Journal of Coastal Research | 18 | 2 | 225–253 | West Palm Beach, Florida | Spring 2002

Late Quaternary Evolution of the Orinoco Delta, Venezuela

Andrew G. Warne[*]**, Edgar H. Guevara, and Andres Aslan**[**]

The University of Texas at
Austin Bureau of Economic
Geology University Station
Box X Austin, Texas 78713-
8924

[*]Current address: U.S.
Geological Survey GSA
Center, 651 Federal Drive
Guaynabo, Puerto Rico,
00965-5703
agwarne@usgs.gov

[**]Current address:
Department of Physical and
Environmental Science
Mesa State College P.O.
Box 2647 Grand Junction,
Colorado 81502

ABSTRACT

WARNE, A.G.; GUEVARA, E.H., and ASLAN, A., 2002. Late quarternary evolution of the Orinoco Delta, Venezuela. *Journal of Coastal Research*, 18(2), 225–253. West Palm Beach (Florida), ISSN 0749-0208.

The modern Orinoco Delta is the latest of a series of stacked deltas that have infilled the Eastern Venezuelan Basin (EVB) since the Oligocene. During the late Pleistocene sea-level lowstand (20,000 to 16,000 yrs BP), bedrock control points at the position of the present delta apex prevented the river channel from incising as deeply as many other major river systems. Shallow seismic data indicate that the late Pleistocene Orinoco incised into the present continental shelf, where it formed a braided-river complex that transported sediment to a series of shelf-edge deltas.

As sea level rose from 16,000 to 9,500 yrs BP, the Orinoco shoreline shifted rapidly landward, causing shallow-marine waves and currents to form a widespread transgressive sand unit. Decelerating sea-level rise and a warmer, wetter climate during the early Holocene (9,500 to 6,000 yrs BP) induced delta development within the relatively quiet-water environment of the EVB embayment. Sea level approached its present stand in the middle Holocene (6,000 to 3,000 yrs BP), and the Orinoco coast prograded, broadening the delta plain and infilling the EVB embayment. Significant quantities of Amazon sediment began to be transported to the Orinoco coast by littoral currents. Continued progradation in the late Holocene caused the constriction at Boca de Serpientes to alter nearshore and shelf hydrodynamics and subdivide the submarine delta into two distinct areas: the Atlantic shelf and the Gulf of Paria. The increased influence of littoral currents along the coast promoted mudcape development. Because most of the water and sediment were transported across the delta plain through the Rio Grande distributary in the southern delta, much of the central and northwestern delta plain became sediment starved, promoting widespread accumulation of peat deposits.

Human impacts on the delta are mostly associated with the Volcán Dam on Caño Manamo. However, human activities have had relatively little effect on the delta processes and environments.

ADDITIONAL INDEX WORDS: *Orinoco Delta, Orinoco River, late Quaternary, late Pleistocene, Holocene, Venezuela, human impacts, Eastern Venezuela Basin, sea-level change, subsidence, paleoclimate, Guayana littoral current, Guiana Coast.*

INTRODUCTION

The Orinoco Delta sustains a vast, largely undeveloped mosaic of tropical wetlands and shallow aquatic ecosystems within the coastal plain of eastern Venezuela. The triangular to trapezoidal delta plain encompasses ~22,000 km^2 of wetland forests and herbaceous marshes that are subdivided by networks of fluvial and tidal channels (Figure 1). The Orinoco River floodplain and delta plain comprise one of the world's largest tropical-wetland complexes (HAMILTON and LEWIS, 1990).

We conducted a multidisciplinary study to identify and evaluate the physical processes and process linkages that control stability and integrity of the Orinoco Delta ecosystems (WARNE *et al.,* 1999). The aim of this preliminary but comprehensive study was to generate, compile, and interpret baseline information needed to anticipate, avoid, and mitigate impacts associated with human activity in the delta.

Our evaluation of the Orinoco Delta is based on geomorphic, sedimentologic, shallow stratigraphic, pedologic, hydrologic, and botanic data generated during a series of delta expeditions during 1998 and 1999. Evaluation is also based on satellite image and historical aerial photograph analyses, and an extensive literature review. This comprehensive study is summarized in WARNE *et al.* (1999), and the regional setting of the Orinoco Delta is presented in WARNE *et al.* (in press). In the present article we describe the geologic setting of the delta and the principal physical processes that influence delta evolution. We then use this information to develop an account of the late Quaternary evolution of the Orinoco Delta.

THE ORINOCO DELTA

Like most major fluvio-marine deltas, the Orinoco can be subdivided into delta-plain, delta-front and prodelta sectors. Most of the Orinoco Delta is composed of delta-plain wetlands, although delta-front and prodelta muds extend offshore as much as 60 km from the coast (NOTA, 1958; Mc-

---

00150 received 31 October 2000; accepted in revision 12 June 2001.

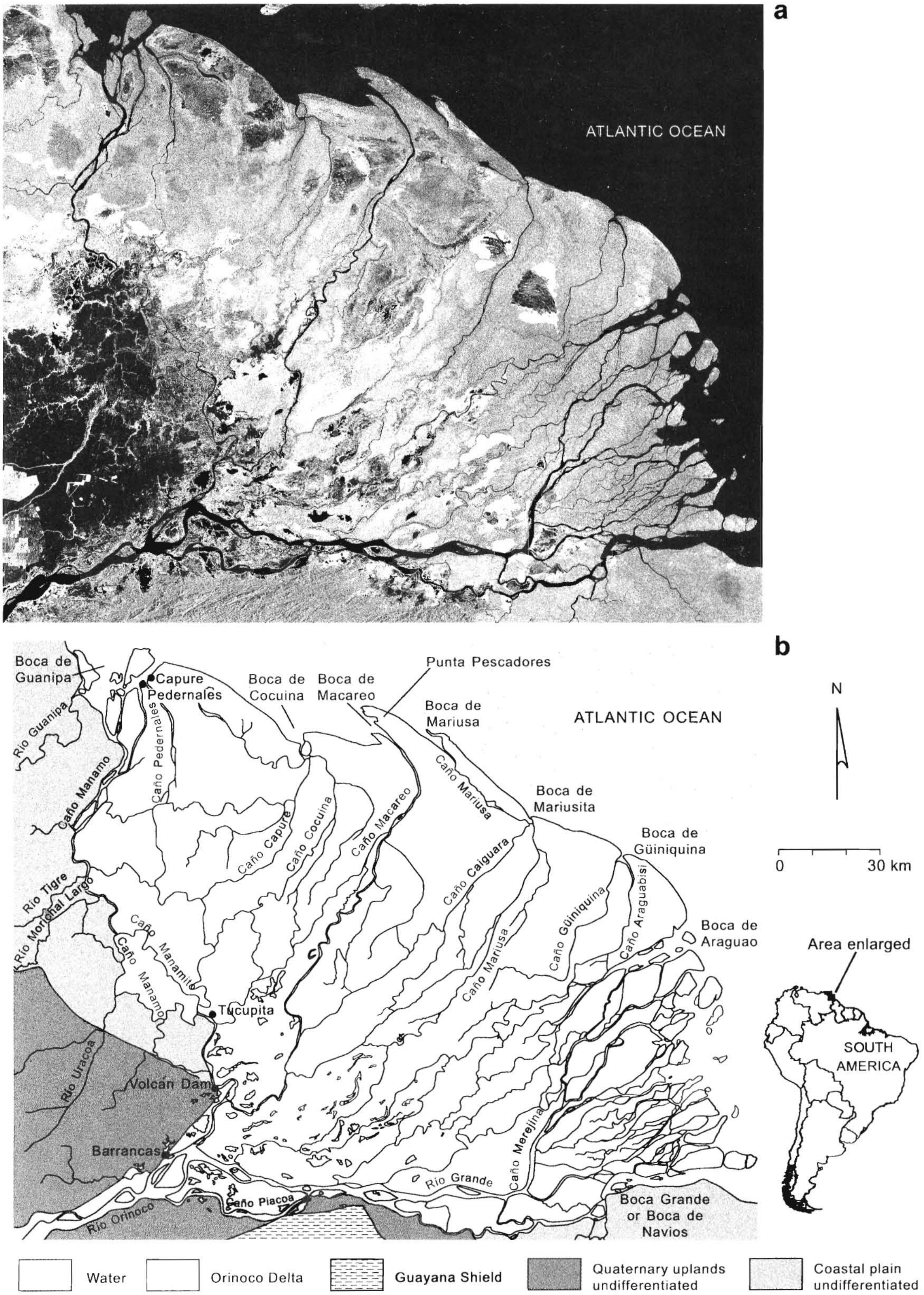


Figure 1. (a) JERS (Radar inferometric) image of the Orinoco Delta. The composite image was acquired September through December 1995. (b) Geographic features of the Orinoco Delta. Note that the seaward limit of major distributaries are referred to both as "Boca" (in reference to the mouth of the water body) and "Barra" (in reference to the distributary mouth bar).

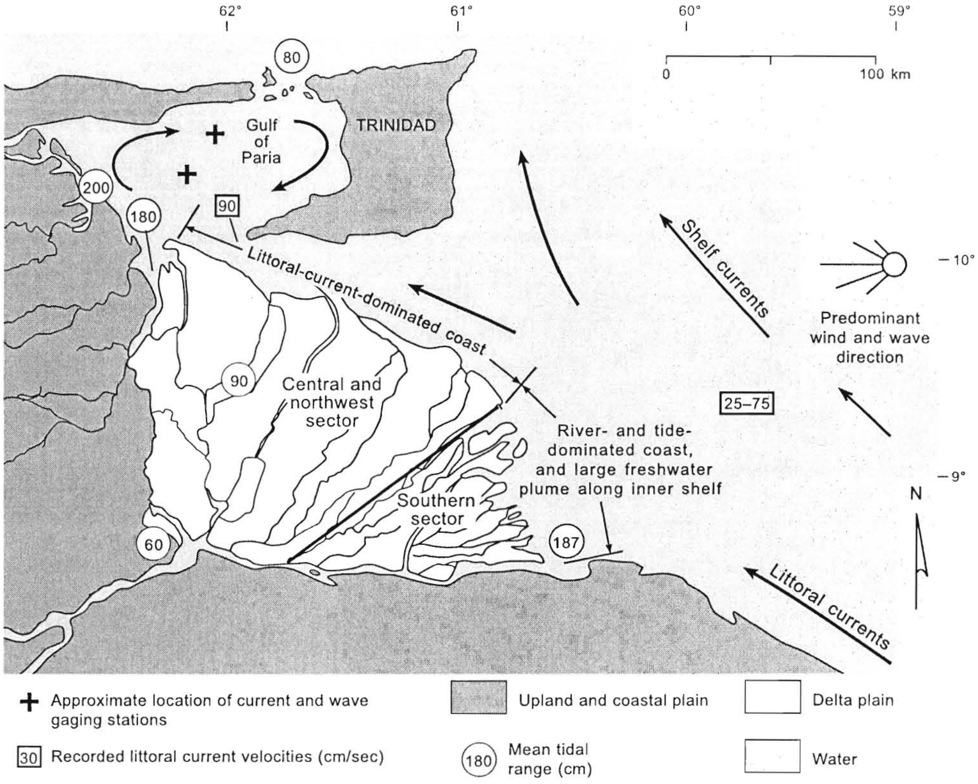


Figure 2. Summary of marine hydrodynamics along the Orinoco Delta coast. Note the location of the two temporary (December 1979 and May through August 1979) wave and current meter stations in central Gulf of Paria. Data generated from these sites are used to characterize the marine hydrodynamics of the Orinoco coast (GEOHIDRA CONSULTORES, C. A., 1997a, b; ENSR VENEZUELA, 1998). Atlantic littoral current and tide data are from KOLDEWIJN (1958), NOTA (1958), VAN ANDEL (1967), HERRERA *et al.* (1981), and HERRERA and MASCIANGIOLI (1984).

CLELLAND ENGINEERS, 1979). The Orinoco Delta is unusual in that the adjacent Gulf of Paria (Figure 2) is a major depositional site for Orinoco deposits, yet depositional processes (and hence the stratigraphy) in the Gulf of Paria are not those typically associated with delta-front and prodelta deposits.

The channel network of the Orinoco delta plain currently consists of six major distributaries radiating seaward from the delta apex near Barrancas (Figure 1). Diurnal tides, which range from 2.0 m at the coast to 0.6 m at the delta apex (Figure 2), maintain a network of channels throughout the delta plain and reflect the dynamic nature and interconnectivity of this deltaic system (VAN ANDEL, 1967). Near the coast, many of the distributary channels (caños) deflect to the northwest under the influence of the strong, northwest-directed Guayana littoral current (Figure 2). Broad arcuate promontories known as mudcapes form at the mouths of intermediate distributary channels, such as Caños Macareo and Mariusa, whereas estuaries occupy the mouths of major distributaries such as Río Grande (Boca Grande) and Caño Manamo (Boca de Guanipa) (Figure 1).

Within the delta plain, two distributary channel types are distinguished: muddy and blackwater (Figure 3a, b). Muddy channels transport nearly all of the sediment and include Río Grande and Caños Araguao, Mariusa, Macareo, and (formerly) Manamo. The muddy channels are characterized by proximal overbank sedimentation that produces natural levees that rise 1 to 3 m above and subdivide adjacent interdistributary basins. Blackwater channels make up most of the channel network in the central and northwestern delta. These carry little sediment except perhaps during the wet season, and tides and direct precipitation maintain bidirectional flow. These channels have poorly developed natural levees.

The hydrology of the interdistributary islands and basins is controlled by a variable combination of direct precipitation, river inflow, and tidal fluctuations. As a result of the complex and variable hydrologic regime, these interdistributary islands and basins support a variety of grass, sedge, and forest ecosystems (WARNE *et al.,* 1999, their Plate 2). More than 80 percent of the interdistributary areas are inundated for most of the year, greatly limiting intentional burning and other anthropogenic alterations.

Across the delta plain, two distinct, roughly fan-shaped sectors are distinguished on the basis of channel abundance and geometry, sediment and soil types, shoreline characteristics, and dominant hydrologic processes (Figures 1, 4). The southern sector consists primarily of an intricate network of anas-

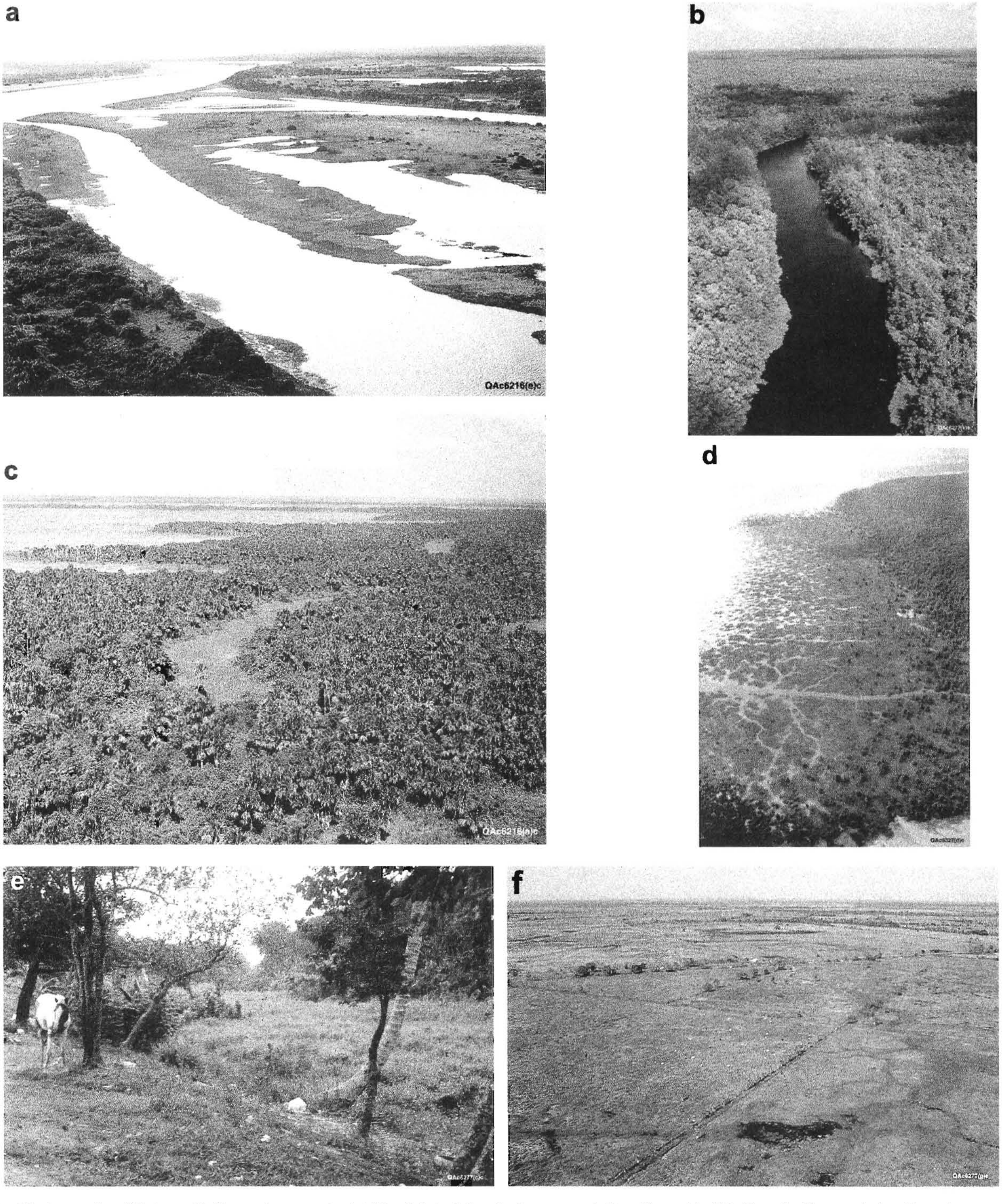


Figure 3. Photographs of Orinoco Delta environments. (a) Floodplain lakes in the upper delta adjacent to Río Grande. Suspended sediment concentrations are much higher in these distributaries than in those of the northwestern delta (March 1998). (b) Middle reaches of Caño Cocuinita, a typical blackwater caño in the northwestern delta. Note that the entire area is covered by low forest, which is common in the middle delta (October 1998). (c) Central delta with an abandoned, partially infilled caño. Note transition from forested (palm) to herbaceous interdistributary basin in the distance. (d) Aggrading mudflats in the Boca de Guanipa area. The mudflats are aggrading by lateral accretion along the seaward edge and colonization by mangroves along landward portions. The density of parallel tidal channels reflects the importance of tidal processes in Orinoco coastal and delta-plain environments (March 1998). (e) Caño Tucupita (upper delta near Tucupita), which has been almost completely infilled with vegetation largely because of elimination of flood discharge since construction of Volcán Dam (March 1998). (f) Cleared and partially drained upper delta plain near Tucupita. Despite the well-developed drainage system, there is abundant standing water, even during the dry season (March 1998).

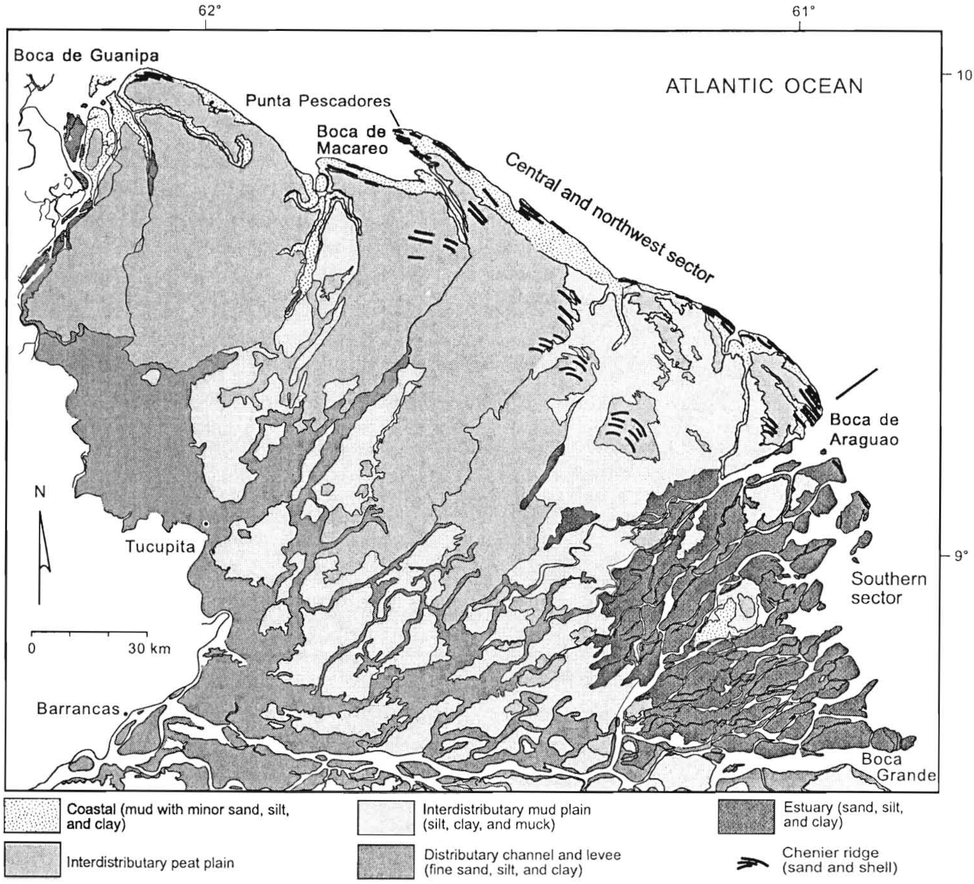


Figure 4. General distribution of environments of deposition in the Orinoco delta plain. These subdivisions were derived from a geomorphic map of the delta plain (WARNE *et al.,* 1999, their Figure 31 and Table 8) by grouping units that were formed by similar geomorphic processes. The majority of terrigenous substrates occur in the south and southwest, reflecting the influence of Río Grande, and formerly Caño Manamo, in the transport and distribution of terrigenous sediment. Vast peat plains of the central and northwestern delta show that these areas currently receive little or no terrigenous sediment and maintain high water levels.

tomosing, muddy, fluvial/tidal channels and channel islands. Water and sediment discharge through Río Grande and adjacent distributaries is the principal hydrologic process in the southern sector. In contrast, the central and northwestern delta-plain sector consists of more widely spaced, blackwater distributary channels and vast herbaceous and forested wetlands that are underlain by organic-rich soils (Figure 4). In this delta-plain sector, tides and direct precipitation are the principal hydrologic processes controlling the geomorphology and biologic composition and structure.

The central and northwestern delta coast typically consists of mudflats 2 to 5 km wide, which are bordered on their landward side by mangrove forests (Figure 3d). The physiography of the Orinoco coast is much like the French Guiana, Suriname and Guyana (Guiana) coast to the south, with alternating estuaries and mudcapes. Mudcapes are similar to sand spits in morphology, but they have a different origin (Figures 1, 4) (ALLISON *et al.,* 1995, 2000; WARNE *et al.,* in press). Typically 5 to 10 km wide (perpendicular to the coast) and as much as 100 km long (parallel to the coast), mudcapes are observed updrift of river mouths discharging along the coast. Along-shore accretion of mudcapes diverts rivers north and northwestward. Accretion is mainatined primarily by longshore drift rather than by the river that the mudcape is diverting.

The delta-front and prodelta deposits of the subaqueous delta are as much as 70 m thick and form a relatively narrow, steep, convex-up profile on the shelf (Figure 5). The Orinoco shelf is a broad, low-gradient (0.02 to 0.5 percent) feature; such broad, low gradient shelves are characteristic of many modern delta settings (WARNE and STANLEY, 1995; PANIN and JIPA, 1998; BERENDSEN, 1998; Coleman *et al.,* 1998a). Along the Atlantic margin, the shelf extends offshore ~100 km to the shelf break, which generally occurs at ~100- to 110-m water depth (KOLDEWIJN, 1958; NOTA, 1958; VAN ANDEL, 1967; BUTENKO and BARBOT, 1980). Like many modern deltas, the outer-shelf and slope surfaces are relict, submerged coastal plains that developed during Pleistocene sea-level lowstands and subsequent transgression (*e.g.,* ALLEN, 1965; CHEN *et al.,* 2000).

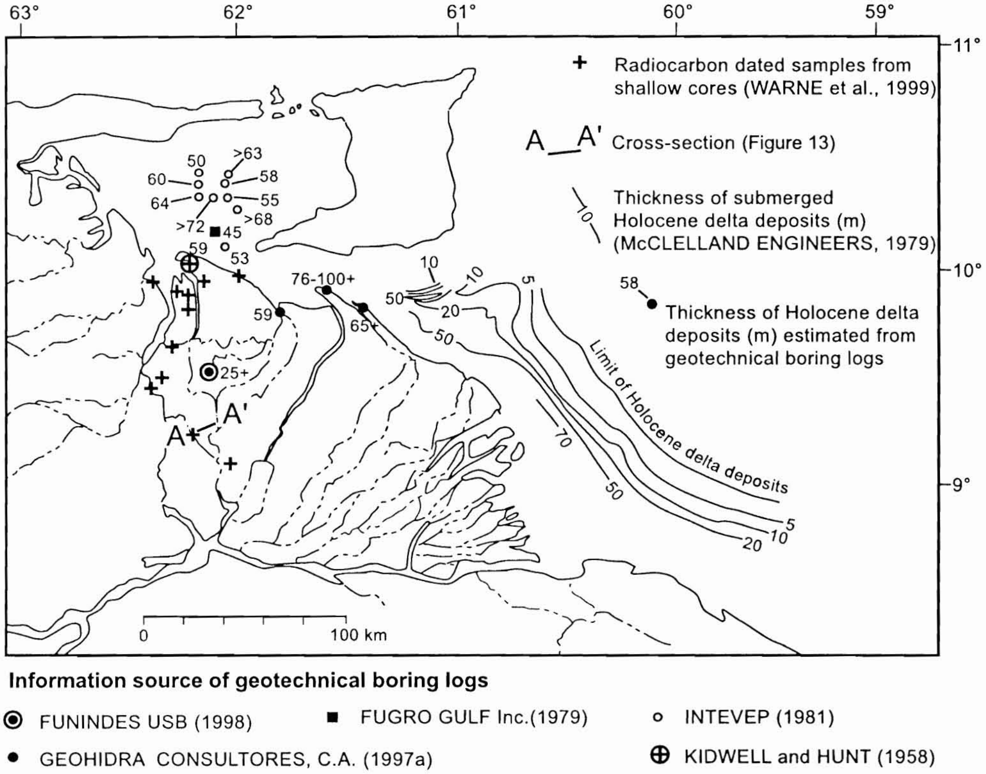


Figure 5. Map showing the thickness of Holocene Orinoco Delta sediments. Data include geophysical surveys and boring (geotechnical) logs. Information regarding the locations, depths, and ages of radiocarbon-dated samples is available in WARNE *et al.* (1999).

Seaward of the delta-front sediments are relict sandy coastal-plain sediments (Figure 6) that were reworked and redeposited during the late Pleistocene to Holocene transgression. Partially cemented, calcareous, coralline mounds occur along the shelf edge (Figure 6); these mounds are interpreted to be late Pleistocene coral reefs (KOLDEWIJN, 1958; NOTA, 1958; McCLELLAND ENGINEERS, 1979; BUTENKO and BARBOT, 1984). These features are similar to those found along the Mississippi Delta shelf (SUTER and BERRYHILL, 1986; ROBERTS *et al.*, 1987).

The Gulf of Paria is a semienclosed, tectonic basin located seaward and adjacent to the northwest Orinoco Delta. The two rather narrow inlet/outlets, Boca de Serpientes in the south and Boca del Dragón to the north, control water and sediment dynamics in the gulf. Boca de Serpientes is the narrower (as little as 15 km) and shallower (thalweg depth as little as 33 m) of the two inlet/outlets (VAN ANDEL and POSTMA, 1954). Delta sediment is transported into the Gulf of Paria by (1) discharge of river sediment from Caño Manamo (prior to construction of Volcán Dam) and (2) advection by waves and littoral currents via Boca de Serpientes (Figure 2). Although most sediment transported to the gulf is deposited there, a portion of the Orinoco sediment is transported through Boca del Dragón and into the southern Caribbean (MILLIMAN *et al.*, 1982; MONENTE, 1989/1990a, b).

MAJOR PROCESSES CONTROLLING LATE QUATERNARY DEVELOPMENT

The geologic setting, climate, river-water and -sediment dynamics, distributary channel-system dynamics, sea-level change, and coast and shelf hydrodynamics are the major factors controlling delta evolution (COLEMAN, 1981; STANLEY and WARNE, 1998). Evaluation of major delta-forming processes, and their change through time, provides a basis for generating a comprehensive and viable account of the Orinoco Delta evolution.

Geologic Setting

The Orinoco Basin covers ~1.1 × 10^6 km^2 of tropical northern South America (Figure 7). The Orinoco drainage basin consists of ~50 percent Llanos, 35 percent Guayana Shield, and 15 percent Andes and Coastal mountain ranges (Figure 7). The vast grassy plains of the Llanos region are underlain by a foreland basin that is filled with Tertiary and Quaternary sediments that were derived from the rising Andes Mountains to the west. The sandy substrate of the Llanos is broadly inundated and extensively reworked by fluvial processes during the wet season. The Guayana Shield is primarily composed of deeply weathered felsic to intermediate plutonic rocks and gneisses (GIBBS and BARRON, 1983; CVG-

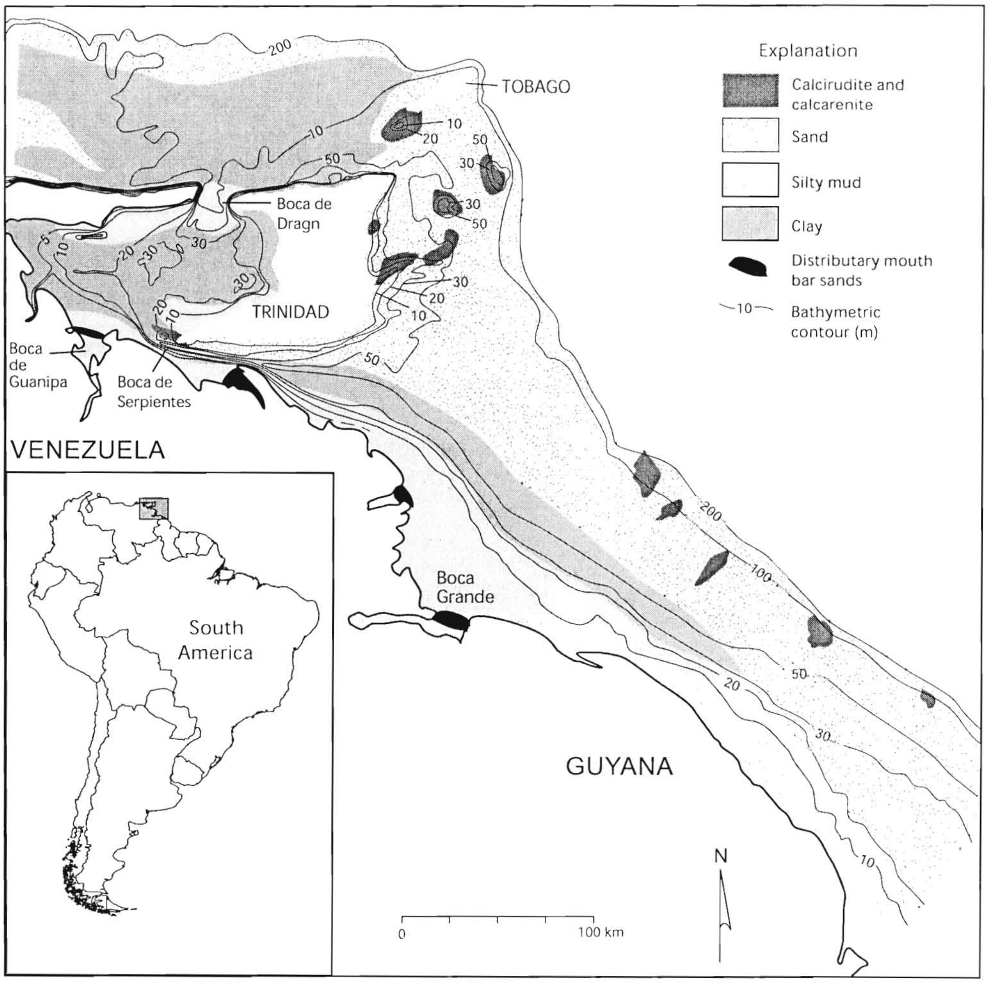


Figure 6. Sediment distribution and bathymetry across the Orinoco shelf. Compiled from Van Andel and Postma (1954), Koldewijn (1958), Nota (1958), Morelock (1972), McClelland Engineers (1979). The clay substrate seaward of the Orinoco coast represents the seaward limit of the modern delta. The distribution of the clay and silty mud substrate indicates that the Gulf of Paria and the south Caribbean Sea near Boca del Dragón are major depositional sites for Orinoco sediment. The clay and silt distribution reveals the importance of littoral currents in distributing of Orinoco and Amazon sediments.

Tecmin, 1991a through f). Maximum relief on the elevated shield is >3,000 m, but most of the shield is low relief. The drainage basin is bordered on the west and north by young, high relief Andes and Coastal Mountains, which supply ~90 percent of the sediment to the Orinoco River but compose only 15 percent of the basin area.

At a regional scale, the Orinoco River channel forms an arc along the contact between the foreland basin sediments of the Llanos and the crystalline basement of the Guayana Shield (Figure 7). Regional tilting to the south-southeast by uplift of the Andes and northern coastal ranges and lateral expansion of the Llanos foreland basin sediments maintain the course of the Orinoco at or near the boundary between the bedrock of the Guayana Shield and the foreland-basin clastic wedge. Lateral expansion of the Llanos onto the left-bank portion of the floodplain maintains a rather narrow fringing floodplain, except at the intersections of major tributaries. Lateral expansion of the Llanos also inhibits development of a meandering channel system, resulting in an anastomosing system in the lower Orinoco River. The location and gradient of the lower Orinoco River are significantly influenced by a series of bedrock outcrop areas (control points) along its course (Hamilton and Lewis, 1990) (Figure 7).

The lower Orinoco River and Delta have developed in the Eastern Venezuela Basin (EVB) structural trough along the south margin of the South Caribbean plate boundary zone (SCPBZ, Robertson and Burke, 1989) (Figure 8). The EVB is a foredeep basin associated with transpressional tectonic activity between the Caribbean and South American plates. The EVB is asymmetric, with distinct south and north flanks (Figure 8). The south flank is moderately faulted, with an overall slope to the north of 25 to 80 m/km (Fiorillo, 1984; Prieto-Cedraro, 1987). The Tertiary sediments within the south flank are gently folded but offset by a series of normal

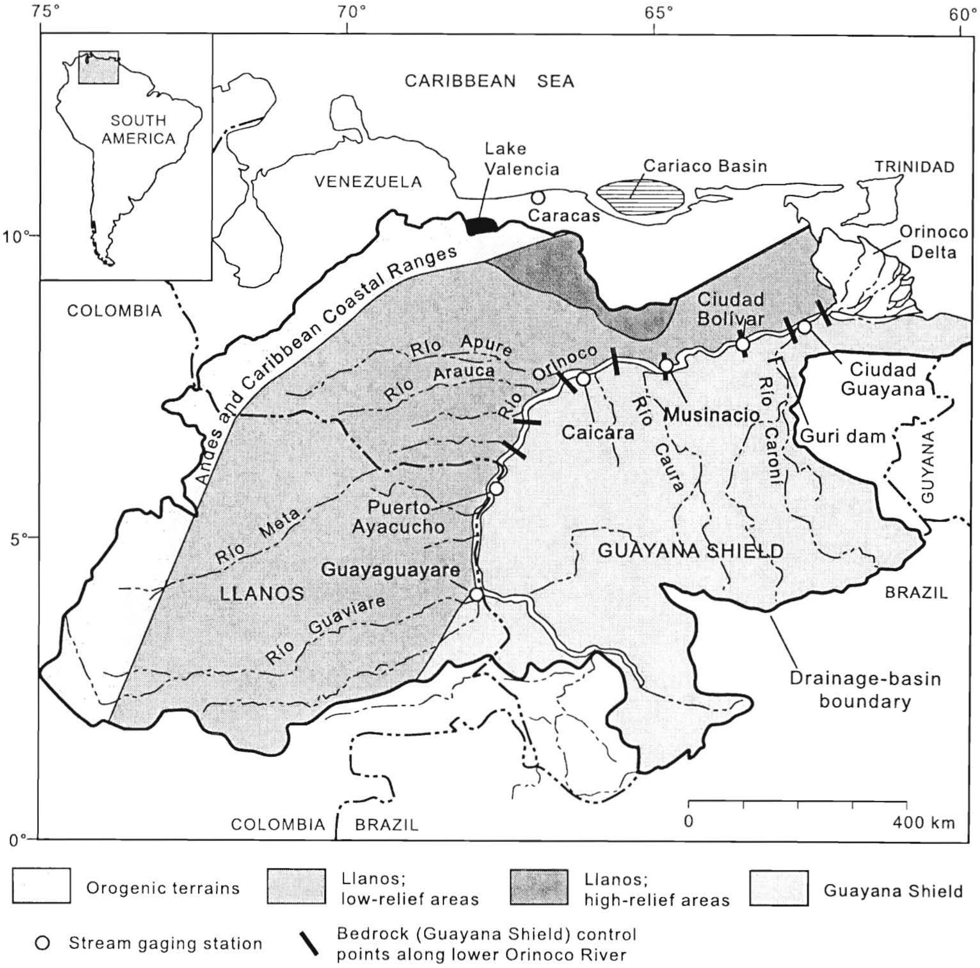


Figure 7. Orinoco drainage basin showing major physiographic provinces, principal tributaries, gaging sites, bedrock control points, and Guri Dam. Compiled from MEADE *et al.* (1983), NORDIN and PÉREZ-HERNÁNDEZ (1989), and HAMILTON and LEWIS (1990).

faults that strike N 60° E and dip north or south. The north flank of the basin is characterized by complex folding and faulting that record intense deformation associated with differential movement between the Caribbean and South American plates. The modern delta is located along the transition between the relatively deformed and undeformed portions of the EVB (Figure 8).

The Offshore Orinoco Platform and Columbus Basin compose the seaward, eastern extension of the EVB along the present continental shelf (LEONARD, 1983; DI CROCE *et al.*, 1999). LEONARD (1983) estimated that as much as 12,000 m of upper Mesozoic and Cenozoic sediments have accumulated in the Columbus Basin (Figure 9). Shallow geophysical surveys on the Orinoco Delta shelf indicate that most of the Pleistocene strata beneath the shelf are uniformly dipping ~8 to 23 m/km to the north or northwest or are generally horizontal (MCCLELLAND ENGINEERS, 1979). A number of researchers have reported extensive faulting of Tertiary and Quaternary strata along the outer shelf and slope (Figure 9a) (MCCLELLAND ENGINEERS, 1979; BUTENKO and BARBOT, 1980, 1984; PRIETO-CEDRARO, 1987; DI CROCE *et al.,* 1999). Many of these faults have seafloor expressions in the form of scarps and linear seafloor troughs, and some of these appear to be active. These faults are generally attributed to oversteepening and rotational slumping of Quaternary delta deposits. The rotational listric normal faults and other soft-sediment deformation at the shelf edge are characteristic of many Tertiary and Quaternary delta sequences (*e.g.,* COLEMAN *et al.,* 1974, 1983, 1998b; WINKLER and EDWARDS, 1983; DOUST and OMATSOLA, 1990; KUEHL *et al.,* 1997).

The modern depocenter is located adjacent to but generally south of the intensely deformed portion of the SCPBZ (Figure 8). However, a number of the fault systems within the SCPBZ extend into the Orinoco region (ROBERTSON and BURKE, 1989) and have been a significant process in delta evolution by influencing the positions and orientation of many of the delta's channels, differential subsidence across the delta, and development of local, near-surface faults and folds.

Currently the Orinoco Delta is seismically quiescent. The only recorded seismic activity of consequence was in 1940,

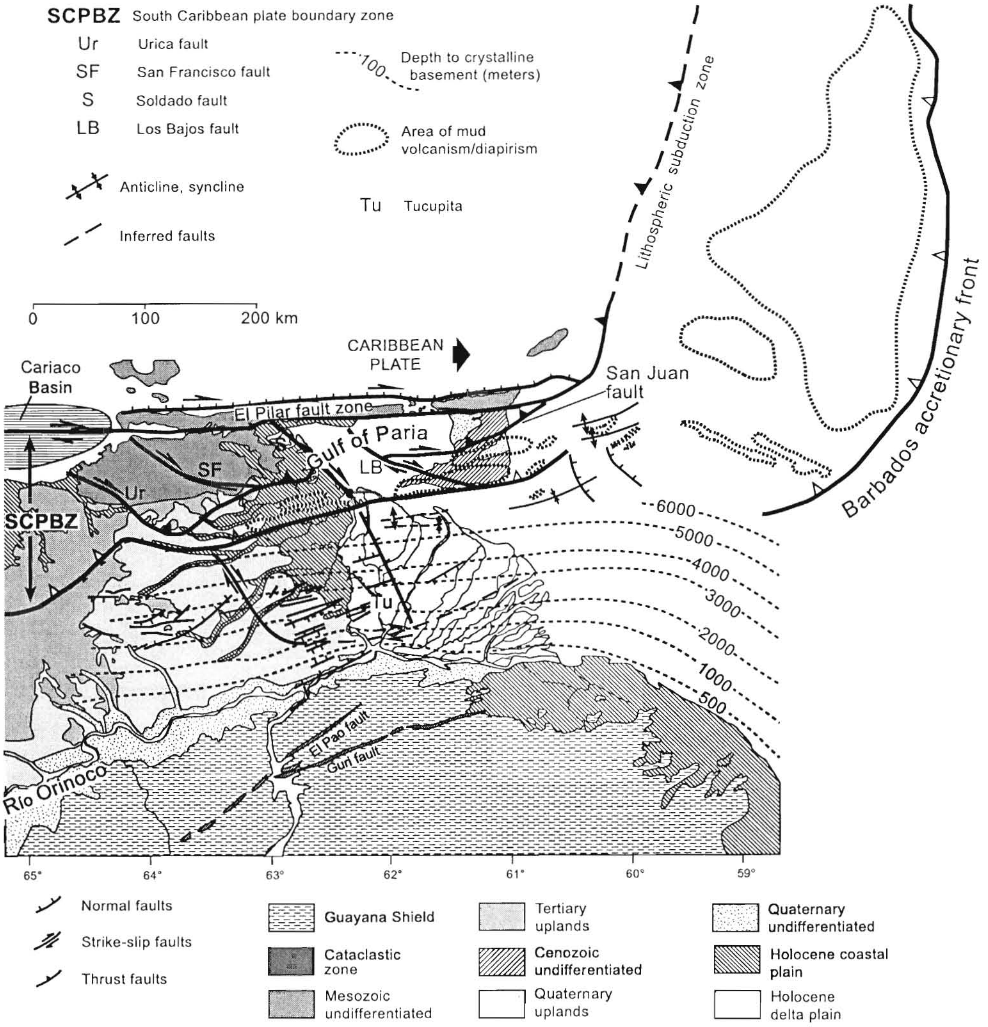


Figure 8. Principal structural features and general geology of the Orinoco Delta region. Information derived from PEES *et al.* (1968), CASE and HOLCOMBE (1980), LEONARD (1983), PIMENTEL-DE-BELLIZZIA (1984), ROBERTSON and BURKE (1989), CVG-TECMIN (1991a-f), BELTRÁN (1993), and DI CROCE *et al.* (1999). The term "basement" in the figure and text refer to the crystalline (igneous and metamorphic) rock that is unconfomably overlain by Tertiary and Quaternary sediments.

when a magnitude-6.0 (Richter) earthquake occurred along the boundary of the Guayana Shield. Faulting in the lower Orinoco River determines the course of the main channel and defines the boundary between the Guayana Shield and the EVB (FIORILLO, 1984; PRIETO-CEDRARO, 1987). In the Gulf of Paria region, on the other hand, reports of magnitude-6.0 (Richter) earthquakes are frequent and widespread (INTEVEP, 1978; CASE and HOLCOMBE, 1980; GEOHIDRA CONSULTORES, C.A., 1997b).

Principal neotectonic features in the delta include the diapiric Pedernales anticline and associated mud volcanoes (KIDWELL and HUNT, 1958; WARNE *et al.*, 1999; ASLAN *et al.*, 2001) and the Sabaneta syncline and Macareo anticline along the central delta coast (Figure 8). On the basis of analysis of satellite imagery and aerial photography, PEES *et al.* (1968), GEOHIDRA CONSULTORES, C.A. (1997a), and WARNE *et al.* (1999, their Figure 57) identified several lineaments that appear to influence the position and orientation of distributaries, hydrology, and distribution of ecosystems in the delta plain. However, the degree and extent of differential movement and the nature and extent of hydrologic and ecologic change across these lineaments remain undefined.

Subsidence

Subsidence-rate measurements are fundamental for determining delta history and are essential for developing effective structural and environmental engineering designs within the delta. We define subsidence as the lowering of the land surface or water-sediment interface relative to a topographic datum. This measure is independent of sea-level changes but includes lowering associated with both sediment compaction

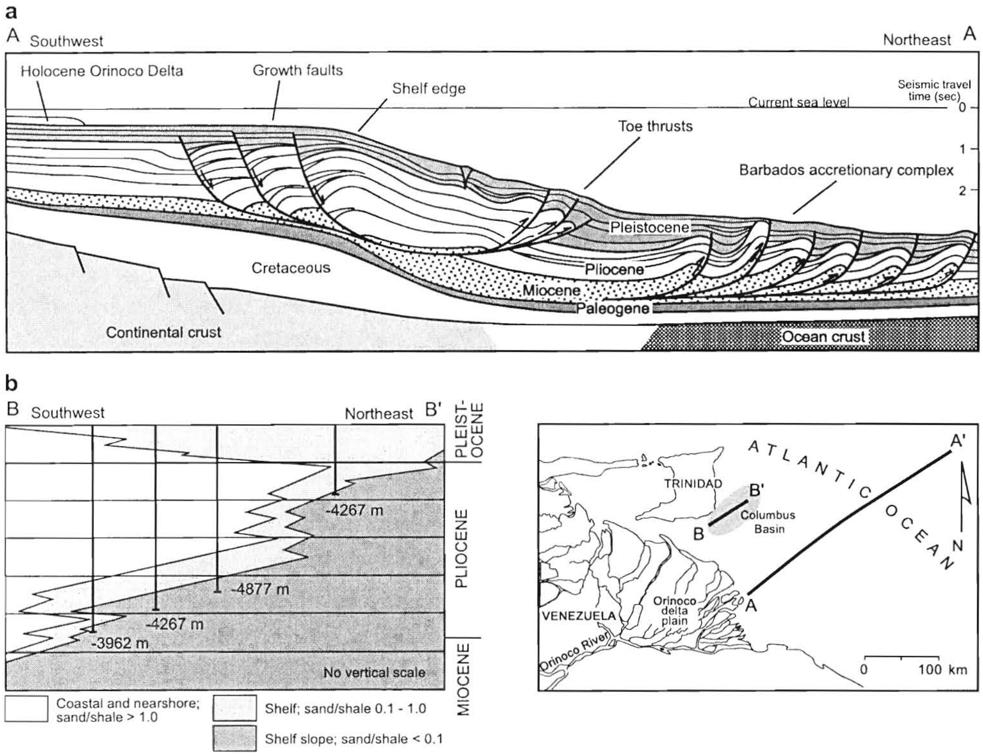


Figure 9. Cross sections showing development and extent of Tertiary and Quaternary Orinoco sediments. (a) Listric growth faulting at present-day shelf edge is associated with rapid delta progradation and oversteepening during sea-level lowstands. Eastward movement of the Caribbean Plate deformation front induced thrust faulting along the eastern limit of the delta deposits. Note that this section is located in the outer halo of the deformation front, and the thrusts and anticlines trend southwest-northeast, oblique to the section. Modified from DI CROCE *et al.* (1999). (b) Schematic cross section showing progradation of the Tertiary and early Quaternary Orinoco Delta across the Columbus Basin. The bulk of the Orinoco sediment was deposited in the Columbus Basin during the Pliocene and led to development of a broad shelf in the Pleistocene, which is a major influence on the evolution of the modern delta. Modified from LEONARD (1983). Note that LEONARD (1983, his Figure 5) identified a large number of normal faults in the area, but this diagram represents the stratigraphy prior to deformation.

and tectonic activity. Data used to generate the subsidence rates are summarized in Table 1 and Figures 5 and 10. For subsidence-rate calculations we used the following formula:

$$S = [SedTh - (SL + WD + El)]/A,$$

in which S = subsidence rate, SedTh = sediment thickness to dated horizon, SL = sea level (below present mean sea level) at time of deposition, WD = water depth at time of deposition, El = the delta-plain elevation where the core was recovered, and A = age of date horizon.

A discussion of the assumptions and methodology used to calculate subsidence (and sediment accumulation) rates is presented in WARNE *et al.* (1999). Sediment-accumulation and subsidence-rate calculations derived from the shallow cores taken during the course of this study are based on radiocarbon dates from in situ peat or large wood fragments; although these data provide accurate age/depth relationships, they provide only short-term estimates for the lower delta plain subsidence. The deeper geotechnical boring logs (Figure 5) are poorly constrained chronologically, but provide insight into longer-term subsidence rates. Calculated subsidence rates are:

0.8 to 1.0 mm/yr for the upper delta,
0.8 to 2.0 mm/yr for the middle delta,
2.8 to >6.0 mm/yr for the lower delta Punta Pescadores area,
0 to 3.3 mm/yr for the lower delta Boca de Guanipa area, and
2.2 to 4.6 mm/yr for Gulf of Paria (Table 1).

Subsidence rates show a clear increase from the upper to the lower delta, which is normal in delta-plain settings (STANLEY and CHEN, 1993; STANLEY and WARNE, 1993; STANLEY and HAIT, 2000). The variable subsidence rates in the Boca de Guanipa and Punta Pescadores areas may be related to active folds (Figure 8) or may be caused by differential compaction, dewatering, and deformation of the underlying delta sediments. Subsidence rates in the Gulf of Paria are similar to those of the lower delta plain. No subsurface data are currently available from the southern delta sector (Figures 1, 4) where we suspect that subsidence rates are relatively high (on the basis of the position of Río Grande and Boca Grande and the generally estuarine character of the southern delta).

Table 1. *Summary of Orinoco Delta subsurface data used to generate subsidence rate estimates*[1,2].

Core ID#	General location[3]	Source of subsurface information	Depth to dated horizon (mm)	Method for dating horizon	Date of dated	Material dated	Sediment accumulation rate (mm/yr)	Subsidence rate (mm/yr)
1998/10/12/2/AA	Upper delta-C. Manamito levee	WARNE *et al.* (1999)	5,300	^{14}C [4]	6,430 ± 60 yrs[6]	Peat	0.8	0.8
1998/10/17/2/AA	Upper delta flood basin	WARNE *et al.* (1999)	5,650	^{14}C [4]	6,280 ± 70 yrs BP[6]	Peat	0.9	0.9
1998/11/20/3/AA	C. Manamito levee swale	WARNE *et al.* (1999)	6,550	^{14}C [4]	6,510 ± 50 yrs BP[6]	Clayey peat	1.0	1.0
1999/2/8/1/RCS	NW Delta along west bank of Boca Guanipa	WARNE *et al.* (1999)	7,500	^{14}C [4]	2,840 ± 50 yrs BP[6]	Peat	2.6	2.6
1999/2/9/1/RCS	Middle Delta- Caño Pedernales tributary	WARNE *et al.* (1999)	7,100	^{14}C [4]	3,500 ± 40 yrs BP[6]	Peat	2.0	2.0
A_2	Gulf of Paria	INTEVEP (1981)	67,000 (+ 22,900) water depth) = 89,900	Estimated[5]	7,500 yrs BP	No sample	8.9	4.6
A_1	Gulf of Paria	FUGRO (1979)	45,400 (+ 26,100 water depth) = 71,500	Estimated[5]	7,500 yrs BP	No sample	6.0	2.2
A_3	NW Delta (Pedernales)	KIDWELL and HUNT (1958)	60,000	Estimated[5]	7,500 yrs BP	No sample	8.0	3.3
B_1	Lower Delta-Punta Pescadores	GEOHIDRA (1997a)	76,000	Estimated[5]	7,500 yrs BP	No sample	10.1	2.8
B_5	Lower Delta-Punta Pescadores	GEOHIDRA (1997a)	100,000+	Estimated[5]	7,500 yrs BP	No sample	13.3	6.0+

[1] WARNE *et al.* (1999) provided more detail on the ^{14}C samples, analysis, and results; [2] the ^{14}C-dated sample set presented here is part of a larger sample set presented in WARNE *et al.* (1999); [3] See Figure 5 for locations; [4] the ^{14}C analysis was done by Beta Analytic, Coral Gables, Florida, and Beta Analytic sample numbers are available in WARNE *et al.* (1999); [5] the estimate of 7500 yrs BP is from Stanley and Warne (1994) who demonstrated that major world deltas began to accumulate at this time, as the rate of sea-level rise rapidly decelerated; [6] these are uncorrected ^{14}C dates—see WARNE *et al.* (1999) for 1 and 2 sigma calibrated ages for these samples.

Although the subsidence-rate calculations shown earlier required a number of assumptions, and chronostratigraphic data available for the Orinoco Delta are limited, these calculated rates are similar to those of the Mississippi, Nile, Changjiang (Yangtze), Ganges-Bramhaputra, and Rhine-Meuse Deltas, where more radiocarbon-dated subsurface data are available (COLEMAN and SMITH, 1964; STANLEY and CHEN, 1993; STANLEY and WARNE, 1993; TÖRNQVIST and VAN DIJK, 1993; ROBERTS *et al.*, 1994; BERENDSEN, 1998; STANLEY and HAIT, 2000).

Late Pleistocene to Holocene Climate

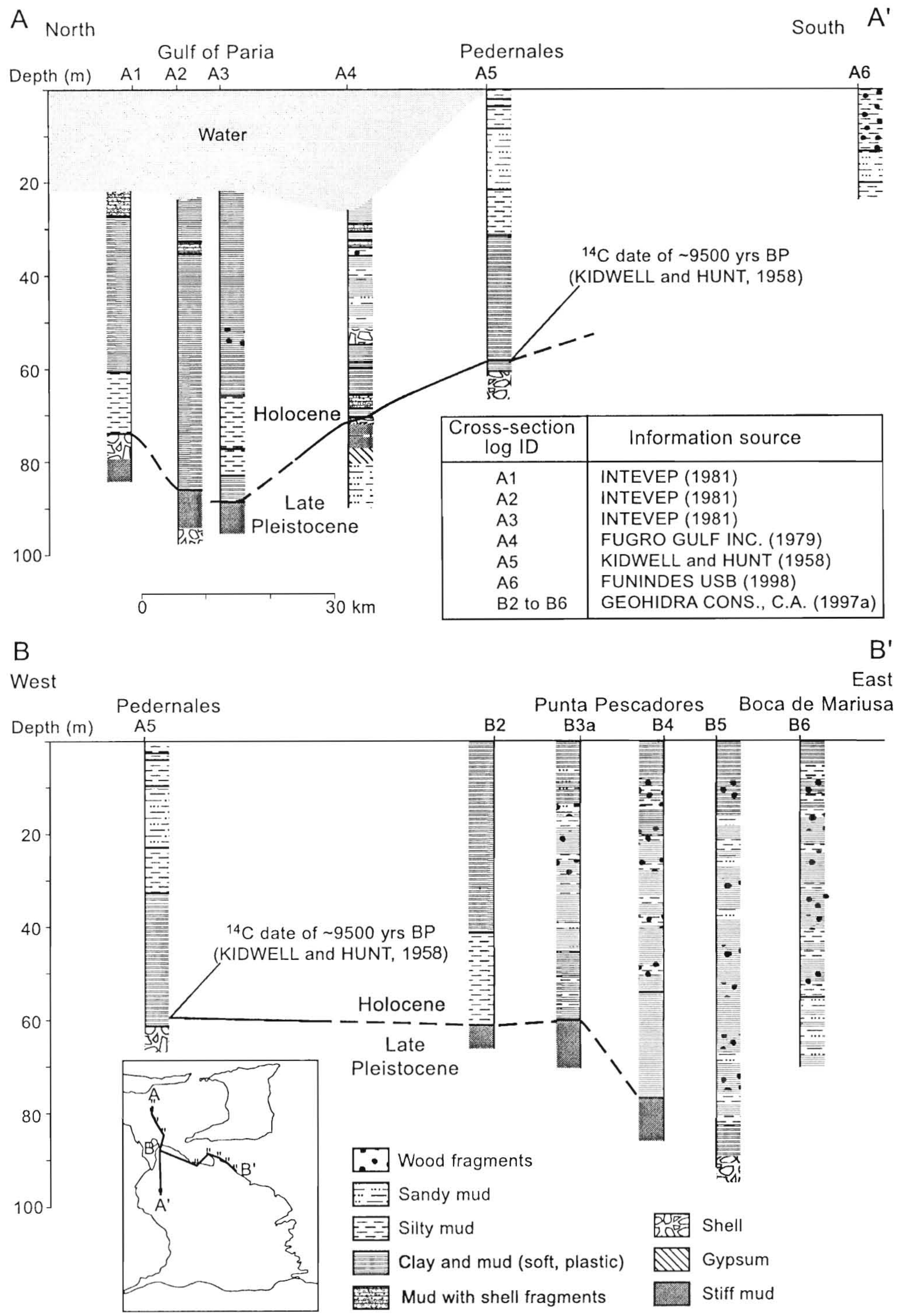
Climate is the driving force for a number of major delta processes, including sea-level change, river and delta-water and -sediment dynamics, coastal-water and -sediment dynamics, and biological composition and structure[1]. Currently the climate of the Orinoco Basin and Delta is mostly tropical with pronounced wet and dry seasons. Orinoco Basin climate is controlled primarily by the Intratropical Convergence Zone (ITCZ), which is the latitudinal belt along the equator where the easterly trade winds of both hemispheres converge, producing warm, humid, unstable air masses that generate large volumes of rainfall. The ITCZ seasonally migrates across ~15° latitude, and because the Orinoco Basin lies along the northern boundary of this migration belt, marked wet (June through November) and dry seasons (December through April) characterize the region. This pattern of marked wet and dry seasons induces large oscillations in water discharge and stage levels in the river and delta (Figure 11a), which promotes a pronounced seasonal inundation of the river floodplain and delta plain that typically lasts for 4 to 6 months (Figure 11a). During the dry season, 30 to 40 percent of the river channel bottom may be exposed, and strong easterly winds largely convert the channel system to an eolian regime (MCKEE, 1989; NORDIN and PÉREZ-HERNÁNDEZ, 1989; CARBÓN and SCHUBERT, 1994).

A number of studies have demonstrated that the climate of northeastern South America was markedly different during the late Pleistocene than it is today. Analysis of ocean-bottom cores from the Bermuda Rise (northern Sargasso Sea) by SACHS and LEHMAN (1999) indicates that the climate of northern South America was variable from 60,000 to 30,000 years before present (yrs BP)[2]. These authors identified 10 to 12 major oscillations in sea-surface temperatures (SST's) comparable in magnitude to the change from late Pleistocene glacial maximum to the early Holocene. On the basis of analyses of pollen and sediment from the Eastern Cordillera region of Colombia, KUHRY *et al.* (1993) also recognized that the late Pleistocene was a time of alternating cool/dry and warm/wet periods and that the period of lowest temperatures and least effective precipitation occurred between ~21,000

---

[1] Biological composition and structure refers to the variety and types of plant and animal taxa (composition), and the relative coverage or density of the various taxa (structure). Of particular concern here is the type and density of woody stem plants, grasses, and sedges, which are a major factor in controlling erosion rates.

[2] All ^{14}C ages are given as uncalibrated values unless otherwise noted.



Cross-section log ID	Information source
A1	INTEVEP (1981)
A2	INTEVEP (1981)
A3	INTEVEP (1981)
A4	FUGRO GULF INC. (1979)
A5	KIDWELL and HUNT (1958)
A6	FUNINDES USB (1998)
B2 to B6	GEOHIDRA CONS., C.A. (1997a)

Figure 10. Cross sections showing thickness and general lithology of Holocene sediments in the Gulf of Paria and northwestern Orinoco Delta. In most cases, the base of the Holocene is poorly defined and is assumed to occur at the transition from sand and stiff, brown, and yellow silty, sandy mud to relatively soft, dark-gray to black, organic clays (WARNE and STANLEY, 1995). In core A5, KIDWELL and HUNT (1958) determined that the clay mineralogy of sediments in the lower Holocene section were indicative of deep-water environment, suggesting that the delta coast was well landward of the Pedernales area at that time. KIDWELL and HUNT (1958) described the ^{14}C sample they dated (~9500 yrs BP) as shell material from the upper transgressive sand, just below the lowermost Holocene delta strata. The large volume of woody debris in wells B3 through B6 is similar to that of the tropical Mahakam delta front and prodelta deposits (COMBAZ and DE MATHAREL, 1978; GASTALDO, 1992).

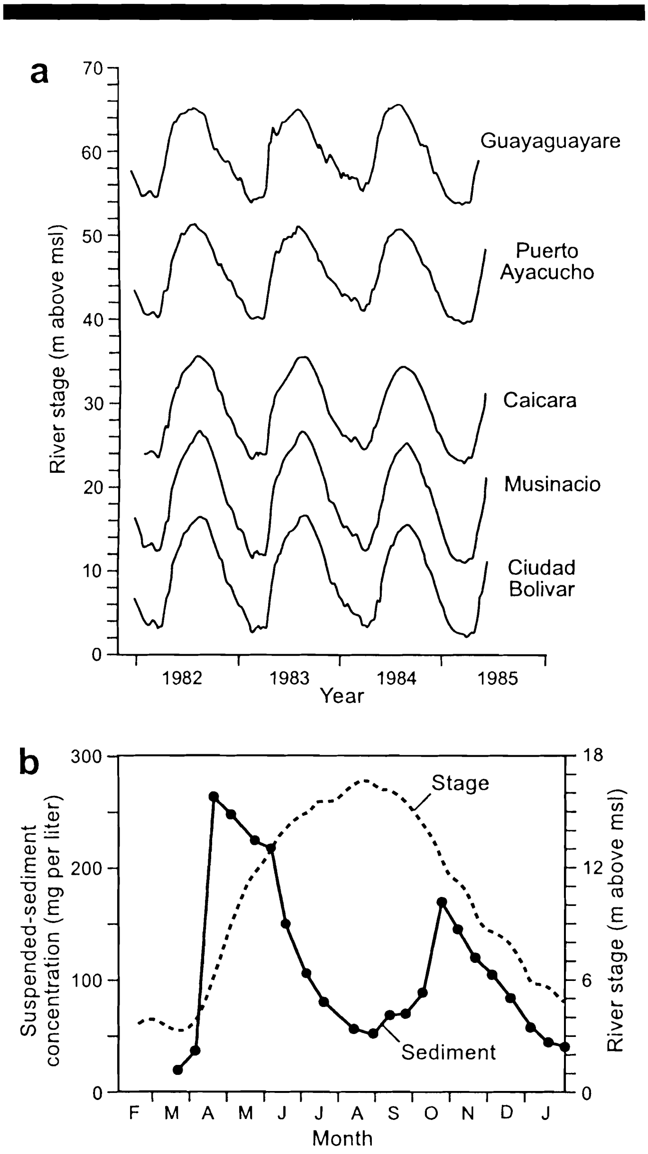


Figure 11. Water and sediment discharge characteristics of the Orinoco River. (a) Stage at several stations along the Orinoco River. See Figure 7 for locations of gauging sites. The near-simultaneous peak discharge along the river reflects the uniform change in seasonal rainfall across the entire drainage basin. Modified from Perez-Hernandez and Lopez (1998). (b) Monthly sediment and water discharge in the lower Orinoco River (Ciudad Bolivar) during 1982 and 1983. Modified from Meade *et al.* (1990).

and 15,000 yrs BP. Mean annual temperatures at that time were ~5° Celsius cooler than those at present.

Analysis of ocean-bottom cores from the south Caribbean Sea, mapping and analyses of extensive, relict dune fields in northeastern South America, identification of polygenetic drainage networks, and analysis of lake sediments provide evidence of a generally arid climate in northeastern South America around the last glacial maximum (21,000 to 18,000 yrs BP) (Cailleux and Tricart, 1955; Damuth and Fairbridge, 1970; Tricart, 1974a, b; Roa, 1979; Leyden, 1985; Schubert, 1988). Schubert (1988), Iriondo and Latrubesse (1994), and Hooghiemstra and Van der Hammen (1998), among others, provided evidence that the drier, late Pleistocene climate promoted widespread development of savannas across northeastern South America such that the tropical rain forests that characterize the modern uplands, were restricted to refugia. Evidence indicates that relatively modest changes in temperature and precipitation conditions can induce changes from forested to tropical conditions in northern South America (Iriondo and Latrubesse, 1994; Hooghiemstra and Van der Hammen, 1998). Damuth and Fairbridge (1970) and Latrubesse and Ramonell (1994) discussed the oceanic and barometric conditions that promoted cool, semiarid to arid conditions during glacial periods and warm, tropical conditions during interglacial periods.

Analysis of Cariaco Basin (Figures 7, 8) sediments demonstrates that the Bølling-C̊llerød period (~14,000 to 12,500 yrs BP) of generally warmer conditions was interrupted by a number of climatic oscillations (Hughen *et al.*, 1996). Analyses of pollen and sediment in the Eastern Cordillera region of Colombia indicate that a warming period between ~14,000 and 13,000 yrs BP was followed by a cooler period between ~13,000 and 12,500 yrs BP (Kuhry *et al.*, 1993). Several researchers recognized a warm (Guantiva) period in northern South America from ~12,500 to 11,200 yrs BP. The Guantiva interstadial was followed by the cool, dry El Abra (or Younger Dryas) period between ~11,200 and 9,500 yrs BP during which mean annual temperatures were ~4° Celsius lower than those at present and Amazon River discharge was 60 percent of present discharge (Fairbanks, 1989; Kuhry *et al.*, 1993; Hughen *et al.*, 1996; Roberts, 1998b; Maslin and Burns, 2000).

Leyden (1985) reported warm, wet conditions in the Lake Valencia region (Figures 7, 8) for the period 9,800 to 8,300 yrs BP. Her data suggest that conditions were warmer and wetter during this interval than at any time later in the middle and late Holocene. Peats in the high plateaus of the Guayana Shield (Schubert, 1988) and palynomorphs of forest vegetation in the highlands of the Eastern Cordillera region (Kuhry *et al.*, 1993) also provide evidence that humid tropical conditions were established in northern South America by ~8,900 to 8,000 yrs BP. Several authors recognized a period of enhanced wind activity in the Cariaco Basin region (Figures 7, 8) between ~8,400 and 7,800 yrs BP, which was part of a brief but apparently widespread transition to cooler, drier, windier conditions (Hughen *et al.*, 1996; Alley *et al.*, 1997; Stager and Mayewski, 1997).

Leyden (1985, her Figure 9) provided evidence for a number of climatic oscillations during the middle and late Holocene in the Lake Valencia region (Figures 7, 12). Hooghiemstra and Van der Hammen (1998) presented evidence of a period of generally wet conditions ~6,000 yrs BP. Meggers (1979) identified a generally cooler and drier period in northeastern South America between ~4,000 and ~2,000 yrs BP, which was sufficient to induce widespread changes in forest biota. Eisma *et al.* (1991) recognized dry periods in the Colombian Andes at ~1,300 yrs BP, from 900 to 600 yrs BP, and from 400 to 200 yrs BP; the authors inferred that these dry periods reduced sediment discharge from the Amazon River.

The Black *et al.* (1999) study of Cariaco Basin sediments identified enhanced trade-wind activity between 835 and 640, 590 and 410, and 310 and 120 yrs BP (Figure 12), which concurs with the findings of Eisma *et al.* (1991). The Holocene climate summary of Broecker (2001) shows the relatively warm period at about 8,500 to 9,000 yrs BP, the cool period at about 7,400 to 8,200 yrs BP, and the relatively cool period from 2,000 to 4,000 yrs BP.

The El Niño - Southern Oscillation phenomenon was an important weather pattern in northern South America during the Holocene (Diaz and Markgraf, 1992; Meggers, 1996; Cole, 2001; Trudhope *et al.*, 2001). The El Niño - Southern Oscillation events recur irregularly every 6 to 10 yrs; during El Niño years the ITCZ tends to remain in its southern position 2 to 4 months longer than normal, promoting drought conditions in the Orinoco Basin (Iriondo and Latrubesse, 1994).

Orinoco River Water and Sediment Dynamics

The Orinoco River is the third-largest river in the world in terms of water discharge, eleventh-largest in terms of sediment discharge, and is the principal supplier of water and sediment to the Orinoco Delta (Milliman and Meade, 1983). Because the Orinoco River basin lies within but near the northern limit of the ITCZ, there is pronounced annual variation in maximum and minimum discharge. Seasonal stage fluctuations are typically 17 m in the lower river (Figure 11a). Mean monthly discharge at Musinacio (for the period 1970 through 1981) varied between 1,330 and 81,100 m^3/sec. The ratio of maximum to minimum flow during this period was from 8:1 in 1972 to 54:1 in 1978, with an average of 26:1 (Nordin *et al.*, 1994). Such a large difference in seasonal discharge for a major river system is unusual; for example, the wet season to dry season discharge ratio for the Amazon River is typically ~3:1 (Kineke and Sternberg, 1995; Warne *et al.*, in press).

Sediment discharge for the lower Orinoco River is estimated to be 150 to 212 × 10^6 tons/yr (Meade *et al.*, 1990; Funindes Usb, 1999), and dissolved load, 28.6 × 10^6 tons/yr (Ramirez *et al.*, 1992). Sediment discharge in the lower Orinoco River typically has two distinct peaks during the flood season (Figure 11b), with a peak during rising flood (April–May), a minimum during peak water discharge (August–September), and a secondary peak during the recession of flood discharge (October–November) (Nordin and Perez-Hernández, 1989; Meade *et al.*, 1990; Carbón and Schubert, 1994). The two peaks in sediment discharge are attributed to temporary ponding of left-bank tributary flood waters during peak discharge at the intersection with the Orinoco main channel, which results in short-term retention of Andean-derived sediment; as stage in the Orinoco channel recedes, the ponded tributary water and sediment are remobilized, producing the second sediment discharge peak (Meade *et al.*, 1990).

Approximately half of the Orinoco sediment is deposited on the delta plain (Meade, 1994). In addition, sandy distributary mouth bars occur at the seaward edge of many major distributary channels (Figure 6). Most terrigenous sediment

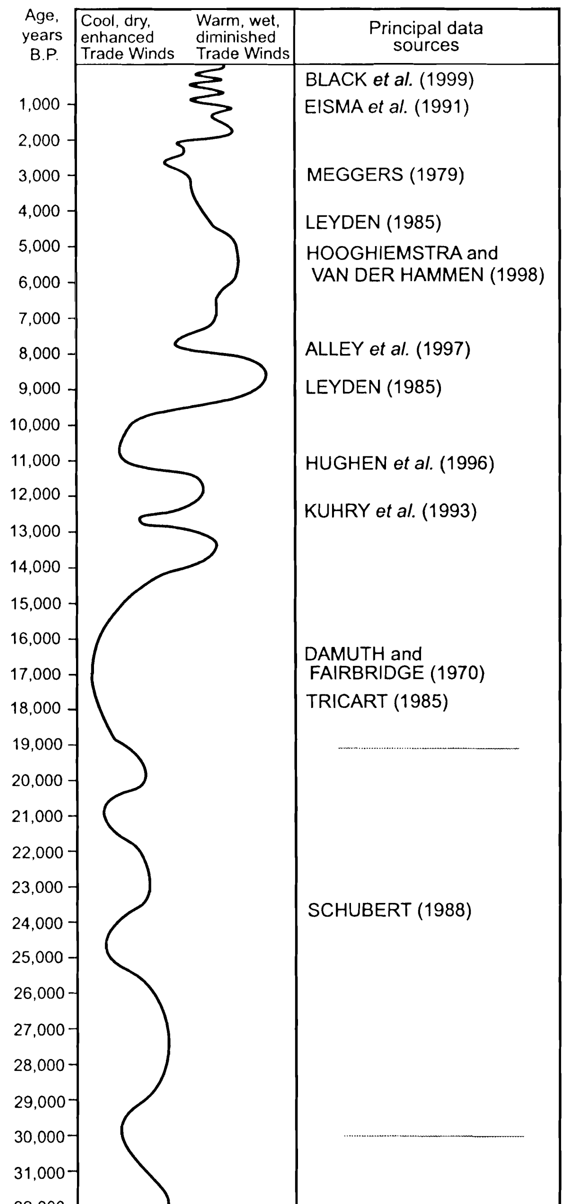


Figure 12. Summary of late Pleistocene and Holocene climatic changes in northeastern South America.

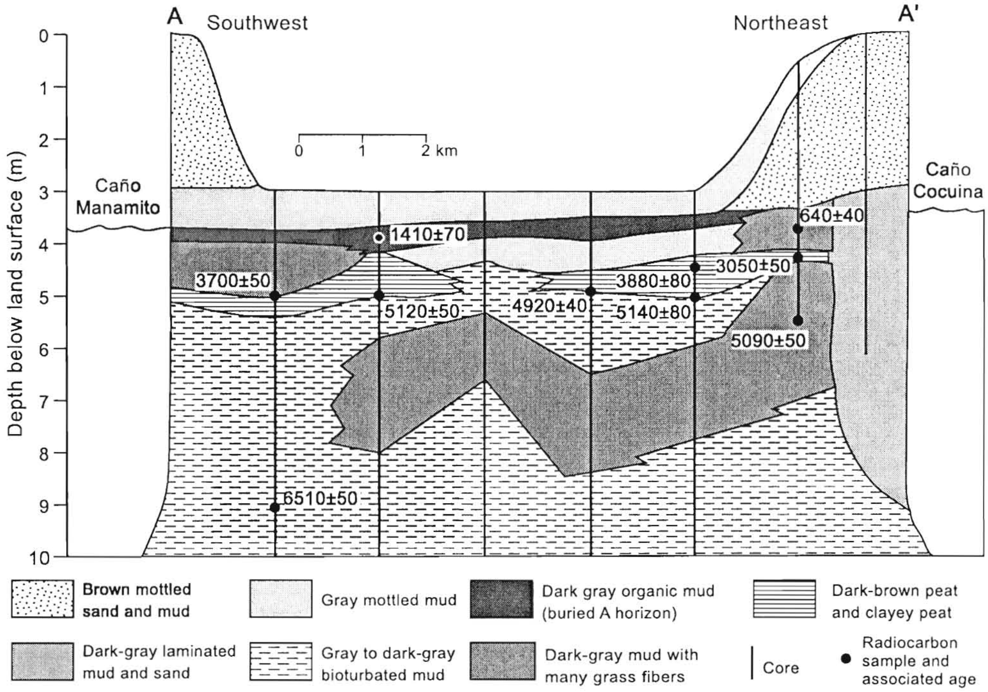


Figure 13. Cross section showing natural-levee and flood-basin deposits of Caños Manamito and Cocuina near Tucupita. Note that radiocarbon-dated peat buried by silty and sandy natural levee and muddy flood-basin deposits provides a maximum age of ~3,000 yrs BP for these channel systems. A radiocarbon-dated organic flood-basin mud (buried A horizon?) passes beneath Caño Manamito natural-levee deposits, which suggests that this channel system may be younger than ~1,500 yrs BP. The cross-section location is shown in Figure 5.

deposited in the delta plain accumulates as natural levees along the flanks of major distributaries and as channel bars.

Approximately 85 percent of the sediment is transported through the Río Grande distributary (MEADE, 1994). As a result, much of the delta plain receives little or no mineral sediment input. However, widespread accumulation of organic material maintains most of the delta-plain surface at or near sea level, which precludes development of interdistributary lakes (Figures 1, 3a, 4). Widespread development of peats provides evidence of long-term, perennial inundation and/or saturation of these interdistributary basins. However, scattered charcoal was observed in shallow borings, suggesting that water tables dropped below the peat surface and fires partially consumed the peat during drier Holocene climatic periods.

Distributary-Channel System Dynamics

Satellite imagery, aerial photography, and field observations reveal a large number of abandoned distributary channels across the delta plain that are in various stages of infilling (*e.g.,* Figure 3c), These abandoned and partially filled channels provide evidence that channel development, avulsion, and abandonment are essential delta-plain processes. Remote-sensing images, field observations, and stratigraphic analysis of radiocarbon-dated shallow borings (Figure 13) provide evidence that major distributaries (comparable in size to Caños Manamo and Macareo) evolved, avulsed, and infilled (Figure 3a, c, e, f) on a regular basis during the late Holocene (VAN ANDEL, 1967; WARNE *et al.,* 1999). Many of the blackwater distributaries, such as Caños Pedernales, Cocuina, Tucupita, and Guayaro appear to occupy channel systems formed by larger distributaries (*i.e.,* they are under fit channels). We infer that several of the small northeast-flowing blackwater rivers along the western delta, such as Río Morichal Largo and Río Tigre, occupy channel systems of coastal-plain rivers that were active in the northwestern delta prior to establishment of Caño Manamo (VAN ANDEL, 1967). Areas of accreted chenier ridges in the central delta plain (Figure 4), which typically form on the down-drift side of major distributary channels, provide evidence of the location of former major distributary channels.

Integration of the coastal and avulsion histories of Boca de Mariusita, Boca de Cocuina, and Boca de Guanipa reveals that episodes of distributary-channel activity and shoreline evolution are closely linked. We infer that shallow bays at the mouths of large distributaries such as Caño Manamo are rapidly filled following distributary avulsion and reduced fluvial discharge (Figure 14). Bay filling probably occurs through a combination of littoral- and tidal-current activity and mudcape development and expansion.

Sea-Level Change

Pleistocene and Holocene sea-level changes had a profound influence on Orinoco Delta evolution, particularly with re-

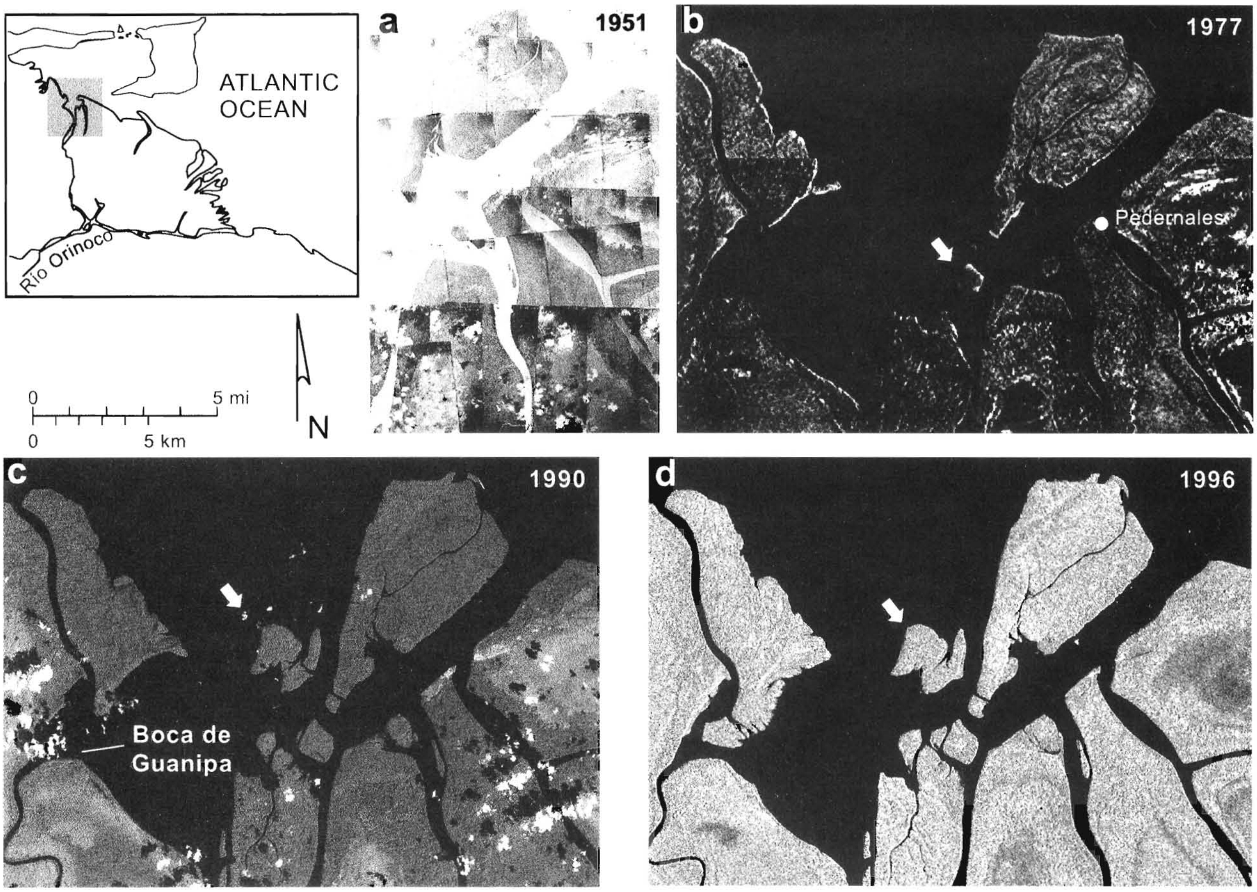


Figure 14. Historic changes in Boca de Guanipa area as shown by (a) 1951 aerial photograph mosaic, (b) 1977 SLAR image, (c) 1990 LANDSAT TM image, and (d) 1996 RADARSAT image. Shaded area of inset map shows approximate portion of delta covered by images. Note rapid shoreline progradation near mouth of Boca de Guanipa and formation of mangrove islands southwest of Pedernales. Construction of Volcán Dam (Figure 1) in 1967 greatly reduced discharge through Caño Manamo, which in turn accelerated infilling of Boca de Guanipa.

spect to river base level, coastline position, and marine flow through the shallow inlet at Boca de Serpientes. We define sea-level change as the change in the ocean-water surface relative to a topographic datum rather than relative sea-level change, which typically includes the influence of both sea-level change and subsidence.

Sea-level studies along the coast of Suriname (Brinkman and Pons, 1968; Roeleveld and Van Loon, 1978) and the Caribbean region (Lighty *et al.*, 1982; Fairbanks, 1989; Pirazzoli, 1991) provide evidence of rapidly rising sea levels during the late Pleistocene and early Holocene, decelerating sea-level rise in the late early Holocene, and slowly rising sea level from middle Holocene to present (Figure 15).

Subsurface, remote sensing, and oceanographic data from the Orinoco Delta (Van Andel and Postma, 1954; Kidwell and Hunt, 1958; Koldewijn, 1958; Nota, 1958; Van Andel, 1967; Danielo, 1976; Butenko and Barbot, 1984) and other major world deltas (Stanley and Warne, 1994; Warne and Stanley, 1995) indicate that the late Pleistocene to recent sea-level history can be summarized as follows: at approximately 18,000 yrs BP, during the last glacial maximum, the shoreline was located near the present shelf edge, about 120 m below present sea level. From ~18,000 to 10,500 yrs BP, glaciers melted, causing sea level to rise rapidly. At about 10,500 yrs BP, glacial melting slowed, resulting in a deceleration in the rate of sea-level rise. By ~6,000 yrs BP, sea level was near its present level (Figure 15).

Many aspects of the sea-level history in this rather structurally complex region remain unclear. Van Andel and Postma (1954) and Van Andel and Sachs (1964) determined that ocean water entered the Gulf of Paria through Boca del Dragón ~13,000 yrs BP, but the marine channel through Boca de Serpientes was not established until sea level reached 45 m below present stand, approximately 9,500 yrs BP. They proposed that, during the Holocene, flow through Boca de Serpientes was interrupted for an undefined period of time by a minor sea-level drop until ~1,500 yrs BP, when sea level rose and the hydraulic connection between the Atlantic shelf and Gulf of Paria was reestablished. Geohidra Consultores, C.A. (1997a), proposed that there was a ma-

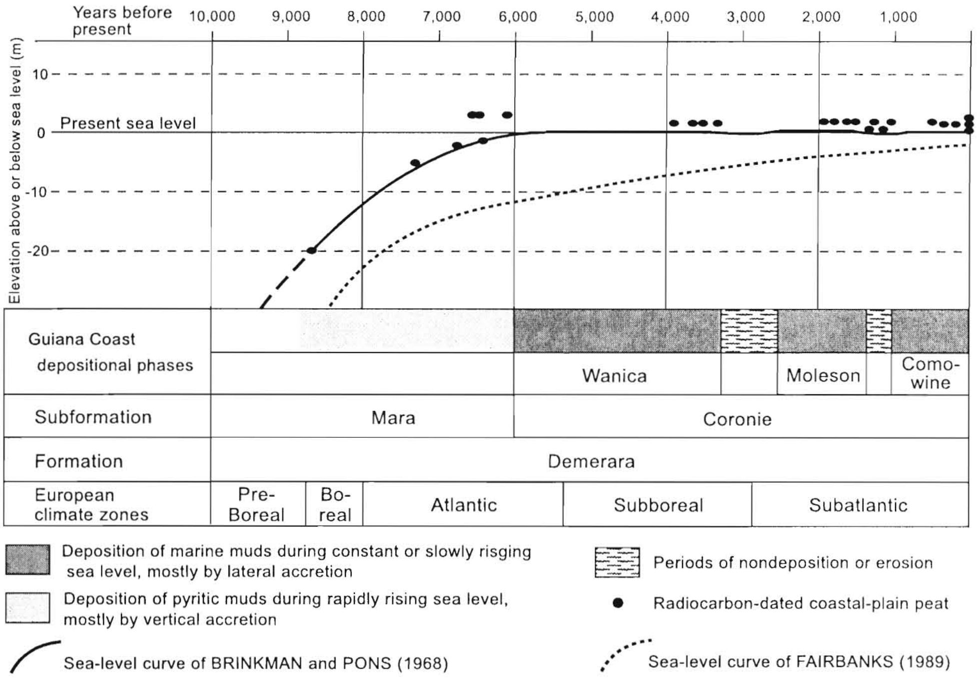


Figure 15. Holocene sea-level curve and principal depositional phases of the Guiana coast region. Diagram modified from BRINKMAN and PONS (1968). Phase, subformation, and formation nomenclature from BRINKMAN and PONS (1968) and ROELEVELD and VAN LOON (1978). This is a relative sea-level curve because no estimates of subsidence were given. However, this sea-level curve is generally concordant with regional and global sea-level change models (CLARK *et al.,* 1978; LIGHTY *et al.,* 1982; FAIRBANKS, 1989; PIRAZZOLI, 1991). In addition, work by NOTA (1958) indicates that this portion of the coastal plain experienced only minor subsidence during the Holocene.

jor change in the coastal current regime ~3,000 yrs BP, and that circulation through Boca de Serpientes was reestablished ~1,000 yrs BP, promoting littoral current processes along the Orinoco coast and development of mudcapes.

Coast and Shelf Water and Sediment Dynamics

The broad shallow Orinoco shelf tends to damp incoming waves, resulting in a low- to moderate-energy wave regime. Moreover, high-intensity storms, including hurricanes, are uncommon (FUNINDES USB, 1998; WARNE *et al.,* 1999), and therefore the coast lacks storm surge and other high-energy erosional and depositional features. Mean diurnal tides along the coast range from ~1.4 to 2.0 m (Figure 2). The coast is strongly affected by the Guayana Current (Figure 2), a primarily northwest-directed littoral-current regime with velocities of 50 to 75 cm/s in the spring and 25 to 40 cm in the autumn (VAN ANDEL, 1967; COLIN and BOURLES, 1992). The Guayana Current transports Amazon sediment northwestward ~1,600 km along the shelf, providing ~50 percent of the sediment deposited along the Orinoco Delta shelf and coast (EISMA *et al.,* 1978, 1991; MEADE, 1994). The Guayana Current acts as a barrier to keep the turbid waters of the Amazon and Orinoco Rivers on the shelf, so that suspended concentrations of surface waters on the inner shelf are tens or hundreds of times greater than those of the outer shelf (EMEL'YANOV and KHARIN, 1974). The Guayana Current flows northwestward generally unimpeded from the Amazon to the Orinoco Delta, where Trinidad disrupts the marine littoral-current system (Figure 2). On the Orinoco shelf, the Guayana Current splits, and one branch flows eastward and northward, passes between Trinidad and Tobago, and is dispersed in the Caribbean Sea. The other branch of the Guayana Current flows into the Gulf of Paria through the Boca de Serpientes (Figure 2). As the branch of the Guayana Current flows toward Boca de Serpientes, it is constricted, which tends to increase littoral-current velocity and hence intensify longshore erosional and depositional processes along the central and northwestern Orinoco coast and shelf.

Combined remote sensing and reconnaissance field analyses indicate that the Orinoco shoreline, although generally prograding, has erosional and nondepositional coastal sectors as well (WARNE *et al.,* 1999, their Figure 39). Erosional shorelines tend to be straight to concave (seaward) in map view; they typically have a small scarp at the shoreface; mature mangrove forests abut the shoreface; and the mangroves are being actively undermined by the encroaching waves, causing them to collapse into the surf. Historical aerial photographs indicate that the coast has eroded landward as much 2 km in some areas between Boca de Cocuina and Pedernales (WAGNER and PFEFFERKORN, 1995). Nondepositional shorelines are typically straight, and mangrove forests abut the shoreface but are not collapsing into the surf; in places, small silty, sandy beaches develop. Accretionary shorelines typically have mudflats that are as much as 2 km wide during low tide. Accretional coastlines, which occupy approximately 50 percent of the Orinoco coast (WARNE *et al.*, 1999, their Figure 39), occur along estuaries, as well as along the Atlantic coast. Mudflats are low gradient and tend to accrete laterally along the break in slope at the seaward edge of the flats. The very shallow water conditions along the mudflats and the soft but cohesive mudflat surface strongly attenuate incoming wave energy, promoting vertical accretion along the landward portions of the mudflats. Colonization by mangroves along the landward portion of the intertidal zone further promotes vertical accretion. Along and down drift from major distributaries, accretional sandy beaches develop. Sandy beaches are particularly well developed on the downdrift side of Boca de Araguao area and most likely represent nascent chenier ridges.

Comparison of the physiography and coastal processes of the French Guiana, Suriname, and Guyana (Guiana) coast with those of the Orinoco Delta reveals several similarities (Figures 1, 16) (WARNE *et al.*, 1999, in press). Both consist of alternating mudcapes and estuaries at the mouths of major rivers. Both receive large volumes of sediment from the Amazon River by longshore transport, and both have been prograding seaward onto the shelf since the early Holocene. Both are mesotidal systems in which large segments of the coast are composed of mudflats bordered by mangrove forest on their landward side. The Guiana and Orinoco coasts are closely linked systems, largely related to the Guayana Current and influx of sediment from the Amazon. Moreover, late Quaternary sea-level and climatic oscillations were very similar along these coastal systems.

There are, however, marked differences between the Orinoco and Guiana coasts: the Guiana coastal plain is largely composed of coalesced beach ridges and interridge marshes (Figures 16, 17), whereas the Orinoco Delta is largely composed of distributary-channel, natural levees, and interdistributary basin deposits, with only a few relict beach ridges apparent (Figure 4). The muddy Guiana coast is a strandplain depositional system between the two major depocenters of the Amazon and Orinoco Rivers. The muddy Guiana coast has high suspended-sediment concentrations that commonly exceed 1,000 mg/L (WELLS and COLEMAN, 1981a). The nearshore fluid muds, combined with the strong northwest-directed Guayana Current, promote the widespread development of mudbanks (WELLS and COLEMAN, 1981a, b; RINE and GINSBERG, 1985; WARNE *et al.*, 1999, in press; ALLISON *et al.*, 2000). Mudbanks are dune-like features that extend obliquely from the nearshore, offshore to about the 20-m isobath and have as much as 5-m relief (RINE and GINSBERG, 1985). Observations along the Orinoco Delta coast indicate that mudbanks are not a major feature (DANIELO, 1976; WARNE *et al.*, 1999). WARNE *et al.*, (1999, in press) proposed that the general absence of mudbanks along the Orinoco coast was related to the large influx of fresh water that has relatively low suspended-sediment concentrations at Boca Grande. Nonetheless, preliminary observations indicate that nearshore waters along the Orinoco coast contain relatively high concentrations of suspended sediment (MONENTE, 1989/1990a; WARNE *et al.*, 1999, their Table 10) that promote progradation by tidal-flat and mudcape accretion, particularly along the central Orinoco coast.

LATE QUATERNARY EVOLUTION OF THE ORINOCO DELTA

The large climatic oscillations that characterized the late Pleistocene caused widespread and significant changes in ecosystems (HOOGHIEMSTRA and VAN DER HAMMEN, 1998; SACHS and LEHMAN, 1999). Biologic composition and structure were generally not as well established as at present (HOOGHIEMSTRA and VAN DER HAMMEN, 1998; IRIONDO and LATRUBESSE, 1994) so that vegetation was less effective at stabilizing soils than the present tropical system.

Late Pleistocene (~20,000 to 16,000 yrs BP)

During the latter part of the late Pleistocene, climate was generally arid, cooler, and more windy than at present (Figure 12). The Orinoco Basin was largely covered by dryland savanna vegetation, and eolian dune formation was widespread (TRICART, 1974a, b, 1985; ROA, 1979; IRIONDO and LATRUBESSE, 1994). The Llanos region was particularly arid during this period (SCHUBERT, 1988).

We propose that river discharge was less, and more erratic than at present, but snowmelt from the Andes provided a perennial source of discharge through the semiarid to arid Orinoco Basin lowlands. Eolian activity produced a poorly defined drainage network across the Llanos region. We suggest that large volumes of sediments were delivered to the river, which promoted development of a braided-river system in the lower river.

Sea level was as much as 120 m lower than the present stand (FAIRBANKS, 1989). As a result, the coastline was positioned near the present shelf edge (Figure 18a). Along the present shelf, shallow seismic data (MCCLELLAND ENGINEERS, 1979) indicate that the sea-level lowstand induced incision of the coastal-plain river valleys. However, the resistant Guayana Shield bedrock precluded deep incision of the river valley upstream of delta apex at Barrancas (Figure 7). Remote sensing data and field observations suggest that the smaller rivers that drain the less resistant Tertiary sediments to the north (Figures 7, 18a) of the Orinoco River developed an incised drainage network that was distinct from the Orinoco system (*cf.* VAN ANDEL, 1967; DANIELO 1976). Subsurface data indicate that the Gulf of Paria was a closed inland or restricted marine basin during this time, in which evaporites (gypsum) accumulated at its center (Figure 10a, core A4).

Available topographic and bathymetric data indicate that seaward (downstream) of the Barrancas knickpoint, the Orinoco River was a relatively steep-gradient (~0.43 m/km) braided river system that transported large volumes of relatively coarse sediment across the coastal plain and to the coast (*cf.* FISK, 1944; STANLEY and WARNE, 1993). We propose that sediment was transported through a network of moderately incised, bedload-dominated channels whose position and discharge capacity changed over time (*cf.* BERRYHILL and SUTER, 1986; SUTER and BERRYHILL, 1986; SUTER, 1986).

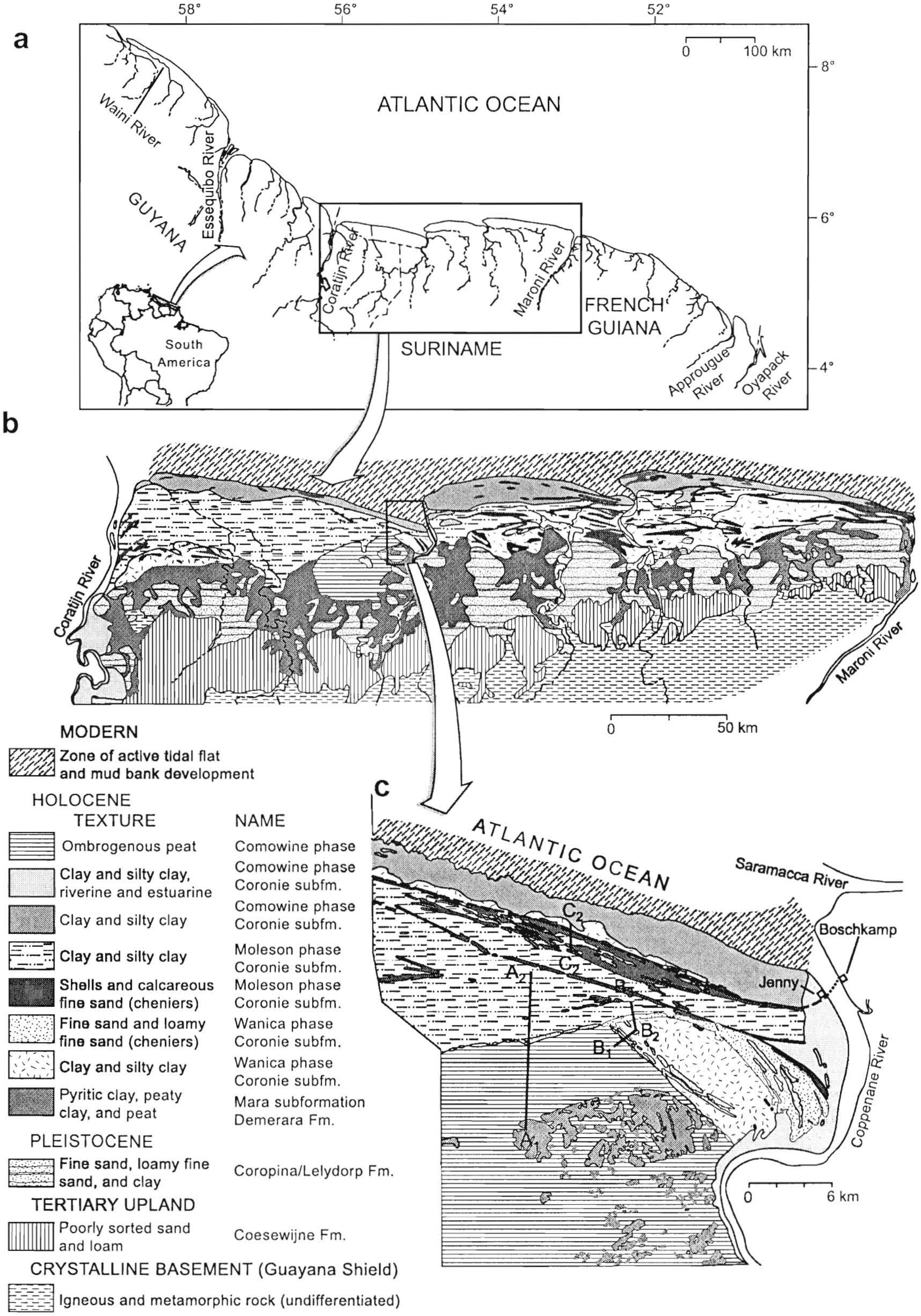


Figure 16. Geology of the coastal plain of the Suriname region. (a) Major physiographic features of the French Guiana, Suriname, and Guyana coast. Features include coastal-plain rivers, estuaries, and mudcapes along the coast. (b) Geology of the coastal plain of Suriname. Modified from ROELEVELD and VAN LOON (1978). (c) Geology of eastern Coronie district, Suriname. See Figure 15 for approximate age ranges of phases, subformations (subfm.) and Formations (Fm.). Cross sections are shown in Figure 17. Modified from BRINKMAN and PONS (1968).

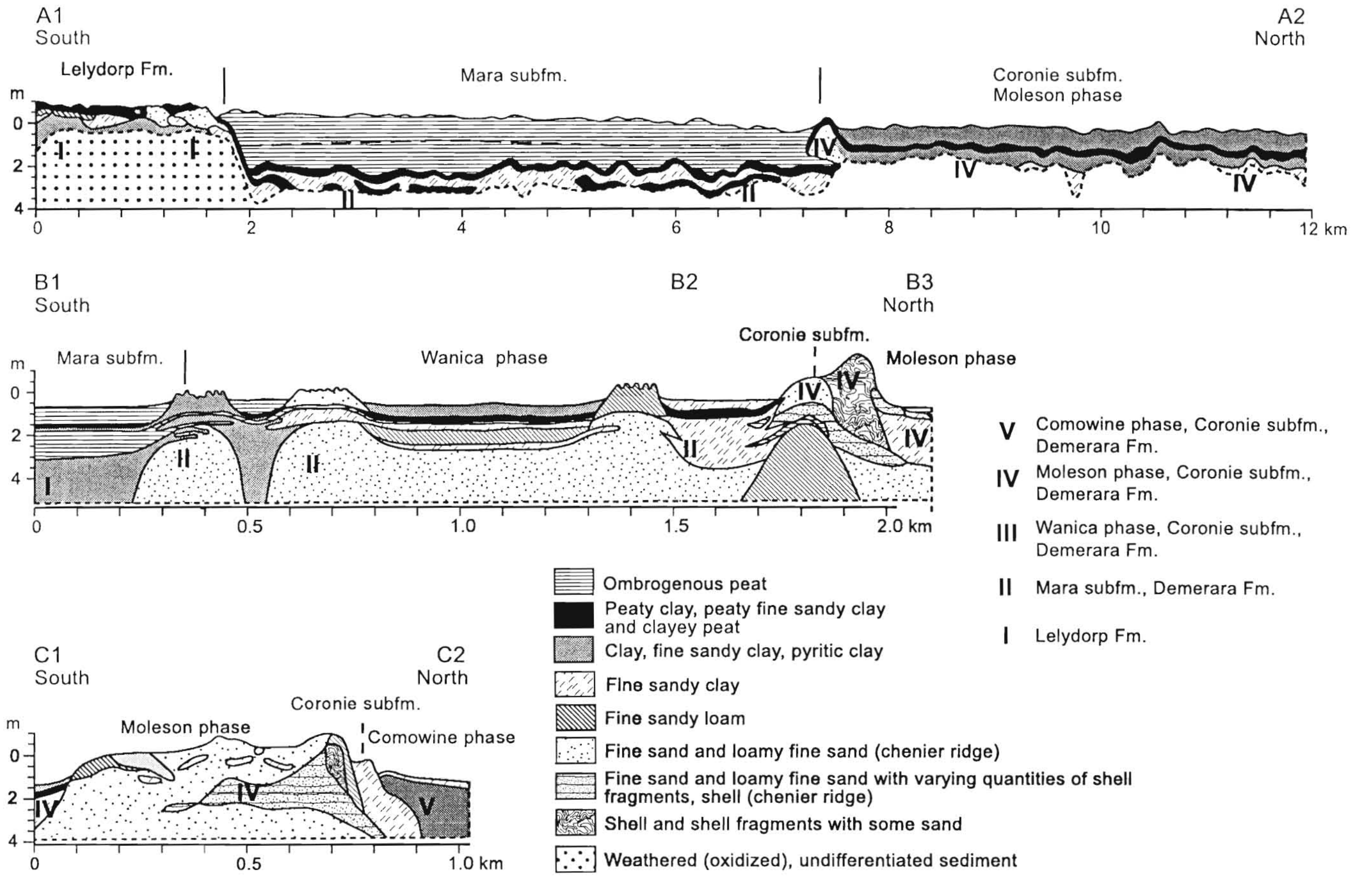


Figure 17. Cross sections of the eastern sector of the Coronie district, Suriname. Cross-section locations are shown in Figure 16c. See Figure 15 for approximate age ranges of phases, subformations (subfm.) and Formations (Fm.). Figure modified from BRINKMAN and PONS (1968).

Largely by comparison with other major delta systems, we propose that the Orinoco coast comprised a series of shelf-edge deltas with associated slope submarine canyons and base-of-slope deep-sea fans that were distributed across a broad region of the coast (*cf.* BERRYHILL, 1986). The shelf was narrow and steep during that period and, therefore, waves and littoral currents reached the coast unattenuated, reworking coarse material in the nearshore and transporting finer material to the slope and abyssal plain, resulting in the development of a series of coalesced, deep-sea fans. Between the shelf-edge deltas, a number of coral reefs formed in the nearshore zone (NOTA, 1958). Reefs generally develop in water that has low concentrations of suspended sediment, and we therefore suggest that fine-grained sediments transported to the coast by the Orinoco River system and adjacent rivers were directly transported onto the slope and abyssal plain, so that the nearshore-zone waters of the interdeltaic areas were low in suspended sediment.

Late Pleistocene to Holocene (16,000 to 9,500 yrs BP)

During this period climate in northeastern South America became generally warmer and wetter but remained unstable, with substantial short-term oscillations that are typical of glacial-interglacial transition periods (HEUSSER, 1993; HUGHEN *et al.,* 1996; ROBERTS, 1998b). The rapid rise in sea level caused the Orinoco shoreline to shift landward from the shelf edge. In the Orinoco drainage basin, unstable but generally wetter climate promoted the erosion and transport of large volumes of sediment to the coastal plain, where most of the relatively coarse-grained material was deposited in the incised alluvial valleys as sea level rose (*cf.* FISK, 1944; FISK and MCFARLAN, 1955).

As the shoreline migrated landward, the near-surface portions of the preexisting coastal-plain deposits were reworked by nearshore marine waves and currents to form a widespread deposit of shelly sand and silty sand. Reworking of coastal-plain sediments by coastal and shallow marine processes promoted infilling of former river valleys and resulted in a broad, rather featureless shelf. Intermittent slowdowns or reversals in sea-level rise induced development of marine terraces (KOLDEWIJN, 1958; NOTA, 1958). During the early phases of rapid sea-level rise, the shelf-edge coral reefs continued to develop (NOTA, 1958) but were eventually drowned and/or overwhelmed by suspended sediment as waters deepened and the shoreline migrated landward.

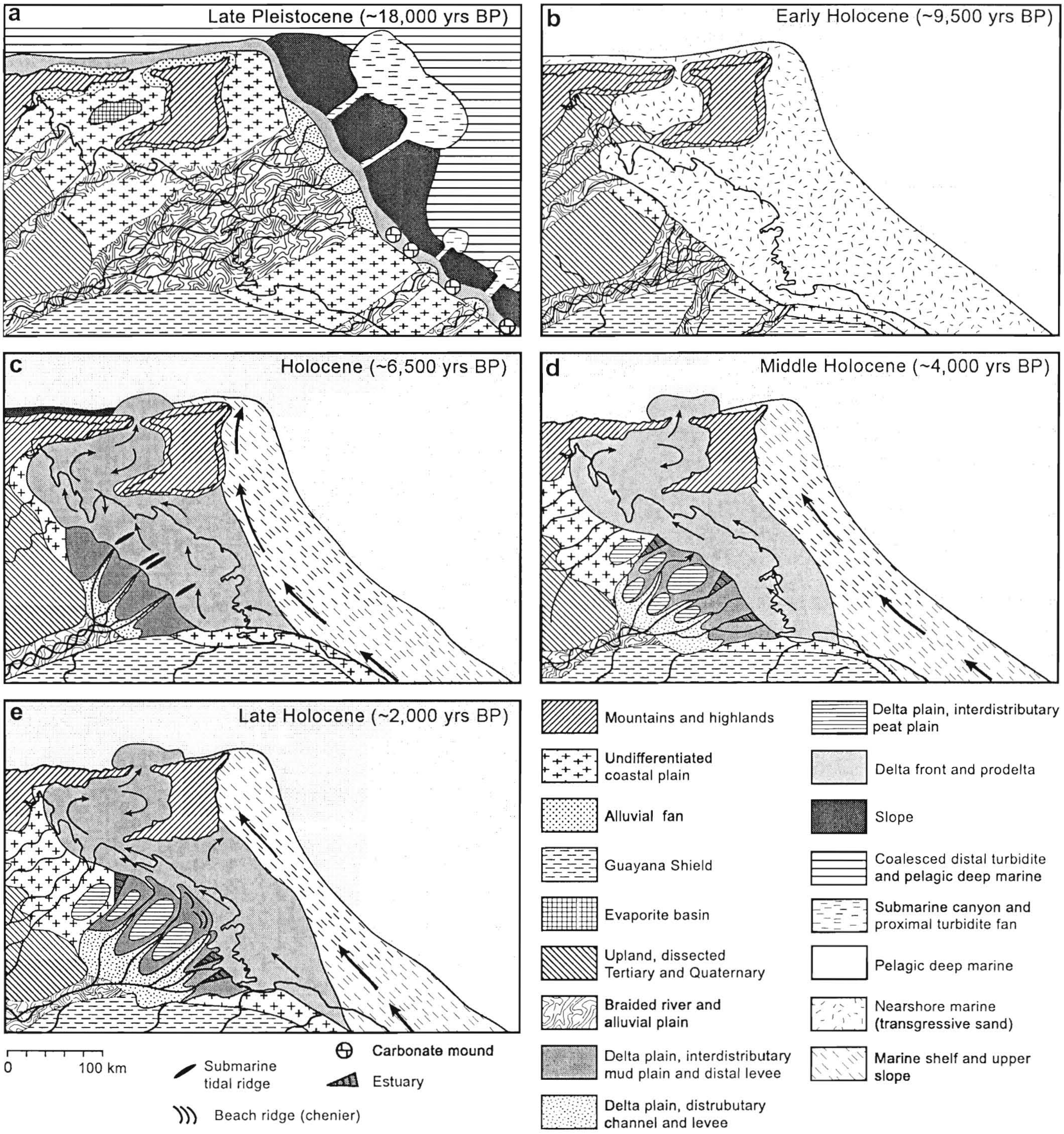


Figure 18. Interpretive summary of Late Pleistocene to Holocene paleogeography of the Orinoco Delta.

By ~9,500 yrs BP, sea level was ~40 to 30 m below present (Figure 15), and the hydraulic connection between the Atlantic shelf and the Gulf of Paria was established through Boca de Serpientes. Establishment of the marine connection between the Atlantic shelf and the Gulf of Paria had a profound influence on shallow marine circulation patterns along the Orinoco coast by increasing the influence of littoral currents in the coastal zone. By ~9,500 yrs BP, the present-day Orinoco shelf and much of the delta plain were covered by shallow sea (Figure 18b) (*cf.* KIDWELL and HUNT, 1958; DANIELO, 1976; WARNE and STANLEY, 1995).

Early Holocene (~9,500 to 6,000 yrs BP)

During the early Holocene the climate was warm and wet, perhaps more so than at any time later in the Holocene (LEYDEN, 1985). Available data indicate, however, that there were millennial-, centennial-, and decadal-scale climatic oscillations (Figure 12), and we propose that these oscillations significantly influenced Orinoco Basin water and sediment dynamics, as well as biologic composition and structure. Based on the findings of modern geomorphic studies (LANGBEIN and SCHUMM, 1958; SCHUMM, 1965; WILSON, 1973; JANSEN and PAINTER, 1974) and regional paleobotanical studies (IRIONDO and LATRUBESSE, 1994; HOOGHIEMSTRA and VAN DER HAMMEN, 1998), we propose that vegetation had not fully stabilized sediments, so that sediment yield from the Orinoco Basin remained relatively high. Consequently, sediment:water discharge ratios in the lower river were substantially greater and sediment accumulation rates in the delta were higher than they are today.

The rate of sea-level rise decelerated and approached the present level (Figure 15), coastline positions stabilized, and the modern Orinoco Delta was well established by this time. Available data indicate that the delta plain was relatively small and was located within the EVB embayment (KIDWELL and HUNT, 1958) (Figure 18c). The delta-plain slope was relatively high because the slope on the small delta plain was controlled by the difference in elevation between the bedrock knickpoint at Barrancas (~15 m above present mean sea level) and sea level. High sediment discharge promoted development of river-dominated delta-plain features, such as levees along the distributary channels and promontories at their mouths. Available subsurface data suggest that interdistributary basins were relatively small and received large volumes of clastic sediments (WARNE *et al.*, 1999).

Because the delta was positioned within an embayment at that time, wave- and littoral-current processes were relatively weak along the coast. We infer that tides were similar to those of today and, in the absence of strong littoral currents, tidal ebb and flow may have promoted development of shore-perpendicular nearshore sand bodies (Figure 18c). The rapid rise in sea level from 15,000 to 9,500 yrs BP created accommodation space seaward of the delta so that the high sediment discharge promoted development of thick prodelta and delta-front facies, and, consequently, rapid infilling of the deep-water portions of the quiet-water EVB embayment.

To the south along the Guiana coast, organic-rich, pyritic Demerara clays were deposited in the late stages of the rapid rise in sea level, and sediment accumulation was primarily by vertical accretion of mangrove swamps (BRINKMAN and PONS, 1968; ROELEVELD and VAN LOON, 1978; AUGUSTINUS *et al.*, 1989; EISMA *et al.*, 1991). The contribution of Amazon sediment to the Guiana and Orinoco coast at that time was relatively small because much of the Amazon River sediment was deposited in the incised Amazon estuary and shelf.

Middle Holocene (~6,000 to 3,000 yrs BP)

The climate was generally warm and wet (LEYDEN, 1985; SCHUBERT, 1988; HOOGHIEMSTRA and VAN DER HAMMEN, 1998), and we infer that the Orinoco Basin assumed the modern character of large, seasonal, unimodal water discharge and relatively low sediment discharge of mostly silt and clay (Figures 11, 12).

The delta plain continued to expand and the seaward gradient declined so that riverine influence diminished relative to the influence of tides and direct rainfall. As a result, promontories at the mouths of major distributaries diminished and estuaries began to develop. In addition, interdistributary basins expanded and peat began to accumulate in the basin centers.

Sea level approached its present level by 6,000 yrs BP (Figure 15). The delta continued to prograde eastward as prodelta and delta-front deposits infilled the EVB embayment. We infer that progradation constricted the inlet at Boca de Serpientes, which subdivided the EVB embayment into two sectors (Atlantic and Gulf of Paria) and progressively increased the influence of littoral currents on coastal evolution, such that local chenier plains and mudcapes developed. However, tides and river discharge continued to be the predominant coastal processes.

To the south along the Guiana coast, mud, shell, and sand accumulated by lateral (seaward) accretion of tidal mudflats and chenier ridges (BRINKMAN and PONS, 1968; VANN, 1969; ROELEVELD and VAN LOON, 1978; AUGUSTINUS *et al.*, 1989; EISMA *et al.*, 1991). Progradational phases were interrupted by two intervals of erosion and nondeposition resulting in development of continuous, prominent, sand-ridge complexes (Figures 16, 17) (BRINKMAN and PONS, 1968). EISMA *et al.* (1991) and SOMMERFIELD *et al.* (1995) attributed these late Holocene changes in coastal-plain water and sediment dynamics to oscillations in wind and precipitation regimes in northeastern South America. Widespread lateral accretion along the Guiana coast during this period (BRINKMAN and PONS, 1968; ROELEVELD and VAN LOON, 1978), indicates that Amazon sediment was available for transport and deposition along the Guiana and Orinoco coast.

Late Holocene (~3,000 to 1,500 yrs BP)

After a relatively cool and dry period between 4,000 and 2,000 yrs BP, the climate became generally warm and wet. Documented millennial-, centennial-, and decadal-scale climatic (wet-dry) oscillations (Figure 12) most likely influenced water and sediment dynamics within the Orinoco Basin, as well as wind, wave, and littoral-current regimes along the Orinoco Delta coast and shelf (*cf.* EISMA *et al.*, 1991). As the delta plain continued to expand, the influence of river stage and discharge on the lower delta diminished, and tides and direct rainfall became more important processes in the development of the central and northwestern delta. Because little accommodation space remained in the upper delta plain, lateral sedimentation/erosion processes were predominant, whereas vertical accretion processes predominated in the interdistributary basins in the middle and lower delta, where subsidence rates were more or less equivalent to sedimentation rates. Local faults, diapiric structures, and low-amplitude synclines and anticlines (Figure 8) continued to influence ecosystem development and distribution.

As the interdistributary basins expanded, the influence of direct river discharge was limited to areas adjacent to distributary channels so that river-borne sediments were no longer transported and deposited in the basin centers. Subsidence, coupled with tides and direct rainfall, maintained perennially inundated and saturated conditions across the basins. The negligible input of clastic sediments into the middle and lower delta-plain interdistributary basins, in conjunction with perennially wet substrates, induced development of widespread peat deposits (Figures 4, 18e). El Niño years induced pronounced dry seasons, which may have been conducive to burning of the upper portions of the peat plains.

Distributary-channel development, abandonment, and infilling were important processes throughout the low-gradient delta plain. Development of major distributary channels appears to be linked to development of estuaries along the coast, and remote sensing analysis of a number of estuaries along the coast indicates that partial or complete abandonment of distributaries promoted infilling of their estuaries by tidal and littoral-current processes (Figure 14). Chenier ridges developed at the mouths of major distributaries; chenier ridge development was likely enhanced during periods of climatically-induced, increased river sediment discharge.

During this period, delta progradation subdivided the EVB embayment into two distinct submarine depocenters—the Atlantic shelf and the Gulf of Paria, each having its own set of wave, current, and sediment regimes. As the channel through Boca de Serpientes continued to narrow, littoral-current flow was focused along the Orinoco coast, promoting mudcape development. Narrowing of the Boca de Serpientes channel also intensified currents along the shelf, which inhibited deposition of delta-front and prodelta deposits in the east-central delta and promoted sediment transport through Boca de Serpientes and along southern Trinidad (Figure 2).

The Guiana coast continued to prograde seaward, although there was a depositional hiatus with associated development of a large chenier ridge between ~1,300 and 1,000 yrs BP (Figures 15, 16, 17). By this time, large volumes of Amazon sediment were transported to the Orinoco coast by the Guayana Current, such that Amazon sediment composed ~50 percent of the sediment deposited along the Orinoco shelf and coast (EISMA *et al.*, 1991; MEADE, 1994).

HUMAN-INDUCED CHANGES IN THE ORINOCO DELTA

Human activities tend to alter the timing, volume, and distribution of water and sediment discharge within deltas (CHEN, 1998; ROBERTS, 1998a; STANLEY and WARNE, 1998). Humans have occupied and manipulated many major deltas since the early to middle Holocene, but human modification of deltas has been particularly pronounced during the past century (STANLEY and WARNE, 1997). We summarize the effects of human activity on the Orinoco Basin and Delta to (1) describe the latest stage in delta evolution and (2) to help define relationships among (a) human activity, (b) water and sediment dynamics within the delta plain, and (c) biologic composition, structure, and distribution.

The Orinoco River remains largely undeveloped, except for hydropower development at Macagua and Guri Dams on the Caroní River (Figure 7) and at small impoundments in the upper reaches of the Andean tributaries. Although the Orinoco Basin makes up 75 percent of Venezuela's land area, only 5 percent of the population resides there, and most are indigenous. This region contains abundant natural resources, including iron ore, bauxite, and petroleum (VÁSQUEZ, 1989; HAGGERTY, 1993), and exploitation of these natural resources is a potential threat to ecosystems in the Orinoco River Basin and Delta. At present, however, the cycle of river water and sediment input to the delta remains much the same as it has been during the late Holocene.

Although the impact of human activity on the delta has been modest, construction of the Volcán Dam across Caño Manamo has significantly influenced the hydrology and ecology of the northwestern Orinoco Delta. Clearing of forests for agriculture, livestock grazing, and human habitation in the upper delta have also impacted delta ecosystems (Figures 1, 3f).

Volcán Dam

This impoundment was constructed across Caño Manamo (Figure 1) in 1966 and 1967 to (1) protect Tucupita from flooding, (2) expand agriculture in the delta by controlling flood regimes and providing the opportunity for drainage of soils, and (3) raise water levels in the Río Grande to enhance commercial navigation (COLONNELLO and MEDINA, 1998). The dam has been effective in controlling flooding in Tucupita, the major city of the region. Expansion of agriculture in the delta plain, however, was unsuccessful because of high pyrite content in soils; draining induces oxidation of pyrite, which produces sulfuric acid, which in turn renders the soils inhospitable for agriculture and even native plants.

Discharge through Caño Manamo prior to dam construction was generally between 3,500 and 8,000 m^3/sec, with a minimum discharge of 800 m^3/sec. Sediment discharge was estimated to be 25 × 10^6 tons/yr (Funindes USB, 1998). Since dam construction, Caño Manamo water discharge has been regulated at 150 to 250 m^3/sec, representing a reduction of from 10 to 0.5 percent of the total Orinoco discharge (BRACHO *et al.*, 1998; COLONNELLO, 1998). Sediment discharge through upper Caño Manamo has been essentially reduced to zero, and the only sediment discharge from the lower distributary channel is supplied by streams, such as Ríos Morichal Largo and Tigre, flowing from the west.

There are many impacts associated with modification of the natural water and sediment-discharge regime by the Volcán Dam, and these include

- A marked increase in upstream tidal flow of marine waters that has induced upstream incursion of estuarine (brackish) water. Cascading effects of the landward saltwater incursion include expansion of mangrove forests upstream and changes to a more marine fish population (COLONNELLO, 1998; COLONNELLO and MEDINA, 1998). Expansion of mangroves has significantly increased rates of sed-

iment entrapment, which in turn has accelerated expansion of channel islands in lower Caño Manamo and infilling of Boca de Guanipa (Figure 14) (COLONNELLO, 1998).
- Increase in water temperatures and decrease in dissolved oxygen content in the caños.
- Reduction of sediment discharge through Manamo and onto the surrounding delta plain and coast.
- Clogging of caños by floating vegetation (especially water hyacinth). Water hyacinth in Caños Pedernales and Capure can be so dense that navigation is impeded. Caño Tucupita is almost completely infilled (Figure 3e). Moreover, upon dying, the floating vegetation settles to the bottom of caños, consuming available oxygen (through microbial consumption of the organic material), accelerating channel infilling, and causing loss of sandy channel-bottom habitat for fish and invertebrates.

The marked reduction in river-sediment discharge to the northwestern delta has converted large areas adjacent to the major distributaries (Manamo, Pedernales, Cocuina) from predominantly river-influenced to almost completely tide- and precipitation-influenced wetlands, which may induce wetland loss as the delta plain subsides and open-water conditions prevail, similar to the situation on the Mississippi Delta (DELAUNE and PEZESHKI, 1994; COLEMAN *et al.*, 1998a). Reduction in mineral-sediment influx may be offset by bioaccumulation associated with peat development, which occurs naturally across large portions of the delta (Figure 4). However, the hydrology, nutrient base, water chemistry, and consequently the ecosystems, of the river-influenced wetlands differ markedly from tide- and precipitation-influenced wetlands.

Water and sediment discharge through Caño Macareo has doubled as the result of dam construction, increasing from ~6 to 13 percent of total Orinoco River discharge (FUNINDES USB, 1998). The doubling of water and sediment discharge has accelerated lateral channel migration and has increased overbank discharge of fresh water and suspended sediment into the adjacent interdistributary basin. Satellite images and historical photographs show little crevasse development across the delta plain, and we therefore surmise that the well-developed crevasse splays along upper Caño Macareo have developed largely in response to the sudden increase in discharge.

Guri Dam

A major dam was constructed across Río Caroní at the site of the former Necuima waterfall (Figure 7). The reservoir, which has the world's fourth-largest capacity for hydroelectricity, extends along 212 km of the lower Río Caroní and covers 4,260 km^2. Río Caroní accounts for 11 percent of lower Orinoco River discharge (Lewis, 1988), and the dam has had a modest effect on discharge to the delta, reducing peak and increasing low discharge (WARNE *et al.*, 1999, their Figure 66). Approximately 50 percent of the suspended sediment entering the Guri reservoir is retained (LEWIS and SAUNDERS, 1990). Río Caroní historically contributed <3 percent of sediment input to the delta, and so the impact of Guri Dam on the Orinoco Delta sediment budget is small.

SUMMARY AND CONCLUDING REMARKS

The Orinoco Delta is a vast mosaic of tropical wetland and shallow aquatic ecosystems that support unique and diverse plant and animal communities (Figures 1, 3, 4) (WARNE *et al.*, 1999, their Plate 2). The wide variety of ecosystems that occur across the delta plain is largely a function of the complex variation in hydrologic inputs from the river, rainfall, and tides.

The modern Orinoco Delta represents the latest in a series of Tertiary and Quaternary deltas that have prograded into and infilled the EVB. Development of the broad shelf in the Pleistocene (Figure 9b) has strongly influenced modern shelf and coastal hydrodynamics and, thus, modern delta evolution. The modern depocenter began to accumulate as the rate of early Holocene sea-level rise decelerated (Figure 15) such that the rate of Orinoco River sediment input exceeded the capacity of nearshore and coastal processes to redistribute river sediments. Early Holocene sediment discharge was relatively high and there was a quietwater embayment seaward of the largely river-dominated delta plain, and, hence, prodelta and delta-front accumulation rates were high (Figures 10, 12, 18c). During the middle Holocene, the delta plain rapidly expanded and assumed a gentler gradient so that the delta plain became a more mixed, river-and tide-dominated system (Figure 18d). Delta progradation led to constriction of Boca de Serpientes, which subdivided the EVB embayment into two distinct submarine depocenters. Sediment input from the Amazon River became a major part of the sediment budget along the coast and shelf during this period. During the late Holocene, the Orinoco delta plain continued to expand, causing a decline in the rate of terrigenous sediment influx to large areas of the delta plain that promoted widespread development of peat plains (Figure 4). Expansion of the delta plain also promoted diversification in ecosystems, which were controlled by interaction of an increasing number of processes, including river input, subsidence, direct precipitation, tides, and littoral currents. Continued infilling of the EVB embayment and constriction of Boca de Serpientes progressively increased the influence of littoral currents along the coast and shelf (Figure 2), which in turn promoted development of mudcapes but inhibited accumulation of prodelta and delta front deposits (Figures 6, 18e).

Holocene climate in northeastern South America was generally tropical with a pronounced dry season. Evidence suggests that there were significant oscillations in temperature, precipitation and wind regimes during the Holocene (Figures 12, 15) and we propose that these climatic fluctuations markedly influenced river and coastal processes, and consequently biologic composition, structure, and distribution in the delta plain (Figures 16, 17).

The coastal wave and current regimes along the Guiana and Orinoco coasts, as well as the Holocene histories of these coastal plains, are linked by the influence of the Guayana littoral current, sediment supply from the Amazon River, and climatic oscillations. As a result, the Guiana and Orinoco contain a number of similar Holocene coastal-plain features (Figures 1, 2, 4, 16). However, DANIELO (1976) and WARNE *et al.* (1999) were unable to relate the Holocene sedimentary phases of the Guiana coastal plain to the Orinoco Delta. Warne *et al.* (1999) attributed the difficulties in correlation to the relatively high sediment input and subsidence rates in the Orinoco Delta, as well as poorly-defined chronostratigraphic framework in the Holocene delta deposits.

The middle and late Holocene evolution of the Orinoco was similar to that of the Changjiang (Yangtze) Delta in that progradation occurred along tidal mudflats downdrift of major distributary channels (Chen, 1999). In addition, a significant portion of the sediment deposited along the Changjiang coast and shelf during the middle Holocene was supplied by littoral-current transport of sediment derived from the Huanghe (Yellow) River (Chen, 1998). Holocene Orinoco Delta evolution resembles that of the Nile and Danube Deltas in that (1) these deltas consisted of several major distributary channels within a single, generally fan-shaped depocenter; (2) the discharge and position of the major distributaries varied over time, although progradation was generally uniform, without significant regressional cycles; (3) the depocenters developed within a tectonic reentrant feature; (4) littoral currents were a major delta-forming process along the shelf and coast; and (5) they underwent a progressive and marked change in overall character during the course of the Holocene as the ratio of river sediment discharge: delta-plain area diminished and the influence of marine processes increased (Stanley and Warne, 1993, 1998; Panin and Jipa, 1998). Holocene Orinoco Delta evolution resembles that of the Rhine-Meuse and Mahakam Deltas in that these delta plains were significantly influenced by tides and were sites of widespread peat accumulation (Combaz and De Matharel, 1978; Gastaldo, 1992; Törnqvist, 1993a; Berendsen, 1998). Holocene evolution of the Orinoco is unlike that of the Mississippi Delta in that Mississippi Delta evolution involved cyclic progradation and retrogradation of five to seven major subdeltas (depocenters) in a microtidal setting, and progradation was focused at promontories at the mouths of active distributary channels (Frazier, 1967; Boyd and Penland, 1988; Coleman *et al.*, 1998a).

Because human-induced changes in the Orinoco drainage basin and delta remain relatively small, it is still possible to clearly distinguish natural from human-induced changes. This river and delta system provide the opportunity to study the effects of modest alterations of water and sediment discharge on the stability and integrity of natural ecosystems. This major river and delta system thus offers an excellent opportunity to gather baseline data on a relatively undisturbed, large-scale ecosystem complex. The data can also be used to minimize impacts of development in the delta.

ACKNOWLEDGMENTS

Financial support for this research was provided by Coordinación Desarrollo Armónico de Oriente (DAO) of Petróleos de Venezuela, S.A. (PDVSA/DAO). We thank Dr. Osmel Manzano of PDVSA/DAO, Caracas, for his support of our studies. We are grateful to Drs. Germán Febres and Heriberto Echezuría, who have served as project Technical Coordinators for PDVSA/DAO. Drs. Rodulfo Prieto, Freddy Chiquito, and José Ruiz (PDVSA) also provided invaluable information and logistical support. We thank Drs. José Méndez-Baamonde and Carlos Yanes of Universidad Central de Venezuela for their participation in the delta field excursions. Fieldwork would not be possible without the logistical support of Mr. Abelardo Lara and his boat crews and Dr. Freddy Rodulfo (PDVSA-Palmaven) in Tucupita.

We are grateful to Dr. Robert Meade who contributed compelling ideas, provided essential data, and pointed out key references during compilation and analysis of the regional data. We thank Dr. Betty Meggers for her suggestions and insights regarding paleoclimate. The article was substantially improved as a result of thorough and insightful reviews and comments of Drs. Daniel Jean Stanley and Torbjörn Törnqvist.

We thank William A. White, James C. Gibeaut, Rebecca C. Smyth, Thomas A. Tremblay, and Jay Raney of the University of Texas at Austin, Bureau of Economic Geology (BEG) for their contributions to this study. We are grateful to William Bergquist, John T. Ames, Patricia Alfano, Jana S. Robinson, Joel L. Lardon, and David M. Stephens (BEG) for generating the figures. We thank Susan Doenges, Lana Dieterich for editing and Susan Lloyd and Scarlett Hurt (BEG) for word processing. The Director of the Bureau of Economic Geology authorized publication of this paper.

LITERATURE CITED

Allen, J.R.L., 1965. Late Quaternary Niger Delta, and adjacent areas: sedimentary environments and lithofacies. *American Association of Petroleum Geologists Bulletin* 49, 547–600.

Alley, R.B.; Mayewski, P.A.; Sowers, T.; Stuiver, M.; Taylor, K.C., and Clark, P.U., 1997. Holocene climatic instability: a prominent, widespread event 8200 years ago. *Geology* 25, 483–486.

Allison, M.A.; Lee, M.T.; Ogston, A.S., and Aller, R.C., 2000. Origin of Amazon mudbanks along northeastern coast of South America. *Marine Geology* 163, 241–256.

Allison, M.A.; Nittrouer, C.A., and Faria, L.E.C., Jr., 1995. Rates and mechanisms of shoreface progradation and retreat downdrift of the Amazon River mouth. *In:* Nittrouer, C.A. and Kuehl, S.A. (eds.), *Geological significance of sediment transport and accumulation on the Amazon continental shelf. Marine Geology* 125 (3–4), 373–392.

Aslan, A.; Warne, A.G.; Smyth, R.C.; Raney, J.A.; Guevara, E.H.; White, W.A., and Gibeaut, J.C., 2001. Mud volcanoes of the Orinoco Delta, eastern Venezuela. *Geomorphology* 41, 323–336.

Augustinus, P.G.E.F.; Hazelhoff, L., and Kroon, A., 1989. The chenier coast of Suriname: modern and geological development. *Marine Geology* 90, 269–281.

Beltran, C., 1993. *Mapa neotectónico de Venezuela.* Caracas, Venezuela: FUNVISIS Departmento de Ciencias de la Tierra, scale 1: 2,000,000, 1 sheet.

Berendsen, H.J.A., 1998. Birds-eye view of the Rhine-Muese Delta (the Netherlands). *Journal of Coastal Research* 14, 740–752.

Berryhill, H.L., Jr., 1986. Sea level lowstand features of the shelf margin off southwestern Louisiana. *In:* Berryhill, H.L., Jr. (ed.), *Late Quaternary facies and structure, northern Gulf of Mexico.* Tulsa, OK: *American Association of Petroleum Geologists Studies in Geology* 23, pp. 225–240.

Berryhill, H.L., Jr. and Suter, J.R., 1986. Deltas. *In:* Berryhill, H.L., Jr. (ed.), *Late Quaternary facies and structure, northern Gulf of Mexico.* Tulsa, OK: *American Association of Petroleum Geologists Studies in Geology 23*, pp. 131–189.

Black, D.E.; Peterson, L.C.; Overpeck, J.T.; Kaplan, A.; Evans, M.N., and Kashgarian, M., 1999. Eight centuries of North Atlantic atmospheric variability. *Science* 286, 1709–1713.

Boyd, R. and Penland, S., 1988. A geomorphic model for Mississippi Delta evolution. *Gulf Coast Association of Geological Societies Transactions* 38, 443–452.

Bracho, H.; Gerendas, G.; Arreaza, M.; Sanchez, E.; De Santis, P., and Balladares, C., 1998. Diagnóstico ambiental en Delta Amacuro. *In:* Lopez-Sanchez, J.L.; Saavedra-Cuadra, I.I., and Dubois-Martínez, M. (eds.), *El Río Orinoco aprovechamiento sustentable: Primeras jornadas Venezolanas de investigación sobre el Río Orinoco.* Caracas, Venezuela: Instituto de Mecánica de Fluídos, Facultad de Ingeniería, Universidad Central de Venezuela, pp. 24–35.

Brinkman, R. and Pons, L.J., 1968. *A pedo-geomorphological classification and map of the Holocene sediments in the coastal plain of the three Guianas.* Wageningen, Netherlands: *The Netherlands Soil Survey Institute, Soil Survey Papers No. 4,* 41 p.

Broecker, W.S., 2001. Was the Medieval Warm Period global? *Science* 291, 1497–1499.

Butenko, J. and Barbot, J.P., 1980. Geological hazards related to offshore drilling and construction in the Orinoco River Delta of Venezuela. *In: Offshore Technology Conference,* Houston, May 1979, Paper 3395, pp. 323–329.

Butenko, J. and Barbot, J.P., 1984. *Características geotécnicas de los sedimentos marinos costafuera Delta del Orinoco.* Caracas, Venezuela: Report to Instituto Tecnológico Venezolano del Petróleo, Report No. INT-0116, 78, 31p.

Cailleux, A. and Tricart, J., 1955. *Cours de géomorphologie.* Paris, France: Centre Documentation Université, 236 p.

Carbon, J. and Schubert, C., 1994. Late Cenozoic history of the eastern Llanos of Venezuela; geomorphology and stratigraphy of the Mesa Formation. *In:* Iriondo, M. (ed.), *Quaternary of South America. Quaternary International* 21, pp. 91–100.

Case, J.E. and Holcombe, T.L., 1980. Geologic-tectonic map of the Caribbean region. *U. S. Geological Survey Miscellaneous Investigation Series Map I-1100,* scale 1:1,000,000, 3 sheets.

Chen, X., 1998. Changjian (Yangtze) River Delta, China. *Journal of Coastal Research* 14(3), 838–858.

Chen, Z., 1999. Geomorphology and coastline change of the lower Yangtze delta plain, China. *In:* Miller, A. J. and Gupta, A. (eds.), *Varieties of fluvial form.* New York: John Wiley & Sons, pp. 427–443.

Chen, Z.; Song, B.P.; Wang, Z.H., and Cai, Y.L., 2000. Late Quaternary evolution of the sub-aqueous Yangtze Delta, China: sedimentation, stratigraphy, palynology and deformation. *Marine Geology* 162, 423–441.

Clark, J.A.; Farrell, W.F., and Peltier, W.R., 1978. Global changes in post-glacial sea level: a numerical calculation. *Quaternary Research* 9, 265–287.

Cole, J., 2001. A slow dance for El Niño. *Science* 291, 1496–1497.

Coleman, J.M., 1981. *Deltas: processes of deposition and models for exploration.* Boston, MA: International Human Resources Development Corporation, 124 p.

Coleman, J.M.; Prior, D.B., and Lindsay, J.F., 1983. Deltaic influence on shelf edge instability processes. *In:* Stanley, D.J. and Moore, G.T. (eds.), *The shelfbreak: critical interface on continental margins. Society of Economic Paleontologists and Mineralogists Special Publication 33,* pp. 121–137.

Coleman, J.M.; Roberts, H.H., and Stone, G.W., 1998a. Mississippi River delta: an overview. *Journal of Coastal Research,* 14(3), 698–716.

Coleman, J.M. and Smith, W.G., 1964. Late Recent rise of sea level. *Geological Society of America Bulletin* 75, 883–890.

Coleman, J.M.; Suhayda, N.N.; Whelan, T., and Wright, L.D., 1974. Mass movement of Mississippi River delta sediments. *Gulf Coast Association of Geological Societies Transactions,* 24, 49–68.

Coleman, J.M.; Walker, H.J., and Grabau, W.E., 1998b. Sediment instability in the Mississippi River delta. *Journal of Coastal Research,* 14(3), 872–881.

Colin, C. and Bourles, B., 1992. Western boundary currents in front of French Guiana. *In:* Prost, M.T (ed.), *Évolution des littoraux de Guyane et de la zone Caraïbe méridonale pendant le Quaternaire.* Paris, France: Editions de l'ORSTOM Institut Français de Recherche Scientifique pour le Développement en Coopération, pp. 73–91.

Colonnello, G., 1998. El impacto ambiental causado por el represamiento del Caño Manamo: cambios en la vegetación riparina, un caso de estudio. *In:* Lopez-Sanchez, J.L.; Saavedra-Cuadra, I.I., and Dubois-Martínez, M. (eds.), *El Río Orinoco, aprovechamiento sustentable: Primeras jornadas Venezolanas de investigación sobre el Río Orinoco.* Caracas, Venezuela: Instituto de Mecánica de Fluídos, Facultad de Ingeniería, Universidad Central de Venezuela, pp. 24–35.

Colonnello, G. and Medina, E., 1998. Vegetation changes induced by dam construction in a tropical estuary: the case of the Mánamo river, Orinoco Delta (Venezuela). *Plant Ecology* 139, 145–154.

Combaz, A. and De Matharel, M., 1978. Organic sedimentation and genesis of petroleum in Mahakam Delta, Borneo. *American Association of Petroleum Geologists Bulletin* 62, 1684–1695.

Cvg-Tecmin, C.A., 1991a. *Informe de avance NC-20-11 y 12. Clima, geología, geomorfología. Tomo I.* Caracas, Venezuela: Gerencia de Proyectos Especiales, Proyecto Inventario de los Recursos Naturales de la Región Guayana, pp. 1–222.

Cvg-Tecmin, C.A., 1991b. *Informe de avance NC-20-11 y 12. Suelos, vegetación. Tomo II. Caracas,* Venezuela: Gerencia de Proyectos Especiales, Proyecto Inventario de los Recursos Naturales de la Región Guayana, pp. 223–621.

Cvg-Tecmin, C.A., 1991c. *Informe de avance NC-20-15. Clima, geología, geomorfología. Tomo I.* Caracas, Venezuela: Gerencia de Proyectos Especiales, Proyecto Inventario de los Recursos Naturals de la Región Guayana, pp. 1–474.

Cvg-Tecmin, C.A., 1991d. *Informe de avance NC-20-15. Suelos, vegetación. Tomo II.* Caracas, Venezuela: Gerencia de Proyectos Especiales, Proyecto Inventario de los Recursos Naturales de la Región Guayana, pp. 475–1088.

Cvg-Tecmin, C.A., 1991e. *Informe de avance NC-20-16. Clima, geología, geomorfología. Tomo I.* Caracas, Venezuela: Gerencia de Proyectos Especiales, Proyecto Inventario de los Recursos Naturales de la Región Guayana, pp. 1–313.

Cvg-Tecmin, C.A., 1991f. *Informe de avance NC-20-16. Suelos, vegetación. Tomo II.* Caracas, Venezuela: Gerencia de Proyectos Especiales, Proyecto Inventario de los Recursos Naturales de la Región Guayana, pp. 314–817.

Damuth, J.E. and Fairbridge, R.W., 1970. Equatorial Atlantic deep-sea arkosic sands and ice-age aridity in tropical South America. *Geological Society of America Bulletin* 81, 189–206.

Danielo, A., 1976. Photointerprétation, sédimentation et géochronologie dans le delta de l'Orenoque. *Revue de Géographie, Physique et de Géologie Dynamique,* 18(5), 407–414.

DeLaune, R.D. and Pezeshki, S.R., 1994. The influence of subsidence and saltwater intrusion on coastal marsh stability, Louisiana Gulf Coast, U.S.A. *Journal of Coastal Research,* 12, 77–89.

Diaz, H.F. and Markgraf, V. (eds.), 1992. *El Niño: historical and paleoclimatic aspects of the Southern Oscillation.* New York: Cambridge University Press, 321p.

Di Croce, J.; Bally, A.W., and Vail, P., 1999. Sequence stratigraphy of the Eastern Venezuelan Basin. *In:* Mann, P. (ed.), *Caribbean Basins: Sedimentary Basins of the World.* Amsterdam: Elsevier, pp. 417–474.

Doust, H. and Omatsola, E., 1990. Niger Delta. *In:* Edwards, J.D. and Santogrossi, P.A. (eds.), *Divergent/passive margins.* Tulsa, OK: *American Association of Petroleum Geologists Memoir 48,* pp. 201–238.

Eisma, D.; Augustinus, P.G.E.F., and Alexander, C., 1991. Recent and subrecent changes in the dispersal of Amazon mud. *Netherlands Journal of Sea Research,* 28(3), 181–192.

Eisma, D.; Van Der Gaast, S.J.; Martin, J.M., and Thomas, A.J., 1978. Suspended matter and bottom deposits of the Orinoco Delta: turbidity, mineralogy and elementary composition. *Netherlands Journal of Sea Research,* 12(2), 224–249.

Emel'Yanov, E.M. and Kharin, G.S, 1974. Sedimentation in the Guiana and North American basins in relation to sediment discharge of the Amazon and Orinoco Rivers. *Litologia I Polezne Iskopaemye,* 2, 22–25.

Ensr Venezuela, 1998. *Estudio de impacto ambiental, Proyecto I, Perforación exploratoria 1998, Bloque Golfo de Paria Este.* Caracas, Venezuela: Report for the Ministry of the Environment and Renewable Natural Resources of Venezuela by the Gulf of Paria East Operating Company, 458p.

Fairbanks, R.G., 1989. A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. *Nature*, 342, 637–642.

Fisk, H.N., 1944. *Geological investigations of the alluvial valley of the Lower Mississippi River.* Vicksburg, MS: U.S. Army Corps of Engineers, Mississippi River Commission, 78 p.

Fisk, H.N. and McFarlan, E., 1955. Late Quaternary deltaic deposits of the Mississippi River. *Geological Society of America Special Paper 62*, pp. 279–302.

Fiorillo, G., 1984. Exploration and evaluation of the Orinoco Oil Belt. *In:* Meyer, R.F. (ed.), *Exploration for heavy crude oil and natural bitumen.* Tulsa, OK: *American Association of Petroleum Geologists Studies in Geology No. 25*, pp. 103–114.

Frazier, D.E., 1967. Recent deposits of the Mississippi River, their development and chronology. *Gulf Coast Association of Geological Societies Transactions*, 17, 287–311.

Fugro Gulf, Inc., 1979. *Geotechnical investigation, Golfo de Paria, offshore Venezuela.* Caracas, Venezuela: Report to INTEVEP, Report No. 79-005-5, 63 p.

Funindes Usb, 1998. *Estudio de impacto ambiental proyecto de perforacion exploratoria Bloque Delta Centro, Fase I.* Caracas, Venezuela: Delta Centro Operating Company, 548 p.

Funindes Usb, 1999. *Caracterización climática y del funcionamiento hidráulico-fluvial del Delta del Río Orinoco, summary of development activities during the first year of study.* Caracas, Venezuela: Progress Report to PDVSA/DAO, 70 p.

Gastaldo, R.A., 1992. Sedimentary facies, depositional environments, and distribution of phytoclasts in the Recent Mahakam River delta, Kalimantan, Indonesia. *Palaios* 6, 574–590.

Geohidra Consultores, C.A., 1997a. *Estudio de impacto ambiental proyecto de perforación exploratoria area prioridad Este – Bloque Punta Pescador.* Caracas, Venezuela: AMOCO Venezuela Energy Company, Project 96017-E4, variously paginated.

Geohidra Consultores, C.A., 1997b. *Estudio de impacto ambiental del proyecto Uno de perforación exploratoria del Bloque Guarapiche.* Caracas, Venezuala: Agencia Operadora Guarapiche S. A. (AOGSA), Project DA96037, Version 1, variously paginated.

Gibbs, A. and Barron, C.N., 1983. The Guiana Shield reviewed. *Episodes*, 1983(2), 7–14.

Haggerty, R.A. (ed.), 1993. *Venezuela: a country study.* Washington DC: Federal Research Division, Library of Congress, 287p.

Hamilton, S.K. and Lewis, W.M., Jr., 1990. Physical characteristics of the fringing floodplain of the Orinoco River, Venezuela. *Interciencia*, 15(6), 491–500.

Herrera, L.E.; Febres, G., and Avila, R., 1981. Las mareas en aguas venezolanas y su amplificación en la región del Delta del Orinoco. *Acta Científica Venezolana*, 32, 299–308.

Herrera, L.E. and Masciangioli, P., 1984. Características de las corrientes frente al delta del Orinoco, sector occidental del Océano Atlántico. *Revista Técnica INTEVEP* 4(2), 133–144.

Heusser, C.J., 1993. Late-glacial of southern South America. *Quaternary Science Reviews*, 12, 345–350.

Hooghiemstra, H. and Van Der Hammen, T., 1998. Neogene and Quaternary development of the neotropical rain forest: the forest refugia hypothesis, and a literature review. *Earth Science Reviews*, 44, 147–183.

Hughen, K.A.; Overpeck, J.T.; Peterson, L.C., and Trumbore, S., 1996. Rapid climatic changes in the tropical Atlantic region during the last deglaciation. *Nature*, 380, 51–54.

Intevep, 1978. *Investigación sobre riesgo sísmico delta del Orinoco reporte de avance.* Caracas, Venezuela: Report to PDVSA, Report INT-0073.78, variously paginated.

Intevep, 1981. *Diseño conceptual de plataformas para el Norte de Paria y el Golfo de Paria.* Caracas, Venezuela: Report to PDVSA, Report INT-834.81, v. 1, 73 p.

Iriondo, M. and Latrubesse, E.M., 1994. A probable scenario for a dry climate in central Amazonia during the late Quaternary. *Quaternary International*, 21, 121–128.

Jansen, J.M.L. and Painter, R.B, 1974. Predicting sediment yield from climate and topography. *Journal of Hydrology*, 21, 371–380.

Kidwell, A.L. and Hunt, J.M., 1958. Migration of oil in Recent sediments of Pedernales, Venezuela. *In: Habitat of Oil.* Tulsa, OK: American Association of Petroleum Geologists, pp. 790–817.

Kineke, G.C. and Sternberg, R.W., 1995. Distribution of fluid muds on the Amazon continental shelf: *International Journal of Marine Geology, Geochemistry, and Geophysics*, 125, 193–233.

Koldewijn, B.W., 1958. *Guiana shelf region: marine geology, sedimentation, South America: sediments of the Paria-Trinidad shelf.* Amsterdam: The Hague, Netherlands, Mouton & Co., 109p.

Kuehl, S.A.; Levy, B.M.; Moore, W.S., and Allison, M.A., 1997. Subaqueous delta of the Ganges-Brahmaputra river system. *Marine Geology*, 144, 81–96.

Kuhry, P.; Hooghiemstra, H.; Van Geel, B., and Van Der Hammen, T., 1993. The El Abra stadial in Eastern Cordillera of Colombia (South America). *Quaternary Science Reviews*, 12, 333–343.

Langbein, W.B. and Schumm, S.A., 1958. Yield of sediment in relation to mean annual precipitation. *American Geophysical Union Transactions*, 39, 1076–1084.

Latrubesse, E.M. and Ramonell, C.G., 1994. A climatic model for southwestern Amazonia in last glacial times. *Quaternary International*, 21, 163–169.

Leonard, R., 1983. Geology and hydrocarbon accumulations, Columbus Basin, offshore Trinidad. *American Association of Petroleum Geologists Bulletin* 67(7), 1081–1093.

Lewis, W.M., Jr., 1988. Primary production in the Orinoco River. *Ecology*, 69, 679–692.

Lewis, W.M., Jr. and Saunders, J.F., III, 1990. Chemistry and element transport by the Orinoco main stem and lower tributaries. *In:* Weimbezahn, F.H.; Alvarez, H., and Lewis, W.M., Jr. (eds.), *El Río Orinoco como ecosistema.* Caracas, Venezuela: Impresos Rubel, pp. 211–239.

Leyden, B.W., 1985. Late Quaternary aridity and Holocene moisture fluctuations in the Lake Valencia Basin, Venezuela. *Ecology*, 66(4), 1279–1295.

Lighty, R.G.; Macintyre, I.G., and Stuckenrath, R., 1982. *Acropora palmata* reef framework: a reliable indicator of sea level in the western Atlantic for the past 10,000 years. *Coral Reefs*, 1, 125–130.

Maslin, M.A. and Burns, S.J., 2000. Reconstruction of the Amazon Basin effective moisture availability over the past 14,000 years. *Science*, 290, 2285–2291.

McClelland Engineers, 1979. *Interpretation and assessment of shallow geologic and geotechnical conditions.* Caracas, Venezuela: Orinoco regional survey areas, offshore Orinoco Delta, Venezuela, v. 1, 109 p.

McKee, E.D., 1989. Sedimentary structures and textures of Río Orinoco channel sands, Venezuela and Colombia. *U.S. Geological Survey Water-Supply Paper W 2326-B*, p. B1–B23.

Meade, R.H., 1994. Suspended sediments of the modern Amazon and Orinoco Rivers. *In:* Iriondo, M. (ed.), *Quaternary of South America. Quaternary International*, 21, 29–39.

Meade, R.H.; Nordin, C.F., Jr.; Perez-Hernandez, D.P.; Mejía-B.A., and Godoy, J.M.P., 1983. Sediment and water discharge in Rio Orinoco, Venezuela and Colombia. *In:* Proceedings of the Second International Symposium on River Sedimentation, 11–16 October, Nanjing, China. Nanjing, China: Water Resources and Electric Power Press, pp. 1134–1144.

Meade, R.H.; Weibezahn, F.H.; Lewis, W.M., Jr., and Perez-Hernandez, D., 1990. Suspended-sediment budget for the Orinoco River. *In:* Weibezahn, F.H.; Alvarez, H., and Lewis, W.M., Jr. (eds.), *El Río Orinoco como ecosistema.* Caracas, Venezuela: Impresos Rubel, pp. 55–79.

Meggers, B.J., 1979. Climatic oscillation as a factor in the prehistory of Amazonia. *American Antiquity*, 44(2), 252–266.

Meggers, B.J., 1996. Possible impact of the mega-Niño events on precolombian populations in the Caribbean area. *In:* Maggiolo, M.V. and Fuentes, A.C. (eds.), *Ponencias Primer seminario de arqueología del Caribe.* Altos de Chavón, Dominican Republic: Museo Arqueologico Regional Altos de Chavón and Organización de los Estados Americanos. pp. 156–176.

Milliman, J.D.; Butenko, J.; Barbot, J.P., and Hedberg, J., 1982. Depositional patterns of modern Orinoco/Amazon muds on the northern Venezuelan shelf. *Journal of Marine Research*, 40(3), 643–657.

Milliman, J.D. and Meade, R.H., 1983. World-wide delivery of river sediment to the oceans. *Journal of Geology*, 91, 1–21.

Monente, J.A., 1989/1990a. Materia en suspensión transportada por el Río Orinoco. *Sociedad de Ciencias Naturales La Salle, Memoria IL/L* 133–134, 5–13.

Monente, J.A., 1989/1990b. Influencia del Río Orinoco en el Caribe, materia en suspensión. *Sociedad de Ciencias Naturales La Salle, Memoria IL/L* 133–134, 14–27.

Morelock, J., 1972. Guayana-Orinoco continental shelf sediments. *Boletin del Instituto Oceanográfico*, 11(1), 57–61.

Nordin, C.F.; Mejía, A., and Delgado, C., 1994. Sediment studies of the Orinoco River, Venezuela. *In:* Schumm, S.A. and Winkley, B.R. (eds.), *The Variability of Large Rivers*. New York: American Society of Civil Engineers Press, pp. 243–265.

Nordin, C.F. and Perez-Hernández, D., 1989. Sand waves, bars, and wind-blown sands of the Río Orinoco, Venezuela and Colombia. *U.S. Geological Survey Water-Supply Paper W 2326-A*, pp. A1–A74.

Nota, D.J.G., 1958. Sediments of the western Guiana shelf. Wageningen, Netherlands: H. Veerman and Zonen. *Wageningen Landbouwhogeschool, Med*, 58(2), 62 p.

Panin, N. and Jipa, D., 1998. Danube delta: geology, sedimentology, evolution. *Association des Sédimentologistes Français*, 29, 63 p.

Pees, S.T.; Banks, L.M., and Segovia, A., 1968. Petroleum geology of the Territorio Federal Delta Amacuro, Venezuela. *Boletín Informativo, Asociación Venezolana de Geología, Minería y Petróleo*, 11(4), 93–122.

Perez-Hernandez, D. and Lopez, J.L., 1998. Procesos geomorfológicos y estructuras sedimentarias en el Río Orinoco. *In:* Sanchez, J.L.L.; Cuadra, I.I.S., and Martínez, M.D. (eds.), *El Río Orinoco, aprovechamiento sustentable*. Caracas, Venezuela: Instituto de Mecánica de Fluídos, Universidad Central de Venezuela, pp. 138–155.

Pimentel-De-Bellizzia, N., 1984. *Mapa geológico estructural de Venezuela*. Caracas, Venezuela: República de Venezuela Ministerio de Energía y Minas Dirección General Sectorial de Minas y Geología, scale 1:2,500,000, 1 sheet.

Pirazzoli, P.A., 1991. *World Atlas of Holocene Sea-Level Changes*. New York: Elsevier, 300 p.

Prieto-Cedraro, R., 1987. *Seismic Stratigraphy and Depositional Systems of the Orinoco Platform Area, Northeastern Venezuela*. Unpublished Ph.D. dissertation. Austin, TX, The University of Texas at Austin, 43p.

Ramírez, A.J.; Mogollon, J.L.; Bifano, C., and Yanes, C.E., 1992. Water, dissolved solids and suspended sediment discharge to Venezuelan coastline. *In:* Prost, M.T. (ed.), *Évolution des littoraux de Guyane et de la zone Caraïbe méridonale pedant le Quaternaire*. Paris, France: Editions de l'ORSTOM Institut Français de Recherche Scientifique pour le Développement en Coopération, pp. 437–456.

Rine, J.M. and Ginsberg, R.N., 1985. Depositional facies of a mud shoreface in Suriname, South America—a mud analogue to sandy, shallow marine deposits. *Journal of Sedimentary Petrology*, 55(5), 633–652.

Roa, P., 1979. Estudio de los médanos de los Llanos centrales de Venezuela: evidencias de un clima desértico: *Acta Biologica Venezolana*, 10, 19–49.

Roberts, H.H., 1998a. Delta switching: early responses to the Atchafalaya River diversion. *Journal of Coastal Research*, 14(3), 882–899.

Roberts, H.H.; Bailey, A., and Keucher, G.J., 1994. Subsidence in the Mississippi River delta: important influences of valley filling by cyclic deposition, primary consolidation phenomena, and early diagenesis. *Gulf Coast Association of Geological Societies Transactions*, 44 619–629.

Roberts, H.H.; Sassen, R., and Aharon, P., 1987. Carbonates of the Louisiana continental slope. *Proceedings of the 19th* Annual Offshore Technology Conference, Houston, TX, April 27–30, 1987, v. 2, pp. 373–382.

Roberts, N., 1998b. *The Holocene, an environmental history*. Malden, MA: Blackwell Publishers, second edition, 316p.

Robertson, P. and Burke, K., 1989. Evolution of the Southern Caribbean Plate Boundary, vicinity of Trinidad and Tobago: *American Association of Petroleum Geologists Bulletin*, 73, 490–509.

Roeleveld, W. and Van Loon, A.J., 1978. The Holocene development of the young coastal plain of Suriname. *Geologie en Mijnbouw*, 58, 21–28.

Sachs, J.P. and Lehman, S.J., 1999. Subtropical North Atlantic temperatures 60,000 to 30,000 years ago. *Science*, 286, 756–759.

Schubert, C., 1988. Climatic changes during the last glacial maximum in northern South America and the Caribbean: a review. *Interciencia*, 13(3), 128–137.

Schumm, S.A., 1965. Quaternary paleohydrology. *In:* Wright, H.E. and Frey, D.G. (eds), *Quaternary of the United States*. Princeton, NJ, Princeton University Press, pp. 783–794.

Sommerfield, C.K.; Nittrouer, C.A., and Figuiredo, A.G., 1995. Stratigraphic evidence of changes in Amazon shelf sedimentation during the late Holocene. *International Journal of Marine Geology, Geochemistry, and Geophysics*, 125, 351–371.

Stager, J.C. and Mayewski, P.A., 1997. Abrupt early to mid-Holocene climatic transition registered at the equator and poles. *Science*, 276, 1834–1836.

Stanley, D.J. and Chen, Z., 1993. Yangtze delta, eastern China: 1. geometry and subsidence of Holocene depocenter. *Marine Geology*, 112, 1–11.

Stanley, D.J. and Hait, A.K., 2000. Holocene depositional patterns, neotectonics and Sundarban mangroves in the western Ganges-Brahmaputra delta. *Journal of Coastal Research*, 16, 26–39.

Stanley, D.J. and Warne, A.G., 1993. Nile Delta: recent geological evolution and human impact. *Science*, 260, 628–634.

Stanley, D.J. and Warne, A.G., 1994. Worldwide initiation of Holocene marine deltas by deceleration of sea-level rise. *Science*, 265, 228–231.

Stanley, D.J. and Warne, A.G., 1997. Holocene sea-level change and early human utilization of deltas. *GSA Today*, 7(12), 1–7.

Stanley, D.J., and Warne, A.G., 1998. Nile Delta in its destruction phase. *Journal of Coastal Research*, 14, 794–825.

Suter, J.R., 1986. Ancient fluvial systems and Holocene deposits, southwestern Louisiana continental shelf. *In:* Berryhill, H.L., Jr. (ed.), *Late Quaternary facies and structure, northern Gulf of Mexico*. Tulsa, OK: *American Association of Petroleum Geologists Studies in Geology* 23, pp. 81–129.

Suter, J.R. and Berryhill, H.I., 1986. Late Quaternary shelf-margin deltas, northwest Gulf of Mexico. *American Association of Petroleum Geologists Bulletin*, 69, 77–91.

Törnqvist, T.E., 1993a. Holocene alternation of meandering and anastomosing fluvial systems in the Rhine-Meuse Delta (central Netherlands) controlled by sea-level rise and subsoil erodibility. *Journal of Sedimentary Petrology*, 63, 683–693.

Törnqvist, T.E. and Van Dijk, G.J., 1993. Optimizing sampling strategy for radiocarbon dating of Holocene fluvial systems in a vertically aggrading setting. *Boreas*, 22, 129–145.

Tricart, J., 1974a. Apports de ERTS-1 notre connaissance ecogenétique des Llanos de l'Orenoque (Colombie et Venezuela). *In:* Plevin, J. (ed.), *European earth-resources satellite experiments*: pp. 317–324.

Tricart, J., 1974b. Existence de periodes sèches au Quaternaire en Amazonie et dans les régions voisines. *Revue de Géomorphologie Dynamique*, 23(4), 145–158.

Tricart, J., 1985. Evidence of Upper Pleistocene dry climate in northern South America. *In:* Douglas, I. and Spencer, T. (eds.), *Environmental Change and Tropical Geomorphology*. London: Allen and Unwin, pp. 197–217.

Trudhope, A.W.; Chilcott, C.P.; McCulloch, M.T.; Cook, E.R.; Chappell, J.; Ellam, R.M.; Lea, D.W.; Lough, J.M., and Shimmield, G.B., 2001. Variability in the El Niño—Southern Oscillation through a glacial—interglacial cycle. *Science*, 291, 1511–1517.

Van Andel, Tj.H., 1967. The Orinoco Delta. *Journal of Sedimentary Petrology*, 37(2), 297–310.

Van Andel, Tj.H. and Postma, H., 1954. Recent sediments of the

Gulf of Paria. Wageningen, Netherlands: *Kon. Nederlandse Akad. Wetensch Adf Verh*, 20(5), 245 p.

Van Andel, Tj.H. and Sachs, P.L., 1964. Sedimentation in the Gulf of Paria during the Holocene transgression: a subsurface acoustic refraction study. *Journal of Marine Research*, 22, 30–50.

Vann, J.H., 1969. Landforms, vegetation, and sea level change along the Guiana coast of South America. Buffalo, NY: *State University College at Buffalo Technical Report No. 3*, 128p.

Vásquez, E., 1989. The Orinoco river: A review of hydrobiological research. *Regulated Rivers Research & Management*, 3, 381–392.

Wagner, T. and Pfefferkorn, H.W., 1995. Tropical peat occurrences in the Orinoco Delta: preliminary assessment and comparison to carboniferous coal deposits. *In:* Proceedings of the XIII International Congress on the Carboniferous and Permian. *Prace Panstwowego Instytutu Geologiznego CLVII*, pp. 161–168.

Warne, A.G.; Aslan, A.; White, W.A.; Gibeaut, J.C.; Tremblay, T.A.; Smyth, R.C.; Guevara, E.H.; Gutierrez, R.; Hovorka, S.D., and Raney, J.A., 1999. *Final Report Year Two: Geoenvironmental characterization of the Delta del Orinoco.* Austin, TX: Report to Petróleos de Venezuela, S. A., The University of Texas at Austin, Bureau of Economic Geology, 327 p, 3 plates, 1 CD.

Warne, A.G. and Stanley, D.J., 1995. Sea-level change as a critical factor in development of basin margin sequences: new evidence from Late Quaternary record. *In:* Finkl, C.W. (ed.), *Holocene cycles: climate, sea levels, and sedimentation. Journal of Coastal Research Special Issue No. 17*, pp. 231–240.

Warne, A.G.; Meade, R.H.; White, W.A.; Aslan, A.; Guevara, E.H.; Gibeaut, J.C.; Smyth, R.C., and Tremblay, T., in press. Regional controls on geomorphology, hydrology, and ecosystem integrity of the Orinoco Delta, Venezuela. *Geomorphology.*

Wells, J.T. and Coleman J.M., 1981a. Physical processes and fine-grained sediment dynamics, coast of Suriname, South America. *Journal of Sedimentary Petrology,* 51(4), 1053–1068.

Wells, J.T., and Coleman J.M., 1981b. Periodic mudflat progradation, northeastern coast of South America: a hypothesis. *Journal of Sedimentary Petrology,* 51(4), 1069–1075.

Wilson, I., 1973. Variations in mean annual sediment yield as a function of mean annual precipitation. *American Journal of Science,* 273, 335–349.

Winkler, C.D. and Edwards, M.B., 1983. Unstable progradational clastic shelf margins. *In:* Stanley, D.J. and Moore, G.T. (eds.), *The Shelfbreak: Critical Interface on Continental Margins. Society of Economic Paleontologists and Mineralogists Special Publication No. 33,* pp. 139–157.