippi, are not directly tied to sea-level positions and reflect the height of foredune ridge remnants.

The highest elevations of the lowest swale floors, +20 to +23 ft (+6 to +7 m) in Harrison County, contrast with the +10 to +13 ft (+3 to 4 m) values at nearby Belle Fontaine and the maximum levels of about +1.6 to 3.2 ft (+0.5 to 1 m) in Bon Secour Bay strandplain sectors, southeastern Alabama (Otvos, 1985, 1991a). In the absence of post-depositional and tectonic subsidence in these relatively stable or slightly rising coastal areas east of the subsiding south Hancock area, falling late Sangamonian sea levels may account for the lower swale-floor elevations in given strandplains. In another tectonically stable area at Port St. Joe on the Apalachicola coast, the highest swale-bottom elevations in wetland-filled inter-ridge lows exceed +23 ft (+7.0 m). Seaward, swale and ridge elevations drop rapidly. Finally, the ridge tops disappear below sea-level. Oval intertidal marsh islands that top submerged ridges, outline shallow ridges in southeastern St. Joseph Bay (Otvos, 1992).

Correlation with Texas Coast barriers

The Sangamonian age of the Texas Ingleside barrier sectors and their correlation with northeastern Gulf barriers have been challenged, and a mid-Wisconsinan "interstade" age has been suggested instead (Wilkinson and others, 1975). Shideler (1986) cited radiocarbon dates as proof for the late Wisconsinan age of a 200-ft (about 60 m) Pleistocene nearshore-shelf sequence beneath the Encinal-Flour Bluff barrier sector and Mustand Island at Corpus Christi, Texas. With the realization that the Wisconsinan Gulf did not reach elevations that were assumed by Shideler and by others to be associated with these marine deposits, the units undoubtedly predate the last glacial period. Some of the upper units correlate with Sangamonian Ingleside units. The rest predate the last interglacial period. Comparable amino-acid racemization (D/L) ratios from several Ingleside and northeastern Gulf barrier sectors (Otvos and Howat, 1996) also support these conclusions.

Wisconsinan

Mid-Wisconsinan marine highstand?

Even before the idea of an alleged mid-Wisconsinan ("Peorian") interglacial, with an associated marine highstand and terrace progradation, was erroneously introduced into Louisiana (Fisk, 1938), the concept was already refuted in the glaciated upper Midwest (Johnson, 1986, and other references in Otvos and Howat, 1992). In the face of firm evidence to the contrary, claims of a high Wisconsinan sea level and its purported effect on the Coastal Plains have resurfaced in various publications.

Two intriguing examples of allegedly middle Wisconsinan deposits located slightly above present sea level come from the Delmarva Peninsula (Owens and Denny, 1979; Finkelstein and Kearney, 1988). The wide age range (23.3 to 34.0 ka) in the top unit that contains lagoonal muds with associated boreal, cold-climate flora, casts doubt on their role as eustatic highstand indicators during a warm interstade. On similar grounds, Harrison and others (1965) postulated a possible late Pleistocene uplift at the Chesapeake Bay entrance. Provided with additional evidence, without invoking high sea levels, this claim may explain the present high position of elevated units.

Ice-free episodes between 28 and 25 ka in the Midwest, Pacific Northwest, and southern Canada (Farmdalian, Plum Point, and other local interstades) were identified by several authors as marine-highstand episodes (e.g. Shideler, 1986). While these interstades experienced continental ice-sheet retreat, loess deposition, and soil development in areas briefly vacated by ice, ice volume and consequent sea-level changes were minor in comparison to those of interglacial times.

In contrast with the subsequent full-glacial interval, about 23 to 16 ka, the early and mid-Wisconsinan continental ice sheet covered smaller areas in the upper Midwest, south Ontario, and Quebec during Wisconsinan interstades (Johnson, 1986; Schwarcz and Eyles, 1991). Despite reductions in the mid-Wisconsinan ice cover, the associated eustatic peak sea levels still remained about 65 to 300 ft (20 to 100 m) below the present level (Shackleton, 1987; Toscano and York, 1992; Murray-Wallace and others, 1993; Andrews, 1993).

Coastal climate indicators: Sediments and flora

Significantly lower sea levels and somewhat cooler and drier climate conditions characterized the northeastern Gulf Coast during full-glacial times, especially when the Illinoisian ice lobe terminated only about 500 mi (800 km) from the present Gulf shore. At that time, streams became deeply incised near the shoreline.

A long-cone spruce variety is found inland of the present coastal area in late Wisconsinan deposits of Louisiana (Jackson and Givens, 1994). It may be a subspecies of *Picea glauca*, a tree that is widespread in modern Canada, the upper Midwest, and New England.

Large and medium-sized eolian dunes accumulated during the Wisconsin and the early Holocene in coastal northwest Florida and southeast Alabama over the Sangamonian barrier ridges (Fig. 2; Otvos, 1991a, 1992; Otvos and Price, 2001). These features, and gently rolling sandflats, formed by eolian reworking of Gulfport barrier sands. Extensive late Pleistocene inland dunes were also reported from the Carolinas and Georgia (Markewich and Markewich, 1994) and from southeastern Louisiana (Otvos, 1991a, 1992; Otvos and Price, 2001). The thick Wisconsin loess cover in the Louisiana and Mississippi interior along the Mississippi River also points to seasonally dry episodes in the presently humid-subtropical Deep South.

High alluvial terraces that intermittently flank several river valleys ("Deweyville terraces" of the Pascagoula, Pearl, Biloxi, and other rivers) were cut into the bluff-forming Prairie deposits during the Wisconsinan sea-level decline (Otvos, 1985).

Holocene

The late Holocene transgression covered the present Mississippi Sound area and gradually inundated the Mobile, Pascagoula, Pearl, and other incised river valleys. By 5.7 ka, sea levels reached about -23 ft (-7 m) in the present Biloxi Back Bay area (Otvos, 1985). The Gulf shore may have briefly coincided with the current Mississippi mainland shore. Abundant stream runoff kept nearshore Gulf areas brackish and muddy. High-energy conditions at Belle Fontaine Beach created a small barrier-spit complex that overlies 11.5 to 20 ft (3.5 to 6 m) of dark-gray, medium-gray, light-gray, and medium-olive-black, fine sandy mud, and a muddy medium-sand interval.

A radiocarbon age of 2,540 yrs (+/- 120 yrs) came from sandy-muddy deposits at 11.8 ft (3.6 m) below land surface beneath late Holocene barrier sand in the USGS BelF#1 corehole (Sample # W-6266; USGS Radiocarbon Laboratory). As indicated by the overlying barrier spit complex, powerful Gulf waves and consequent intensive beach drift were active on the Belle Fontaine shore a few millenia ago. Presently this shore is generally exposed to a very low energy sound-wave regime. Gulf wave erosion of the Belle Fontaine headland (Figs. 12a-c) provided ample sand supply for the narrow, 2.5-mi-long (4-km) barrier spit on the west (Fig. 1). A wide, very shallow subtidal muddy sand flat skirts the headland, further reducing sound wave energies.

Similarly, Magnolia Ridge (Fig. 13) is a narrow late Holocene mainland barrier (Otvos, 1988b). The much more extensive Alabama-west Florida strandplain complex formed concurrently in the Morgan Peninsula-Perdido Key area (Otvos, 1991, fig. 5).

Figure 13. Campbell Island (foreground), southern Hancock County, Mississippi. Landward view. Forested ridge in background is Magnolia Ridge, located along the former mainland shoreline.

Accumulation of the large Mobile Bay ebb-tidal delta and the east-west shoal belt west of the delta preceded development of the Mississippi-Alabama barrier island chain. Its first link on the east, Dauphin Island, formed around a high Pleistocene core, part of the Gulfport barrier trend. Cores from Mississippi Sound and the barrier islands show that the rest of the chain (Petit Bois, Horn, Ship, and Cat Islands) evolved by shoal formation over sandy-muddy sediments, characterized by typical high-salinity, inner-shelf foraminifer assemblages, followed by shoal aggradation up to intertidal levels (Otvos, 1981a, 1985). Most of the Mississippi island areas are characterized by progradational strandplain ridge topography underlain by white sand. The original core areas of island emergence are no longer identifiable. Sands in the presumably slightly older Horn and Ship Island sectors display sharply contrasting pale-orange and light-yellowish-brown pigmentation that resembles dune reddening (Otvos, 1992, p. 227; 1995b).

The most recent radiocarbon and luminescence dates from the Mississippi-Louisiana barrier islands, preserved in part as relict landforms in and beneath the southeast Louisiana–southwest Mississippi coastal marshlands, indicate that the islands earliest development dates back to ca. 4.2-4.0 ka B.P. The Mississippi Sound basin formed through the separation from the Gulf by this emerging island chain and the St. Bernard subdelta lobe on the west. Oligohaline to mesohaline depositional facies are present. Westward progradation of Morgan Peninsula constricted Mobile Bay's entrance. As beneath the Sound, this also resulted in a late Holocene regressive hemicycle sequence (Otvos, 1991a). Originally, the barrier island chain extended across present southern Hancock County and well into Louisiana's Orleans Parish (Otvos, 1978, 1985, 1988b). Transitional Mississippi River-eastern Gulf heavy mineral assemblages, and fluvially recycled Cretaceous foraminifers found in Pleistocene and Holocene units and derived from the continental interior, document the localized westward-directed sediment transport in southwestern Mississippi and adjacent Louisiana (Otvos, 1985).

Vibracores taken off the Belle Fontaine headland (Oivanki and Otvos, 1994; Oivanki, 1996) revealed the variable thicknesses of the muddy Holocene sediments (BF core series, Fig. 8). The greatest thickness values, associated with channel-fill deposits, exceed 13 ft (4 m). Nearshore muds reflect highly brackish conditions. *Ammotium salsum* (80-100%) predominates, with minor amounts of *Ammonia beccarii*, *Nonion depressulum matagordanum*, and *Elphidium galvestonense*. A subrecent, somewhat higher salinty brackish horizon was encountered in the upper 2- to 4-ft (0.6 to 1.2 m) interval of vibracores BF-5 to BF-9 (Fig. 8). Abundant *Ammonia beccarii tepida*, *A. beccarii parkinsoniana*, and *Elphidium galvestonense* in that horizon may reflect an episode of greater Gulf water influx; a time when Dog Keys Pass and (or) Horn Island Pass widened (also in Oivanki and Otvos, 1994).

Beach sectors have retreated by 82 to 545 ft (25 to 166 m), and 473 acres of high ground and marsh have disappeared into the Mississippi Sound at Belle Fontaine shores between 1850 and 1986 (Suhayda and Oivanki, 1993; Oivanki and others, 1993; Oivanki and Otvos, 1994). Destruction of the relict Escatawpa delta, and the associated, thinly sand-veneered, narrow Grande Batture marsh island (Otvos, 1993), after the Escatawpa was pirated by the Pascagoula River may have been accelerated by the impact of occasional storm waves that reached this shore segment from the widened Petit Bois Pass, opposite the eastern Jackson County shore. The elongated delta islands vanished in recent decades.

Diversion of the Mississippi River to create the St. Bernard subdeltas in late Holocene times led to formation of a large supratidal wetland area south of the Mississippi island chain. The energy-blocking action of these subdeltas led to extensive marshland growth in the Pearl River delta and south Hancock County. Island development was blocked west of Ship Island. Western members of the Mississippi-Louisiana barrier island chain near the mainland shore (Campbell, Point Clear Islands in southern Hancock County, and an others in the Lake St. Catherine area, eastern Orleans Parish, Louisiana) became engulfed by prograding marshlands (Fig. 13).

As transgression slowed, depletion of inner-shelf sand resources, a major source of beach sands, may have been partly responsible for accelerated erosion. These conditions steadily narrowed and truncated the Holocene southeastern Alabama-northwestern Florida strandplain and significantly reduced barrier-island areas. Four islands lost a total of 2,655 acres between 1850 and 1986 (Oivanki and others, 1993). While prograding 3 mi (5 km) westward on the east, Petit Bois was reduced in length by 8.7 mi (14 km), and Horn Island was reduced by 3.7 mi (6 km) (Byrnes and others, 1991).

After cessaton of Mississippi flow through the St. Bernard subdeltas and the initial breakup of the delta plain (Otvos, 1988b), subsidence of southern Hancock County, and Cat Island on the fringe of the steadily sinking Mississippi delta, contributed to large-scale marshland erosion (Fig. 14). In addition to shore retreat at Belle Fontaine, marshland erosion was intensive on the southwest Mississippi and southwest Alabama shores as well.

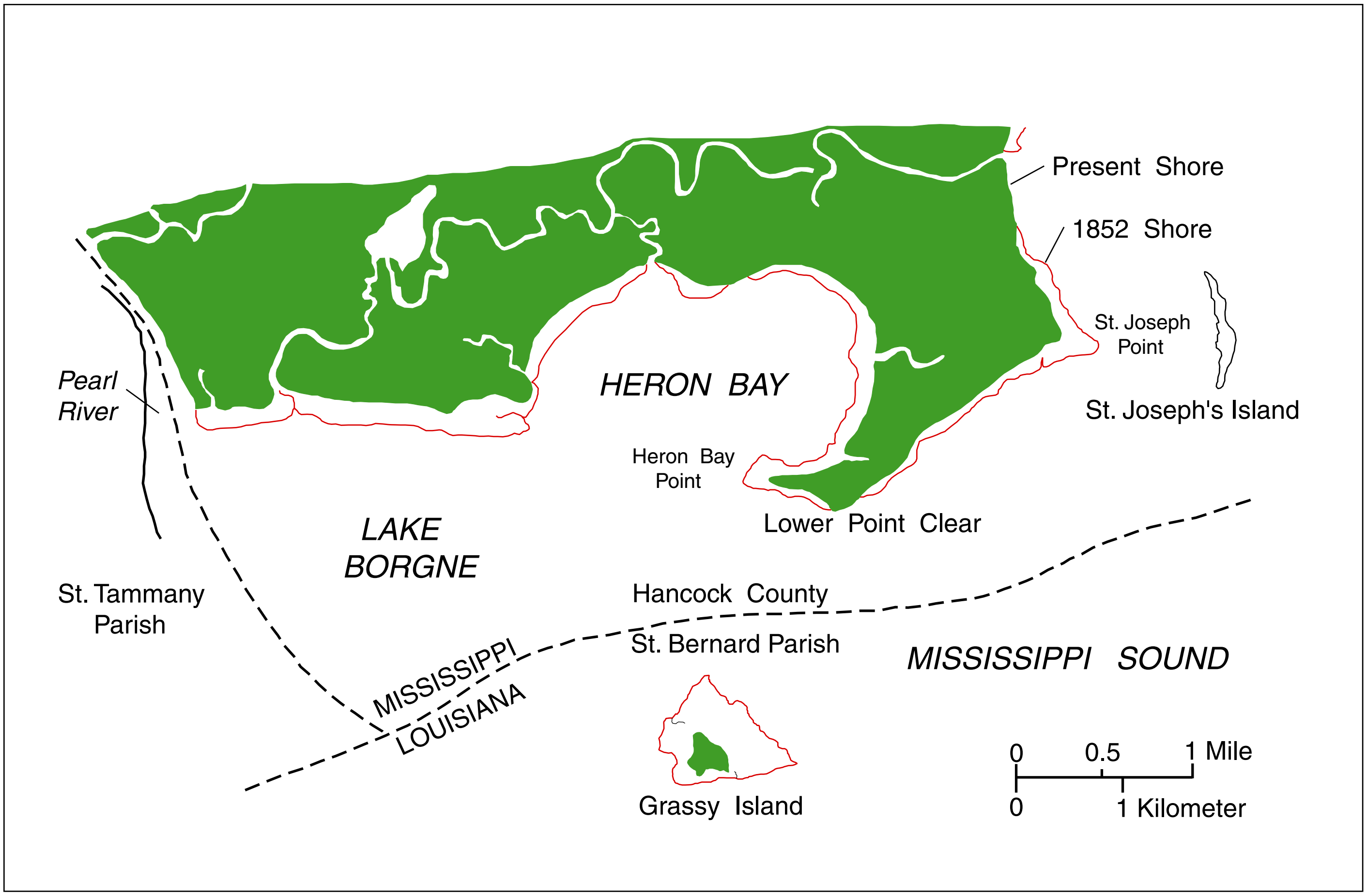


Figure 14. Marshland shore retreat in southern Hancock County, 1852-1977. Solid green = present marshland area; blank coastal area = land lost since 1852 (from Otvos, 1991d). Analysis based on U.S. Coast Survey Chart No. 371, 1852; photorevised USGS Grand Island Pass quadrangle, 1970; and NOAA aerial photography, roll 2846, 1979.

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