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THE EFFECT OF SEA-LEVEL AND CLIMATE CHANGE ON THE DEVELOPMENT OF A MIXED SILICICLASTIC–CARBONATE, DELTAIC COASTLINE: SUWANNEE RIVER, FLORIDA, U.S.A.

ERIC E. WRIGHT,[1] ALBERT C. HINE,[2] STEVEN L. GOODBRED, JR.,[3] AND STANLEY D. LOCKER[2]
[1] Department of Marine Science, Coastal Carolina University, Conway, South Carolina 29526, U.S.A.
[2] College of Marine Science, University of South Florida, 140 7th Avenue South, Saint Petersburg, Florida 33701, U.S.A.
[3] Marine Sciences Research Center, Stony Brook University, Stony Brook, New York 11794 U.S.A.
e-mail: ewright@coastal.edu

ABSTRACT: **Florida's mixed siliciclastic–carbonate, northwest-central Gulf of Mexico coastline is characterized by a 300-km-long, low-energy, sediment-starved, open-marine marsh system fronted by a broad, shallow limestone shelf. The only significant point source of sediment to this system is the Suwannee River, which forms a small (20 km^2) delta at the center of this coastline.**

Late Pleistocene eolian dune formation along the Suwannee River coastline reflects slightly drier conditions and local sediment sources influencing the early geologic development of this region. As sea level rose in the early to middle Holocene, dunes on the low-gradient shelf were transgressed and provided the core for the modern offshore sandy shoals. With decelerating sea-level rise in the middle to late Holocene and probable increased riverine sediment input, coastal sedimentation switched from transgressive to aggradational. Paleo-distributary channels seaward of the delta coastline at approximately 4,000 cal yr BP indicate initial deltaic formation. At this same time, oyster reefs from the delta southward were able to keep pace with sea-level rise and began to form large ($<$ 20 km^2) offshore oyster bioherms. Away from the river mouth, the coastline continued to transgress until 2,350 cal yr BP to 1350 cal yr BP, when the shoreline stabilized and the modern marsh system, south and north of the river mouth respectively, began to aggrade. The geologic development of this coastline and the relict eolian dunes preserved within the modern marsh system indicates that middle to late Holocene sea level did not exceed current elevations along this portion of the Gulf of Mexico coastline. This finding agrees with other studies from the low-gradient west-central Florida coast but contrasts with evidence for middle to late Holocene highstands along other Gulf of Mexico shorelines.

INTRODUCTION

The 300-km-long northwest peninsular Florida coastline is one of the longest open-marine marsh shorelines in North America. Studies of this marsh coastline (Hine et al. 1988; Goodbred et al. 1998; Goodbred and Hine 1995), located at the center of the Florida carbonate platform, have shown that, despite its outwardly monotonous appearance, this coastline has distinct morphologic variations that result from the underlying limestone bedrock topography, spring-water discharge, and storm sedimentation. Where solely spring-fed coastal rivers enter the Gulf of Mexico, embayments are formed with seaward oyster bioherms, back-biohermal basins, and landward fringing open-marine salt marshes. By virtue of the broad seaward carbonate shelf that gently slopes into the Gulf of Mexico and the mircotidal regime, initial studies of this coastline viewed the region as a ''zero-energy'' coast (Price 1954; Tanner 1960). However, more recent studies (Hine et al. 1988; Goodbred et al. 1998; Goodbred and Hine 1995; Leonard et al. 1995) have shown it to be a low-energy coastline, influenced by higher energy wind tides and storm events.

The Suwannee River enters the Gulf of Mexico at the center of this extensive open marine marsh coastline (Fig. 1). In contrast to the other previously studied spring-fed river systems (Hine et al. 1988; Goodbred et al. 1998), the larger, only partially spring-fed, Suwannee River also drains the coastal plain of Georgia, which provides a limited point source for input of siliciclastic sediment along this otherwise sediment-starved coastline. As a result, the river has constructed a small (20 km^2) river-dominated delta located between Cedar Keys and Horseshoe Point. Of perhaps greater significance to coastal geomorphology and sedimentology is the reworking of ancestral fluvial sands that served as a source for sandier marsh sediments north of the river, for a thin sediment sheet that extends onto the inner shelf, and for sandy coastal islands located within the marsh system. These U-shaped sandy islands, identified as relict eolian dunes, are uniquely different from the more common limestone-controlled hammocks described for the coastal embayments farther to the south (Hine et al. 1988; Goodbred et al. 1998).

The stratigraphic framework of this low-accommodation mixed siliciclastic–carbonate, deltaic system has been influenced by and reflects late Quaternary climate and sea-level changes. During the late Pleistocene, drier conditions (Grimm et al. 1993; Watts et al. 1992; Watts 1983) allowed mobilization of riverine sands into eolian dunes in the southeastern United States (Ivester et al. 2001; Carver and Brook 1989) and of coastal-plain sands into isolated dunes along the northern Gulf of Mexico coastline (Otvos and Price 2001). In west-central Florida, storage of sands in the upper river valley at this time was interpreted to have reduced riverine sediment transport to the marine environment (Guccione 1995). Early Holocene sea-level transgression along the sediment-starved northwest peninsular Florida coastline resulted in a thin to absent marine sediment cover along the inner shelf. The subsequent deceleration of sea-level rise during the middle to late Holocene allowed the establishment of bioherms and the modern coastline (Hine et al. 1988; Parkinson 1989; Goodbred et al. 1998). A shift to a wetter climate at this time has been inferred to have caused increased riverine sediment discharge to the marine environment in west peninsular Florida as a result of increased discharge and vegetation stabilization of overland sediment supply causing erosion of upper riverine sediments (Guccione 1995).

In addition to understanding development of this low-accommodation, deltaic system, documentation of the geologic development of the Suwannee River and delta provides insight into the controversial middle to late Holocene sea-level record of the Gulf of Mexico. Some researchers have

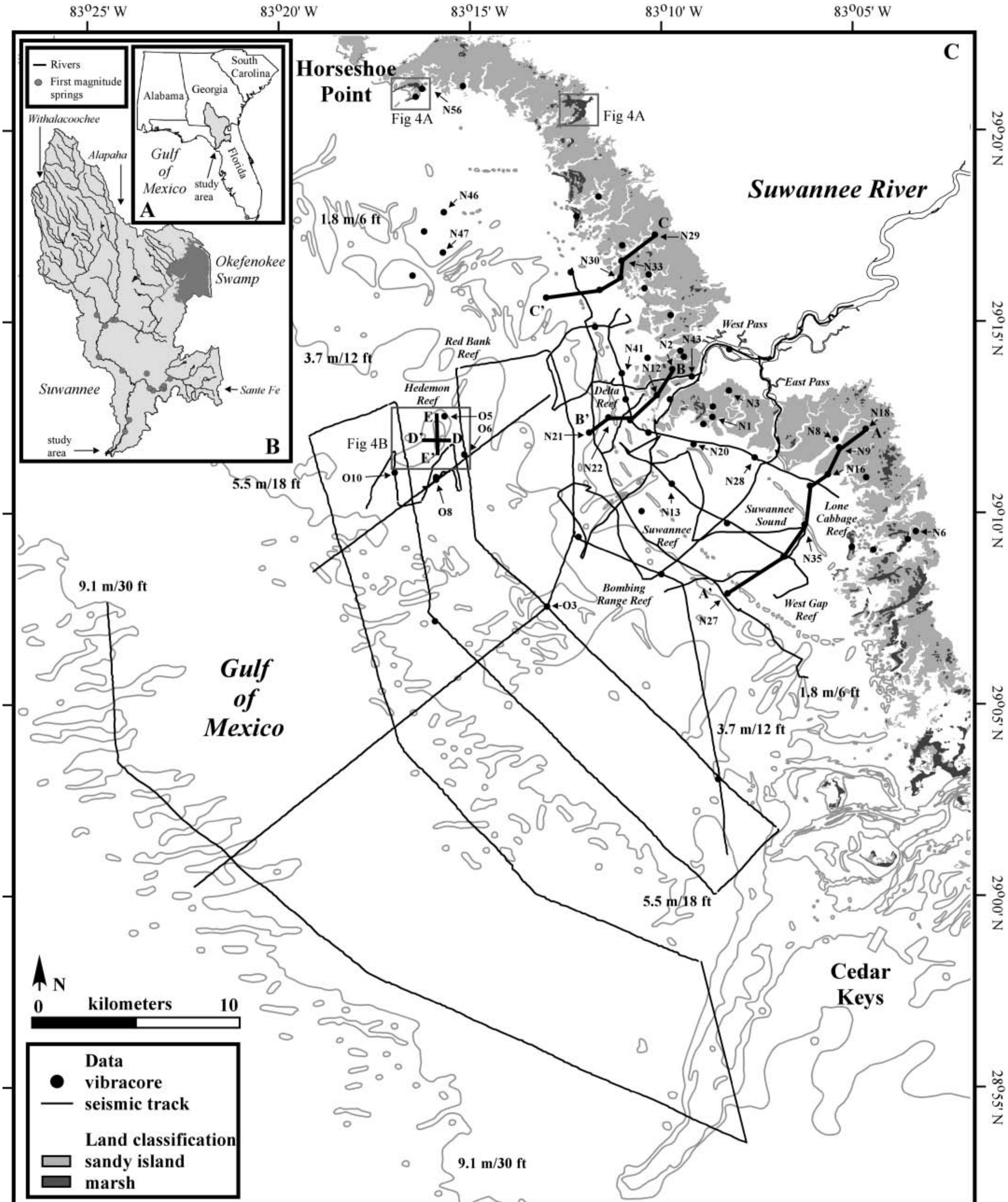


FIG. 1.—**A, B)** Location map of the Suwannee River drainage basin, major distributaries, and location of study area. **C)** Location map of study area and data collected. Features and data presented in Figures 2 through 8 are labeled (vibracore labels are N## or O##).

TABLE 1.—*Summary of radiocarbon age estimates.*

Core ID	BETA ID	Latitude (°N)	Longitude (°W)	Material	Environment	Depth in Core[1] (m)	Elevation[2] (m)	$\delta^{13}C$ (‰)	^{14}C Age BP ± σ	Calibrated Age Cal yr BP (±2σ)
N01	76030	29.28879	−83.14446	Organic sed	Marsh	1.30	−1.15:−1.44	−25.9	2130 ± 70	2120 (2330–1930)
N02	65821	29.31267	−83.15800	Woody peat	Swamp	2.68	−2.43:−2.97	−27.0[5]	4890 ± 100	5610 (5890–5340)[7]
N03	73722	29.30333	−83.13333	Organic sed	Meander fill[3]	2.95	−.270:−3.03	−26.0	3140 ± 70	3360 (3480–3210)
N06	69144	29.24212	−83.05179	Organic sed	Salt marsh	0.63	−0.68:−0.75	−27.0[5]	1710 ± 60	1600 (1740–1510)
N06	76031	29.24212	−83.05179	Peat	Marsh[4]	1.00	−1.05:−1.17	−27.0	3090 ± 60	3340 (3440–3150)
N06	65820	29.24212	−83.05179	Woody peat	Swamp	2.70	−2.75:−3.08	−27.0[5]	5910 ± 100	6730 (6980–6480)
N08	72073	29.26550	−83.07350	Organic sed	Salt marsh	1.30	−1.15:−1.28	−22.0	2370 ± 60	2350 (2710–2320)[7]
N09	51075	29.27867	−83.08533	Wood	Swamp	1.20	−1.05:−1.15	−27.0[5]	3620 ± 110	3910 (4240–3640)
N12	74487	29.30133	−83.16467	Organic sed	Salt marsh	0.90	−0.75:−0.83	−28.7	1650 ± 70	1540 (1710–1390)
N12	74903	29.30133	−83.16467	Peat	Marsh	1.65	−1.50:−1.64	−28.5	2370 ± 50	2350 (2700–2330)[7]
N12	74488	29.30133	−83.16467	Peat	Marsh	3.65	−3.50:−3.82	−27.5	5600 ± 70	6400 (6510–6280)
N13	73727	29.26267	−83.15817	Woody org sed	Swamp	1.20	−3.14:−3.34	−25.1	5180 ± −70	5920 (6160–5750)[7]
N16	78450	29.26683	−83.09017	Organic sed	Salt marsh	1.35	−1.20:−1.33	−23.6	2310 ± 80	2340 (2700–2140)[7]
N18	78451	29.28667	−83.07367	Organic sed	Marsh	0.48	−0.33:−0.43	−26.5	1210 ± 80	1160 (1290–950)
N20	76032	29.28000	−83.14867	Organic sed	Pond[3]	2.70	−3.71:−3.91	−27.1	4740 ± 60	5540[6] (5600–5320)
N21	78452	29.28500	−83.19417	Organic sed	Swamp	1.00	−4.00:−5.00	−26.8	5320 ± 50	6110[6] (6270–5940)[7]
N22	73091	29.29167	−83.18583	Oyster shell	Oyster bioherm	1.65	−2.58:−3.19	−4.2	3840 ± −70	3810 (3970–3620)
N27	73092	29.21433	−83.13750	Oyster shell	Oyster bioherm	1.90	−3.61:−3.77	−4.1	4340 ± 70	4440 (4650–4280)
N28	76033	29.27417	−83.12200	Organic sed	Salt marsh	1.20	−3.19:−3.31	−24.9	4680 ± 70	5390[6] (5590–5290)
N29	78453	29.37133	−83.16550	Organic sed	Salt marsh	0.53	−0.48:−0.48	−24.9	970 ± 150	920 (1230–650)[7]
N30	72074	29.35265	−83.18057	Organic sed	Salt marsh	0.30	−0.25:−0.33	−24.3	60 ± 80	0 (290–0)
N30	73728	29.35265	−83.18057	Organic sed	Salt marsh	0.80	−0.75:−0.95	−27.4	1500 ± 80	1380 (1550–1280)
N33	78454	29.36000	−83.18017	Organic sed	Salt marsh	0.70	−0.65:−0.81	−26.9	850 ± 70	750 (930–660)
N35	73729	29.24500	−83.10033	Oyster shell	Oyster bioherm	1.20	−1.90:−2.26	−5.6	3720 ± 90	3630 (3860–3420)
N35	73730	29.24500	−83.10033	Woody org sed	Swamp	1.45	−2.15:−2.58	−27.5	5090 ± 80	5890 (5990–5640)
N41	69145	29.29950	−83.17833	Woody org sed	Swamp	1.23	−2.12:−2.25	−27.0[5]	4290 ± 100	4850 (5260–4560)[7]
N43	73093	29.30950	−83.14950	Wood	Channel[3]	3.42	−5.80:−8.28	−29.1	4250 ± 70	4840 (5310–4400)
N46	76034	29.38100	−83.25767	Organic sed	Swamp	1.25	−2.52:−2.57	−23.6	4160 ± 100	4700[6] (4870–4420)
N47	73094	29.36350	−83.25800	Oyster shell	Oyster reef	1.45	−3.14:−3.50	−5.9	5370 ± 80	5720 (5910–5580)[7]
N47	76035	29.36350	−83.25800	Organic sed	Marsh[4]	1.60	−3.29:−3.69	−24.7	5520 ± 90	6300 (6470–6170)
O03	75759	29.20917	−83.21267	Oyster shell	Oyster reef	2.00	−5.55:−6.88	−02.9	5240 ± 120	5590 (5880–5320)
O06	71109	29.27550	−83.24867	Wood	Upland	2.98	−7.16:−8.10	−25.0	7340 ± 60	8160 (8320–8010)[7]
O08	69928	29.26450	−83.26100	Oyster shell	Channel[3]	4.75	−10.05:−12.84	0.0[5]	5770 ± 100	6190 (6390–5930)
O10	71111	29.26750	−83.27900	Organic sed	Salt marsh	1.65	−6.37:−6.81	−25.0	6520 ± 70	7430 (7560–7290)
O10	74905	29.26750	−83.27900	Oyster shell	Oyster reef	1.80	−6.52:−7.00	−8.0	8840 ± 80	9180 (9620–9060)
Modern	71108			Oyster shell	Oyster reef	0.00	:−0.55	0.0[5]	100.9 ± 1	57 (58–56)

[1] Depth from core top; [2] Calculated elevation with no correction for rodding and/or compaction : calculated elevation with correction for rodding and/or compaction evenly distributed over the length of the core; [3] Not an indicator of sea level; [4] Freshwater to brackish-water wetland located along the coast away from the river mouth; [5] Assumed ^{13}C value; [6] Middle of multiple intercept values; [7] End members of multiple intercept ranges.

suggested a general deceleration of sea-level rise (Toscano and Macintyre 2003; Törnqvist et al. 2002; Robbin 1984; Scholl et al. 1969), whereas other researchers have suggested small rapid rises occurring during the overall late Holocene deceleration, with a rapid rise at ~ 1,700 years ago recorded in the embayment immediately to south of this study (Goodbred et al. 1998). Still other researchers have suggested possible higher than present sea-level positions during this same time period (Blum et al. 2001; Morton et al. 2000; Stapor et al. 1991). This study examines the effect of sea-level change and climate change on the development of the Suwannee River coastline and provides new sea-level data from Florida's low-gradient, open-marine marsh coastline located along the eastern Gulf of Mexico.

METHODOLOGY

The geomorphology and stratigraphy of the coastline between Cedar Keys, Florida, and Horseshoe Point, Florida, were determined using high-resolution seismic and side-scan sonar data combined with vibracores, bottom grab samples, and diver inspection (Fig. 1). Over 325 trackline-kilometers of high-resolution seismic data were collected across the inner shelf (from 30 km offshore, 10 m depth, to just seaward of the Suwannee Reef, > 2 m depth), nearshore (landward from the Suwannee Reef), and 10 km upriver using a 175 J ORE Geopulse boomer system. Seismic data were filtered between 1–3 kHz frequencies with a 60 ms sweep. Approximately 250 km of side-scan sonar data were gathered along track lines across the inner shelf, and from the distributary-channel mouths of the Suwannee River upstream to a distance of 10 km upriver using a 100 kHz, slant-range corrected, EG&G Model 260 analog system. Where geophysical data indicated thicker sediment sections on the inner shelf, eleven vibracores were collected using standard techniques (Lanesky et al. 1979). Within Suwannee Sound, with its shallow water depths (< 2m) and thin sediment cover (< 2 m), resolution from geophysical data was more difficult and vibracore collection was based upon shoreline morphology. Within the nearshore environment, 52 vibracores were collected along a series of transects extending across the nearshore to the landward edge of the salt marsh or the equivalent limit upriver. In addition, 75 bottom grab samples were collected in a loose grid across the nearshore environment and to 10 km upriver using an Ekman-type grab sampler.

Vibracores were split, photographed, and described. Selected core halves were X-rayed to view sedimentary structures. To determine sedimentary characteristics, subsamples from vibracores were analyzed for: (1) grain size based upon the traditional techniques of Folk (1980); (2) organic content by weight loss-on-ignition (LOI) at 450°C for 4 hours; (3) percent carbonate by weight lost from HCl digestion; (4) mineralogy using a SCINTAG X-ray diffractometer; and (5) macroscopic and microscopic identification of organic constituents. Surface grab samples were analyzed using similar methodology.

To determine stratigraphic age, twenty-six bulk samples of organic-rich salt marsh and brackish-water or freshwater wetland sediment samples, two wood samples, and seven oyster shells with little evidence of biogenic or physical erosion were sent to Beta Analytic, Miami, Florida for standard radiocarbon dating (Table 1). Dating of undifferentiated bulk sediment was used because of the absence of preserved rhizomes, but high organic content suggests dominance of autochthonous marsh carbon over refractory organics. Autocompaction is not considered a source of error in determining these results because basal marsh samples that overlie freshwater or brackish-water wetland sediments show relatively good agreement with basal samples that overlie limestone or sand, which should not compact as easily. Oyster shells with little evidence of abrasion were assumed to have not been transported far and oyster shells located in areas of greater sili-

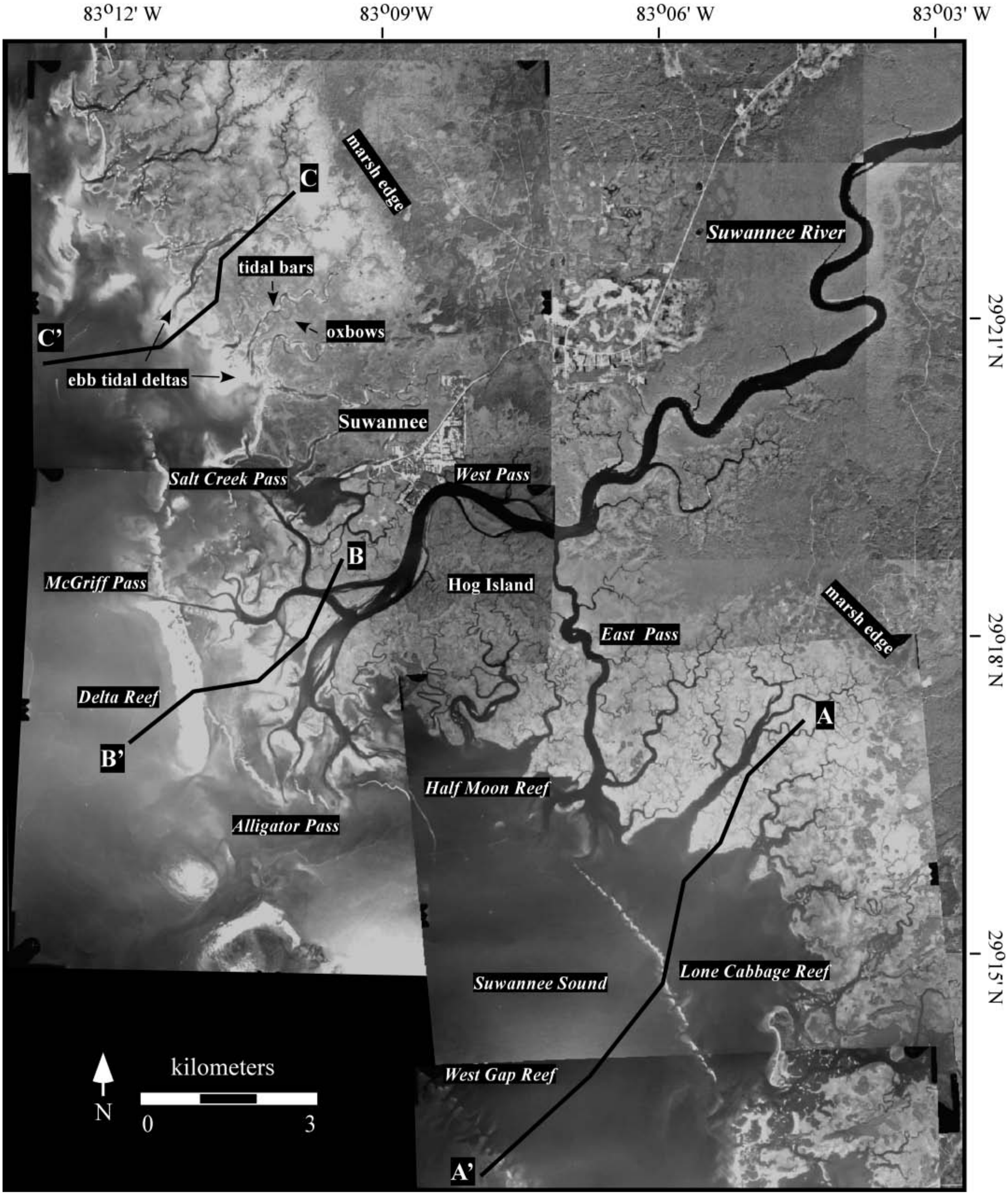


FIG. 2.—Mosaic of aerial photography of the Suwannee River coastline. The Suwannee River forms a small (20 km²) river-dominated delta. North of the river, the coastline is sandier with prominent ebb-tidal deltas and sand bars. South of the river, oyster bioherms and landward biohermal basins are formed.

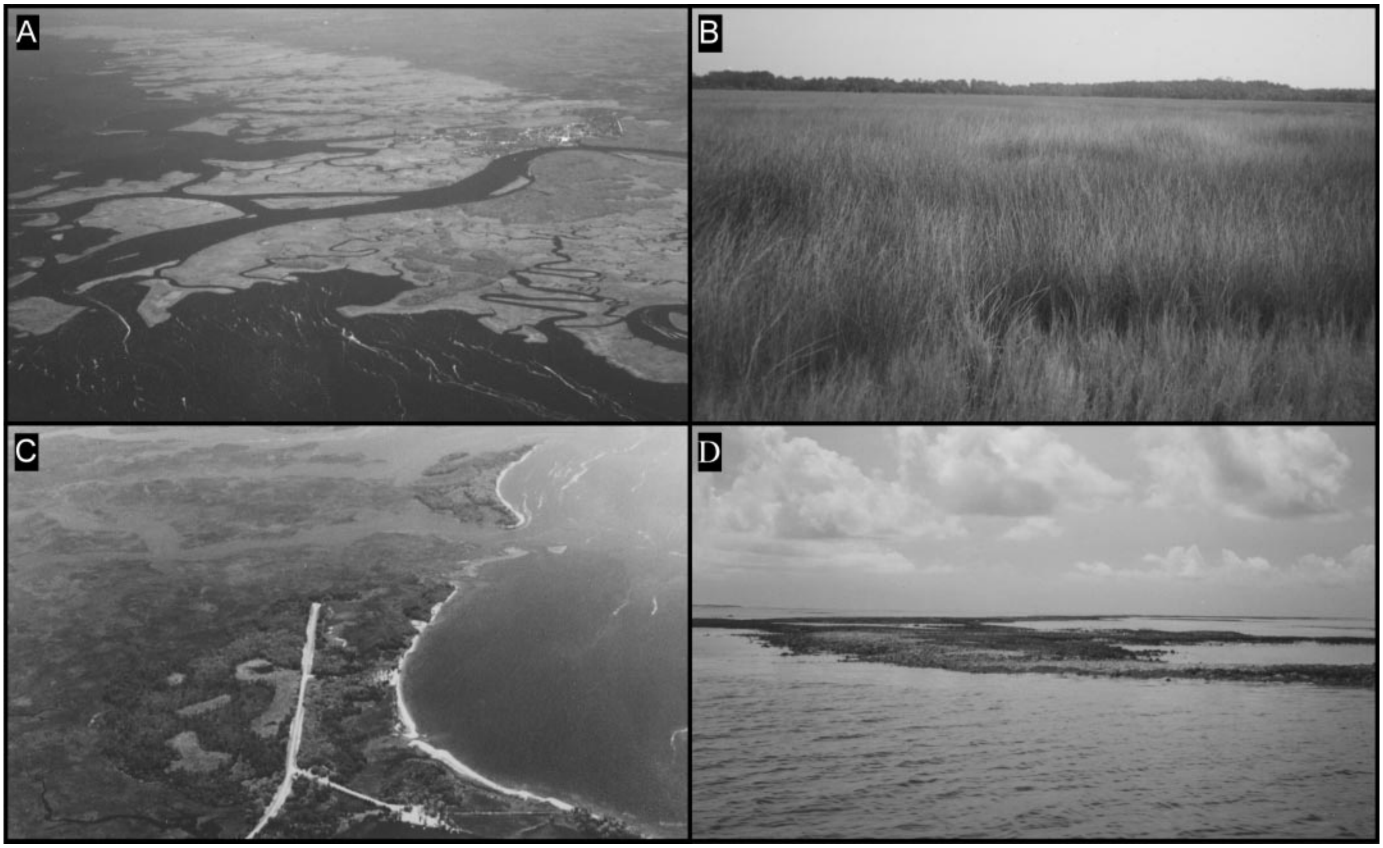


FIG. 3.—Oblique aerial photographs of: **A)** the Suwannee River and open-marine marsh coastline. (northward facing); **B)** *Juncus roemerianus* marsh flat; **C)** Shired Island, which is currently intersecting the coastline; **D)** oyster bioherm, which forms as a result of the river's fresh water entering the Gulf of Mexico.

ciclastic sediment were assumed to not be greatly affected by incorporating water containing older carbon derived from the underlying limestone.

Radiocarbon ages were calculated by Beta Analytic after correcting for carbon isotope fractionation (if corrections were not analyzed, an assumed δ^{13}Cvalue of -27‰ was used for peat or wood and 0‰ for shells) and calibrating results using the Pretoria Calibration Procedure program, which uses the ^{14}C half-life of 5730 yr, against tree-ring counts. A marine reservoir correction was applied to shell dates. Radiocarbon ages are reported as years before present (cal yr PB) along with the two-sigma probabilities of the calibration. A single thermoluminescence (TL) age estimate on 4–11 μm quartz grains from a sample from Butler Island was determined at Ohio State University (Forman, personal communication 2001).

RESULTS

Geomorphology of the Modern Systems

Suwannee River.—The Suwannee River drainage basin covers 25,000 hectacres and flows approximately 370 km from its headwaters in the Okefenokee Swamp of southern Georgia to its mouth at the center of the west-central marsh coastline of Florida. The upper river drainage is fed by the tannin-rich waters of the Okefenokee Swamp as well as two tributaries, the Alapaha and Withlacoochee rivers, which drain the coastal plain of southern Georgia. Along its lower portion, where the river is incised into the carbonate platform, the Suwannee River is fed by 72 springs (9 class 1 springs ($>$ 2.8 cm^3/y)) and a single spring-fed tributary, the Sante Fe (Rosenau et al. 1977). In this highly karstic setting, the Sante Fe flows underground for 4.8 km before returning to the surface and entering the Suwannee River (Kenner et al. 1975). Average annual discharge of the river is 300 m^3/s with a maximum discharge of 2400 m^3/s and a minimum discharge of 83 m^3/s (Meadows et al. 1993). The river carries a low suspended-sediment load, typically less than 20 mg/L (Wright 1995). However, side-scan sonographs and bottom grab samples indicate that the river transports a bedload component of medium to coarse sands moving as large subaqueous dunes (10–50 m spacing, 1 m height; Wright 1995).

Coastal and/or Nearshore.—As the Suwannee River approaches the Gulf of Mexico, it branches into East and West Passes (Fig. 2). As indicated on side-scan sonographs, and confirmed by bottom grab samples, East Pass is floored primarily by limestone with little sediment movement. This pass forms only a minor (2 km^2) delta within Suwannee Sound. The main discharge of the river follows West Pass, where sediment waves floor the channel until the river shallows from 10 to 2 m depth, and splits into distributary channels. As it enters the low-energy Gulf of Mexico, the river forms a small (20 km^2), river-dominated, elongate delta, with three main distributary channels (Fig. 3A). As indicated by comparison of 1989–1990 USDA aerial photographs and historical NOAA bathymetric charts from the 1880s, these distributary channels have remained stable over the last 100 years. A mosaic of freshwater to brackish-water marshes (dominated by *Juncus roemerianus* Steele, *Cladium jamaicense* Crantz, and *Scirpus olneyi* Gray) form between the distributary channels. Seaward of the distributary mouth, oyster patch reefs are quite common within the delta front.

North and south of the delta, a marsh system 1–3 km wide fronts the Suwannee River coastline (Fig. 3B). The salt marsh is primarily *J. roemerianus* but becomes a mixture of saltwater to freshwater marsh plants towards the delta. Marsh sediments thin landward, with limestone becoming exposed and the marsh vegetation giving way to upland forest or extensive freshwater swamps. North of the delta, the vegetation is typical of west Florida coast marshes (Dawes 1981: 507), with a seaward fringe of *Spartina alterniflora* Loissel, backed by a berm of *Distichlis spicata* (L.)

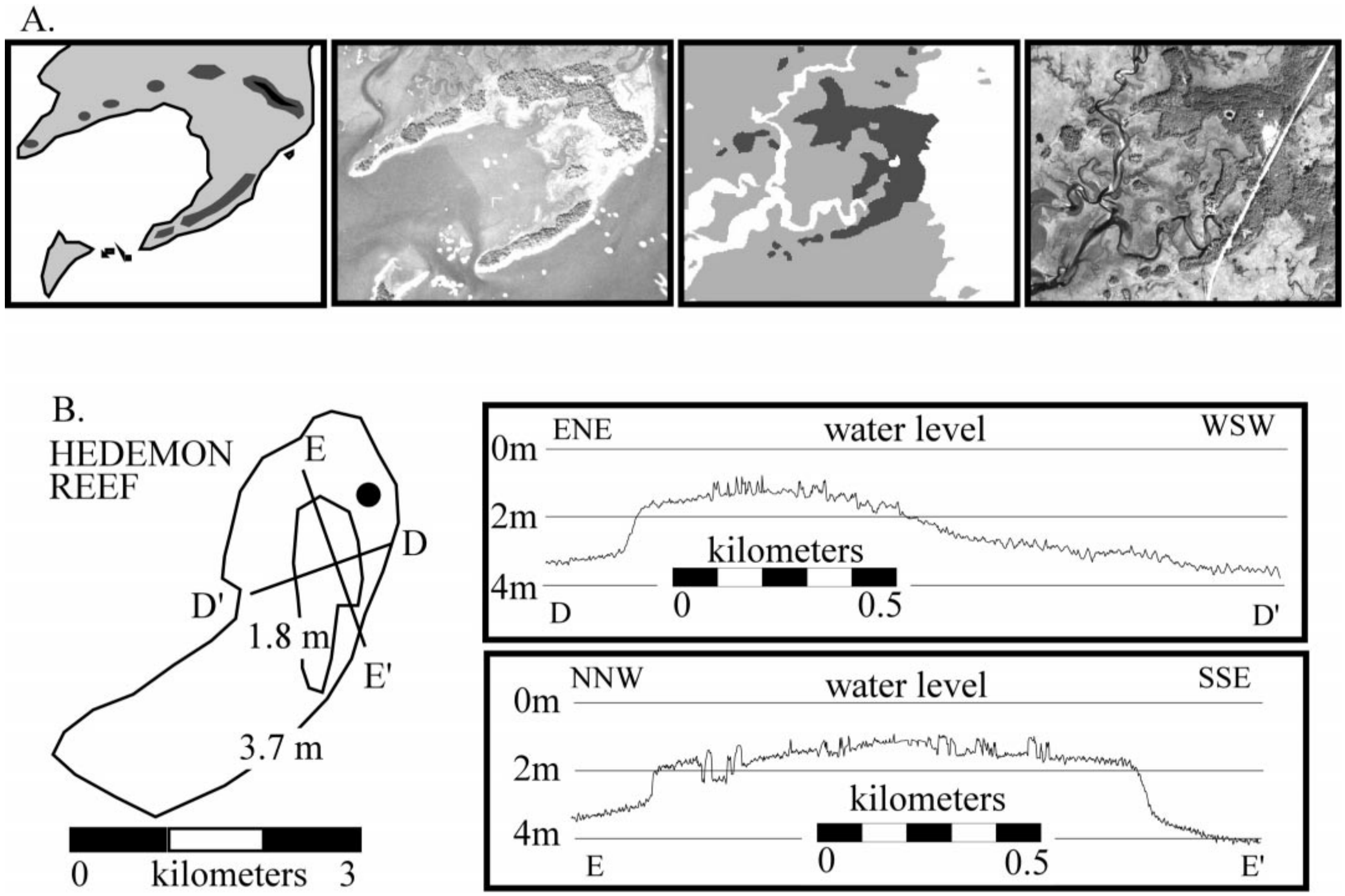


FIG. 4.—**A)** Topographic diagrams and aerial photographs of Butler Island and another unnamed island north of the delta. Locations are shown in Figure 1, which also illustrates other sandy U-shaped islands. These sandy islands are interpreted as paleodunes. **B)** Hedemon Reef is typical of offshore sandy shoal. This shoal exhibits distinct shore-normal asymmetry and is interpreted as a reworked paleodune resulting from Holocene sea-level rise.

Greene, a wide *J. roemerianus* flat, and a landward fringe of *C. jamaicense.* On aerial photographs, this northern coastal region exhibits meandering tidal creeks, which contain prominent sand bars and form well developed ebb tidal deltas at their mouths. South of the delta, river water is trapped behind the 20-km-long Suwannee oyster bioherm. In this region, *J. roemerianus* fronts the Suwannee Sound and tidal creeks are wider and more stable with ebb tidal deltas absent.

A series of sandy islands are located within the marsh system (Fig. 3C). These islands range from hundreds of meters to over 1 km in width and from 1 to 10 m in height, with most less than 3 m. Many islands appear to be composite structures formed by smaller highs of varying orientation, but most exhibit an overall U-shaped plan-view geometry, with the open end oriented to the southwest (ranging from 195° to 270° with the majority around 240°; Fig. 4A). A single TL age estimate for Butler Island in the northern portion of the study area yielded an age of 20 $\pm$ 4 ka (Foreman, personal communication 2001). Where these islands intersect the open marine shoreline, their western limbs have been reworked to form sandy beaches with localized sandy overwash deposits.

Seaward of the marsh system, long ($<$ 20 km), linear oyster bioherms protect landward sounds (Fig. 3D). Prominent bioherms are located from the delta region south and include Lone Cabbage, Halfmoon, and Delta Reefs at roughly 2 km offshore and West Gap Reef at approximately 5 km offshore (Fig. 1). West Gap Reef is thought to be older, because it lacks live bioherms of other more landward reefs (Grinnel 1971). West Gap and Suwannee Delta Reef merge to form the arcuate Suwannee Reef, which extends for 20 km from just north of Cedar Keys to just north of the delta and whose seaward face is blanketed by sand shoals. As indicated by analysis of bottom grab samples, Suwannee Reef forms a protective barrier to waves, allowing more muddy ($<$ 30% dry wt.), organic-rich ($<$ 8% dry wt.) sediments to be deposited in Suwannee Sound. North of the delta, where oyster bioherms are absent, the shallow nearshore is covered with clean sand, which forms the bottom cover.

Inner Shelf.—Sediments thin seaward of the Suwannee Reef and limestone again becomes exposed at approximately 30 km offshore or 10 m depth. The inner-shelf sediment sheet generally consists of gently undulating highs and lows. Clustered to the west of the delta, however, several distinct bathymetric highs (including Bombing Range Reef, Hedemon Reef, and Red Bank Reef) are over 1 km in width and shallow to $<$ 2 m depth (Fig. 1). Bottom inspection reveals these highs to be composed of clean sand. A bathymetric profile across Hedemon Reef shows an abrupt transition from the surrounding flat seafloor with a steep 2 m lee slope along the landward edge of the shoal (Fig. 4B). At the seaward edge of the sediment sheet, side-scan sonographs, bottom inspection, and bathymetry (the 9.1m/30 ft contour in Fig. 1) reveal a series of shore-normal asymmetrical ridges, ranging up to 1.5 m in height and 0.5 km in width, alternating with exposed limestone. These features are similar to linear sand ridges seen on many shelves (Duane et al. 1972; Parker et al. 1992).

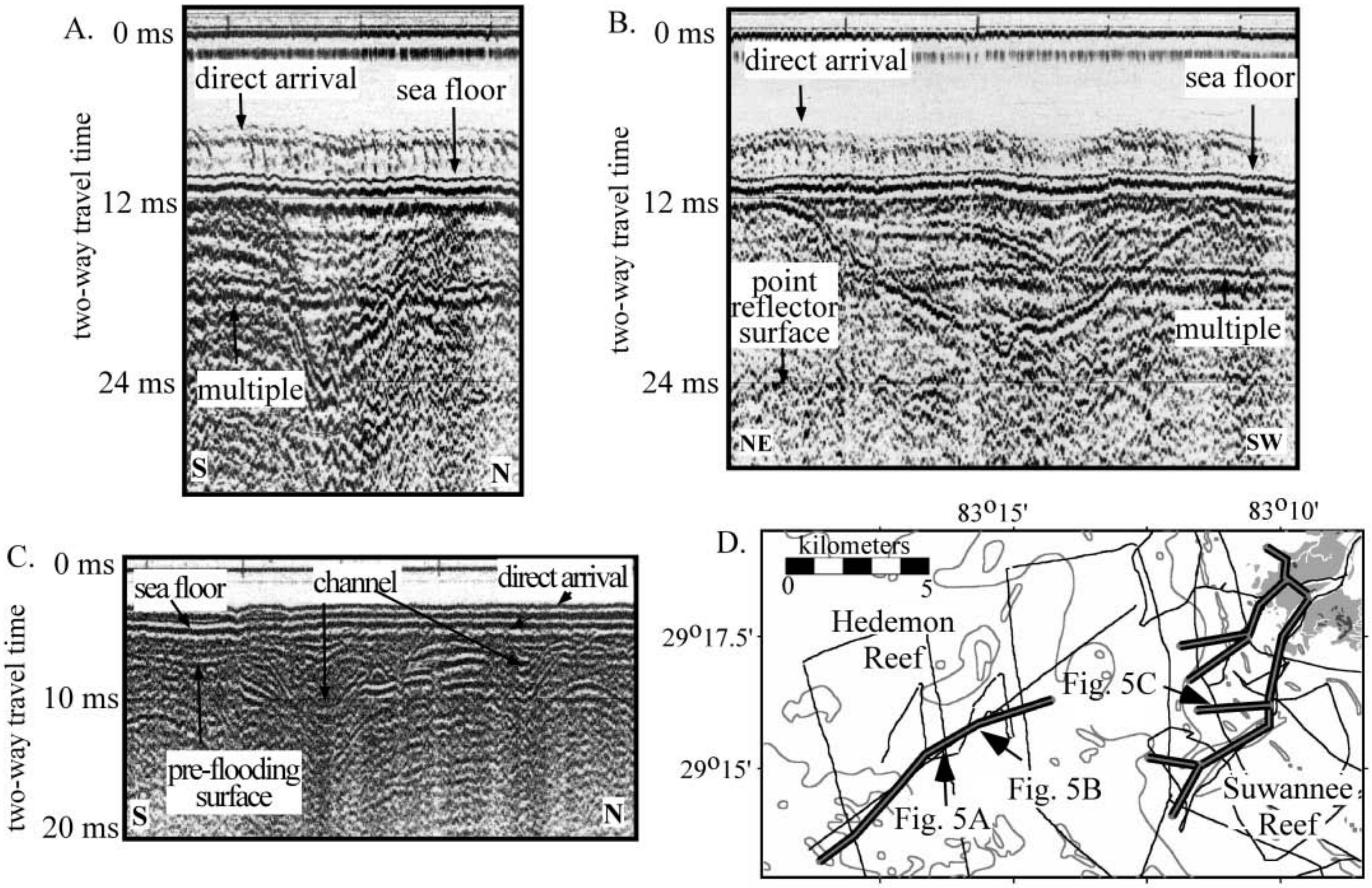


FIG. 5.—**A, B)** High-resolution seismic image of the single incised paleochannel on the inner shelf. **C)** High-resolution seismic image of a paleo-distributary channel from seaward of the delta reef. **D)** Location map of paleochannels.

High-Resolution Seismic Stratigraphy

High-resolution seismic profiles reveal karstic limestone facies underlying the sediments, with sinkholes, sags, and other karstic features common. The upper surface of this facies represents an unconformity with truncated lower reflectors. This boundary with the overlying sediments was not always resolvable because of the thin overlying sedimentary layers, weathering of the limestone surface, and collection in shallow water. Where the sedimentary cover was resolvable, the overlying sediments are often acoustically transparent.

The seismic data did provide the opportunity to identify cut-and-fill structures interpreted to represent paleochannels or paleovalleys (Fig. 5). A single incised paleochannel approximately 9 m deep and 200 m wide extends west from seaward of Suwannee Delta Reef across the inner shelf. Channel morphology includes meander bends similar in scale to the modern river channel. This channel was not identified in the farthest seaward seismic transect. Just seaward of Suwannee Delta Reef, four primary infilled channel incisions were identified. These channels are approximately 5 m deep and 150 m wide and appear similar to the branching distributary passes formed by the modern river. Unlike the channels seaward of the delta reef, resolution of more landward channels is difficult because of attenuation by biogenic gas. North of the river, an older paleovalley 8 m deep and 1 km wide was found parallel to shore. This valley can be traced northward of the modern delta for 6 km.

Lithofacies and Environments of Deposition

Primarily Holocene sediments have accumulated over the gently sloping Eocene limestone surface in the study area. Net sediment accumulations are typically thin (< 2 m) but thicken (< 10 m) within paleo-river channels. Paleoenvironmental interpretation of these deposits, with categories similar to Hine et al. (1988), is based on lithology and morphology of the deposit. These categories include Eocene limestone; Pleistocene sands and muds categorized as eolian, riverine, and undifferentiated facies; and Holocene sands, muds and peats, variably categorized as riverine, freshwater or brackish-water wetland, salt-marsh wetland, sandy intertidal to subtidal, oyster reef, restricted marine, and open marine facies. These facies are described in detail in Table 2.

Stratigraphic Cross Sections

Representative descriptions of vibracores are shown in Fig. 6, and the reader is referred to Wright (1995) for additional descriptions of other vibracores. A series of shore-normal stratigraphic cross sections were constructed for the Suwannee delta and adjacent coast from these vibracore data (Fig. 7).

Southern Transect (A–A′).—The southern transect is characterized by thin sediment cover that overlies the gently sloping limestone surface. Pre-Holocene sediments are composed of discontinuous muddy sand and clay that infill karstic features in the limestone. Freshwater to brackish-water wetland sediments were found to underlie salt-marsh sediments in the most landward core, thin intertidal to subtidal sediments underlie the seaward marsh fringe and also offshore below the most seaward oyster bioherm, and freshwater swamp deposits underlie the most landward oyster bioherm. Thicker salt-marsh, oyster-reef, and restricted marine transgressive deposits overlie these sediments. Salt-marsh facies thicken seaward from exposed limestone at the upland fringe to 1.2 m at the shoreface. Basal radiocarbon

TABLE 2.—*Paleoenvironmental interpretations based on lithology and geomorphology. Categories are similar to those of Hine et al. (1988).*

Environment	Lithology	Distribution
Eocene		
Undifferentiated	White to buff, highly fossiliferous limestone, containing foram, bryozoan, and echinoderm fragments in a micritic matrix. When buried, the upper surface is often marked by a white to light gray weathered micritic residuum, which is typically less than 25 cm but may be over 2 m thick. Often honeycombed with irregularly shaped voids infilled by very poorly sorted muddy sand to mud when closer to river valley or sinkholes. The surface of the residuum is uneven but the contact with the overlying sediment is sharp. It is interpreted as shallow marine sediments of the Ocala Formation.	Throughout study area.
Pleistocene		
Eolian	Clean gray to tan, dominantly fine to medium sand (with very coarse sand generally absent and <5% coarse sand) with subround to round polished medium grains located in the upper part of the Quaternary sand sheet. Based on sedimentology and geomorphology, it is interpreted as eolian.	While eolian processes modified much of the study area, deposits are most easily identified in association with U-shaped islands.
Riverine	Clean, bedded, medium sands, with sharp upper contact marked by orange oxidized iron. Similar to modern, it is interpreted as riverine sediments.	Located within the paleo-river valley north of the delta
Undifferentiated	Non-fossiliferous sand and mud unconformably overlying Eocene limestone. Base is typically massive mud to muddy sand, varying in color from blue-gray to light-olive brown, and occasionally imbedded with limestone pebbles. It generally grades upward into overlying pale yellow/light gray to yellowish brown quartz sand, with the upper 50 cm containing woody roots. Contact with overlying Holocene deposits is typically sharp but may be blurred due to bioturbation.	Located throughout the study area, within paleo-riverine valleys and isolated lows within the limestone (likely sinkholes).
Holocene		
Riverine	Clean, dark brown to grayish brown, often iron-stained, medium sands, with few wood fragments (Fig. 6C). It is interpreted as riverine sediments.	Located in modern river channels.
Freshwater or brackish-water swamp or wetland	(1) Black, muddy peat to organic-rich slightly muddy sand, containing roots, leaf fragments, and wood chips (Fig. 6F). Organic-rich sand is typically located toward the base and grades upward into finer peat. It forms a sharp contact with the underlying Quaternary sand and is a transitional contact with overlying salt-marsh wetland sediment or an abrupt contact with other overlying intertidal sediment. Transition to brackish marsh sediment is recognized by a decrease in organic content and an increase in grain size (like Orson et al. 1990 and Nyman et al. 1990). (2) Calcite marl containing *Planorbella cf* Weatherby (freshwater snails) and unidentified plant fragments are considered freshwater ponded sediments.	Peats are thickest in the delta and other topographic lows like sinkholes. Ponded freshwater calcite was found only in a topographic low landward of Hedemon Reef.
Salt-marsh wetland	Dark gray, organic-rich, rooted muddy sand to mud (Fig. 6F, G, H). In modern marsh, rhizomes and associated root mat extend to 10 cm depth, with no preservation down core. Below this depth, yellowish brown to black anchoring roots of *J. roemerianus* are observable by visual inspection. Thin sand layers within the marsh sediments are uncommon, usually occurring in the more seaward cores, and likely represent storm events. This unit typically overlies Quaternary sand or Holocene brackish-wetland peat and underlies Holocene intertidal sediment. It is interpreted as salt-marsh sediments.	Found underneath the modern marsh area, and within thin deposits in Suwannee Sound and a single location southwest of Hedemon Reef on the inner shelf
Intertidal to subtidal	(1) Tan to gray, dominantly fine to medium sand and may include burrows (including *Ophiomorpha*) and occasional shell fragments. It grades into pre-marine flooding sand below and is commonly overlain by oyster reef lithofacies. It is interpreted as intertidal to subtidal sediments, including delta-front, tidal-channel, and reworked pre-marine flooding sands. (2) Muddier sediments are dark gray, organic-rich muddy sand to sandy mud with small (<1 cm) sand-filled burrows with small mollusks and gastropods. This thin unit (<1 m thick) grades into marsh deposits below and is often overlain by oyster-reef lithofacies. It is interpreted as reworked marsh sediments.	Located seaward of modern marsh system and within the biohermal basins
Oyster reef	Whole oyster valves within black muddy sand to sandy mud matrix (Fig. 6I). Oyster shells may be cemented by growth position and occur at repeated depths. Shell valves not in growth position show only slight boring. Thicker sections (<2 m) are composed of multiple shell units separated by less shelly muddy sand to mud and are capped by a layer of imbricated shell hash. It forms a discrete contact with underlying upland and intertidal deposits and sharply underlies restricted marine sediments. It is interpreted as oyster bioherm and reef sediments.	Localized to oyster bioherms
Restricted marine	Mottled dark grayish black, low-organic (<5%), poorly to very poorly sorted, muddy fine to fine sand that is heavily bioturbated. The facies is recognized by the presence of thin-walled bivalve shell fragments, such as *Macoma* spp. and *Tellina* spp. Whole shells are more common toward the base, while scattered shell fragments are found higher in the section. The unit ranges in thickness from 20 to 85 cm, with greater thickness found landward of the oyster bioherms. It is typically bounded below by oyster and intertidal lithofacies and grades upward into open marine lithofacies. It is interpreted as forming in the low-energy, shallow-marine nearshore landward of the oyster bioherms.	Widespread within the nearshore and biohermal basins
Open marine (inner shelf)	Dominantly mottled gray, low-organic (<3%) muddy sand to sand with open marine shells (echinoderms, scallops, and branching bryozoans). Shell fragments are more numerous than in the restricted marine lithofacies. The unit is bioturbated with rare thin (<2 cm) shell layers preserved. Up to 20 cm of shelly sand may cap the unit. Ranging up to 1.5 m thick, the unit grades landward into restricted marine deposits and thins seaward to exposed Eocene limestone. Clean sand deposits are located within the shelf sand shoals (Fig. 6B) and thick (>4 m), poorly sorted, bedded medium to coarse sediment consisting of shell fragments in a mud matrix infill a paleoriverine channel (Fig. 6D). Branching coral fragments were also described within the sediments infilling this paleochannel.	Widespread across the inner shelf. Clean sand restricted to shoals and channel infill restricted to paleochannel on of the inner shelf.

estimates from the central and seaward portion of the salt marsh suggest an initial age of formation at 2350 cal yr BP, and age estimates of the landward portion indicate initial formation at 1160 cal yr BP. The nearshore is characterized by two large oyster bioherms, capped by imbricated shell fragments, and associated wide biohermal basins. Restricted marine sediments, which thicken seaward, infill the shallow basins. Radiocarbon dating of an oyster shell from the base of the seaward bioherm indicates formation by 4,440 cal yr BP; age estimates from the swamp lithofacies underlying the landward bioherm indicate an age of formation after 5890 cal yr BP; and age estimates of an oyster shell from the base of the bioherm suggest formation by 3,630 cal yr BP (Fig. 6I).

Delta Transect (B–B′).—The delta transect contains thicker deposits (> 7 m) overlying the limestone. The limestone is deepest under the Delta Reef and shallows landward and seaward. Pre-Holocene clayey sand over-

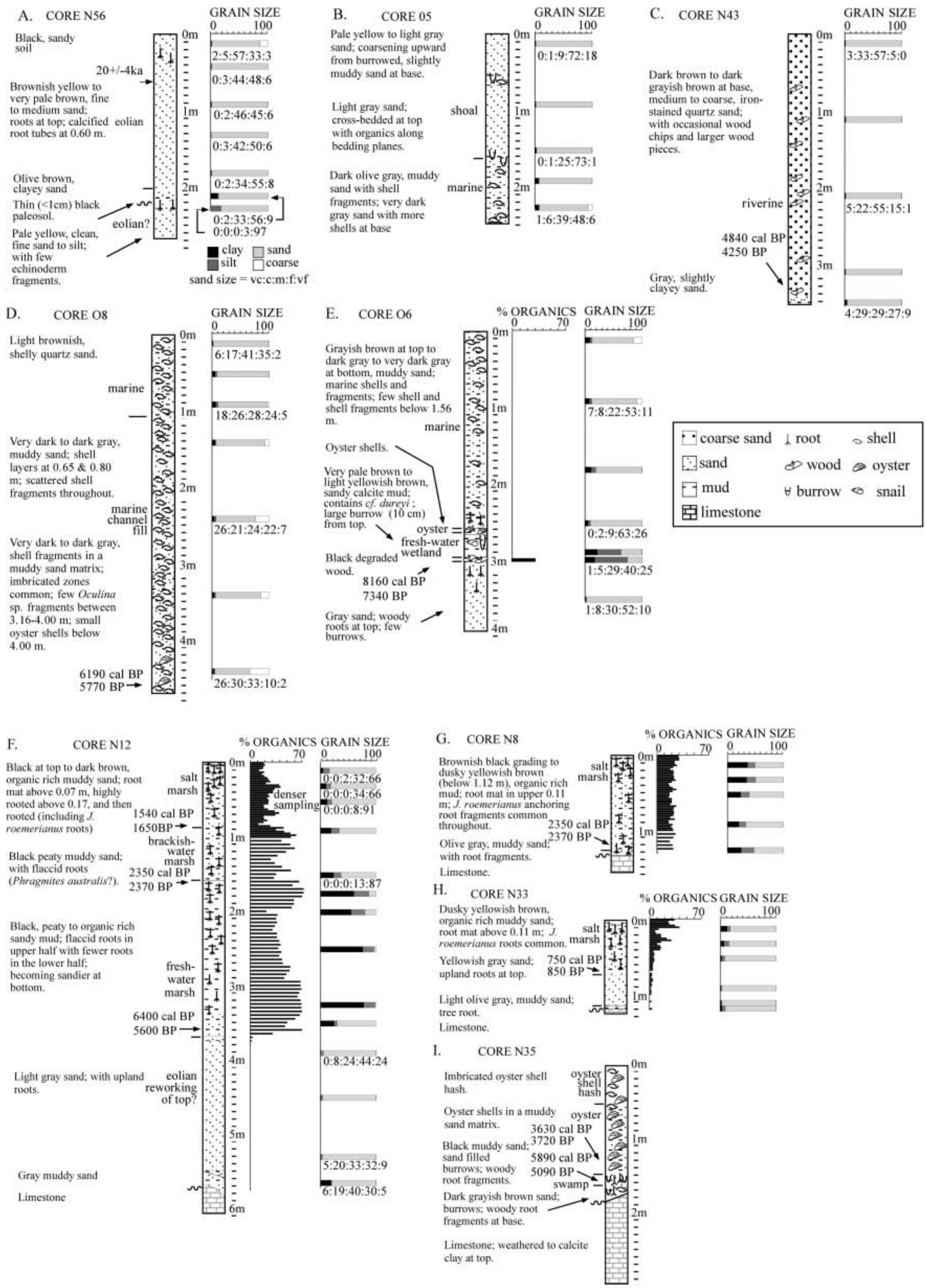
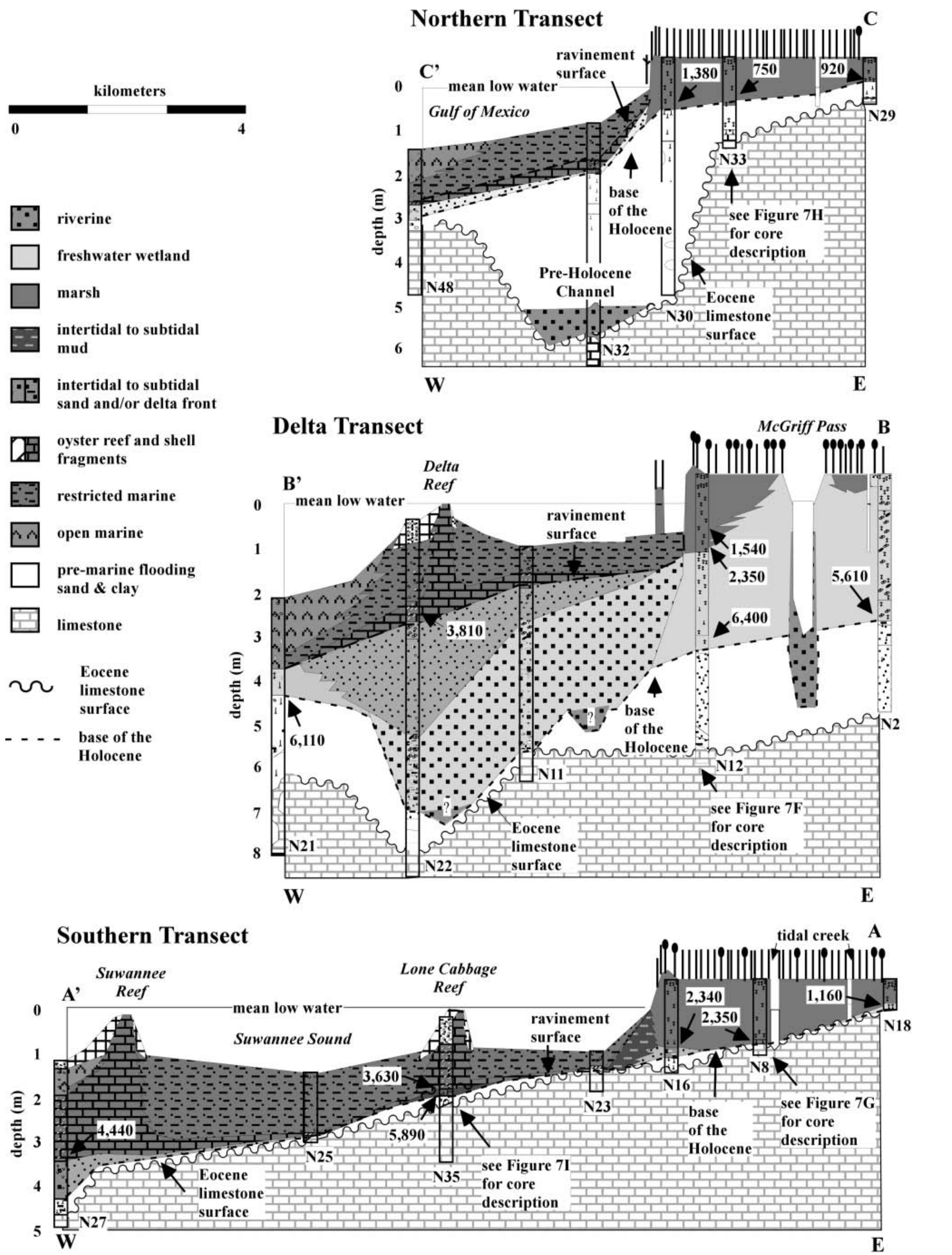


FIG. 6.—Representative vibracore descriptions from a variety of environments: **A)** modern sandy island (Butler Island, a paleodune); **B)** shelf shoal (Hedemon Reef); **C)** modern river; **D)** offshore paleo-riverine channel; **E)** shelf marine sediments (with freshwater calcite deposit); **F)** delta marsh (with freshwater swamp deposit); **G)** marsh south of the river; **H)** marsh north of the river; **I)** oyster bioherm (Lone Cabbage Reef). See Figure 1 for locations.



Northern Transect
C'
C
kilometers
0
4
mean low water
Gulf of Mexico
ravinement surface
1,380
750
920
N29
N33
N48
N30
N32
base of the Holocene
see Figure 7H for core description
Pre-Holocene Channel
Eocene limestone surface
depth (m)
W
E
riverine
freshwater wetland
marsh
intertidal to subtidal mud
intertidal to subtidal sand and/or delta front
oyster reef and shell fragments
restricted marine
open marine
pre-marine flooding sand & clay
limestone
Eocene limestone surface
base of the Holocene
Delta Transect
B'
B
Delta Reef
McGriff Pass
mean low water
ravinement surface
1,540
2,350
5,610
6,400
3,810
6,110
base of the Holocene
N2
N11
N12
N21
N22
see Figure 7F for core description
Eocene limestone surface
depth (m)
W
E
Southern Transect
A'
A
Suwannee Reef
Lone Cabbage Reef
tidal creek
mean low water
Suwannee Sound
ravinement surface
2,340
2,350
1,160
3,630
4,440
5,890
N18
N8
N16
N23
N25
N35
N27
base of the Holocene
see Figure 7G for core description
see Figure 7I for core description
Eocene limestone surface
depth (m)
W
E

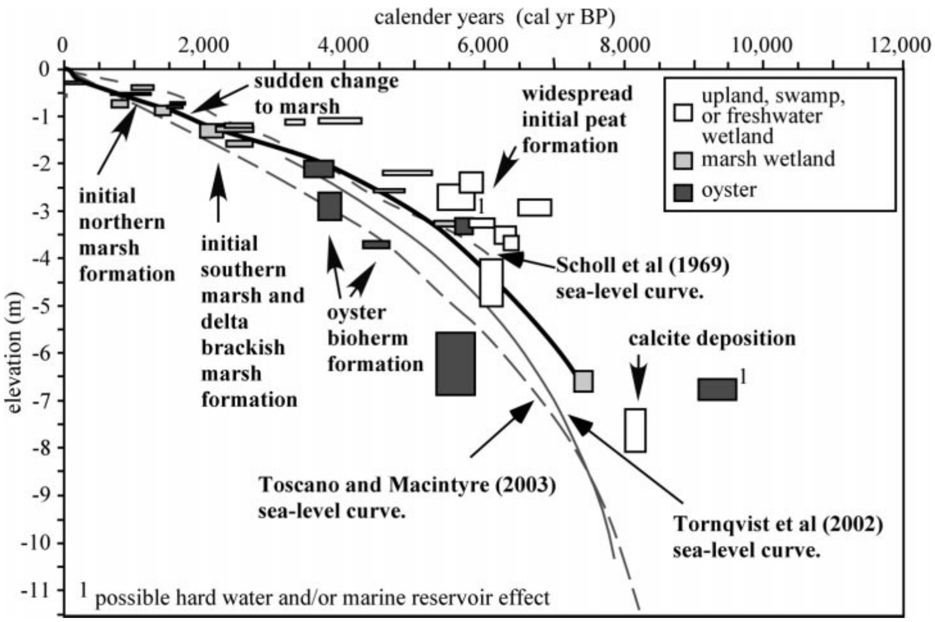


FIG. 8.—Plot of age versus depth for Suwannee River samples, where boxes outline variation in age estimates and elevation (as calculated by assuming no rodding and/or compaction and evenly distributed rodding and/or compaction). Studies of mangrove peat and coral deposits by Scholl et al. (1969) and Toscano and Macintyre (2003) for South Florida are included. The Scholl et al. (1969) sea-level curve based on mangrove peat has been replotted to better match more recent correlation to calibrated years. In addition, the recent deceleration curve by Törnqvist et al. (2002) for basal marsh deposits in Louisiana is plotted. Stratigraphic features suggest points where small sea-level fluctuations may have occurred during the overall Holocene deceleration.

lain by nonfossiliferous clean sand infill the limestone lows. Overlying this sand, swamp to brackish-water marsh form thick (2 to 3.7 m) deposits under the modern salt marsh and also a thin seaward deposit under the bioherms. Basal radiocarbon age estimates suggest an initial formation of Holocene freshwater wetland sediments at ~ 5600 to ~ 6400 cal yr BP. Salt-marsh sediments, as indicated by a sudden decrease in organic content, overlie the swamp sediments and have a basal age of ~ 1,550 cal yr BP. In the nearshore, bedded intertidal to subtidal sand deposits suggest the presence of nearby river channels. Oyster bioherm sediments of the Suwannee Delta Reef and landward restricted marine sediment overlie the subtidal sediments. Age estimates from an oyster shell from near the base of the bioherms indicate formation by 3,810 cal yr BP.

Northern Transect (C–C′).—The dominant feature of the northern transect is a paleochannel, located just seaward of the modern shoreline. The channel has incised into the surrounding limestone and is infilled by basal riverine deposits and unfossiliferous clean sand, with woody roots penetrating the top of the sand. Along the landward edge of the marsh, the clean sand is absent and instead a thin clayey sand infills the karstic limestone surface. Marsh deposits thicken seaward from exposed limestone to 0.80 m depth and formed between ~ 1380 to ~ 750 cal yr BP. Seaward of the shoreline, thin subtidal sand and oyster shell deposits grade into restricted to open marine sediments.

Holocene Sea-Level Change

The record of Holocene relative sea-level change was determined using marsh deposits from near mean sea level, freshwater to brackish-water peat and wood deposited at or above mean sea level, and oyster shells deposited at or below mean sea level. Analysis of sea-level change within the study area identifies a middle to late Holocene decelerating sea-level rise with an average rate of rise of ~ 0.16 cm/y between 7500 to 5500 cal yr BP, slowing to ~ 0.07 cm/y between 5,500 and 2,500 cal yr BP and further slowing to ~ 0.05 cm/y between 2,500 cal yr BP and 750 cal yr BP (Fig. 8).

DISCUSSION

Climate Control on Pre-Marine Flooding Sedimentation

Eolian Processes.—During the late Pleistocene to early Holocene (late Marine Isotope Stage (MIS) 2 to early MIS 1), drier climatic conditions characterized Florida (Fig. 9A; Grimm et al. 1993; Watts et al. 1992; Watts 1983). The scattered sandy U-shaped islands along the coast of the Suwannee delta region are interpreted here to represent relict eolian dunes derived from local riverine sands and are similar in morphology, grain size, and orientation to other parabolic dunes identified for the southeastern United States (Carver and Brook 1989; Ivester et al. 2001). Because the sands composing these features are moderately to poorly sorted, these dunes may have undergone only slight migration, forming from local sand sheets. Some of the dunes along this coastline are located away from the modern river channel, for example the dunes located near Cedar Keys and Horseshoe Point, suggesting previous reworking of the riverine sands. Increased *Ambrosia*-type pollen recorded in regional studies (Grimm et al. 1993; Watts et al. 1992; Watts 1983) implies disturbance of sand and supports that eolian processes were modifying the land surface.

Studies by Ivester et al. (2001), and Otvos and Price (2001), and as summarized by Carver and Brook (1989), indicate greater periods of dune activity for the southeastern United States associated with drier conditions during the late Pleistocene, with continued limited activity or reactivation reported for Louisiana extending into the early Holocene (Otvos and Price 2001). Most eolian structures in the study area are considered to be late Pleistocene, as suggested by the TL age of Butler Island, but may have undergone slight modification until the early Holocene, when regional water tables rose (Grimm et al. 1993; Watts et al. 1992; Watts 1983). The

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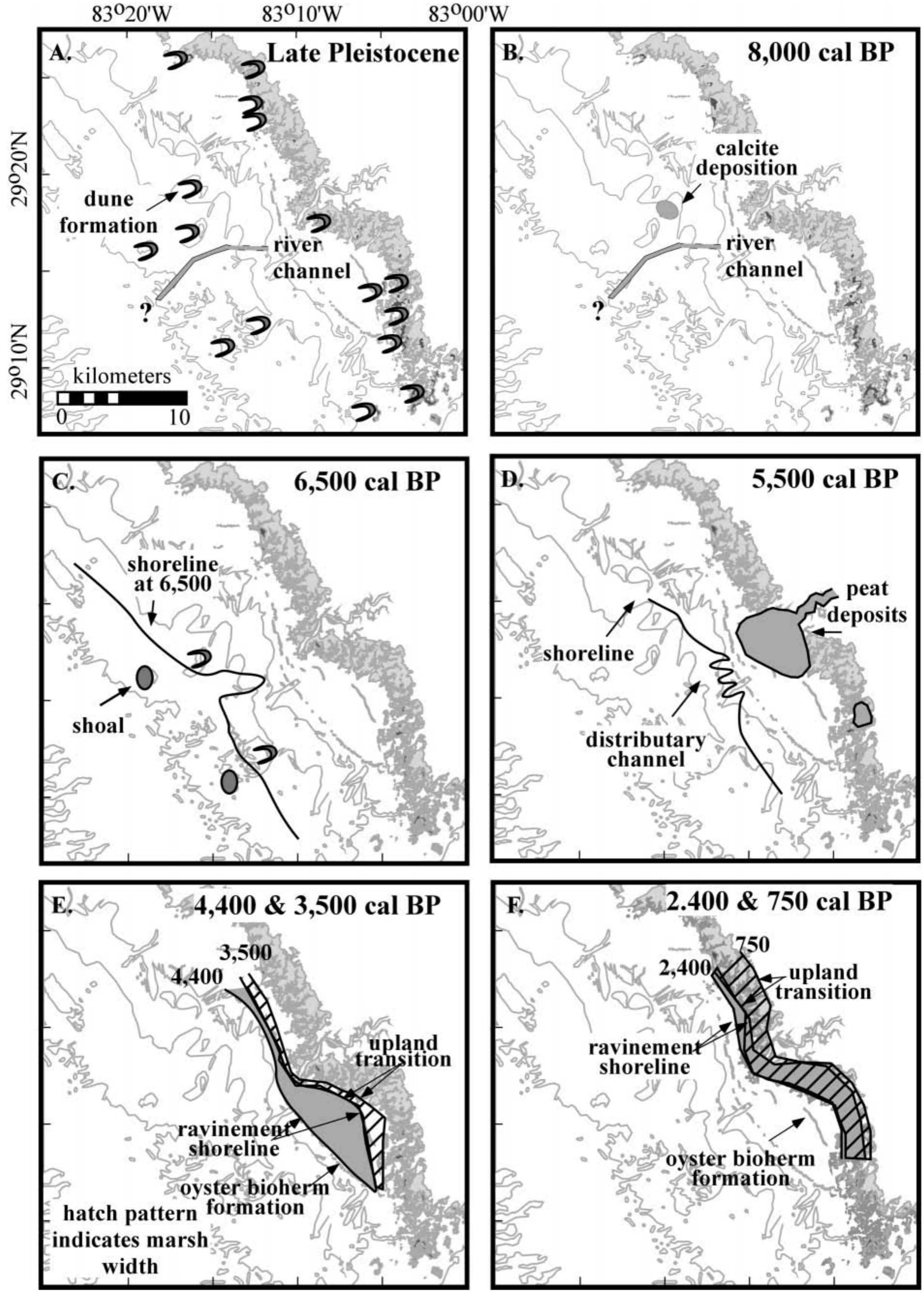
FIG. 7.—Shore-parallel cross sections from south of the delta (A–A′), the delta (B–B′) and north of the delta (C–C′). See Figure 1 for location of cross sections. The southern transect shows thin transgressive deposits overlying the gently sloping Eocene limestone. The delta transect shows thicker deposits associated with the river near paleochannels. The northern transect shows an infilled pre-Holocene paleochannel, whose sand source has influenced northern marsh system morphology during the Holocene transgression.


83°20'W
83°10'W
83°00'W
29°20'N
29°10'N
A.
Late Pleistocene
dune formation
river channel
?
kilometers
0
10
B.
8,000 cal BP
calcite deposition
river channel
?
C.
6,500 cal BP
shoreline at 6,500
shoal
D.
5,500 cal BP
peat deposits
shoreline
distributary channel
E.
4,400 & 3,500 cal BP
3,500
4,400
upland transition
ravinement shoreline
oyster bioherm formation
hatch pattern indicates marsh width
F.
2.400 & 750 cal BP
750
2,400
upland transition
ravinement shoreline
oyster bioherm formation

localized deposition of freshwater calcite on the shelf after 8,160 cal yr BP, as suggested by an age estimate from underlying wood (Fig. 6E), is the first preserved indicator of a locally rising water table (Fig. 9B). Widespread calcite deposits, which predate wetland deposition, are similarly reported for the Everglades at this time (Gleason 1974). These biologically mediated calcite deposits are thought to form during seasonally fluctuating water tables (Gleason 1974). After 6,730 cal yr BP, the regional water table rose, as indicated by wide spread swamp deposits preserved within topographic lows (Fig. 9C). While this rise in fresh water levels is attributed to climate change, as suggested by the pollen record of inland lakes (Grimm et al. 1993), the corresponding marine flooding of the region at this time suggests that sea-level rise is also likely a primary control on rising water-table height and swamp development.

Riverine Processes.—A drier late Pleistocene climate likely caused reduced discharge of the Suwannee River. The shallow Okefenokee Swamp was dry prior to 6,700 yr BP ($\sim$ 7,500 cal yr BP; Cohen et al. 1984) and the shallow springs also likely provided little input because of lowered Florida aquifers (Watts and Stuiver 1980). Similarly to its modern tributaries, the Sante Fe and Alapaha rivers, and as inferred for fluvial systems elsewhere along peninsular Florida (Evans et al. 1989), the Suwannee River may have flowed underground, with the springs acting as conduits of vertical flow. Flow through shafts is suggested by the large ($>$ 1.5 m) infilled voids located within the weathered limestone typically found in cores along the river valley and may be further supported by the absence of a riverine channel of proportions similar to the modern channel on the most seaward seismic data. Its absence, however, could result from ravinement of shallow channels that did not incise into the limestone or a channel location outside of the data collected.

Sea-Level Control on Holocene Sedimentation

Early Holocene.—By 8000 cal yr BP, sea-level rise created a sparse sediment cover overlying the seaward portion of the shelf. This more rapid but decelerating sea-level rise produced little preservation of intertidal sediments, primarily a very thin ($<$ 0.25 m) intertidal sand deposit. The only recovered marsh deposit was located southwest of Hedemon Reef and may be the result of a short-term stabilization of the shoreline or sheltering from wave energy by the seaward sandy shoals.

These sandy shoals are interpreted as reworked late Pleistocene dunes (Fig. 9B). The limbs of these relict dunes have been modified during the initial transgression to form islands, similar to those intersecting the coast today, with nearshore sand overwashing the islands during storm surges. As a result of the early Holocene sea-level rise and low wave energy of the Gulf of Mexico, these islands were drowned to form shoals. These shoals have apparently undergone and continue to undergo some landward transport after submergence, as indicated by bathymetric and vibracore data from Hedemon Reef (Figs. 4, 6B).

The Suwannee River during this time occupied a channel, approximately 9 m deep, located on the inner shelf south of Hedemon Reef. The absence of quartzose riverine coarse sand infill within the channel may be the result of a combination of reduced riverine sediment transport to this distal position and/or nondeposition due to more rapid sea-level rise. As sea level rose, the river channel was filled by shelly and muddy deposits (Fig. 6D). Oyster shells near the base of the infill indicate initial nearshore deposition, probably beginning prior to 6,190 cal yr BP. The overlying bedded sediment, containing marine shell fragments, was likely formed by tidal currents as continued sea-level rise inundated the channel.

Middle Holocene.—Landward movement of the shoreline south of the river delta slowed and oyster bioherms were able to aggrade as sea-level rise decelerated after 5,400 cal yr BP (Fig. 9D). Similar aggradation occurred in oyster bioherms located to the south along the marsh coast (Hine et al. 1988; Goodbred et al. 1998) and in vermetid reefs still farther to the south in the Ten-Thousand Islands area (Parkinson 1989). However, unlike the oyster reefs to the south, which were initiated on drowned limestone highs (Hine et al. 1988), oyster reefs in the Suwannee River region are not controlled by limestone topography but rather overlie intertidal sand. These bioherms are thought to have originated at the mouths of tidal creeks, with oyster bars building laterally from these sites and eventually coalescing during continued sea-level rise and shoreline transgression (Grinnel 1971). During this growth, these oyster bioherms maintained a shore-parallel position to allow exposure to nutrient-rich tidal waters. Growth of the extensive Suwannee Reef, one of the longest bioherms along the coast, is inferred to reflect increased Suwannee River flow, which limited marine predation during the middle Holocene. Bioherm growth in turn created back-reef lagoonal basins. Baffling of wave energy by the bioherms, and input of riverine mud, has allowed accumulation of $>$ 1 m of fine sediment in these lagoonal basins.

While biogenic-related sedimentation along the outer reef was able to keep pace with sea-level rise by 4,440 cal yr BP, sediment accumulation closer to shore apparently could not and the shoreline continued to retreat. The presence of a wider marsh system at this time is indicated by a 5,390 cal yr BP salt-marsh deposit preserved seaward of East Pass. As the shoreline retreated, the marsh area narrowed as a reduction in sea-level rise may have prevented rapid marsh encroachment landward. Eventually, the inner oyster bioherm became established by 3,630 cal yr BP. The absence of additional oyster bioherms, as observed elsewhere along the marsh coastline, may result from altered currents and salinity produced by a much more extensive seaward oyster bioherm and a slightly slower coastline retreat due to riverine sediment input.

In the delta region, decelerating middle Holocene sea-level rise, perhaps combined with potentially increased riverine sediment supply, similar to other west central peninsular Florida rivers (Guccione 1995), allowed deltaic construction at the river mouth. Initial delta formation occurred seaward of the present location of the delta reef bioherm, as suggested by infilled deltaic passes recorded in seismic data and sand shoals apparently reworked from deltaic deposits seaward of the bioherm. Wood dated near the base of riverine sands within the modern channel suggests that transport of modern riverine sediments had begun by 4,840 cal yr BP. With rising sea level, the delta reef bioherm was established by 3,810 cal yr BP as the shoreline continued to retreat landward. As the shoreline transgressed, marine sediments overtopped and buried widespread but thin floodplain deposits. The river was able to backfill its passes during this period of slow transgression, and the shoreline would eventually stabilize its shoreline position near its present location.

North of the river, the shoreline would have transgressed over the area's underlying sand sheet. The absence of continued oyster development on this region may be due to Cat Island blocking fresh water flow from the Suwannee River to the north, and a thicker sand cover that provided a poor surface for attachment of oysters.

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FIG. 9.—Cartoon maps of the Suwannee River area showing significant developmental events and shoreline movements. **A)** Dunes, likely Pleistocene, have formed from paleo-riverine sediments. **B)** Around 8,000 cal yr BP, calcite deposition indicates fluctuating water tables. **C)** By 6,500 cal yr BP, the shoreline has transgressed the most seaward relict dunes, which form the core for offshore shoals. **D)** By 5,500 cal yr BP, deltaic distributary channels are established and peat deposits are formed around the river mouth and in limestone lows. **E)** By 4,440 cal yr BP, the seaward oyster bioherm forms, and by 3,500 cal yr BP the landward oyster bioherm forms. **F)** Between 2,400 cal yr BP and 750 cal yr BP, the modern marsh north and south of the river mouth begin to stabilize and aggrade.

Late Holocene.—South of the river, the landward edge of the marsh system transgressed to the middle of the present marsh system by 2,350 cal yr BP (Fig. 9E). After stabilizing, these marshes aggraded vertically and encroached landward as rising sea level inundated freshwater swamps, as well as upland sand and limestone. Similarly, organic deposits along the west central Florida marsh coast to the south had become aggradational by this time (Hine et al. 1988). The rising sea level also flooded portions of the relict dunes, forming the modern sandy islands. These islands lack the western limbs of the dunes within the marsh system, which suggests that the limbs were reworked by higher-energy storm and tidal events along this otherwise low-energy coastline (Fig. 3C). Backshore overwash deposits further suggest reworking. By 1,380 cal yr BP, continued transgression overtopped the elevated sand sheet north of the river, and the landward edge of the marsh system transgressed past the position of the present shoreline, as had occurred earlier in the southern marshes.

In the delta region, slight shoreline stabilization and backfilling of the channels continued during the late Holocene deceleration of sea-level rise. Long-term stability is suggested by continuity of channel-fill facies, with thick accumulation of delta-front sediment seaward of Alligator Pass, riverine sand with *Ophiomorpha* burrows within the pass, and riverine sand within the main river. The channel fill was able to form the extensive mouth bar in Alligator Pass as downstream-migrating subaqueous dunes backfilled the pass. The other passes likely formed as a result of infilling of Alligator Pass, as friction-dominated processes on the effluent shaped bifurcating channels and mouth bars. The subaqueous dunes currently turn toward and end into Salt Creek pass, suggesting that this northern pass is an actively building area of the delta.

Implications for Lowstand and Transgressive Deposits

Lowstand system tract riverine deposits were restricted to the incised channels. Riverine sediments in the study area thin seaward, which may reflect lowered late Quaternary sediment discharge by peninsular west Florida rivers resulting from climate change and storage in the upper river valley (Guccione 1995). The inability to trace the paleochannel to the seaward edge of the study area, and common infilled voids in the limestone along the incised channels, may also indicate vertical flow within the karstic limestone. This type of flow could produce interrupted incised channels, as has been suggested for the Charlotte Harbor region of west Florida (Evans et al. 1989), and would result in discontinuous lowstand riverine deposits. Lowstand eolian deposits resulting from modification of local sand sheets also are present. Long-term preservation of eolian dune morphologies are, however, restricted to elevations above previous sea-level highstands.

The transgressive systems tract comprises thin ($<$ 2 m) sedimentary units representing freshwater or brackish-water wetlands, salt-marsh deposits that fringe the modern coast, small deltaic deposits at the mouths of distributary channels, isolated linear oyster bioherms, and widespread marine deposits. Because most of these sedimentary deposits are reworked as a result of shoreline ravinement, preservation on the shelf during this transgression is limited to marine deposits, reworked coastal deposits, cemented oyster bioherms, and preserved coastal sediments within limestone lows. Previous sea-level rises and falls across this low-sedimentation, low-accommodation setting limit long-term preservation of transgressive deposits to the lows within the Eocene limestone.

Implications for Gulf of Mexico Sea Level

Middle to late Holocene sea-level change in the Gulf of Mexico and elsewhere has been debated in the literature. Along the west Florida coast, Stapor et al. (1991) examined a series of geomorphic beach ridges along the central west Florida barrier system. On the basis of beach-ridge height and the age of youngest shell dates, they propose that sea level was higher than present at 2,000 yr BP continuing until a fall at 1,500 yr BP. On the basis of archeological analysis of shells within middens, Walker et al. (1995) suggest higher than present sea-level change in this barrier system between 1,750 to 1,450 yr BP. In recent work in the Gulf of Mexico, Morton et al. (2000) have proposed several higher than present sea-level events from 5,500 to 1,200 cal yr BP along the Texas coast based upon geomorphic features, such as raised marshes and subtidal flats, wave-cut benches, wave-cut scarps, and recurved spits. Blum et al. (2001) report foraminiferal data and radiocarbon ages from one set of higher ridges in central Texas that suggest a sea-level highstand between 6,800 to 4,800 yr BP.

In contrast to periods of higher than present sea level, other researchers along the west Florida coast have used mangrove and organic-rich salt-marsh sediments to suggest a general deceleration in late Holocene relative sea-level rise. This deceleration has been proposed to be gradual (Scholl et al. 1969; Robbin 1984) or with potential for a small rapid rise at $\sim$ 1,700 cal yr BP within an overall period of decelerating rise (Goodbred et al. 1998). More recently, Törnqvist et al. (2002) have suggested a gradual deceleration of relative sea-level rise from 8,000 cal yr BP to 3,000 cal yr BP for the Mississippi delta region on the basis of basal peats, and Toscano and Macintyre (2003) also suggest a comparable gradual deceleration of sea-level rise for Florida and the Caribbean based on mangrove peats and corals.

Similar to other locations along the west coast of Florida (Goodbred et al. 1998; Parkinson 1989; Scholl et al. 1969), stratigraphic evolution of the Suwannee delta region suggests an overall deceleration of sea-level rise allowing a switch from a retrogradational to aggradational or slightly progradational shoreline. This study suggests that sea level was at an elevation of ~ -7 m by 7,430 cal yr BP. This is in relative agreement with results of Blum et al. (2001), Törnqvist et al. (2002), and Toscano and Macintyre (2003). Sea-level rise then decelerated, with changes in shoreline position and coastal environments related primarily to sea-level rise and perhaps secondarily to changes in sediment supply. An abrupt change from brackish-water sediments to salt-marsh sediments at $\sim$ 1600 cal yr BP is similar to a more rapid rise that has been also proposed elsewhere along the west Florida coastline (Goodbred et al. 1998). While other small variations of sea-level changes are possible within this overall context of decelerating rates of rise, the stratigraphic results of this study and the presence of relict dune morphologies near sea level with preserved western limbs in the marsh system suggest that relative sea level was never higher than at present during the middle to late Holocene.

CONCLUSIONS

Major geomorphic features of the coastline between Cedar Keys and Horseshoe Point in the northeastern Gulf of Mexico in Florida include the small, 20 km^2 river-dominated Suwannee delta at the center of the coastline, large bioherms and back-biohermal basins that front open-marine salt marsh to the south of the delta, and sandier open-marine salt marshes north of the delta. Bathymetric highs seaward of the Suwannee Reef, an oyster bioherm, are composed of sand and are interpreted to represent relict eolian dunes. An offshore sand sheet thins seaward, with limestone becoming exposed by 10 m depth, which is about 30 km offshore.

Thicker ($>$ 3 m) sedimentary deposits are restricted to paleochannels, karstic topographic lows, or relict dunes. A paleochannel, presumably from the Suwannee River, was mapped to the west-southwest of the present riverine mouth and is infilled with marine sediments. Seaward of 15 km offshore, the channel could no longer be identified. Another older paleochannel was mapped to the north of the current delta, and sand from this feature has been reworked to produce sandier marshes in this region.

Late Quaternary climate changes have been influential in the stratigraphic development of this region. Slightly drier conditions in the late Pleistocene resulted in the formation of eolian dunes on the exposed subaerial shelf. Rising water tables during the early to mid Holocene allowed increased freshwater wetland deposits in the Suwannee region after ~7,000 cal yr BP.

Geologic development of the coastline switched from retrogradational to aggradational as a result of middle to late Holocene deceleration of rising sea level. The initial sea-level rise of the early Holocene quickly transgressed across the shelf, allowing little development of nearshore sediments. Offshore sand shoals are interpreted as relict eolian dunes flooded at this time. Deceleration of sea-level rise after approximately 4,500 cal yr BP allowed oyster bioherms to aggrade and deltaic deposition to begin. Continued deceleration of sea-level rise has allowed the modern marsh to form after 2,350 cal yr BP as marine waters flooded swamp deposits, sandy uplands with relict dunes and exposed limestone.

As suggested by the preservation of the westward limbs of the relict eolian dunes within the marsh system, the shoreline has not transgressed landward of its current position and middle to late Holocene sea-level variations have not risen above present sea level along the coastline of Florida.

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