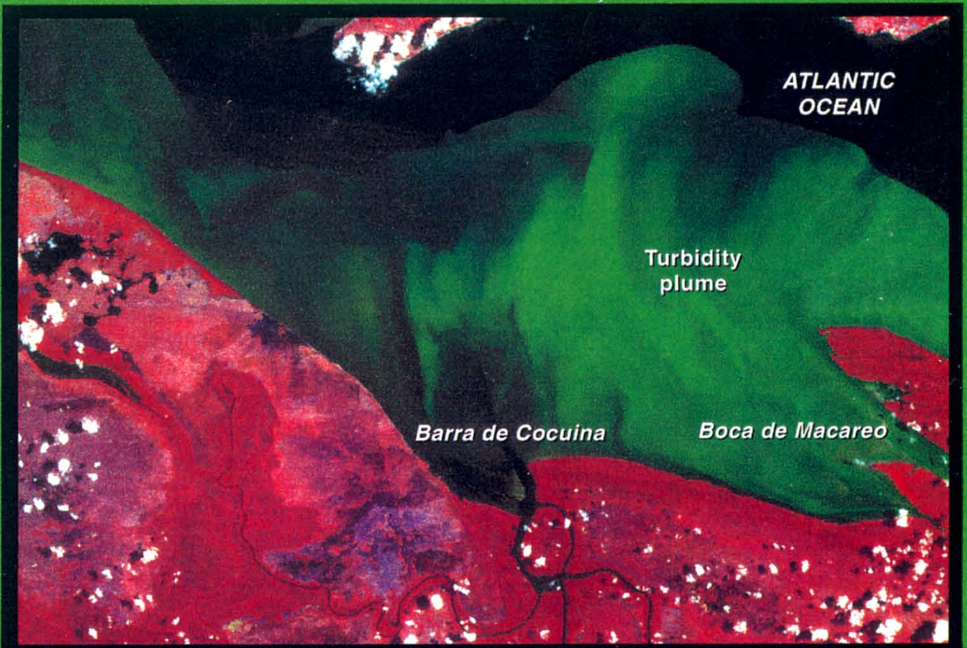
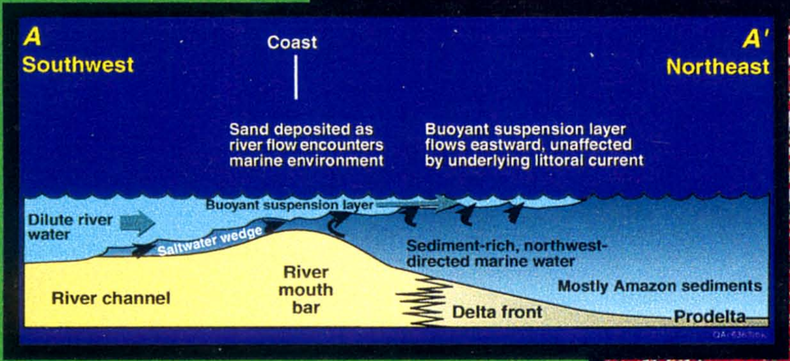
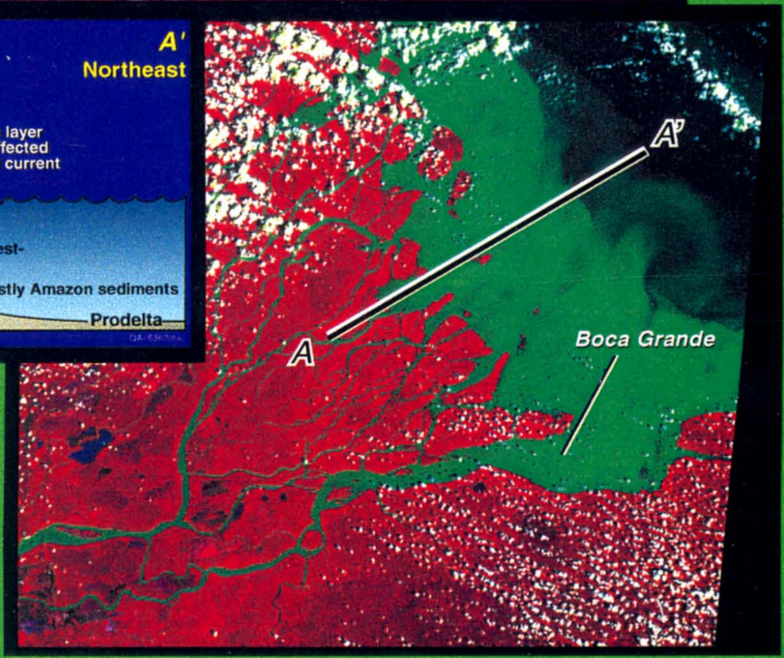
1999 Final Report

Year Two: Geo-Environmental Characterization of the Delta del Orinoco, Venezuela







November 1999

Center for Space Research
The University of Texas at Austin

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PDVSA/DAO
Petróleos de Venezuela, S.A.
Desarrollo Armónico de Oriente

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1999 Final Report

Year Two: Geo-Environmental Characterization of the Delta del Orinoco, Venezuela

Integrated studies of the environmental characteristics, active processes, and depositional systems of the Delta del Orinoco region, Northeastern Venezuela

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Final Report prepared for
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Coordinación Desarrollo Armónico de Oriente (DAO)

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Front cover: Landsat TM images and interpreted coastal processes, Orinoco Delta, Venezuela.

Back cover: Human activities in the Orinoco Delta, Venezuela.

CONTENTS

Figures

Tables

Appendices

Plates (in pocket)

CD-ROM

EXECUTIVE SUMMARY

This report summarizes the results of research conducted at The University of Texas at Austin (UT), Bureau of Economic Geology (BEG), for the project titled "Geo-Environmental Characteristics of the Delta del Orinoco, Venezuela—Integrated Studies of the Environmental Characteristics, Active Processes, and Depositional Systems of the Delta del Orinoco Region, Northeastern Venezuela." It contains results of BEG activities, analyses, and interpretations for the period December 1997 through November 1999. In this study we integrated information generated by satellite image processing and analysis, four field expeditions to the delta, and an extensive literature review.

Main objectives of our investigations are to (1) characterize the physical setting of the Orinoco Delta; (2) identify, evaluate, and describe the physical processes active in the delta; and (3) define and evaluate the relationships between active physical processes and delta-ecosystem composition and long-term stability. Our efforts in 1999 focused on analyses of (1) remote-sensing data and historical aerial photomosaics available to the project; (2) field data acquired in four field expeditions conducted in 1998 and early 1999; (3) environmental reports by petroleum companies operating in the delta area; and (4) publications and reports describing the Holocene and Recent physical setting of northeastern South America, including climatology, ecology, river and coastal hydrology, oceanography, and geology.

We generated two geo-environmental maps of the western delta: the northwestern sector including the coastal area and the Tucupita area in the southwestern sector of the delta. These geo-environmental maps provide an inventory of present delta ecosystems and a basis for evaluating the relationship between physical setting and ecosystems.

We also generated a preliminary shoreline classification of the Boca de Araguao to Boca de Guanipa sector to identify areas of coastal erosion and progradation, define and delineate major coastal habitats, and characterize ongoing hydrological and erosion/deposition processes. The shoreline-classification map provides a fundamental explanation of shoreline-change mechanisms, greatly improving our ability to predict future shoreline changes. The shoreline-classification map also serves as a basis for formulating future coastal monitoring and analysis programs.

We produced the most comprehensive geomorphic assessment of the Orinoco Delta plain to date, which is summarized on a geomorphic map where we emphasized the relationships between landform and physical processes. The geomorphic and hydrologic analyses point out that many of the interdistributary basins are sediment starved and are therefore sites of ombrogenous peat development. The geomorphic map can serve as a planning tool for responsible development of the delta plain and for formulation of further data research.

Geomorphic and geologic analyses of the northwestern delta highlight the importance of riverine, climatic, and tidal-process interactions in the water and sediment dynamics of the Orinoco Delta. Analysis of radiocarbon-dated shallow borings reveals that the extensive network of distributary and tidal channels is highly dynamic. The major distributaries typically avulse and infill within time spans of about 1,000 yr. The smaller caños and tidal channels have a much shorter period of avulsion and infill, on the order of tens to hundreds of years.

We calculated preliminary subsidence and sediment-accumulation rates for different delta sectors. These determinations are based on newly acquired and previously existing radiocarbon dates and on all the available surface and subsurface information. These new data are essential for local and regional planning, including impact assessments and environmentally sound engineering criteria.

We investigated the climatic, oceanographic, geologic, and hydrologic setting of northeastern South America to identify and characterize major sources of water and sediment inflow to the delta, and we developed a broader context for understanding internal delta-plain processes. Among the many findings, our regional analysis indicates that a large, buoyant, freshwater plume is present offshore Boca Grande. Apparently this buoyant suspension layer significantly alters the coastal regime that predominates for about 1,600 km from the Amazon to the Orinoco Rivers.

The coastal sediment and hydrologic regimes are such that the principal site of coastal progradation extends from Boca de Araguao to Punta Pescadores. The main mechanism of coastal progradation is by mudcape development. The Boca de Serpientes constriction accelerates the Guayana littoral current along the Orinoco Delta coast, thus enhancing mudcape development but limiting coastal progradation in the northwestern delta.

To summarize the regional analysis, we present a regional model that describes the major sources and mechanisms of water and sediment inflow and outflow from the delta. This conceptual model provides a basis for regional planning, as well as a template for developing research programs for the delta.

We produced two topical papers that are included as appendices to this report. The first paper illustrates typical plants of the Orinoco (app. 1); these plant descriptions can serve as a general guide to Orinoco Delta vegetation for individuals interested in the ecology of the delta. The other paper describes mud volcanoes of the Pedernales area, which are conspicuous structural and geomorphic elements of the delta landscape (app. 2). We also prepared a comprehensive bibliography of the Orinoco delta (app. 3). This bibliography is an invaluable resource for current and future Orinoco Delta researchers.

Highlights of our studies are illustrated on a web page contained on a CD that forms part of this report. The web page is designed to present our geo-environmental investigations and to stimulate interest in the Orinoco Delta ecosystem among a diverse audience. The CD additionally contains a series of data bases that document our research during the course of the study.

The delta is currently in an almost pristine state. However, future environmental pressures in this area pose potential threats to this highly sensitive ecosystem complex. Because most major human-induced changes involve alterations of the hydrological and sediment regime, baseline geo-environmental investigations, as presented in this report, are essential for a responsible and sustainable development of the region. This information is also essential for adequate management of two protected areas located in the Orinoco Delta, the Biosphere Reserve created by the United Nations and the National Park established by the Republic of Venezuela.

RESUMEN EJECUTIVO

Este informe resume los resultados de investigaciones efectuadas en el Buró de Geología Económica (BEG) de la Universidad de Texas en Austin en el proyecto titulado "Caracterización Geo-Ambiental del Delta del Orinoco, Venezuela – Estudios Integrados de las Características Ambientales, Procesos Activos, y Sistemas Depositacionales de la Región del Delta del Orinoco, Venezuela Nororiental." Contiene los resultados de actividades, análisis, e interpretaciones del BEG en el período Diciembre de 1997 a Noviembre de 1999. En este estudio nosotros integramos la información generada por el procesamiento y el análisis de imágenes de satélites, cuatro expediciones de campo en el delta, y una extensa revisión bibliográfica.

Los objetivos principales de nuestras investigaciones son (1) caracterizar el marco físico del Delta del Orinoco, (2) identificar, evaluar, y describir los procesos físicos activos en el delta, y (3) definir y evaluar las relaciones entre los procesos físicos activos y la composición y estabilidad a largo plazo de los ecosistemas del delta. Nuestros esfuerzos en 1999 se enfocaron en el análisis de (1) información de sensores remotos y aerofotomosaicos históricos disponibles en el proyecto, (2) información de campo adquirida en cuatro expediciones efectuadas en 1998 y a comienzos de 1999, (3) informes ambientales de compañías petroleras que operan en el área del delta, y (4) publicaciones e informes que describen el marco físico del Holoceno y Reciente en el noreste de Sur América, incluyendo climatología, ecología, hidrología fluvial y costanera, oceanografía, y geología.

Nosotros generamos dos mapas geo-ambientales de la parte occidental del delta: uno del sector noroccidental que incluye el área costanera, y el otro del área de Tucupita, en el sector suroccidental del delta. Estos mapas geo-ambientales proveen tanto un inventario de los ecosistemas actuales del delta como una base para la evaluación de la relación entre el marco físico y los ecosistemas.

Nosotros también generamos una clasificación preliminar de líneas de costa para el sector Boca de Araguao a Boca de Guanipa, para identificar áreas costaneras de erosión y progradación, definir y delinear los habitat costaneros mayores, y caracterizar los procesos hidrológicos y de erosión/depositación actuales. El mapa de clasificación de líneas de costa proporciona una explicación fundamental de los mecanismos de cambio de la línea de costa, lo cual mejora notablemente nuestra capacidad para predecir cambios futuros de la línea de costa. El mapa de clasificación de líneas de costa es también una base para la formulación de programas futuros de monitoreo y análisis de la línea de costa.

Produjimos la evaluación geomórfica más completa hasta la fecha del plano deltaico del Orinoco, la cual está resumida en un mapa geomórfico en el cual enfatizamos las relaciones entre las formas del relieve y los procesos físicos. Los análisis geomórfico e hidrológico indican que muchas de las cuencas interdistributarias carecen de aporte de sedimentos ("sediment starved") y son por consiguiente sitios de desarrollo de turbas ombrogénicas ("ombrogenous"). El mapa geomórfico puede servir como una herramienta de planificación para el desarrollo responsable del plano deltaico y para la formulación de investigaciones adicionales.

Los análisis geomórfico y geológico del delta noroccidental resaltan la importancia de las interacciones entre los procesos riverinos, climáticos, y de mareas en la dinámica de agua y sedimento del Delta del Orinoco. El análisis de dataciones por carbono radiactivo en perforaciones someras revela que la extensa red de canales distributarios y de marea es altamente dinámica. Los distributarios mayores típicamente cambian de curso abruptamente ("avulse") y se rellenan en períodos de alrededor de 1.000 años. Los caños menores y los canales de marea tienen un período de avulsión mucho más corto, en el orden de decenas a centenares de años.

Nosotros hicimos cálculos preliminares de las ratas de subsidencia y acumulación de sedimentos para diferentes sectores del delta. Estas determinaciones están basadas en dataciones por carbono radiactivo tanto recientemente adquiridas como previamente existentes, y en toda la información de superficie y de subsuelo disponible. Estos nuevos datos son imprescindibles para planificación local y regional que incluya evaluaciones de impacto y criterios ingenieriles ambientales adecuados.

Investigamos el marco climatológico, oceanográfico, geológico, e hidrológico del noreste de Sur América para identificar y caracterizar las fuentes mayores de influjo de agua y sedimento hacia el delta, y desarrollamos un contexto más amplio para el entendimiento de los procesos internos del plano deltaico. Entre los varios hallazgos, nuestro análisis regional indica que una gran pluma flotante de agua dulce está presente costafuera de Boca Grande. Aparentemente, esta capa flotante en suspensión altera significativamente el régimen costanero que predomina por cerca de 1.600 km entre los ríosAmazonas y Orinoco.

Los regímenes costaneros de sedimento e hidrológico son tales que el sitio principal de progradación de la costa se extiende desde Boca de Araguao hasta Punta Pescadores. El mecanismo principal de progradación costanera es a través del desarrollo de cabos de lodo ("mudcapes"). La constricción de Boca de Serpientes acelera la corriente litoral de Guayana a lo largo de la costa del Delta del Orinoco, y de esta manera favorece el desarrollo de cabos de lodo pero limita la progradación costanera en el delta noroccidental.

Para resumir el análisis regional, presentamos un modelo que describe las fuentes y mecanismos mayores de influjo y reflujo de agua y sedimento en el delta. Este modelo conceptual provee una base para la planificación regional, así como también una referencia para desarrollar programas de investigación para el delta.

Produjimos dos artículos sobre tópicos específicos que estan incluídos como apéndices en este informe. El primer artículo ilustra plantas típicas del Orinoco (apéndice 1); estas ilustraciones de plantas pueden servir como una guía general de la vegetación del Delta del Orinoco para personas interesadas en la ecología del delta. El otro artículo describe volcanes de lodo del área de Pedernales, los cuales son elementos estructurales y geomórficos conspícuos del paisaje del delta (apéndice 2). También preparamos una extensa bibliografía del Delta del Orinoco (apéndice 3). Esta bibliografía es un recurso invalorable para investigadores actuales y futuros del Delta del Orinoco.

Puntos resaltantes de nuestros estudios están ilustrados en una página "web" contenida en un CD que forma parte de este infome. La página web está diseñada para presentar nuestas investigaciones geo-ambientales y para estimular el interés sobre el Delta del Orinoco en una audiencia amplia. Adicionalmente, el CD contiene una serie de bases de datos que documenta nuestras investigaciones durante el curso del estudio.

El delta está actualmente en un estado casi prístino. Sin embargo, futuras presiones ambientales en esta área crean amenazas potenciales para este ecosistema complejo y altamente sensible. Debido a que gran parte de los cambios mayores inducidos por el hombre envuelve alteraciones del régimen hidrológico y de sedimento, investigaciones geo-ambientales de línea base, como las presentadas en este informe, son imprescindibles para un desarrollo responsable y sustentable de la región. Esta información es también imprescindible para el manejo adecuado de dos áreas protegidas que existen en el Delta del Orinoco, la Reserva de Biósfera creada por las Naciones Unidas y el Parque Nacional establecido por la República de Venezuela.

INTRODUCTION

This report summarizes investigations carried out in 1999 at The University of Texas at Austin's Bureau of Economic Geology (BEG), during Year 2 of the project titled "Geo-Environmental Characterization of the Delta del Orinoco, Venezuela: Integrated studies of the environmental characteristics, active processes, and depositional systems of the Delta del Orinoco region, northeastern Venezuela." It includes a description of the Delta del Orinoco, with emphasis on the northwestern part of the delta, where the areas currently under petroleum exploration and exploitation are located and where the BEG 1998–1999 field campaigns were focused. Results of field studies that BEG researchers conducted in 1998–1999, in conjunction with scientists of Universidad Central de Venezuela, are discussed in this description. The report also includes the synthesis of an extensive literature review of the climatologic, hydrologic, oceanographic, and geological characteristics of the Orinoco drainage basin and the coastal plain of northeastern South America to identify major regional processes affecting the Orinoco Delta area.

Delta del Orinoco Project

In late 1997, the *Coordinación Desarrollo Armónico de Oriente* of *Petróleos de Venezuela, S.A.* (PDVSA-DAO) commissioned the BEG to carry out and lead an interdisciplinary, comprehensive study to identify and evaluate the physical processes and process linkages that control integrity of the Delta del Orinoco ecosystem. The principal aim of the study was to generate and interpret baseline information needed to anticipate and minimize impacts associated with (1) exploitation of hydrocarbon resources and (2) other projects undertaken to enhance the economic and social welfare of the region.

The BEG investigations form part of what was to be a 5-yr, interdisciplinary study of the Orinoco Delta by BEG and Venezuelan researchers. Originally, the primary product of the project was intended to be a GIS-based atlas documenting the environmental baseline characteristics of the delta and its ecosystems. Specific goals of BEG research were to (1) provide baseline information on the geoenvironmental conditions of the delta, (2) determine the major processes controlling these conditions, (3) develop a comprehensive model of the delta's recent evolution (to serve as a template to anticipate and thereby minimize changes induced by the exploration and exploitation of natural resources and the development of the region), (4) integrate the data produced by BEG and Venezuelan researchers into a GIS-based geoenvironmental atlas of the delta, and (5) strengthen national and local organizations participating in, or related to, the project in Venezuela, through effective technology transfer. This integrated data base and the GIS-based geoenvironmental atlas were to be used by national and local planners to define strategies for the responsible and sustainable development of the delta region. The GIS was intended to serve as a base for a comprehensive assessment and analysis of Orinoco Delta ecosystems.

As a result of redefinition of objectives at PDVSA in early 1999, the budget of the BEG investigations was modified, the project period was shortened to end on November 30, 1999, and the project's deliverables were modified to reflect the reduced budget and period of study. As a result of these modifications, only a 9-day field campaign was conducted in 1999, in early February, before the project's modifications were enacted.

Ongoing reassessment of the project by PDVSA points to continuation of the studies starting in January 2000. The revised project would be coordinated by the Venezuelan Ministry of the Environment and Natural Renewable Resources (MARNR). Project sponsorship would be by Venezuelan governmental organizations, including PDVSA, and Venezuelan and international funding agencies, such as the United Nations Global Environmental Facility (UN-GEF). Focus of the redefined project would be to define and evaluate biodiversity within the delta and to identify processes critical to the preservation of such biodiversity. In addition to the assessment of the delta regional landscape, the studies would focus on ecologically sensitive areas, including portions of the Biosphere Reserve and National Park.

General Characteristics of the Orinoco Delta

The Orinoco Delta of the northeastern Venezuela coastal plain, a vast mosaic of tropical wetlands and shallow aquatic ecosystems, supports unique and diverse plant and animal communities. It is a triangular to trapezoidal depocenter encompassing approximately 22,000 km^2 of pristine lowland forests and swamps subdivided by networks of fluvial and tidal channels (figs. 1 and 2 and plate 1). This area, combined with the Orinoco River floodplain, represents one of the largest tropical-wetland complexes in the world (Hamilton and Lewis, 1990). Hydrologic inputs of river, tides, and rainfall vary across the delta plain, fostering diverse, environmentally sensitive channel and delta-plain ecosystems.

The fluvial network of the Orinoco comprises six major tributaries radiating from the delta apex, near Barrancas, to the coast (figs. 1 and 2 and plate 2). The low-gradient delta plain is a mesotidal system with daily tidal amplitudes ranging from 2.5 m at the coast to 0.6 m at the delta apex. Nearly 90 percent of the water and sediment discharge is through the Río Grande along the southern margin of the delta so that the northwestern delta is more marine in character.

Tides maintain an intricate network of channels throughout the delta and reflect the dynamic nature and interconnectivity of this deltaic system. Near the coast, many of the distributary channels (caños) deflect to the northwest under the influence of the strong, northwest-directed Guayana littoral current. Broad 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 area) (fig. 2).

The Orinoco Delta is part of the northeastern Venezuelan coastal plain that extends from Guyana in the southeast to the Gulf of Paria in the northwest (figs. 2 and 3). This coastal plain region is commonly divided into three parts: (1) a southern sector, which includes rivers that drain the Guayana Shield and flow into the Río Grande; (2) the Orinoco Delta proper, which extends between the Río Grande in the south and Caño Manamo in the west; and (3) the northwestern sector west of Caño Manamo, which includes a series of smaller rivers that drain into the Gulf of Paria (Davey, 1946). The focus of this report is on the Orinoco Delta proper between the Río Grande and Caño Manamo (fig. 2).

Deltas are transitional environments that are continuously subject to the interaction among climatic, upland, riverine, and marine processes, together with longer-term processes such as subsidence and sea-level change. The transitional terrestrial-aqueous delta systems depend on the balance of inputs and outputs of many terrestrial and biological systems. Therefore, they typically respond quickly and markedly to even modest changes in water and sediment inflow and throughflow. Furthermore, ecosystems within deltas are strongly linked, and so changes tend to cascade into other delta processes. Hence human modifications have profound and commonly adverse impacts on delta ecosystems (DeLaune and Pezeshki, 1994; Bracho and others, 1998; Colonnello, 1998; Stanley and Warne, 1998).

Many major world deltas have been long-term centers of human activity (Stanley and Warne, 1997). Global surveys of modern deltas show that most deltas have been significantly impacted by human activity, and many are no longer naturally functioning deltas (Stanley and Warne, 1994; 1997; 1998). In the Orinoco, more than 80 percent of the delta plain is perennially inundated, which greatly limits intentional burning and other common anthropogenic alterations. Moreover, little has been done within the delta or upstream along the Orinoco River to alter the natural cycle of water and sediment to the delta. Hence, the Orinoco Delta remains one of the world's largest pristine jungle and coastal wetland ecosystem complexes. Because of the extraordinarily pristine condition of the delta, the Orinoco offers a unique opportunity to study environmental conditions of a major tropical delta and evaluate geologic influences on the stability and biodiversity of these ecosystems.

Compared with those of other major deltas, studies of the Orinoco Delta are surprisingly few in number (Van Andel and Sachs, 1964; Van Andel, 1967; Pees and others, 1968; Danielo, 1976a, b). Previous investigations focused principally on the offshore geology and oceanography of the delta (for example, Van Andel and Sachs, 1964; Van Andel, 1967; Butenko and Barbot, 1980). In contrast, only a small number of investigations have focused on the delta plain (for example, Pees and others, 1968; Danielo, 1976a, b; ENSR Venezuela, 1998; Geohidra Consultores, C.A., 1997a, b; FUNINDES USB, 1998). Only Van Andel (1967) and CVG-TECMIN (1991a through h) provided comprehensive analyses of the Orinoco Delta.

Methods of Study

We integrated information generated by an extensive literature review, satellite image and historical aerial photograph analyses, and a series of delta expeditions. The literature survey included descriptions and analyses of the Orinoco drainage basin, Eastern Venezuelan Basin (EVB), the Orinoco and Trinidad shelf, the Gulf of Paria, Amazon River and Delta, the coastal plain and shelf of French Guiana, Surinam, and Guyana, as well as the Orinoco Delta itself. The literature survey focused on climatic, geologic, and hydrologic aspects of the region to identify major physical processes affecting the delta. The survey encompassed analyses of the recent processes, as well as change over time.

Satellite imagery was particularly useful because many sectors of the delta are difficult to access, and so satellite imagery offers the best way of delineating major geoenvironmental and geomorphic units and extrapolating field observations to broader areas. The scope of our study were ideal for satellite-imagery analysis, which provides a more systematic and synoptic view than do aerial photographs. Moreover, satellite images are available in digital format, providing the opportunity for digital processing to highlight geomorphic, hydrologic, and floral characteristics.

Remote-sensing analysis was largely based on images generated by the RADSAT satellite in November and December 1996 (table 1). The Radarsat Synthetic Aperture Radar (SAR) satellite generates images using C-band frequency range transmitting at 5.3-GHz frequency and 5.6-cm wavelength. Six scenes were georeferenced and digitally integrated to produce a seamless mosaic of the delta with a spatial resolution of ~30 m (fig. 1 and pl. 1). The georeferenced Radarsat image was used as a basis for generating a georeferenced hydrographic map of the delta.

We also used SAR images generated by the JERS-1 satellite in September–December 1995 (fig. 4). These images were created using the L-band at a frequency of 1.275 GHz and wavelength of 20 cm. The JERS image, which was obtained from U.S. National Aeronautics and Space Administration's (NASA) Jet Propulsion Laboratory, has a spatial resolution of ~100 m. The longer wavelength of the JERS SAR penetrates deeper into the vegetation canopy than does the shorter wavelength Radarsat, providing a slightly different RADAR image (fig. 4).

Eleven Landsat Thematic Mapper ™ and two Landsat Multispectral Scanner (MSS) images spanning 1986–1997 and covering the entire delta region were acquired and digitally processed to identify and map geoenvironments, identify and evaluate active physical processes, and conduct change analysis (fig. 5). Cloud cover, which is nearly always present in the delta, limited the utility of TM and MSS imagery. Five Side-Looking Airborne RADAR (SLAR) images that cover the entire delta were also used. The SLAR images used were acquired during December 1997 flights and have ~30-m resolution. The SLAR images were especially useful in identifying subtle topographic features and analyzing change.

A number of aerial photograph mosaics, dating from 1951 to 1983, were acquired by PDVSA/DAO from Cartografía Nacional de Venezuela (table 2). These photographs were particularly useful in geomorphic change analysis. During this initial investigation we did not obtain individual photographs for more detailed analysis.

BEG carried out four field expeditions, three in 1998 and one 1999, that included a series of airplane flyovers and site surveys. UCV's Earth Sciences Institute researchers Dr. José Méndez-Baamonde and Carlos Yánes contributed significantly to our field observations and data collection. Major goals of the field expeditions were to systematically document the geomorphology, vegetation, hydrology, and soils of representative environments identified in remote-sensing images.

Eight airplane flyovers (fig. 6a) were conducted to verify and enhance interpretations of geoenvironments initially identified on satellite imagery, photodocument these environments, and help plan field expeditions. Geomorphic, hydrologic, and floral characteristics were documented during on-site investigations at more than 75 individual locations in the northwestern delta. On-site investigations served to further define geoenvironments initially identified on satellite images. Lithologic logs of hand-auger borings were recorded at 42 sites, and sediments were studied and sampled to depths as great as 8 m (fig. 6b) to evaluate the late Holocene history of the delta.

Thirty-one samples of organic materials, including peat, organic sediment, plant material, and wood fragments were radiocarbon dated using conventional radiometric dating for large samples and accelerator mass spectrometry (AMS) techniques for small samples and all peats. Channel-sediment samples and channel-depth data were collected along 16 transects using a Ponar bottomsampler, hand-held transducer, and GPS (fig. 6b) to characterize the channel network. Channel-transect measurements include channel width, depth, and substrate composition. DGPS was collected at more than 50 sites to georeference the Radarsat image.

Locations of observation points, channel transects, and airplane flyovers were documented using differential global positioning systems (DGPS) data with a spatial accuracy of 10 to 100 m. DGPS data were obtained at 36 locations in the northwestern delta to georeference the Radarsat image.

Scope and Objectives

The objective of this study has been to characterize the physical setting of the Orinoco Delta ecosystem. To do so, we carried out the following tasks :

- evaluation of the lower Amazon River and Delta to assess sediment volume along the coast and shelf of northeastern South America, including the Orinoco Delta;
- evaluation of the accreting muddy coastal plain of French Guiana, Surinam, and Guyana (collectively, the Guiana coast) to help understand the mechanisms of transport of Amazon sediment northwestward to the Orinoco coast, as well as evaluation of erosional and depositional processes that control Guiana coastal plain evolution to provide input for analysis of coastal processes along the Orinoco Delta coast;
- description of the Orinoco drainage basin and river to understand the timing, magnitude, frequency and duration of water and sediment inflow to the delta;
- investigation of the Tertiary and Quaternary history of the Eastern Venezuelan Basin (EVB) and the Orinoco Delta to help determine the morphotectonic and sequence stratigraphic setting of the modern delta;
- description of current physical environment of the delta, including the climate, hydrology, and geomorphology, to identify and evaluate physical processes that are critical to delta ecosystem stability and maintenance;
- investigation of the influence of longer-term delta processes, such as subsidence, sea level, neotectonism, and Holocene climate, to identify and evaluate natural change among physical processes and their influence on geoenvironmental and associated ecosystems;
- development of geoenvironmental classification and maps of the western delta to provide a baseline of current environmental conditions and to highlight relationships between physical setting and ecosystem composition;
- development of a shoreline classification to identify major coastal ecosystems and determine areas of erosion, stability, and progradation;
- description of the late Pleistocene to Recent evolution of the Orinoco Delta to evaluate the long-term interaction among the major physical processes, to define the response of delta

ecosystems to changes in these major processes, and to evaluate rates and direction of natural change in delta environments;

- evaluation of historic change in the delta to further define types and rates of change in delta environments, define relationships between physical processes and delta ecosystems, and evaluate the response of delta environments to human-induced changes; and

- generation of a general physical process model for northeastern South America coastal plain and littoral systems to develop a large-scale, holistic assessment of inflow, retention, and outflow of water, material, and energy in the Orinoco Delta.

We also helped PDVSA/DAO in their effort to obtain additional funding from international agencies interested in the preservation of the Orinoco Delta ecosystem complex. This initial study of a vast, pristine, generally inaccessible region is based upon the rather limited number of available data and on limited reconnaissance field surveys and, therefore, a major objective of this regional analysis is to identify and define critical areas of research.

REGIONAL CONTROLS ON ORINOCO DELTA ECOSYSTEM INTEGRITY

To adequately determine the frequency, timing, and magnitude of water and sediment discharge to the Orinoco Delta and its influence on ecosystem integrity, it is essential to evaluate regional-scale river and coastal systems, of which the delta is an integral part. By ecosystem integrity, we mean maintenance of an ecosystem complex that is in turn capable of maintaining and supporting a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization that reflects the natural (unaltered) habitat of the region (Warne and others, in press). This section describes three major geomorphic systems of northeastern South America: the lower Amazon River and Delta, the accreting, muddy Guianas coastal plain, and the Orinoco drainage basin.

Amazon System and Guiana Coast of Northeastern South America

The Amazon is one of the world's great river systems, dwarfing all other rivers in water discharge (and accounting for one-fifth of the total river discharge to oceans) and all but a few in sediment discharge. Comparison of the water and sediment-discharge characteristics of the Orinoco (one of the world's major rivers) with the Amazon provides a clear indication of the immensity of the Amazon system (table 3). Despite its enormous sediment discharge, the Amazon essentially lacks a delta plain because marine waves, tides and current energy at its mouth prevent vertical accretion of the delta to sea level. The high-energy coastal environment disperses large volumes of sediment (as much as 6×10^8 metric tons) northwestward along the shelf, where a large portion is transported as much as 1,600 km to the Orinoco Delta (Eisma and others, 1991; Kineke and Sternberg, 1995). Many major geomorphic features of the Guiana and Orinoco coasts are similar, including estuaries at the mouths of major rivers and rounded promontories called mudcapes; the similarity in coastal morphology suggests that coastal-sediment dynamics in these adjacent areas are similar. Between the Amazon and Orinoco Deltas, the French Guiana, Surinam, and Guyana

(Guiana) coasts compose the world's largest actively accreting muddy shoreline; the Amazon River is the major source of sediment deposited along the Guiana coast.

Amazon System

Amazon River and Delta Hydrology

The Amazon River is the world's largest in terms of water and the third-largest in terms of sediment discharge (table 3). The wet season (May to July) discharge is two to three times greater than that of the dry season (October to December) discharge (Kineke and Sternberg, 1995). The discharge of Amazon water is so large that seawater never enters the river mouth, and many characteristic estuarine processes including circulation and sediment transport occur on the Amazon shelf (Kineke and Sternberg, 1995). At the coast, the tides commonly exceed 6 m, and a tidal current of 100 cm/sec has been measured on the shelf near the river mouth (Nittrouer and others, 1986). The North Brazilian littoral current flows northwestward at speeds generally exceeding 50 cm/sec (Nittrouer and others, 1986). Surface waves are primarily generated by prevailing trade winds, but most wave energy is dissipated by inner-shelf fluid muds before reaching the coast (Nittrouer and others, 1986). Major storms do not affect this tropical coastal region.

Amazon Delta Geology

Approximately 1.2×10^9 tons of sediment is delivered to the Amazon shelf each year, of which 85 to 95 percent is suspended silt- and clay-sized particles (Meade and others, 1985). Upon reaching the coast, the sediment encounters a dynamic coast and shelf environment where tide, littoral, wave, and density currents redistribute the sediment (Kuehl and others, 1986).

Maximum Amazon sediment discharge occurs in March to April, precedes the peak water discharge by 1 to 2 months, and tends to vary from low to high discharge by a factor of 10 (Kineke and Sternberg, 1995). Minimum sediment discharge occurs in October and November (Kineke and Sternberg, 1995). Meade and others (1985) demonstrated that suspended sediment is stored on the lower Amazon floodplain during rising stages of the river and resuspended during falling river stages and that this pattern of storage and resuspension dampens extreme values of high and low sediment discharge and tends to keep discharge between 3.0 to 3.5×10^5 metric tons per day for a large portion of the year.

Although the Amazon has a relatively small delta plain (mostly estuarine islands), a large sedimentary prism (with topset, foreset, and bottomset beds) is developing on the shelf seaward of the river mouth (Nittrouer and others, 1995). Unlike most modern deltas, in which the topset beds are subaerially exposed delta plain, the topset beds of the Amazon are subaqueous and extend no higher than 15-m water depth. Above this, intense and persistent wave and tidal activity preclude deposition of sediment (Kuehl and others, 1996). The clinoform-shaped subaqueous Amazon delta extends northward along the shelf for several hundred kilometers and has a maximum thickness of 30 m (Nittrouer and others, 1995). The muds are deposited seaward or are transported northwestward along the shelf toward the Guiana and Orinoco coast (Nittrouer and others, 1995; Kuehl and others, 1996).

Suspended-sediment transport and distribution on the Amazon subaqueous delta are dominated by dense bottom suspensions (including fluid muds). These concentrated (up to 1,000 mg/L) mud layers are up to 7 m thick on the inner and middle shelf and cover between 5,700 and 10,000 km^2 (Kineke and Sternberg, 1995). Approximately 90 percent of the Amazon suspended sediment is in the form of these concentrated muds. Development and distribution of fluid muds on the Amazon and Guiana shelves have been linked to tide- and wave-induced resuspension and concentration associated with a bottom salinity front (Allison and others, in press). As Amazon River water is discharged into the marine shelf, density differences between the fresh and marine waters induce formation of a freshwater plume that is advected northwestward by the North Equatorial littoral current. A bottom salinity front develops along the seaward boundary of this sediment-rich, freshwater plume. This front migrates across the shelf with the tides but is located 50 to 100 km offshore at about 10- to 20-m water depth (Allison and others, in press).

These fluid mud layers appear to be a requisite for preservation and accretion of the Amazon subaqueous delta. Kuehl and others (1995) estimated that about one-half of the sediment discharged by the Amazon is deposited on the shelf as foreset and bottomset beds, causing progradation of the subaqueous delta toward the shelf break. The remainder of the sediment ($\sim 6 \times 10^8$ tons/yr) is transported northwestward along the shelf toward the Guiana and Orinoco coast and/or accumulates landward of the shelf as coastal accretion (Nittrouer and others, 1995; Kuehl and others, 1996). Approximately one-half of the sediment transported northwest of the Amazon Delta to the Guiana coast is in the form of concentrated mud, and the other half, in a less-concentrated form farther offshore, is advected northwestward by the North Equatorial current (Eisma and others, 1991).

French Guiana/Surinam/Guyana Coast

The French Guiana, Surinam, and the Guyana coast (Guiana coast) is the central portion of the world's largest modern prograding muddy coastal regime, which extends from the Amazon to the Orinoco Delta (fig. 7). The Guiana coastline is similar to that of the Orinoco Delta (figs. 4, 8). Common features include: diversion of smaller river courses to the north and northwest as they approach the coast, estuaries at the mouths of major rivers, regularly spaced rivers separated by poorly drained coastal plain or interdistributary swamps and marshes, and rounded muddy shorelines between river mouths. Fluid muds that characterize the Amazon Delta region also occur along the Guiana coast in the form of mudbanks (Allison and others, 1995). These mudbanks are regularly spaced and migrate northwestward (fig. 9), strongly influencing hydrodynamics and sedimentation along the coast (Wells and Coleman, 1981a, b; Rine and Ginsberg, 1985).

Physiography of the Guiana Coast

The Holocene coastal plain along the Guiana coast extends ~30 km inland and 30 km seaward onto the shelf and reaches a maximum thickness of 24 m. The Holocene coastal plain has a chenier plain morphology of coast-parallel sandy ridges generally 2 to 4 m above mean sea level (msl) that are separated by broad mangrove swamps and minor marsh covering a mud substrate (Brinkman and Pons, 1968; Rine and Ginsberg, 1985). On the landward side of the chenier plains, broad areas of ombrogenous peats cover much of the lower Holocene deposits (figs. 7 and 8), are up to 4 m thick, and form broad mounds with radial drainage patterns (Brinkman and Pons, 1968).

Tidal mud flats along and between mudcapes, typically 2 to 5 km wide at low tide, characterize large segments of the coastline; the flats are backed by mangroves that prograde onto the mud flats (Wells and Coleman, 1981b; Allison and Nittrouer, 1998). Local stretches of the coastline are erosional and are typified by modest beach development and mangroves collapsing into the surf.

Rounded promontories, known as mudcapes, are located at the mouths of many coastal-plain rivers, causing the river mouths to divert to the north and northwest (Allison and others, 1995). Mudcapes have a morphology similar to that of sand spits, although their origins are different (fig. 10). Allison and others (1995) identified 16 major mudcapes along the Guiana coast. Many of the mudcapes are rapidly accreting along their northern and northwestern (downdrift) margin; mudcape width, tidal range, and littoral current regime appear interrelated (Allison and others, 1995).

Hydrology of the Guiana Coast

Tidal range along the Guiana coast is ~1 to 2.5 m. Waves on the shelf are typically 1 to 3 m high and exceed 4 m less than 1 percent of the time. Waves typically approach the shelf N 3^{o} E to N 8^{o} E. On the inner continental shelf, waves are typically 0.5 to 1 m with a period of 8 sec (Wells and Coleman, 1981a). The main strength of the Guayana Current is 100 to 200 km offshore, but sediment concentrations there are <10 mg/L (Gibbs, 1976). Closer to shore (20 to 40 km from the coast), residual currents are 10 to 20 cm/sec, but suspended sediment concentrations are one to three orders of magnitude greater. The high sediment concentrations along the shallow shelf and coast profoundly affect (dampen) the hydrodynamic regime, especially the rate of wave attenuation. Therefore, these muddy coastlines respond to wind, wave, and tide regimes differently than do sandy coasts and can develop in areas with high-energy wave and current regimes.

Wells and Coleman (1981a) demonstrated that as waves propagate into shallow water over a fluid-mud bottom (mudbanks), pronounced changes in wave profile and amplitude occur, and solitarylike wave profiles result. The conventional shoaling transformation in which wave height initially decreases and then increases rapidly prior to breaking does not occur above fluid mud layers (Wells and Coleman, 1981a). Wave attenuation is so great that waves do not reach the shoreline nor do they break, creating areas of calm water that are readily discernible from oblique aerial photographs (for example, Rine and Ginsberg, 1985).

The coastal-plain rivers draining the Guayana Shield and debouching along the Guiana coast contribute relatively little to sediment input along the accreting muddy coast (Brinkman and Pons, 1968; Allison and others, in press). However, the sand that these rivers discharge is the primary constituent of the chenier ridges.

Sediment Dynamics of the Guiana Coast

The muddy Guiana coast is in effect an attenuated Amazon Delta (or a strandplain depositional system between the two major depocenters of the Amazon and Orinoco Rivers). Approximately 250×10^6 m^3 of sediment is moved along the coast of the Guianas (French Guiana, Surinam, and Guyana) each year (Wells and Coleman, 1981b), in which ~150×10^6 m^3 of "through transport" takes place in the form of suspended sediment carried by the Guiana current and ~100×10^6 m^3 moves along the nearshore as mudbanks (Wells and Coleman, 1981b). As do other muddy coasts worldwide, the muddy Guiana coast has extremely high suspended sediment concentrations in the coastal waters, often exceeding 1,000 mg/L (Wells and Coleman, 1981a).

Two major mechanisms for sequestering Amazon sediment along the Guiana coast have been identified: mudbank migration and mudcape accretion (Allison and others, in press). Mudbanks are nearshore/shallow-shelf features (fig. 9) primarily composed of silty clay that has the consistency of fluid mud, comprise ~10^9 m^3 of mud, and extend from the nearshore, obliquely to the coast, offshore to about the 20 m isobath (Rine and Ginsberg, 1985). Mudbanks have as much as 5 m relief, thin both seaward and landward, and may or may not be attached to the coast. Mudbanks greatly attenuate wave energy and thereby promote lateral shoreline accretion as they move along the coast.

Mudbanks and the intervening interbank zone migrate northwestward at an average velocity of 1.1 km/yr off Guyana, 1.5 km/yr off Surinam, and 0.9 km/yr off French Guiana (Eisma and others, 1991). The occurrence of these mudbanks is regular, such that they are commonly referred to as mud waves, with a wavelength of 45 km and a periodicity of 30 yr. Mudbanks can be recognized along the shore by well-developed mud flats (at low tide), areas of calm water, and colonization of young mangroves on the innermost areas of the bank (Wells and Coleman, 1981a; Allison and others, in press).

A well-defined 30-yr coastal erosion-sedimentation cycle is associated with mudbank migration (Wells and Coleman, 1981b). The 10- to 60-km section of coastline enveloped by a bank is subject to rapid accretion (to 200 m/yr of shoreline advance), associated with wave dampening over the soft mudbank surface (Wells and Coleman, 1981a). The areas between banks are subject to higher wave energy that reworks mud-flat deposits and may erode a significant portion of the mangrove fringe. Along interbank areas landward of 5-m water depth, progressive wave energy is dissipated by the soft substrate; therefore, most interbank erosion is offshore, and ~5 cm of sediment remains from each mudbank event to produce a shoreface wedge of mud accumulation (fig. 9).

Mudbanks migrate by the combination of the west- and northwest-flowing Guayana Current and the waves that are generated by the trade winds coming from the northeast. Over the mudbanks, the waves are transformed into solitary waves that push the mud WNW (Wells and Coleman, 1981a). Mudbank migration rates are greatest during high-trade-wind season, which promotes development of solitary surface gravity waves (Wells and Coleman, 1981a). Differences in migration rates along the coasts of Guyana, Surinam, and French Guiana are the result of differences in orientation of the coast relative to the main direction of wave propagation (Eisma and others, 1991). Wells and Coleman (1981b) proposed that periods of enhanced mud accumulation and shoreline progradation are associated with semiannual and 18.6-yr tidal cycles, which expose broad areas of mud flats and provide opportunities for colonization by mangroves. Mudbank deposits consist of massive and laminated muds, subdivided by discontinuities extending from the adjacent interbank zones. Massive beds that range up to 2 m thick and lack burrow traces and fecal pellets are common, indicating rapid deposition events.

Mudcapes are similar to sand spits in morphology, but they have a different origin (fig. 10). They are 5 to 10 km wide (perpendicular to the coast) and up to 100 km long (parallel to the coast) and are observed on updrift bank of river mouths discharging along the coast. Along-shore accretion of mudcapes diverts rivers north and northwestward. Allison and others (1995) documented that mudcapes of northern Brazil are accreting downdrift at a rate of 57 to 114 m/yr. Accretion is primarily fed by sediment flux along shore (supplied by the Amazon) rather than from the river that the mudcape is diverting. Sediment accumulates in the intertidal/subtidal zone during periods of high sediment discharge (of the Amazon); it is subsequently dispersed during periods of low sediment discharge (Allison and Nittrouer, 1998), supplying material to the migrating banks.

Mudcapes are subject to erosion along their seaward margin, which is under the influence of the mudbank migration and the associated accretion-erosion cycle (Allison and others, in press). Mudcape accretion (extension) is episodic, with decadal variations in sediment supply to the shoreface (Allison and others, in press).

Allison and others (in press) proposed that mudbanks form from concentrations of Amazon suspended material that is supplied from the middle shelf and temporarily accumulates in the subtidal/intertidal area of mudcapes (fig. 10a). The bottom salinity front, which is present along the coast of northern Brazil within 20 km of the coast in 5 to 15 m of water depth, provides the opportunity for dense bottom suspensions to reach the mud flats by tidal excursion and by solitary wave shoaling (Allison and others, in press). Seasonal and decadal trade-wind cycles vary the access of fluid muds to the nearshore zone, resulting in alternating periods of mudbank development and sediment reworking along the coast (Allison and others, in press). Mudbank and mudcape sedimentation results in large prisms of mud in the intertidal zone that are rapidly colonized by mangroves. Mudcape development results in a stratigraphic sequence 4 to 6 m thick, composed of three facies (fig. 10a): a basal subtidal/intertidal interval, overlain by mangrove swamp, and capped by supratidal muds (Allison and Nittrouer, 1998).

Holocene History of the French Guiana, Surinam, and Guyana Coastal Plain

The Holocene history of the Guiana coastal plain is subdivided into two main phases: early Holocene (9,000 to 6,000 yr B.P.) and middle and late Holocene (6,000 yr B.P. to present) (Brinkman and Pons, 1968; Roeleveld and van Loon, 1978; Augustinus and others, 1989; Eisma and others, 1991). During the early Holocene phase, 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. During the middle and late Holocene phase, mud, shell, and sand accumulated primarily by lateral (seaward) accretion of tidal mud flats and chenier plains. On the basis of radiocarbon-dated samples of these coastal plain sediments, Brinkman and Pons (1968) and Roeleveld and van Loon (1978) generated a Holocene sea-level curve for the region (fig. 11).

Brinkman and Pons (1968) further subdivided the middle and upper Holocene coastal plain into three progradational phases on the basis of geomorphic and pedologic criteria. These progradational phases were interrupted by two intervals of erosion and nondeposition, resulting in development of continuous, prominent sand-ridge complexes (figs. 7 and 8), which subdivide the Wanica (~6,000 to 3,000 yr B.P.), Moleson (~2,500 to 1,300 yr B.P.), and Comowine (1,000 yr B.P. to present) coastal-plain sediments (Brinkman and Pons, 1968).

Brinkman and Pons (1968) attributed these two hiatuses to temporary periods of slightly lower sea level, but Eisma and others (1991) and Sommerfield and others (1995), among others, showed that these late Holocene millennial-scale changes in sedimentologic regimes along the northeast coast of South America were induced by changes in climate, especially wind and rain. Comowine deposition continues today with fluctuations in depositional processes resulting from centennial-, decadal-, and annual-scale changes in wind, tide, and wave regimes (Wells and Coleman, 1981b; Eisma and others, 1991).

Orinoco River System

The Orinoco basin covers ~1.1×10^6 km^3 of tropical northern South America (fig. 12 and table 3). The drainage basin is bordered on the west and north by young, high-relief mountain ranges that supply ~90 percent of the sediment to the Orinoco River but only compose 15 percent of the basin area. The other 85 percent of the drainage basin is mostly low-relief terrains covered with dense tropical forest and grasslands, which produce large runoff volumes but low sediment yield.

The basin is very rich in natural resources. Petroleum and natural gas resources include the world's largest proven reserve of heavy crude oil. The basin contains abundant deposits of bauxite, iron ore, gold, diamonds, and other minerals (Nordin and others, 1994). The Orinoco basin also has abundant renewable resources including forests, fish and wildlife, agricultural and grazing lands, and water.

Except for hydropower development at Macagua and Guri dams on the Caroní River (fig. 12) and at small impoundments in the upper reaches of the Andean tributaries, the Orinoco River is more or less undisturbed and undeveloped. Although the Orinoco basin makes up 75 percent of Venezuela's land area, only 5 percent of the population reside there, and most are indigenous. However, this situation is changing as Venezuela continues to develop its abundant natural resources, including minerals and petroleum (Vásquez, 1989; Haggerty, 1993).

Climate

The climate of the Orinoco basin is mostly tropical with pronounced wet and dry seasons (fig. 13). Orinoco basin climate is primarily controlled 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 Orinoco drainage basin. During the dry season the basin receives only 10 to 15 percent of the annual precipitation. This pattern of marked wet and dry seasons induces large oscillations in water discharge and stage levels in the river and delta, which in turn produces distinct sedimentologic, geomorphic, and ecological cycles.

Drainage-Basin Geology and Geomorphology

The Orinoco drainage basin consists of ~35 percent Guayana Shield, 15 percent Andes and Coastal mountain ranges, and 50 percent Llanos (fig. 14). The Guayana Shield is primarily composed of deeply weathered felsic to intermediate plutonic rocks and gneisses (Gibbs and Barron, 1983; Corporación Venezolana de Guayana Técnica Minera [CVG-TECMIN, C.A.], 1991a through f). Maximum relief on the elevated shield is in excess of 3,000 m, but the vast majority of the shield is very low relief and comprises some of the world's oldest landscapes.

The mountainous fold and thrust terranes that form the western and northern margin of the basin consist of the Caribbean Coastal Ranges in the north and northeast and the Venezuelan (Mérida) Andes and Colombian Cordillera Oriental in the southwest. The predominant lithologies exposed in the fold and thrust terranes are shallow marine carbonates, shales, sandstones, and continental conglomerates (and their metamorphic equivalents), as well as felsic and mafic plutonic rocks. These mountainous terrains are characterized by steep slopes and sharp peaks with maximum relief of more than 5,000 m and active alpine glaciation at the higher elevations.

The Llanos region in Venezuela is a foreland basin receiving sediments from the rising Andes to the west. The Llanos and the uplands west of the Orinoco Delta are primarily underlain by the upper Pleistocene Mesa Formation, which mainly consists of fluvial sands. Holocene sediments occupy the alluvial plains of the rivers and their tributaries, and primarily consist of reworked Mesa Formation sand (Carbón and Schubert, 1994). As the name implies, the Llanos typically have little relief, but there are localities where deep scarps have formed because of deep erosion (Carbón and Schubert, 1994). The western Llanos is actively subsiding and is veneered by Holocene fluvial and lacustrine gravels, sands, and muds derived from the Andes. The eastern Llanos is undergoing slight uplift, exposing similar sediments of Tertiary age. Extensive areas of the Llanos are subject to shallow inundation during the wet season, which is primarily caused by poor drainage of local rainfall rather than overbank flow of rivers. Hence, most of the Llanos is not river floodplain (Hamilton and Lewis, 1990). The rivers crossing the Llanos are strongly meandering as a consequence of low gradients and erodibility of the sediments, but the alluvial plains follow markedly straight lines, suggesting structural control of the drainage networks (Carbón and Schubert, 1994). Seasonal overbank flooding and extensive fluvial reworking are recorded by complex meandering plains and very unstable interconnecting channel systems. Eolian reworking during the dry season is an important process on the Llanos, particularly in the region between the Apure and Meta Rivers (Johnsson and others, 1988).

The combination of high rainfall, large areas being underlain by impermeable crystalline rock, and perennially high ground-water levels in the Orinoco River basin has resulted in a high discharge:drainage-basin-area ratio (table 3). Such high ratios tend to produce high peak water discharge but low suspended sediment concentrations in the tributaries, river, and delta.

Major Tributaries

Major tributaries of the Orinoco include the Guaviare, Meta, Apure, Caura, and Caroní (fig. 12). The Guaviare River drains the Colombian Andes and contributes ~18 percent water and ~20 percent sediment discharge to the Orinoco River (fig. 14). The Meta River drains the Eastern Cordillera and to a lesser extent the Mérida Andes and contributes ~10 percent water and ~50 percent Orinoco sediment discharge. The Apure drains most of the eastern slope of the high Andes of Venezuela and contributes ~5 percent water and ~20 percent Orinoco sediment discharge. The Caura and Caroní drain the Guayana Shield and contribute ~20 percent water but <5 percent sediment discharge to the Orinoco River (Meade and others, 1990). In essence, the left-bank tributaries are beige-water streams, draining the Andes and Caribbean Coastal Ranges, and the right-bank tributaries are black-water streams draining the Guayana Shield. The left-bank tributaries, however, also convey water with relatively low sediment concentrations, having deposited much of the Andes and Caribbean Coastal Range sediments in the Llanos foreland basin.

River Channel

At a regional scale, the Orinoco River forms an arch along the contact between the foreland basin sediments of the Llanos and the crystalline basement of the Guayana Shield (fig. 15). Regional tilting to the south-southeast induced by uplift of the Andes and Caribbean Coastal Ranges and lateral expansion of foreland basin sediments (the Llanos) maintain the course of the Orinoco at or very near the boundary between the bedrock of the Guayana Shield and the foreland basin clastic wedge.

The river can be subdivided into upper, middle, and lower reaches (fig. 12). The upper Orinoco drains the Guayana Shield highlands' dense rainforest, and flows through a narrow, well-defined valley that has considerable topographic relief (Vásquez and Wilbert, 1992). The middle Orinoco, which extends from the Mavaca to the Guaviare Rivers, continues to drain Guayana Shield and is characterized by alternating depositional and erosional plains that are covered by dense forest (Vásquez and Wilbert, 1992). With the inflow of more sediment-laden water from the Llanos at the Guaviare River, the lower Orinoco is distinctly different than the upper reaches, being much more a depositional than erosional system.

The lower Orinoco River traverses ~2,000 km of low-relief terrain. The alluvial valley is generally confined between igneous and metamorphic outcrops of the Guayana Shield along the right (south) bank and mostly erosional scarps of the Mesa Formation along the left (north or west) bank. At so-called control points along the lower river (fig. 15), Guayana Shield outcrops extend into the floodplain and channel. These control points stabilize channel position and form substantial but navigable rapids. There are eight major control points along the lower Orinoco River that subdivide the channel and floodplain into nine distinct hydrogeomorphic and ecological units (Hamilton and Lewis, 1990). These control-point constrictions also influence floodplain development by limiting lateral channel migration and dampening peak flow.

Downstream of Puerto Ayacucho (fig. 12), the river is a straight (sinuosity <1.1), anastomosing, low-gradient (4.5 cm/km, or 0.000045) system characterized by an irregular succession of lateral expansions and contractions of the channel. The channel typically has a high width:depth ratio (45:145) in which channel widths typically range from 1,200 to 3,500 m (excluding islands), and thalweg depths from 10 to 45 m at high water (Stallard, 1987; Nordin and others, 1994). Bed material is mostly sand with a median diameter of 0.4 mm, and the sand commonly forms broad sand bars 60 to 125 m long and 1.5 to 3 m high that are exposed during the dry season (Stallard, 1987; Nordin and Pérez-Hernández, 1989).

Channel form is complex with ubiquitous islands, sand bars and ridges, and rock outcrops (Pérez-Hernández and López, 1998). Analysis of historical aerial photography reveals that most change in the floodplain and channel system occurs near the intersections of major tributaries draining the Llanos and along and within the channel islands (López and others, 1998). Erosion and sedimentation rates along island margins range from 1 to 80 m/yr and along channel margins from 1 to 20 m/yr, but they are generally less than 10 m/yr (López and others, 1998). These rates of lateral channel migration are small in relation to the width of the floodplain (up to 20 km), providing evidence that lateral channel migration and abandonment are not major processes in the Orinoco River system. Near the delta apex at Barrancas, there has been overall deposition in the channel and floodplain during the past 30 yr, perhaps relating to emplacement of the Volcán dam (figs. 1 and 2) across Caño Manamo in the upper delta (López and others, 1998).

During the dry season, stage level drops to such a degree that as much as 40 percent of the high-water channel bed is subaerially exposed. The exposed, unvegetated channel bottoms comprise large sand waves and bars that are extensively reworked by southwest-directed winds (Nordin and Pérez-Hernández, 1989). These winds also rework floodplain sediments, forming longitudinal and barchan dunes that can alter the course of tributaries entering the Orinoco (Pérez-Hernández and López, 1998).

Stallard and others (1990) and Johnsson and others (1991) discussed the mineralogical composition of the Orinoco River bed sediments, their sources, and weathering processes controlling their composition. The sand fraction derived from the river is very mature although these sediments are derived from fold-and-thrust terrains of the Andes and Caribbean Coastal Ranges and from the igneous/metamorphic terrains of the Guayana Shield. Orinoco River sand composition reflects intense weathering processes and protracted sediment retention times associated with the drainage basin, which transform the immature source area sands into mature, quartz-arenite sands by the time they reach the delta (Franzinelli and Potter, 1983; Johnsson and others, 1988, 1991).

Floodplain

The Orinoco River floodplain can be subdivided into fringing floodplain and internal deltas (Hamilton and Lewis, 1990). Fringing floodplains border and are generally parallel to the river channel and form by lateral migration and avulsion of the river channel and by vertical accretion during seasonal floods. Internal deltas are associated with bedrock constrictions (control points) in the river valley just downstream of intersections with major tributaries such that, during the wet season, Orinoco stage levels exceed those of the tributaries causing water and sediment to pool at the intersections and form extensive floodplains. Welcomme (1979) determined that the Orinoco internal delta floodplains encompass ~70,000 km^2, principally at the intersections of the Apure and Arauca Rivers with the Orinoco River.

The fringing floodplain of the Orinoco main channel extends from the Meta River to the delta apex. Upstream from the Meta River the floodplain is much less extensive (Hamilton and Lewis, 1990). The fringing floodplain covers ~7,000 km^2. The floodplain area per unit channel length of 9.3 km^2/km (as compared with 40 km^2/km for the Amazon river) indicates that (1) the valley is confined by the laterally expanding foreland-basin clastic wedge advancing against the crystalline bedrock of the Guayana Shield and (2) floodplain expansion by lateral migration of the channel is inhibited by bedrock control points (Hamilton and Lewis, 1990; Meade, 1994).

The fringing floodplain is asymmetric, with considerably more area on the left (north) bank than on the right (south) bank (table 4). The asymmetry is primarily caused by large sediment input volumes from the tributaries draining the Llanos region (Stallard, 1987). These sediment-laden waters preferentially deposit their loads along the left (north or west) bank, inducing higher rates of lateral expansion along the left-bank floodplain than along the right (south or east) bank. Over time, enhanced deposition along the left bank has caused the river channel to migrate onto the Guayana Shield. In this way, the Orinoco River continuously occupies the position on the border of the Andean foreland basin and the Guayana Shield. The right-bank (south or east) floodplain is primarily the product of vertical accretion caused by overbank flooding.

The geomorphology of the floodplain has not yet been studied in detail. Ridge and swale topography is not strongly developed, although meander cores are occasionally encountered (Hamilton and Lewis, 1990). Oxbow lakes with dimensions comparable to those of the main river channel do not occur. However, floodplain lakes are common and form from abandoned channels (R. Meade, personal communication, 1999).

The uniform topography of much of the floodplain suggests that overbank deposition, as opposed to lateral accretion, has been the primary mechanism of floodplain development, at least during the late Holocene. This is consistent with the unimodal hydrograph, the abundance of fine silt and clays (Meade and others, 1983), and the confinement of the river system on both sides by resistant geologic formations (Hamilton and Lewis, 1990). Aerial photographs show that floodplain lakes have changed little in the past 20 years, and the majority of the fringing floodplain is covered by dense forest, indicating that large floods (for example, during 1976, 1981) do not induce significant channel migration or scouring and erosion. The relative resistance of the Orinoco floodplain to geomorphic change is largely the result of confinement of the river channel at control points that limit lateral channel migration and modulate peak discharge (Hamilton and Lewis, 1990).

A vast (70,000 km^2) internal delta is situated at the junction of the Apure and Orinoco Rivers; the delta is related to the backwater effect caused by the restriction of the Orinoco River at the bedrock control point just downriver from the intersection of the two rivers. Very little has been reported on the geomorphic features of these internal deltas. Meade and others (1983) estimated that as much as half of the sediment discharged by the Meta River is temporarily deposited in this internal delta and that during subsequent falling stages and during the early period of the next rising stage, the floodplain yields sediment that contributes significantly to the early peak in sediment discharge.

The floodplain receives a pulse of nutrients from the river every year during floods but shows negligible net export of organic carbon, phosphorous, nitrogen, or suspended organisms, despite very high rates of production and metabolic activity (Hamilton and Lewis, 1990; Lewis and others, 1995). As a result, river water reaching the delta is not only dilute, it is also relatively nutrient poor.

Hydrology

The Orinoco River, the third-largest river in the world in terms of water discharge, drains ~1×10^6 km^2 of Venezuela and eastern Colombia 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: mean monthly discharge (for the period 1970 to 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 and others, 1994). Seasonal stage fluctuations are typically 17 m in the lower river.

Seasonal variation in rainfall throughout the basin promotes a unimodal seasonal inundation of the floodplain that typically lasts for 4 to 6 months (fig. 16a). Between July and October, river water flows through most floodplain areas. During overbank conditions, the flowing waters of the Orinoco channel are separated from the floodplain by levees. Water flows into the floodplain at discrete points corresponding to breaks in the levee. After entering the floodplain, the water flows long distances parallel to the levee before regaining contact with the main stem of the river (Lewis and others, 1990). Along the pathway of flow, the water passes through a series of depressions that correspond to the floodplain lakes. After December water levels are generally below the floodplain surface, and the ~2,300 floodplain lakes (table 3) become isolated from the river until the following inundation and consequently diverge in their physical, chemical, and biological characteristics as the floodwaters recede (Hamilton and Lewis, 1990; Lewis and others, 1990).

Sediment Dynamics

The estimated sediment discharge for the lower Orinoco River is 150 to 212×10^6 tons/yr (Meade and others, 1990; FUNINDES USB, 1999). Sediment discharge in the lower Orinoco River is bimodal (fig. 16b), with a maximum 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). As annual flood discharge initiates, the sparsely vegetated sediment deposited during the late flood stage of the previous year, together with the large volumes of sediment redistributed by winds during the dry season, are easily entrained (Nordin and Pérez-Hernández, 1989; Carbón and Schubert, 1994). As the river approaches peak stage, water levels in the main channel exceed those of the tributaries draining the low-gradient Llanos, causing tributary floodwater (particularly the Meta and Apure, which carry 80 percent of the sediment load) to pond at the intersections, in turn causing deposition of sediment loads. As flood stage in the Orinoco main channel lowers, a portion of the sediment deposited at the intersections of the main tributaries is remobilized, causing a late-flood-period peak in sediment discharge (fig. 16b). Recent analysis of FUNINDES USB (1999) indicates that annual sediment discharge in the lower Orinoco River may be unimodal, and it closely correlates with water discharge.

During the dry season, 30 to 40 percent of the river channel bottom may be exposed, and the system reverts to an eolian regime. Prevailing northeasterly winds transport large volumes of river sediment upriver, partially disrupting the active channel system and making available large volumes of sediment for entrainment during the early phases of the following flood period (Nordin and Pérez-Hernández, 1989; Carbón and Schubert, 1994).

ORINOCO DELTA

Like most major marine deltas, the Orinoco can be subdivided into delta plain, coast/delta front, and prodelta. However, its location in a foredeep basin adjacent to a major plate tectonic boundary; tropical but seasonally dry climate; low sediment concentration; high-water-volume river discharge; mesotidal, low-energy wave regime; and large influx of Amazon sediment by strong littoral currents distinguish the Orinoco from other major world deltas. Most of the Orinoco Delta is composed of delta-plain wetlands, although delta-front and prodelta muds extend offshore as much as 40 km (50 m isobath) from the coast (Nota, 1958; McClelland Engineers, 1979).

Regional Geologic Framework

The Orinoco Delta occupies a large structural trough of the Eastern Venezuela Basin (EVB) along the southern margin of the South Caribbean plate boundary zone (SCPBZ, *sensu* Robertson and Burke, 1989) (fig. 17). It overlies more than 10,000 ft of marine and fluvial-deltaic, Cretaceous to Recent clastic and carbonate sediments of the EVB (figs. 18 and 19). The EVB was a large foredeep embayment associated with transpressional tectonic activity between the Caribbean and South American plates. The EVB strata can be characterized as a Neogene foredeep sequence superimposed on an Atlantic passive sequence (Di Croce and others, 1999). The foredeep basin sequence is largely composed of fluvial and deltaic and marine deposits associated with ancestors of the Orinoco River and its tributaries. The basin contains some of the largest petroleum reserves in the world.

The EVB is asymmetric in which there is a clear distinction between the south and north flanks (fig. 18). The south flank is a monocline that gently slopes to the north 25 to 80 m/km. The Tertiary sediments within the south flank are gently folded but are offset by a series of normal faults that strike N 60^{o} E and dip north or south; the south-dipping faults entrap the majority of known petroleum reserves. These normal faults are probably reactivated basement faults. The northern flank of the basin is characterized by complex folding and faulting that records intense deformation associated with differential movement between the Caribbean and South American plates (fig. 17).

The Offshore Orinoco Platform and Columbus Basin compose the seaward, eastern extension of the EVB seaward along the present continental shelf (Leonard, 1983; Di Croce and others, 1999). Leonard (1983) estimated that as much as 12,000 m (~40,000 ft) of upper Mesozoic and Cenozoic sediments have accumulated in the Columbus basin. The section penetrated by wells in the Columbus basin comprises mainly sediments deposited by the proto-Orinoco from the late Miocene to the Holocene in a nonmarine to shelf/slope environment (Leonard, 1983). To the southeast along the shelf, the stratigraphy is typified by a passive-margin sequence.

The Orinoco Delta region is substantially affected by tectonic transpression related to the eastward migration of the Caribbean plate relative to South America from the Miocene to the present (Robertson and Burke, 1989; Algar and Pindell, 1993). Transpressional structures include (1) northwest-trending right-lateral transform faults of the Gulf of Paria (for example, Soldado and Los Bajos faults), and (2) northeast-trending thrust faults of the Serranía del Interior and Trinidad (fig. 17). Southeast-directed transpression and tectonically driven diapirism are also responsible for the development of the Pedernales anticline along the northwest margin of the delta (Pees and others, 1968). Mud volcanoes and petroleum seeps along the coast are situated along the axis of this northeast-trending, mud-diapir-cored anticline. These features are part of a regional belt of mud volcanism and diapirism that extends from eastern Venezuela, across southern Trinidad, to the Barbados Ridge Complex (Kidwell and Hunt, 1958; Pees and others, 1968; Brown and Westbrook, 1987) (fig. 17).

Evolution of the Eastern Venezuela Basin and Orinoco Delta

There are two principal tectonic phases in the development of the EVB: Cretaceous to Oligocene passive margin and Oligocene to present active margin foredeep basin phases (figs. 19 and 20) (Prieto-Cedraro, 1987; Di Croce and others, 1999).

During the Cretaceous, the northeastern South America margin was characterized by an Atlantic-type passive-margin setting. The Guayana Shield was emergent and was the source of the sedimentary prism to the northeast (fig. 21a). Typical passive-margin carbonate and siliciclastic sequences were deposited during the Cretaceous in response to thermal and isostatic subsidence and eustatic sea-level changes, resulting in a seaward-thickening wedge of sediments.

Development of the Eastern Venezuelan foredeep basin is directly related to passage of the Caribbean Plate deformation front through the northeastern Venezuela region during the Neogene. The axis of the basin has migrated southward since Oligocene time as the result of eastward migration of the Caribbean Plate and development of the South Caribbean plate boundary zone (SCPBZ) along the northern margin of the basin. The SCPBZ comprises five or more major fault systems within a 250-km wide, east-west-trending region of deformed metamorphic and sedimentary rock (Robertson and Burke, 1989). Eastward translation of the Caribbean deformation front induced emplacement of a series of thrust sheets along the SCPBZ, and stacking of these thrust sheets induced tectonic loading and foredeep development.

Deltaic sedimentation began south of Trinidad during the late Oligocene to middle Miocene. During this time, the EVB sands and shales were derived from a series of rivers draining the Guayana Shield (proto-Yuruari, Caroní, Aro, Caura, Cuchivero) rivers (fig. 21b) rather than an integrated Orinoco River system (Pirie, 1985; Zamora and others, 1989; Di Croce and others, 1999). These Oligocene to middle Miocene sands constitute some of the principal producing zones of the EVB (Jam, 1985; Pirie, 1985; Isea, 1987). Uplift of the Mérida Andes and Caribbean Coastal Ranges including the Serranía del Interior generated large volumes of sediments to the EVB, which accumulated as a generally eastward-prograding clastic wedge. During the late Tertiary, the foredeep (or perhaps more accurately, the lateral-deep) basin rapidly filled with sediments derived from the emerging cordilleras to the north and to a lesser extent from the Guayana Shield. Principal uplift of the Andes occurred between the late Oligocene and Pleistocene, with a climax during the Pliocene-Pleistocene (Hoorn and others, 1995). Plate-tectonic adjustments induced a reorganization of the drainage system in northern South America during the late Oligocene and Miocene (Hoorn and others, 1995), and development of the modern Amazon and Orinoco drainage basins in particular. The north flank of the EVB basin became emergent during this period, while the basin axis deepened and developed an east-west orientation, transforming the EVB into an elongate, semienclosed, shallow marine basin that was open to the east. As a consequence, the courses of the Guayana rivers, including the Orinoco, were diverted toward the northeast from a northward flow (fig. 21b, c, d), delivering large volumes of deltaic sediments into the rapidly subsiding basin (Díaz de Gamero, 1996). During the Pleistocene the sediments of the Mesa Formation were deposited by a series of rivers and deltas within an embayment that received coarse-grained sediments from the Caribbean mountains to the north (in the form of coalesced alluvial fans) and sandy fluvial and eolian sediments from the Guayana Shield to the south (Mendez-Baamonde, 1997a, b). To the east, delta-front and shelf sediments were deposited on the Orinoco platform (figs. 19 and 22) (Butenko and Barbot, 1984).

The intermittent but progressive progradation of the continental slope during the Pliocene and Pleistocene was the result of offlap of wave-dominated delta deposits. As a result the Quaternary sediments underlying the delta plain and shelf are prodelta and delta-front deposits that are subdivided by a series of third- and fourth-order unconformities related to the glacial-induced sea-level changes. As these sediments prograded to the shelf edge, they became oversteepened, and slumps and growth faulting occurred (Prieto-Cedraro, 1987). During the Pleistocene, a broad shelf developed (fig. 22, 23b). These sediments were periodically eroded during glacially induced sea-level lowstands (fig. 23a), especially during the latest Pleistocene when sea level dropped to as much as 120 m below the present level.

During the late Pleistocene sea-level lowstand, the Orinoco and other northeastern South American coastal-plain deltas were located along the present-day shelf edge ~120 m below its present level; these shelf-edge deltas promoted widespread turbidite deposition across the present-day abyssal plain (fig. 23a) (Damuth and Fairbridge, 1970). As sea level rose during the Holocene, deltas were displaced landward up to 200 km from the edge of the continental shelf to their present locations. Large quantities of clastic detritus were no longer able to reach the deep ocean because there was no mechanism to transport the significant quantities of terrigenous sediment across the wide shelf plain (Damuth and Fairbridge, 1970).

Morphotectonic and Sequence Stratigraphic Setting of Holocene Orinoco Delta

The Orinoco Delta, like many modern deltas (Warne and Stanley, 1995; Emery and Myers, 1996), comprises highstand systems-tract ramp-margin deposits. Its depocenter has developed during the current sea-level highstand, and it is prograding over the topsets of the previous shelf-edge delta (fig. 22a). The extensive shallow-water area seaward of the delta characterizes ramp margins; these broad, shallow shelves significantly modify storms and current processes and thereby influence shelf sedimentation, especially delta-front and prodelta deposition. A series of rotational listric normal faults at the shelf edge record oversteepening of the Tertiary and Quaternary delta deposits and consequent rotational slumping. These shelf-edge, listric normal faults are characteristic of many Tertiary and Quaternary delta successions.

The Barbados Accretionary Complex, which marks the southeast frontal margin of the Caribbean deformation front, is largely composed of Miocene to Pleistocene Orinoco Delta sediments that have been deformed into a system of thrust faults and anticlines (figs. 17, 18, and 22a). Such intense deformation of the basinal facies is unusual for major modern deltas and reflects the proximity of the Orinoco to a major active plate boundary. Deformation of the Barbados Accretionary Complex has precluded development of a deep-sea cone commonly associated with modern deltas (Nittrouer and others, 1986; Stanley and Warne, 1998).

The location and configuration of Trinidad and the Gulf of Paria profoundly influence the marine-current regime and sedimentation and erosion patterns of the subaqueous Orinoco Delta. As the Guayana littoral current flows northwestward toward Trinidad, it bifurcates such that roughly half flows into the Gulf of Paria via Boca de Serpientes and the other half flows eastward and then northward around eastern Trinidad (fig. 24). Boca de Serpientes focuses and thus accelerates littoral current flow, which has a direct influence on Orinoco Delta coast depositional and erosional processes.

Modern Orinoco Delta

The modern subaerial Orinoco Delta occupies a large portion of the northeastern Venezuelan coastal plain. The delta plain is bounded by the Guayana Shield along the Río Grande on the south, Caño Manamo on the west, the Atlantic Ocean on the east and northeast, and the Gulf of Paria on the northwest.

Overview of the Delta

The Orinoco Delta plain is a vast mosaic of interdistributary swamps and marshes encased by distributary and tidal channels (caños). These interdistributary basins can be thought of as islands in the form of plates that are slightly elevated along the borders and are flat to slightly depressed to slightly mounded in the center (CVG-TECMIN, C.A., 1991a through f). These vast interdistributary basins are seasonally to perennially flooded and are typically underlain by mud in the upper and southeastern delta and peat in the central and northwestern delta. The interdistributary basins vary from densely forested to herbaceous with all manner of gradation between, depending on proximity to major caños, duration of flooding, and degree of salinity.

Although it is possible to distinguish fluvial and tidal channels within the delta, essentially all channels are influenced by river discharge during the wet season and by tidal oscillations particularly during the dry season. The caños vary from meandering, relatively narrow fluvial channels in the upper delta to straight, broad, tidal channels in the lower delta (fig. 1, 2). Several major caños are deflected to the northwest in the coastal region under the influence of the suspended-sediment-rich, northwest-flowing Guayana Current and associated mudcape development.

The two major distributaries (Río Grande and Caño Manamo) broaden near the coast, transforming to estuaries (CVG-TECMIN, C.A., 1991e). The Río Grande is the primary distributary channel, transporting nearly 90 percent of the Orinoco River water and sediment discharge. Approximately half of the 150 to 212 × 10^6 tons/yr of Orinoco River sediment transported to the delta apex is deposited on the delta plain, and the remainder is transported to the coast (Meade, 1994). Approximately 85 percent (~63 × 10^6 metric tons/yr) of the Orinoco River sediment that is delivered to the coast is via the Río Grande (fig. 25). Largely as the result of tides, there is an extensive network of channels generally oriented parallel to the coast that hydraulically link the principal distributary channels (fig. 26).

The major caños are bordered by levees that form distinct topographic features in the upper delta plain (fig. 27a, b) but gradually diminish and finally disappear toward the coast. The levees are typically the highest features in the delta plain but are regularly overtopped during flood stage and serve to retain water in the interdistributary basins as the flood recedes. Human activity is typically concentrated on these elevated, relatively well drained landforms (fig. 27b, c).

Climate

Similar to the Orinoco drainage basin, the Orinoco Delta climate is primarily controlled by the ITCZ and its seasonal north-south migration, which results in a pronounced wet and dry season (CVG-TECMIN, C.A., 1991a through f; Geohidra Consultores, C.A., 1997a; ENSR Venezuela, 1998; FUNINDES USB, 1998, 1999). Rainfall volumes are a major environmental factor in the Orinoco Delta, being a major contributor to surface-water inflow to the vast interdistributary basins. Rainfall varies significantly across the delta, ranging from generally ~1,500 mm near the delta apex to ~2,600 mm per year near the coast (figs. 13 and 28a). Although there is a pronounced dry season, rainfall typically exceeds 100 mm per month throughout the year in the lower delta, and therefore can be critical to the hydrology during the low river stage.

FUNINDES USB (1998, 1999) determined rainfall magnitude-frequency and duration relationships using data from eight weather stations across the delta region (table 5). The data show that sustained, intense rainfall events, such as those induced by hurricanes, are not characteristic of the delta. As expected in a tropical environment removed from the track of major tropical disturbances, rainfall is common but generally not intense; when it is intense, it is of short duration. FUNINDES USB (1998; their figure IV-10) demonstrated that intense rainfall tends to be localized. Mean annual precipitation generally increases from west to east across the delta. In the western delta, mean annual precipitation is ~1,500 mm at Tucupita and increases to more than 2,000 mm at Curiapo in the eastern delta (CVG-TECMIN, C.A., 1991a through f).

Temperatures in the delta region are remarkably homogeneous throughout the year (fig. 28b), in which monthly averages at the Tucupita weather station range from 24.8° to 26.7°C. Winds are generally stronger in the winter but may be strong any time of year (fig. 28c). Maximum northeast trade-wind energies occur in February to April, and this sustained wind activity induces a peak in nearshore wave energy. Short-term, high-velocity winds are associated with hurricanes and tropical storms (ENSR Venezuela, 1998; FUNINDES USB, 1999).

The delta is situated near the southern limit of hurricanes that track from the central Atlantic into the Caribbean region. Therefore, hurricanes are not a major climatic influence on delta processes, but they occasionally induce high winds, heavy rains, and high-energy waves in the region. A review of hurricane-tracking charts compiled by the U.S. Weather Bureau for the period

1921 to 1998 (http://www.nhc.noaa.gov/tracks) demonstrates that hurricanes or major tropical storms passed within 350 km of the central Orinoco Delta coast in 15 of the past 77 yr. Most, however, were east-west-moving storms that were well north of the South American coast. Only three (in 1978, 1990, and 1993) made landfall in northeastern South America. Wave heights and periods associated with hurricanes are summarized in table 6. These characteristics are calculated for the Gulf of Paria; hurricane-related waves in the Boca Grande area are undoubtedly smaller. Moreover, the configuration of the northeastern South American shelf (particularly the very broad shallow shelf and position of Trinidad relative to the delta) precludes development of significant storm surges, which typically perform the majority of geomorphic work in coastal regions during hurricanes.

Delta Hydrology

The Orinoco River discharge is the major water source for the delta and induces most of the geomorphic work that determines delta-plain form and ecology. Tides and direct rainfall are also major influences on delta-plain geomorphology and ecology. Although river input is but one of three major inputs in delta hydrology, the annual flood cycle is a fundamental process in the hydrology and geomorphology across the entire delta. Many of the negative environmental impacts associated with the construction of Volcán dam (discussed later) are related to termination of the flood pulse to the northwest delta.

Caños

The hydrology and ecology of the delta are inextricably linked to the extensive network of distributary and tidal channels. These channels (caños) are not only the binding element in delta plain hydrology, they are also a major factor in controlling the distribution of freshwater, sediments, and nutrients to the coast and shelf.

Most caños are conduits for both riverine and tidal flow. For most of the year, tides are the principal agent of discharge in the delta. However, in or about mid-April, river stage begins to rise in response to the rainy season. During July and August tidal amplitude is overwhelmed because the stage typically rises 9.4 m at the delta apex, 3.6 m in the central delta, and 1 to 2 m in the lower delta, resulting in inundation of 95 percent of the delta plain (Geohidra Consultores, C.A., 1997b; FUNINDES USB, 1998). Annual peak stage/discharge varies, with significantly larger than normal stage/discharge recurring between 3 and 5 yr.

Downstream of the apex, the delta contains numerous beigewater and blackwater caños that are characteristic of the tropics (Sioli, 1984). Beigewater caños transport Orinoco water and sediment, whereas blackwater caños drain interdistributary basins and receive water from a combination of direct rainfall, tidal currents, and fluvial discharge. Several north-flowing blackwater rivers that drain the Guayana Shield contribute small amounts of water and sediment to the Río Grande. Similarly, blackwater coastal-plain rivers draining the eastern Llanos, including the Ríos Guanipa, Tigre, and Morichal Largo, contribute minor amounts of water and sediment to Caño Manamo.

Prior to 1965, Caño Manamo was the second-largest distributary of the delta, carrying ~10 percent (~3,600 m^3/s) of the Orinoco flow and a substantial portion of its sediment load. Since completion of a dam in 1965, the flow of water and movement of sediment along Caño Manamo have been substantially reduced, and this reduction has affected the entire northwest delta. Caño Manamo's present-day discharge is a relatively constant 200 m^3/s (Monente and Egañez, undated), approximately 5 percent of its former discharge. In contrast, discharge along Caño Macareo has increased from ~6 to ~10 percent following completion of the dam (Colonnello, 1998).

There are currently few published data on stage and discharge in the caños, especially those that evaluate the relationship between wet- and dry-season discharge. In Boca de Guanipa, ENSR Venezuela (1998) reported low-tide, seaward and high-tide, landward surface-water-flow velocities of 1.2 m/sec during the dry season. At the mouth of Caño Macareo, Geohidra Consultores, C.A. (1997b), measured low-tide, seaward-flow surface velocities of up to 1.6 m/sec and high-tide landward surface-flow velocities of a rather consistent 0.5 m/sec in April 1997. In lower Caño Macareo, Geohidra Consultores, C.A (1997b), reported landward discharge of 940.3 m^3/sec and surface-flow velocities as high as 0.9 m/s at high tide and seaward discharge of 1,731 m^3/sec and surface-flow velocities as high as 1.4 m/c at low tide during May 1997. In lower Caño Mariusa, Geohidra Consultores, C.A (1997b), reported landward discharge of 749.4 m^3/sec and surface-flow velocities of 0.6 m/sec at high tide and seaward discharge of 1076 m^3/sec and surface-flow velocities of 1.4 m/sec at low tide in April and May 1997.

In the central delta, FUNINDES USB (1998) conducted three short-term hydrometric surveys in October 1996 and May and September of 1997. Their findings, summarized in table 7, clearly show the estuarine nature of this portion of the central delta by demonstrating that flow rates and directions are fundamentally controlled by tides. Two factors may enhance the estuarine character of this portion of the central delta: none of the measurements were taken during flood season, and the dam at Caño Manamo has diminished the natural riverine component of the hydrologic budget of the Pedernales-Capure-Cocuina system. The FUNINDES USB (1998) study highlights the importance of caños that link the seaward-oriented caños. These mostly third- and fourth-order caños are relatively short lived and, once inactive, are covered over by vegetation within a few years (fig. 27b, d).

FUNINDES USB prepared a report on a more extensive survey of stage/discharge relationships in the northwestern delta (FUNINDES USB, 1999). However, an integrated survey of stage/discharge relationships of the entire delta plain is needed to adequately model delta hydrology and sediment dynamics.

Interdistributary Basins

A wide variety of plant communities characterize the interdistributary basins (fig. 27e, f, g, h, i, k, l), indicating that these wetland systems support a broad spectrum of hydrologic environments. However, very little is known about the timing and depths of inundation of interdistributary basins. Moreover, essentially nothing is known about the salinity, pH, Eh, or other water-quality parameters within and across these vast wetland areas. Monente and Colonnello (1997) demonstrated that the conductivity of waters in caños across the delta is low between December and March, indicating low suspended- and dissolved-solid concentrations. They attributed these low concentrations to outflow of rainfall-derived waters from interdistributary basins to the caños during the dry seasons. Although rainfall is typically greater from May through September, between December and March rainfall in the delta is generally >100 mm per month (fig. 28a), and significantly greater in some areas. These findings provide evidence that direct rainfall is a principal source of water in the centers of interdistributary basins. The widespread occurrence of domed, ombrogenous peats in the centers of many interdistributary basins reflects the importance of direct rainfall in the delta.

Several delta studies (for example, CVG-TECMIN, C.A., 1991e; FUNINDES USB, 1998, 1999) have calculated water budgets for the delta, which demonstrate that precipitation generally exceeds evaporation for the 6 months of the wet season but that evaporation exceeds precipitation during the dry season (fig. 29). These studies also demonstrate that there is a wide variation across the delta in the balance between inflow by precipitation and outflow by evapotranspiration (ET). Although these water-budget calculations do not take into account inflow and outflow by tides or inflow by river, they clearly demonstrate that hydrologic budgets, and consequently biogeochemistry, across the delta are highly variable.

Marine Processes

Coastal areas of the Orinoco Delta are principally affected by a combination of easterly trade winds, diurnal tides, and littoral currents (fig. 24). The broad, low-gradient shelf of the delta and the rarity of intense storms and hurricanes in the region creates a generally low- to moderate-energy setting (Van Andel and Postma, 1954; Van Andel, 1967; Herrera and others, 1981). Easterly trade winds control predominant wind and wave directions, and mean diurnal tides range from 140 to 187 cm (fig. 24). Tidal ranges are greatest within estuaries along the southeastern third of the coast and at the Boca de Guanipa area along the northwest margin. The highly irregular morphology of these estuaries is attributable to the combined effects of fluvial and tidal currents. During periods of low fluvial discharge, tidal fluctuations as much as 60 cm occur >100 km upstream near the delta apex.

Northwest-directed littoral currents play a major role in sediment transport and the coastal progradation of the delta (figs. 24 and 30). The Guayana Current, the principal current in the region, transports ~200×10^6 tons/yr of Amazon suspended sediment (Kuehl and others, 1986) to the Orinoco region, accounting for as much as 50 percent of sediment deposited along the Orinoco Delta shelf and coast (fig. 30) (Eisma and others, 1978, 1991; Meade, 1994).

Tides

The tide regime in the northeastern Gulf of Paria is mixed with a predominance of semidiurnal tides, whereas in the southwest (along the delta) it is strictly semidiurnal (Herrera and others, 1981). Tidal amplitudes at Boca Grande (Isla Ramón Isidro) generally range between 1.2 and 2.6 m. In the mouth of Caño Macareo, tidal amplitudes generally do not exceed 1.6 m and are typically 1.2 m (Geohidra Consultores, C.A, 1997b). Tidal amplitude in Boca de Guanipa (Pedernales) generally ranges from 0.8 to 2.6 m (Geohidra Consultores, C.A, 1997a).

There is a general but rather small decrease in tidal amplitude northwestward along the delta coast (fig. 24). Tidal amplitudes within the delta estuaries, however, can vary as a function of estuarine geometry. Tides affect the entire delta plain, and tidal amplitudes are 0.7 to 1.1 m in the central delta and ~0.6 m at the delta apex (Eisma and others, 1978; FUNINDES USB, 1998).

Tidal records indicate high tide occurs about 10 min earlier at Boca de Guanipa (Pedernales) than at Boca Grande (San Ramón Island), and low tide approximately 20 min earlier. Hence, tidal lag along the coast is negligible. Time lags of tidal peaks between the coast and inland are as much as 5 h (FUNINDES USB, 1998). Time lags in the central delta are especially large in the smaller caños, away from direct influence of the larger caños. Over the course of a year, tides displace larger volumes of water in the central and lower delta than riverine processes (FUNINDES USB, 1998). Tidal currents (ebb flow) advect large volumes of vegetal material from the interdistributary basins toward the coast (Scheihing and Pfefferkorn, 1984).

Waves

Wave power along the Orinoco Delta coast is relatively low because incoming waves are attenuated by the wide, shallow Orinoco shelf. Orinoco River discharge onto the shallow shelf also tends to attenuate wave energy, as does the complex marine-current pattern across the Orinoco shelf (that is, disruption of the northwest-flowing Guayana Current by Trinidad).

There have been no systematic wave-measurement surveys along the Orinoco Delta coast or shelf. Most studies utilize data compiled for the Gulf of Paria by the U.S. National Climatologic Center and short-term measurements made by INTEVEP (1981), which were taken at two sites in the central Gulf of Paria (fig. 24). No data are available for the Atlantic portion of the Orinoco coast.

Wave patterns are complicated by the coastal configuration, including Boca Grande, the central delta coast, Boca de Guanipa, and the Gulf of Paria. In the Gulf of Paria, the prevalent wind direction is from the east and northeast; 77 percent of the waves have heights of <0.9 m, and wave frequencies are typically 3.0 to 4.0 s (Geohidra Consultores, C.A, 1997a, b). When cold fronts pass through the Venezuelan coast, postfrontal circulation generates waves with amplitudes of up to 2 m, with periods of 8 s. This post-cold-front circulation pattern occurs an average of 3 days/yr, or about 0.8 percent of the time (ENSR Venezuela, 1998). High-energy waves are also generated by hurricanes that occasionally pass by the region (table 6).

Littoral Currents

Marine currents are dominated by the strong, northwest-flowing Guayana Current. 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 shelf are tens or hundreds of times greater than the outer shelf (Emel'yanov and Kharin, 1974). The Guayana Current flows northwestward more or less unimpeded from the Amazon to the Orinoco Delta, where the marine littoral-current system is disrupted by Trinidad. At the Orinoco shelf, the Guayana Current splits, and part 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 (fig. 24). As the branch of the Guayana Current flows toward Boca de Serpientes, it is constricted and, therefore, velocity increases, profoundly influencing Orinoco Delta coastal hydrodynamics.

There have been few rigorous and comprehensive littoral-current surveys along the Orinoco Delta coast and shelf to determine the rate, direction, and timing of littoral-current flow. The work of Van Andel and Postma (1954), Koldewijn (1958), Nota (1958), INTEVEP (1981), and Geohidra Consultores, C.A (1997b) are the most comprehensive surveys to date.

Current velocities on the Atlantic shelf range from 25 cm/sec in the summer to 75 cm/sec in the winter (Nota, 1958; Eisma and others, 1978). Offshore on the middle and outer Atlantic shelf, northwestward-directed Guayana Current velocities are 50 to 75 cm/sec in the spring and 25 to 40 cm/sec in the autumn (Van Andel, 1967). Currents within the Gulf of Paria generally flow clockwise. Penetration of the Guayana Current through Boca de Serpientes, tides, the bathymetry of the gulf, and freshwater input through Caño Manamo, Río Guanipa, and Río San Juan also influence the circulation system in the gulf (Van Andel, 1967). The maximum current velocities occur in Boca de Serpientes and Boca de Dragón, where velocities of 100 and 130 cm/sec have been recorded.

Geohidra Consultores, C.A (1997b), measured current velocities and direction at 10 locations along Punta Pescadores from September 29 to October 2, 1996, demonstrating the importance of tides on coastal water and sediment dynamics. These measurements demonstrate that the currents flow to the southwest along the coast and seaward in the caño mouth as tide is falling, and to the northeast along the coast and landward as tides rise.

On the basis of hydrodynamic modeling, Herrera and Masciangioli (1984) reported that mean water flow on the middle and outer shelf northeast of Boca Grande is to the north-northwest, with highest velocities between February and April (20 to 90 cm/sec) and lowest between August and October (15 to 40 cm/sec). They also determined that the rate and direction of marine currents are similar to those at a depth of 65 m. However, at 150 m the dominant flow direction is SSW and NNE.

INTEVEP (1981) applied a model to determine current velocities associated with a major cyclone that occurred within the gulf in 1933. During the cyclone, winds reached >90 km/hr, and the model estimated current velocities of 35 cm/hr in the gulf and 83 and 92 cm/hr in Boca de Serpientes and Boca de Dragón, respectively (Geohidra Consultores, C.A, 1997b).

Salinity in the Gulf of Paria generally varies between 13.4 and 25.6 parts per thousand (ppt) between the wet and dry season, respectively. Salinity is below 19 ppt in Boca de Serpientes because of freshwater input from the Orinoco Delta (ENSR Venezuela, 1998). Historically, salinity varied seasonally as a direct result of freshwater input from Caño Manamo (Van Andel and Postma, 1954); since construction of Volcán dam, salinity in the gulf is undoubtedly more consistently marine, but it has not been documented.

Geomorphology

The Orinoco Delta comprises a mosaic of shallow-water basins inhabited by emergent (forested and/or herbaceous) vegetation and subdivided and linked by an extensive network of caños. The geomorphology of the modern delta plain is largely defined by the relative proportion of vegetal material relative to terrigenous material; it is interesting to note that the geomorphology is defined more by water depth than by elevation. Offshore, the broad shelf, which is palimpsest, is a major control on the wave and littoral-current regime that controls deposition along the coast, delta front, and prodelta.

Although the geomorphology of the delta has been mapped (fig. 31) and principal geomorphic processes have been identified (table 8), little is currently known about the timing, magnitude, frequency, and duration of physical processes controlling ecosystem health and long-term instability because few direct measurements have been recorded (CVG-TECMIN, C.A., 1991a through f; Scheihing and Pfefferkorn, 1984). In the current and previous studies, sedimentary and erosional processes are inferred from hydrologic, geomorphic, sedimentologic, and pedologic observations. However, comprehensive, deltawide studies of the relationship between hydrology, sediment dynamics, and ecosystem composition are needed to develop geomorphic models to predict the influence of human activity in the delta.

Delta Plain

CVG-TECMIN, C.A. (1991a through f) developed a systematic, hierarchical geomorphic classification scheme for the delta plain and generated a series of geomorphic and soils maps of the delta and surrounding region. Figure 31 and table 8 present a geomorphic description of the delta that is based on (1) principal hydrologic regime (fluvial, marine, mixed fluvial and marine), (2) landscape position and/or substrate composition (littoral, mud plain, peat plain), and (3) drainage class (inundated, very poorly drained). This classification is primarily based on the work of CVG-TECMIN, C.A. (1991a through f).

Table 8 is designed to relate delta landscape setting to hydrologic, sediment, and erosion processes active in these areas. It is also designed to show the relationships among geomorphology, hydrology, and floral communities. Main data sources of table 8 are field and remote-sensing analyses and the regional study by CVG-TECMIN, C.A. (1991a through f). Table 8 also includes observations and concepts from Dost and Pons (1971), Danielo (1976a, b), Geohidra Consultores, C.A (1997a, b), ENSR Venezuela (1998), and FUNINDES USB (1998).

Subdivision of the principal geomorphic provinces into three that are tide dominated, nine that are mixed tide and river dominated, and two that are river dominated reflects the relative importance of the interaction of river discharge and diurnal tidal oscillation in delta hydrology but understates the importance of direct rainfall.

Caños

As the Orinoco River exits from its alluvial valley near Barrancas, it splits into several major distributaries near the delta apex (figs. 1, 2, and 26). The Río Grande is the principal Orinoco distributary; it flows east and carries the principal flow (84 to 88 percent) of the river in the delta. Caño Piacoa also flows east and merges with the Río Grande ~30 km downstream from their point of divergence. Caño Manamo and Caño Macareo are historically the two major second-order distributaries of the Orinoco River. They flow north and northeast, respectively (figs. 1, 2, and 26).

During late 1998 and early 1999, BEG researchers conducted a series of reconnaissance-level channel-transect surveys in upper Caño Macareo, Caño Manamo, Caño Pedernales, as well as higher-order caños in the northwestern delta using differential GPS and a portable depth sounder (fig. 6b; table 9). Principal caños (Manamo, Macareo, Pedernales) have sandy substrates, especially in the thalweg; the thickness and lateral extent of these sandy substrates have not been determined. The principal caños broaden and somewhat deepen toward the coast in response to increasing tidal influence. These major caños (Macareo, Mariusa, and Río Grande) have developed large, sandy, river-mouth bars (fig. 2) along the coast. The higher-order, more tidal-influenced caños of the lower delta tend to have muddy substrates with abundant vegetal debris and tend to be relatively narrow and deep (table 9).

Delta-Plain Subdivisions

Two distinct, roughly fan-shaped delta-plain sectors are distinguished on the basis of differences in channel abundance and geometry, sediment and soil types, shoreline characteristics, and dominant geologic processes: the southern and southeastern and the central and northwestern sectors (fig. 32a). The southern and southeastern sector, which is dominated by the Río Grande and major distributaries with large sediment supplies (such as Caño Araguao and Caño Merejina), comprises a complex of anastomosing, mostly tidal channels and islands. Its geomorphology, hydrology, and ecology are controlled by the complex interaction of riverine and tidal processes, and it is estuarine in character near the coast. The large number of anastomosing distributaries subdivides the southeastern delta into a network of densely forested interdistributary islands and provides efficient pathways for distributing Orinoco water and sediment. Clastic sediments and mineral soils are widespread in this delta sector (fig. 33) (CVG-TECMIN, 1991a through f). The highly irregular coastline between Boca Grande and Boca de Araguao is dominated by fluvial and tidal currents and consists of both sandy beaches and muddy mangrove shorelines.

In contrast, the central and northwestern sector contains fewer distributaries and mineral soils and a greater proportion of herbaceous and forested interdistributary basins with abundant peat (fig. 33). Relatively straight, parallel channels subdivide broad wetlands (fig. 32a). It is fundamentally controlled by tides and rainfall, and to a lesser extent by riverine processes, and can be characterized as coastal-plain tidal swamp and marsh systems. The proportion of tidally influenced blackwater channels with small sediment supplies is greater than in the southeast delta. Shorelines are generally smoother, muddier, and more arcuate than those along the southeastern coast, and major distributaries are deflected to the northwest near the coast.

On the basis of elevation, sediment and soil types, landforms, hydrology, water chemistry, vegetation, and land-use criteria, the delta plain can also be subdivided into three coast-parallel sectors: riverine (upper), river- and tide- influenced (middle), and marine, mostly tidal influenced (lower) (fig. 32b). The upper delta plain is primarily influenced by fluvial processes, whereas the middle and lower delta plain is influenced by a combination of fluvial and tidal processes, the coastal portion of the lower delta plain being more affected by marine processes, including waves, tides, and littoral currents. Direct rainfall is an important hydrologic input and geomorphic agent in all three sectors.

Upper (fluvial-influenced) delta plain

More is known about the upper delta largely because it is less prone to inundation and is therefore more easily accessible than the middle and lower delta plain. The upper delta geomorphology, hydrology, and ecology are fundamentally controlled by river discharge and, to a lesser degree, local rainfall. It is seasonally inundated and naturally covered by deciduous forests, although much has been cleared by humans. The substrate is a complex mixture of clay, silt, and sand, with minor peat (fig. 33).

The upper (fluvial) delta is characterized by (1) elevations generally between 1.5 and 7 m; (2) low (<5 percent) slopes; (3) a subtle microtopography controlled by the juxtaposition of fluvial erosional and depositional features and interdistributary basins; (4) hydrology that is variable but primarily controlled by river stage and discharge; (5) widespread occurrence of flood-basin lakes with water depths to ~0.5 m; (6) a variety of fluvial landforms, including levees, crevasse splays, and meander scrolls; and (7) relatively well developed soils.

The major caños are bordered by levees that are typically high and wide in the upper delta plain and that gradually diminish to nothing within 40 km of the coast. Proximal levees are composed of fine sand to clay, with most sediment in the silt size range (Lorente, 1990). The levees are typically the highest features in the delta plain, averaging 3 to 4 m, but as much as 8 m above low water during the dry season. Levees are naturally covered with deciduous forest vegetation but are commonly cleared for human habitation and agriculture (fig. 27a, b, c). Distal levees are composed of silty clay and commonly have an irregular to hummocky topography, indicating modification by overbank flooding and by vegetation. Distal levees are typically covered with deciduous forest vegetation. Levee deposits along the major caños are commonly underlain by peats; radiocarbon analysis on samples from Caños Araguao, Manamo, and Pedernales demonstrate that these peats are less than 1,000 years old. The relatively young age of these basal levee peats implies that the rate of development and abandonment of caños is quite high.

Point bars occur along inside bends in the meandering portions of the caños in the upper and middle delta but are commonly covered by forest vegetation, making them difficult to discern. Moreover, they are not common and generally have less than 1 m relief because meandering and channel cutoff is not a major delta-plain process (especially in the middle and lower plain) and because active levees generally do not attain significant relief. Point bars rise to the levees in a series of stepwise erosional faces, which presumably represent brief stands during lowering of floodwaters (Scheihing and Pfefferkorn, 1984). On cut faces, the point-bar deposits are primarily composed of fine- to medium-grained sands with trough cross-stratification, large-scale planar cross-stratification, parallel-laminated beds to 1 m thick, and mud drapes (Scheihing and Pfefferkorn, 1984). Field observations in conjunction with remote-sensing analysis indicate that point-bar deposits (ridge and swale landforms) are not widespread features in the delta. However, grass-covered point bars are well developed along the middle and upper reaches of Caño Macareo. These newly developed point bars are likely associated with enhanced discharge through Caño Macareo subsequent to emplacement of the dam in Caño Manamo.

Crevasse splays are common features in the upper (fluvial) delta. They are most prevalent along the upper reaches of the larger caños, such as in Caño Macareo and Caño Manamo (fig. 34). Sediment grain size ranges from medium sand to clay. However, grain-size analysis by Lorente (1990) identifies a bimodal distribution among the crevasse splay deposits along Caño Macareo, in which there is a deficit of fine and very fine sand. She suggests that the bimodal distribution may reflect hydraulic characteristics of the overbank discharge.

Flood-basin lakes are conspicuous and widespread features in the upper delta plain (figs. 1, 4, 26, and 27m, n). They are typically highly irregular in outline (fig. 26), generally <0.1 to 5 km longways and 30 to 50 cm deep. They are surrounded by marshy perimeters of slightly higher elevation and are connected to principal caños by small channels. Lake-bottom sediments from a lake along Caño Araguao consist of black, fusain-rich clay 10 to 20 cm thick underlain by clayey peat (Scheihing and Pfefferkorn, 1984). Wood fragments are common and appear to be derived from previously existing forests. The large amount of partially fusainized wood and underlying fusain-rich, black clay suggests forest fires in this area during low water (Scheihing and Pfefferkorn, 1984). In many respects the only difference between flood-basin lakes and other upper-delta-plain interdistributary basins is the lack of emergent vegetation in the lakes, which is probably related to water depth. Many of the lakes are curvilinear (fig. 27m), indicating that they formed from abandoned channels. Others are more irregular in outline (fig. 27n), indicating that they originated as interdistributary basin features (that is, some combination of infilling and subsidence).

Middle (fluvial- and marine-influenced) delta plain

The geomorphology, hydrology, and ecology of the middle (fluvial- and marine-influenced) delta are the result of complex interaction among river discharge, tides, and local rainfall. The middle delta plain is flooded for the majority of the year, and it is covered by evergreen and palm forests and herbaceous swamps. The substrate is largely a mixture of mud and peat (figs. 32b, 33).

The middle delta plain is characterized by (1) elevations between 1 and 2.5 m; (2) slopes less than 1 percent; (3) a general plano-concave surface profile; (4) hydrology that is highly variable and is controlled by the interaction of tides, rainfall, and overbank flooding; (5) vast interdistributary basins filled with peat and/or sulfur-bearing, organic mud; (6) an extensive network of tidal channels that link the major caños and maintain the tidal cycle in the interdistributary basins; and (7) numerous estuarine islands such as those in the Río Grande and Caños Manamo, Pedernales, and Araguao.

Interdistributary basins filled with mud are widespread in the south-central delta (fig. 33), where the delta-plain hydrologic and sedimentologic regime are heavily influenced by the annual flood cycle of the Río Grande. Peat basins are more widespread in the north-central and northwestern delta, away from the caños transporting large volumes of suspended sediment during overbank discharge conditions.

Between Caños Araguao and Capure, the interdistributary drainage network is consistently oriented northeast-southwest (fig. 26). Between Caños Capure and Manamo, however, the interdistributary network has no preferred orientation, indicating multiple agents of formation, perhaps caused by influence of rivers, such as Morichal Largo and Tigre, which drain areas to the west and northwest of the delta (Danielo, 1976a).

Lower (marine-influenced) delta plain

The geomorphology, hydrology, and ecology of the lower delta are primarily controlled by tides but also significantly influenced by the river and local rainfall. It is perennially flooded, and it is covered by evergreen shade forests, grasses, and sedges with mangrove along the coast and caños (Colonnello, 1996). The substrate is mostly peat, but mud, silt, and sand (cheniers) are significant in some areas (fig. 33).

The lower delta plain is characterized by (1) elevations of <1 m, (2) slopes no greater than 1 percent, (3) a general plano-concave surface profile, (4) hydrology primarily driven by tides and secondarily by rain, (5) widespread occurrence of broad interdistributary basins with thick (up to 10 m) peat deposits, or (6) organic mud substrates that are relatively high in sulfur content, (7) active vertical accumulation of sediments so that there is very poor soil development, (8) weakly developed and/or partially buried relict beach ridges, which are more pronounced in the Boca de Guanipa and Boca Araguao areas (figs. 4, 33, and 35a), and (9) development of mud volcanoes and asphalt seeps in the northwest delta plain.

Much of the lower delta plain consists of featureless marsh traversed by many tidal channels. This area is largely covered by herbaceous vegetation except for forest rims along principal caños and mangroves near the coast (figs. 27d, e, f, h, i, k; 35e, f). However, there are areas of extensive forest cover as well (fig. 27g, j, l). At the coast, these areas grade imperceptibly into extensive mud flats, generally without beach development. In other areas of the lower delta plain, groups of long, low (<1 m), subparallel or diverging relict beach ridges occur locally, especially between Caños Araguao and Manamo (figs. 33 and 35a). These chenier ridges commonly occur adjacent to (just downdrift of) the mouths of present and former distributary channels (Van Andel, 1967; Scheihing and Pfefferkorn, 1984). These are composed of fine- to medium-grained sand. At the coast, these areas commonly maintain rather poorly developed sandy beaches that are backed by peaty clays of the mangrove swamps. Inland, chenier ridges are covered by scrub and herbaceous vegetation (Scheihing and Pfefferkorn, 1984). Chenier development is not as prevalent along the Orinoco as it is along the Guiana coast.

The lower delta plain appears to be composed of coalesced, relict and active mudcapes (fig. 36). The relict mudcapes become difficult to discern landward, probably because (1) the thickening of peat over time obscures their morphology and (2) as subsidence continues, caños traverse and dissect the original mudcape morphology.

Mud volcanoes and oil seeps are conspicuous features of the lower delta plain in the northwestern delta (figs. 37, 38). Orinoco mud volcanoes are typically mound shaped, 10 to 15 m high, and as much as 400 m in diameter (app. 2). Active vents are typically free of vegetation (fig. 38a, b, c). Historic accounts indicate that mud-volcano eruptions involve fluidized mud, gas, and water and that they can be violent. Recent mud flows and craters filled with waters that bubble intermittently as a result of gas exsolution demonstrate that four out of the five mud volcanoes visited during the studies summarized in this report are currently active. As the features become inactive, as in the case of the Pedernales mud volcano, they partially subside, forming a hummocky to cratered surface.

Hydrocarbon seeps associated with mud volcanoes have been a major impetus for oil and gas exploration in the Orinoco Delta and Trinidad. Vents having oil films and minor tar flows are common at the Palm Grove mud volcano (fig. 37). La Brea, an asphalt seep in the Capure area, is a bench that is adjacent to and parallels the coast for ~1 km, and extends inland for ~100 m, and rises ~1 m above adjacent mangrove swamps. It comprises multiple asphalt vents and pools, in which the substrate consists of an upper asphalt layer 20 to 30 cm thick underlain by >1 m of thoroughly asphalt impregnated mud. It is wave eroded along the side adjacent to Boca de Pedernales, and numerous exhumed mangrove trunks are present along the shore (figs. 37, 38e).

Coast

Features such as relict beach ridges and mudcapes provide a clear indication that the Orinoco prograded seaward during the late Holocene. However, late Holocene delta progradation is primarily by mud-flat accretion and eventual stabilization by mangrove rather than advancement of promontories at mouths of major distributaries (Danielo, 1976a, b; Van Andel, 1967). In fact, the Orinoco is much like the Guiana coast to the south, with alternating estuaries and rounded promontories (figs. 4 and 7). The estuaries reflect the influence of riverine and tidal processes, whereas the mudcape promontories reflect the influence of littoral currents.

Orinoco coast and submarine sediments are primarily black and gray-black mud and silty mud that typically contain quartz, feldspar, chamosite aggregates, ilmenite-magnetite, epidote-zoisite, hornblende, clinopyroxenes, orthopyroxenes, andalusite, sillimanite, tourmaline, and apatite (Emel'yanov and Kharin, 1974). The >2-μm clay-mineral fraction is mainly kaolinite, mica-illite, a small amount of chlorite, and some swelling minerals (Van Andel and Postma, 1954; Eisma and others, 1978). The >2-μm clay fraction contains up to 2 percent pyrophyllite (Eisma and others, 1978). Mineral assemblages along the Orinoco coast are similar to those of the Amazon, except for the higher proportion of sillimanite and andalusite and the presence of pyrophyllite, which can be used to map the distribution patterns of Orinoco sediments in the Atlantic Ocean and Caribbean Sea (Emel'yanov and Kharin, 1974; Eisma and others, 1978; Bowles and Fleischer, 1985). There have not yet been any invertebrate faunal studies of the Orinoco coast to date, although Van Andel and Postma (1954; their figs. 59 and 61) indicated that invertebrate fauna along the coast is sparse due to large fluctuations in salinity.

Like other modern deltas and the adjacent Guiana coast, the Orinoco shoreline has segments that are erosional and nondepositional and segments that are progradational (fig. 39). Erosional shorelines tend to be straight to concave (seaward) in map view, and 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 that cause them to collapse into the surf (fig. 35e). Historical aerial photographs indicate that the coast has eroded landward as much 2 km in some areas between Boca 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 are developing.

Accretional shorelines typically have well-developed mud flats that are up to 2 km wide during low tide (fig. 35b). Accretional coastlines are common along the coast of estuaries as well as along the Atlantic coast. These mud flats are extremely 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 mud flats and the soft but cohesive mud-flat surface strongly attenuates incoming wave energy, promoting vertical accretion along the landward portions of the mud flats. Colonization by mangroves along the landward portion of the intertidal zone (fig. 35b, d) further promotes vertical accretion. Along the Boca Grande and Boca de Guanipa, the combination of abundant sand, wave reworking, and littoral currents promotes development of sandy beach ridges on the downdrift (northern) side of estuarine islands along the coast. These beach ridges (fig. 35a) represent nascent chenier ridges.

The Orinoco coast is dissipative in that the majority of wave energy is attenuated along the broad shallow shelf. Although both the Orinoco and Guiana coasts are dissipative (Orton and Reading, 1993), the Orinoco coast and shelf do not have widespread fluid mud layers, mud banks, or extensive mud flats that characterize the Guiana coast. Eisma and others (1978) identified a fluid mud layer at the bottom of the navigation channel at Boca Grande. This fluid mud layer was confined to the navigation channel, and no turbidity exceeding 0.7 g/l has so far been detected elsewhere on the delta coast or shelf (fig. 40a; table 10; Eisma and others, 1978). It is not clear whether the fluid mud reported by Eisma and others (1978) forms there as a direct result of deepening of the channel by dredging (fluid mud layers are common along the bottoms of dredged channels). It is of note that Danielo (1976a) recognized mudbanks along the coast of Corocoro Island (mudcape) just southeast of Boca Grande.

Eisma and others (1978) estimated that 50 to 66 percent of the fine-grained sediment deposited along the Orinoco coast consists of Amazon mud. Moreover, ~80 to 90 percent of the sediment delivered to the coast by the Orinoco River is through Boca Grande and Boca Araguao, such that the caños in the northern two-thirds of the delta deliver very little Orinoco sediment to the coast (fig. 25). Hence, marine littoral, tide, and wave (rather than river) processes largely control Orinoco coastal development northwest of Boca Araguao. However, the timing and volume of discharge of Orinoco sediment from Boca Grande is critical to the development and maintenance of the central Orinoco coast.

Suspended sediment concentrations of Orinoco River water are very low and are composed predominantly of mud and silt, even during flood season (table 10). On the other hand, littoral marine waters flowing from the Guiana coast into Boca Grande contain high concentrations of suspended Amazon mud (Eisma and others, 1991). We infer that a freshwater surface plume occurs as the Orinoco River water encounters the dense, muddy, marine waters (fig. 40b). Development of freshwater plumes at delta distributary mouths is common (Orton and Reading, 1993; Nemec, 1995). In the Orinoco, we infer that the buoyant suspension layer is especially well developed because of the strong density difference in the river and marine water and the continuous renewal of dense, mud-rich marine waters at Boca Grande by the strong Guayana Current. Figure 40a provides evidence of the Orinoco freshwater plume in that the sediment plumes directly seaward of Boca Grande are orthogonal to the coast, indicating that the surface-water flow regime is primarily controlled by river flow and is distinct from the regional, northwest-flowing shallow-shelf regime. Toward Boca Araguao, the sediment plumes assume a northwestern orientation, indicating the enhanced influence of the regional shallow-shelf regime.

We infer that, as the freshwater plume overrides and is segregated from the denser marine waters in the vicinity of Boca Grande, only a limited volume of Orinoco sediment is deposited directly seaward of Boca Grande (fig. 40b). It is of note that Van Andel and Postma (1954) determined that during the rainy season, water masses in (the pre-Volcán dam) Boca de Guanipa separated into two units: an upper brackish water unit that flows seaward and a lower compensatory saline unit that flows landward. They postulated that these saline bottom currents penetrate well into the estuaries during wet-season high discharge. They inferred that during lower discharge of the dry season, the buoyant suspension layer disintegrates. We propose that in the Río Grande, with its large freshwater discharge volume, the buoyant suspension layer is maintained for much of the year.

Largely on the basis of remote-sensing analysis (fig. 40a), we infer that the buoyant Orinoco River plume is transported northwestward by the Guiana Current along the shelf and coast, where it eventually mixes with marine waters. We infer that (1) part of the Orinoco sediment mixes with Amazon-derived sediment and is transported landward by waves and tides and deposited along the central Orinoco coast; (2) another part of the Orinoco sediment plume is transported through Boca de Serpientes and into the Gulf of Paria; and (3) a third, smaller, portion of the Orinoco/Amazon sediment is transported northeastward along the south coast of Trinidad and then northward along the eastern margin of Trinidad (fig. 24).

Offshore

Shelf

The distribution of sediments on the shelf from the Amazon to Orinoco Delta follows a general pattern of nearshore mud, inner-shelf silty mud, mid- and outer-shelf sand, slope silty mud, and abyssal-plain pelagic mud (Zakharov, 1974). The Orinoco shelf is a broad, low-gradient (0.02 to 0.5 percent) feature that commonly occurs seaward of major modern deltas (Butenko and Barbot, 1979; Coleman, 1982). Along the Atlantic margin, the shelf extends offshore ~100 km to the shelf break, which generally occurs at ~100- to 110-m water depth. Like many modern deltas, much of the shelf and slopes are relict, submerged coastal plains that developed during Pleistocene sea-level lowstands (fig. 23a). The Orinoco delta front and prodelta are restricted to a narrow belt oriented parallel to the shoreline, extending only ~60 to 80 km seaward to the coast (figs. 41, 42, and 43).

These marine deltaic deposits are typically dark-gray to green-gray, soft, plastic clay and silty clay. The clays are primarily composed of kaolinite and illite, with a variable proportion of montmorillonite (Van Andel and Postma, 1954). Van Andel and Postma (1954; their figs. 59 and 61) reported that invertebrate fauna is dead and probably relict because modern fluctuations in salinity are not conducive to development in invertebrate faunal communities.

The delta-front and prodelta deposits of the subaqueous delta are as much as 70 m thick and form a narrow, steep, concave-up profile on the shelf (fig. 41). We infer that the constriction at Boca de Serpientes accelerates the rate of northwest-directed littoral- and bottom-current flow, which in turn reworks and partially erodes the delta-front and prodelta deposits along the central and northwestern delta. This steep profile also suggests that rates of seaward progradation of the subaqueous delta near Boca de Serpientes are currently low. This situation implies that currently delta foreset and bottomset beds are thin relative to the topset beds. Limited data from Boca de Serpientes indicate that the geometry of the subaqueous Holocene delta in this area is more complex than to the southeast (figs. 41 and 42).

Seaward of the clay-rich sediments are sandy sediments (fig. 43) that were deposited during the Holocene transgression (Koldewijn, 1958; Nota, 1958). These sands are composed of fine quartz sand and shell fragments, with minor portions of feldspar, mica, ferromagnesian minerals, and metamorphic rock fragments (Butenko and Barbot, 1984). Grain-size analysis of samples seaward of the Orinoco Delta demonstrate that no sand is currently being transported from the mouths of the caños to portions of the shelf exceeding 20-m depth (Koldewijn, 1958; Nota, 1958). Nota (1958) considered that two hydrographic agents control sediment distribution on the shelf: (1) wave turbulence, in particular long oceanic swell, and (2) current action related to the Guayana Current. The combined actions of these processes have produced a wide zone of agitated waters across the shelf, resulting in broad areas of sediment bypass on the middle and outer shelf.

Near the shelf edge, cemented sandstones with corals were delineated (figs. 42 and 43) and are interpreted to be upper Quaternary coral reefs (Koldewijn, 1958; Nota, 1958). They rise ~10 m above the their surroundings and are ~ 200 m in width (Koldewijn, 1958; Nota, 1958; McClelland Engineers, 1979; Butenko and Barbot, 1984). Radiometric dating of reef samples (Nota, 1958) produced an age of ~11,500 yr B.P., indicating that at least part of the upper slope is currently an area of sedimentary bypass. These reefs developed during the late Pleistocene sea-level lowstand (Koldewijn, 1958).

Prieto-Cedraro (1987) subdivided the middle and outer shelf (platform) into two areas. A stable southern sector occurs where a Cretaceous platform was established with continuous subsidence and where large volumes of post-Miocene deltaic sediments were deposited (figs. 21, 22a, and 43). The second, northern area is characterized by deformation of a thick sedimentary wedge by growth faulting (north-northwest trending) and associated east-northeast anticlines and shale diapirs. Shelf configuration east of Trinidad is complicated by tectonism (Koldewijn, 1958).

Amazon mud is transported to and mixed with Orinoco sediment along the Orinoco coast and shelf, and these sediments are redistributed such that a portion is deposited along the Orinoco coast, another part of the Orinoco sediment plume is transported through Boca de Serpientes and into the Gulf of Paria, and a third portion of the Orinoco sediment plume is transported northeastward along the south coast of Trinidad and then northward north along the eastern margin of Trinidad (fig. 24). However, little is known about the relative or absolute volumes of sediment that are redistributed to these areas or about the processes involved in transport and deposition of these sediments. On the basis of analyses of suspended sediment, Monente (1989/1990a, 1989/1990b) estimated that 20 percent of the Orinoco sediment delivered to the coast is transported and deposited in the Gulf of Paria and farther north in the Caribbean Sea, whereas the majority is deposited in front of the delta. Because the island of Trinidad and Boca de Serpientes make the hydrodynamics of the Orinoco shelf complex, characterization of the sediment dynamics is difficult. Some currently undefined amount of suspended Orinoco sediment is transported to the North Paria-Trinidad area via the shelf east of Trinidad and through the wide channel between Trinidad and Tobago. These sediments are prevented from accumulating on the eastern Trinidad shelf primarily by the Guayana Current (Koldewijn, 1958), resulting in a shelf mantled by relict transgressive sands and reefs (fig. 43). Modern Orinoco sediment has not been detected in the abyssal parts of the Guiana or the North American basin (Emel'yanov and Kharin, 1974).

Gulf of Paria

The Gulf of Paria is a semienclosed, tectonic basin located seaward and adjacent to the northwest Orinoco Delta. Studies demonstrate that the gulf receives and retains a significant portion of Orinoco sediment that enters the gulf directly from Caño Manamo (prior to construction of Volcán dam) and by littoral currents via Boca de Serpientes. The two rather narrow inlet/outlets, Boca de Serpientes in the south and Boca de Dragón on the north, control water and sediment dynamics in the gulf. Boca de Serpientes is the narrower (as little as 15 km) and shallower (a thalweg depth as little as 33 m) of the two inlet/outlets (Van Andel and Postma, 1954). The interaction of neotectonism, delta progradation, and sea-level change has altered water circulation through Boca de Serpientes during the Holocene and thereby profoundly influenced water and sediment dynamics along the Atlantic coast and shelf, as well as within the Gulf of Paria. However, the Holocene history of the Orinoco shelf and Gulf of Paria remains poorly defined.

Gulf of Paria bottom sediments vary by location and are mostly black and gray-black muds adjacent to Boca de Guanipa, greenish gray muds in the middle of the basin and sandy glauconitic muds along the coast of Trinidad (fig. 43). Van Andel and Postma (1954) provided a detailed analysis of grain size and mineralogy of gulf-bottom sediments. They determined that the gulf-bottom sediments typically contain small proportions of carbonate and organic material but relatively high proportions of iron sulfides. The sand is primarily derived from the Guayana Shield via the Orinoco River and Caño Manamo and the clays from across the Orinoco drainage basin (Van Andel and Postma, 1954). Van Andel and Postma (1954) reported that clays now being deposited adjacent to the Orinoco Delta are high in illite and kaolinite and low in montmorillonite. Seaward in the Gulf of Paria, however, they found that the montmorillonite content increases appreciably. They proposed that the seaward increase in montmorillonite is caused by the tendency for illite and kaolinite to flocculate at lower salinities than montmorillonite; hence, the illite/kaolinite flocs are deposited near shore, whereas unflocculated montmorillonite is advected to deeper water.

Van Andel and Postma (1954; their figs. 59 to 64) identified and mapped the distribution of invertebrate fauna in the gulf. They found that, except for some freshwater shells in the river estuaries, all shells are dead. They attributed the destruction of invertebrate communities to the onset of Caño Manamo discharge into the gulf approximately 700 yr B.P., resulting in a marked decrease of bottom-water salinity during wet season.

On the basis of analysis of shallow cores, Van Andel and Postma (1954) recognized two distinct Holocene units separated by an unconformity: an upper unit composed of soft, greenish-gray mud and a lower unit composed of bluish-gray, stiff mud. Radiocarbon dating of shell at or near the unconformity surface provides evidence that the age of the uppermost bluish-gray clay unit is between 1,000 and 1,500 yr B.P. Van Andel and Postma (1954; their fig. 66) mapped the thickness of the upper greenish-gray clay and determined that it generally ranges from 0 to 22 m in thickness. On the basis of analysis of a series of geotechnical boring logs, we estimate that the Holocene sediments in the gulf of Paria are as thick as 72 m (figs. 41 and 44).

Sediment concentrations along the coast and in the Gulf of Paria appear to be lower during the rainy season than during the dry season. Van Andel and Postma (1954) proposed that landward flow of saline bottom water into the Orinoco Delta estuaries during the high river stage creates a zone of dense, low-velocity flow along the base of the estuary. This wedge of saline bottom water induces a large portion of the suspended matter to temporarily accumulate along the bottom of the lower reaches of the rivers and in the estuaries. These bottom sediments are later reentrained and transported into the gulf as discharge diminishes and the saline bottom-water wedge becomes unstable and eventually breaks down. It is likely that the out-of-phase relationship between Orinoco River peak water and sediment discharge (fig. 16b) also contributes to the out-of-phase relationship between peak Orinoco water discharge and peak sediment concentrations in the Gulf of Paria. We infer that sediment concentrations are generally lower in the gulf since construction of Volcán dam, although this change has not yet been documented.

BEG Studies of the Northwest Delta

We reviewed available information on the entire delta. However, because of time and resource constraints, our studies in years one and two focused only on the northwest part of the delta, which is the area where petroleum-exploitation activities and the exploration blocks are located.

Depositional Systems of the Northwest Delta

Depositional systems are informal lithostratigraphic units made up of assemblages of process-related sedimentary facies; they are the stratigraphic equivalents of aggradational portions of geomorphic or physiographic units (Scott and Fisher, 1969). Fluvial, delta, barrier-island, and slope are examples of depositional systems. Genetically related facies deposited in a variety of depositional environments are the fundamental component elements of the depositional systems. Point bar, levee, flood basin, marsh, and shoreface are examples of component facies of the depositional systems. We defined and analyzed depositional systems and associated facies in order to determine late Holocene evolution of the delta plain, particular environmental distribution, and rates of change among depositional facies.

Four principal depositional systems were recognized in the northwest delta on the basis of differences in major environments, facies, vegetation, and the dominant geologic processes affecting various parts of the delta. These are (1) distributary channel systems, (2) interdistributary basins, (3) fluvial-marine transitional environments, and 4) marine-influenced coastal environments.

Distributary-Channel Systems

Distributary-channel systems are networks of channels, natural levees, crevasse splays, and levee-flank environments that extend across the entire delta (figs. 45 and 46). In the case of the larger channel systems, proximal overbank sedimentation has produced alluvial ridges that rise 1 to 3 m above and subdivide surrounding interdistributary basins. Orinoco channel systems are formed by a broad spectrum of rivers that include (1) major distributaries (fig. 47a), (2) large blackwater Caños (fig. 47c), and (3) small blackwater Caños.

Major distributaries such as Caños Manamo and Macareo receive water and sediment from the Rio Grande and thus have large sediment loads and discharges (fig. 25). Channels are generally 0.5 to 1.0 km wide and 10 to 20 m deep, and thalweg channel-bed textures range from muddy, very fine sand to medium sand (fig. 48). The major exception to this pattern occurs in the vicinity of the Volcán dam on Caño Manamo, where mud covers the channel bed upstream and downstream of the dam. Major distributaries show little evidence of lateral channel migration, although several large sandy point bars occur on Caño Manamo near Volcán dam (fig. 49a) and along the upper reaches of Caño Macareo. In the upper delta, natural levees are 3 to 5 m high, 100 to 200 m wide, and consist of brown muddy sands and sandy muds with abundant bioturbation features and mottles (fig. 49b). Crevasse splays with lobate geometries and fan-shaped channel networks also occur along the upper reaches of Caños Manamo and Macareo (fig. 47b). Crevasse splay deposits are similar to natural levee deposits and consist of as much as 5 m of brown and gray muddy fine sand that covers areas up to 5 km^2 (fig. 49c).

Large blackwater caños, such as Caños Tucupita, Pedernales, Cocuina, and Caiguara, receive little or no water or sediment directly from the Orinoco system and instead drain interdistributary basins of the delta plain (fig. 47c). The caños have small sediment loads, high concentrations of dissolved organic acids, channel widths of 100 to 200 m, and channel depths of 5 to 10 m. Flow is controlled by a combination of tides and water levels in the major distributaries. Banks are heavily vegetated, and the channels show little evidence of lateral channel migration. Sandy natural levees are present only along the uppermost reaches of these caños, and crevasse splays are rare. Channel-bed textures are generally muddy in the upper delta plain and become sandier toward the coast (fig. 48 and table 9). Small, sediment-poor blackwater caños are most abundant in the tidally influenced lower delta and function as both small distributaries and tidal channels. These channels have poorly developed muddy levees, and channel widths are <100 m and depths are <10 m.

Major distributaries and large blackwater caños show systematic changes toward the coast. In general, channel systems widen downstream and along Caño Manamo as the channel bifurcates around midchannel islands. Tidal fluctuations increase, and sediment is supplied to the caños during rising tide from shallow bays such as Boca de Guanipa and Barra de Cocuina. Channels are also less sinuous near the coast, and lower channel courses are deflected northwest and in some instances, converge (for example, confluence of Caños Pedernales and Angostura). Overbank flooding occurs seasonally and constructs prominent levees in the upper delta. Toward the coast, the effects of flooding diminish as demonstrated by decreasing levee heights, widths, and sand contents. Near the coast, levee deposits are gray bioturbated muds and along the large blackwater Caños, peat veneers levee muds (fig. 49d). The effects of tides are especially evident along the blackwater Caños that typically deepen and have higher percentages of channel-bed sand toward the coast. In addition, decreasing effects of flooding downstream and increases in brackish-water conditions produce major changes in the delta vegetation. Upper-delta-plain levees have vegetation communities similar to those of the rain forest described by Muller (1959) and semideciduous forest of La Salle (1996). Genera include *Ceiba, Ficus spondias, Erthrina,* with increasing abundance of *Maritia* and *Pterocarpus* on lower delta levees. Near the coast, dense stands of *Rhizophora* (red mangrove) partially fill the margins of major distributaries (fig. 47d) and line the banks of small blackwater Caños (fig. 47e).

Interdistributary Flood Basins

Broad, saucer-shaped, interdistributary basins bounded by distributary-channel levees and covered by forested and herbaceous swamps occupy most of the delta but differ substantially between the upper, middle, and lower delta (figs. 31, 45, and 46). They are drained by complex networks of blackwater caños, and water levels are controlled by a combination of overbank flooding, tides, and direct rainfall. Seasonal flooding by major distributaries dominates interdistributary flood basins in the upper delta (fig. 50a). These areas are covered primarily by herbaceous swamps (Canales, 1985), which represent a combination of the effects of anthropogenic clearing of forested swamps and perennial saturation (figs. 27p and 50b).

Substrates range from terrigenous to organic, depending on the proximity of the levees to major distributary channels (figs. 33 and 51a). Soils and sediment consist primarily of gray mottled mud, dark-gray organic mud, and minor quantities of peat and peaty clay. Yellow-brown mottling is most abundant in the upper 1 to 2 m of the soils, especially along the perimeter of the basins, and indicates that soils are periodically oxidized, probably during the dry season when water levels are low. Unweathered muds beneath the soils are massive or laminated and contain abundant organic material and bioturbation features such as roots. Probable authigenic pyrite and siderite also occur along roots and bedding planes. Pyrite and siderite are indicators of reducing conditions in these deposits. Shallow lakes are common in the upper delta but are conspicuously rare in the lower delta. In the upper delta, lakes occur within the center of interdistributary basins and along meanders of abandoned distributaries.

By comparison, middle and lower delta interdistributary basins are a combination of herbaceous and forested swamps that are perennially saturated mostly because of rainfall (figs. 27j, k, l, and 50c). Because overbank flooding and sedimentation are not widespread, herbaceous swamps receive little clastic input and contain organic sediments and soils (figs. 33 and 51b). Forested swamp vegetation includes *Mauritia flexuosa, Manicaria saccifera, Euterpe oleracea, Pterocarpus officinalis, Bactris* spp., *Montricardia aborescens,* and others. Among species in the herbaceous swamps are *Rhynchospora gigantea, Thalia* sp., *Ludwigia* spp., *Cyperus* spp., *Eleocharis* spp., and *Paspalum* spp.

Fluvial-Marine Transitional Environments

Fluvial-marine transitional environments, or the middle and lower delta plain, are located in a 10- to 20-km-wide zone of herbaceous and forested swamps that parallels the coast (figs. 27h, k, 31, 32b, and 45). These areas are permanently flooded by direct rainfall and, to a lesser extent, by tides. Overbank flooding and clastic sedimentation is restricted to areas along channels. Herbaceous swamps are widespread, covering areas as large as 200 km^2 (fig. 50d). Within the fluvial-marine transitional system, herbaceous swamps form a discontinuous northwest-southeast-trending belt (figs. 27h, i, 31, and 45). The swamps are underlain by several meters of peat and humic clay, which overlie gray mud. Distributary channels interrupt the belt of herbaceous swamp and vegetation contacts between forested swamps bordering channels, and adjacent herbaceous swamps are generally sharp and curve to the northwest (figs. 5 and 31). Compared with the interior of interdistributary basins, herbaceous swamp caños are rare and drainage networks are poorly integrated. During periods of high rainfall or falling tide, blackwaters rich in organic acids discharge from the herbaceous swamps into distributaries bordering the swamps.

Observations along transects from channel margins to adjacent herbaceous swamps indicate that at least portions of herbaceous swamps, although flooded, are slightly elevated relative to channel-margin environments. For example, a transect beginning on the east bank of Caño Pedernales ~10 km southeast of Pedernales showed that the forested swamp depression adjacent to the natural levee is ~0.5 m lower than the surface of the herbaceous swamp, which is located farther from the caño than the forested swamp. This subtle rise in topography suggests that some of the Orinoco herbaceous swamps contain ombrogenous peat (Dost and Pons, 1971). Similar herbaceous swamps in tropical Malaysia and Indonesia and along the Guiana coast are associated with domed peats that have relief of 2.5 to 10 m measured over distances ranging from a few kilometers to tens of kilometers (Brinkman and Pons, 1968; Anderson, 1983). Subtle doming of the herbaceous swamp surface may also account for radial fabrics related to vegetation differences that are observed on radar and Landsat TM images of several Orinoco herbaceous swamps. Herbaceous swamp vegetation includes *Lagenocarpus guianensis*, *Blechnum serrulatum*, and *Rhynchospora gigantea.*

Marine-Influenced Coastal Environments

Marine-influenced environments parallel the coast and extend inland as much as 20 km (figs. 31, 32b, 33, and 45). Environments include dense mangrove forests that border much of the north coast and lower reaches of caños, forested and herbaceous swamps, and tidal channel networks. Except for narrow, sandy/silty beaches and berms along portions of the shoreline, these environments are permanently flooded or waterlogged throughout the year by tides and direct rainfall. Sandy coastal environments increase in abundance to the southeast, especially east of Caño Mariusa and north of Caño Araguao.

The generally smooth and arcuate shape of the north coast is attributable to the effects of northwest-directed littoral currents that deposit sediments along the inner shelf and tidal mud flats. These currents combine with onshore-directed waves and tides to produce prominent mudcapes, such as Punta Pescadores and Punta Mariusa (figs. 1 and 10). The Orinoco mudcapes are tens of kilometers long, several kilometers wide, and covered by muddy mangrove forest similar to those reported from the Guayanas and Suriname (Allison and others, 1995). Remote sensing images show that mudcape progradation occurs rapidly (fig. 52). The Punta Mariusa mudcape has prograded ~10 km over the past 20 yr. As mudcapes prograde, they deflect the course of major distributaries to the northwest (figs. 1 and 36). Past episodes of mudcape progradation are probably responsible for the convergence of distributaries near the coast at places such as Boca de Guanipa, Barra de Cocuina, and Boca de Mariusita. Fluvial- and tidal-current action at mouths of major distributaries prevents mudcapes from prograding across and filling channels at river mouths, but abandonment of distributaries is probably followed by rapid bay filling.

Herbaceous swamps east of Pedernales have an arcuate geometry similar to that of the mangrove mudcapes, and segments of the shoreline fronting the swamps are currently eroding (fig. 35f). The swamps differ from the mangrove-covered mudcapes in that substrates are peat overlying gray mud (fig. 51d). These areas are permanently flooded, and low elevations are sites of standing water, which may indicate higher rates of subsidence. Landsat TM images show that rectangular swaths of herbaceous vegetation representing various stages of regrowth widen to the southwest parallel to prevailing wind direction. This observation indicates that the swamps are subject to periodic burning probably during dry seasons associated with decadal-scale or longer droughts.

Shallow estuaries at the mouths of major distributaries interrupt the generally smooth shape of the north coast. The most important bays include Boca de Guanipa, Boca de Macareo, Barra de Cocuina, Boca de Mariusa, and Boca de Mariusita (figs. 1 and 2). Boca de Guanipa is a large shallow estuary with several large mangrove-covered islands located at the mouth of Caño Manamo. Mangrove forests extend to the edge of the estuary at many locations, and in plan view, the digitate morphology of the mangroves along the west side of the bay provides evidence of recent progradation (fig. 35c, d). Radar images show that sedimentation in the bay has been extremely rapid over the past 20 to 30 yr, and several islands near Pedernales have formed since 1977. Sediments within and along the perimeter of the bay are a combination of mud and sand, and radiocarbon dating confirms that recent sedimentation has been rapid (~2.6 mm/yr, fig. 51c).

Boca de Macareo is a funnel-shaped estuary at the mouth of Caño Macareo. Like Boca de Guanipa, Boca de Macareo is an area of rapid historic sedimentation. An arcuate, mangrove-covered muddy peninsula has developed along the southern margin of the channel's mouth (fig. 35g). This feature has prograded several kilometers seaward since 1977 possibly because of increased discharge through Caño Macareo following completion of the dam on Caño Manamo (fig. 52). Barra de Cocuina differs from the other estuaries in that it is not currently a site of significant coastal progradation or estuarine infilling. This observation is attributable to the small sediment supply of Caños Cocuina and Capure that discharges to Barra de Cocuina.

Mangrove communities include red mangrove (*Rhizophora* sp.), black mangrove (*Avicennia germinans*), and white mangrove (*Laguncularia racemosa*). Forested species landward of the mangrove community include *Symphonia globulifera, Tabebuia insignis* var. *monophylla, Euterpe* sp., and *Virola surinamensis* (Geohidra Consultores, C.A., 1997a, b; Dr. Valois González, personal communication, 1998). Herbaceous vegetation is dominated by *Lagenocarpus guianensis, Blechnum serrulatum*, and *Rhynchospora gigantea.*

Geo-Environmental Maps of the Northwest and West Delta

Geo-environmental maps provide a preliminary environmental inventory of land and water resources of the northwestern part of the delta to establish baseline information that document change and provide a framework for formulating more specific scientific studies of environmental parameters, including geomorphology, substrate lithology, hydrology, active processes, vegetation, and interrelationships among these parameters. In addition, the geo-environmental map establishes preliminary map units for analysis and evaluation to determine their applicability for classifying land and water resources in other parts of the delta.

The Orinoco Delta is a dynamic and complex system characterized by relatively rapid geologic and physical changes, which produce modifications in related environmental characteristics. Dynamic systems are particularly vulnerable to human activities, which can result in degradation of delta ecosystems. Geo-environmental maps help to define and delineate natural resources and thereby assist in the prudent and sustainable management and use of delta environments.

Geo-Environmental Map of the Northwestern Delta Area

The northwest-delta map area encompasses more that 6,000 km^2 in the northwestern quarter of the Orinoco Delta (fig. 53). It is bounded on the north by the marine shoreline from Punta Pescadores to Boca de Guanipa and extends inland ~90 km along Caño Manamo, which marks the western boundary. The eastern boundary is near Caño Macareo.

General Methods

Classification and delineation of map units integrated remote sensing and field analysis. Initially map units were delineated on Landsat imagery on the basis of visual interpretations. Field observations and overflights in early 1998 and published data (specific sources are noted in text) were used as guidance for the preliminary identification of the characteristic vegetation of the mapped environments. To complement these preliminary interpretations, a computer-assisted automated classification of the Landsat image was conducted using digital statistical methods. Digital classifications depend on reflectance and spectral response and cannot substitute for the visual interpretation of environments. Visually interpreted units were locally adjusted on the basis of the statistical analysis. Details of the computer classification methodology and results are presented in a later section of this chapter. A revised geo-environmental map was then field-checked during visits to the delta in October and November 1998. Field observation included both aerial reconnaissance and onsite observations. Field collaboration with Venezuelan colleagues was helpful in the interpretation and delineation of delta environments. Field discussions and insights provided by Professor Valois González of Universidad Central de Venezuela regarding botanical aspects of the delta were especially beneficial (see app. 1).

Geo-Environmental Map Compilation Methodology

Landsat imagery was used to interpret, classify, and delineate delta environments. Mapped environments and geomorphic units are associated with marine, fluvial/marine, distributary channels, and interdistributary flood-basin processes. The distinctions among mapped delta environments are integrally connected to geomorphology, lithology, hydrology, and associated vegetation. Of the factors that affect imagery reflectance, vegetation, and degree of inundation/saturation are most important. Map units, however, are also distinguished on the basis of physical characteristics and setting of the environment.

Geo-environmental map units were interpreted from August 1996 Landsat TM imagery using a combination of bands 4, 5, and 7 plotted at a scale of approximately 1:125,000. Units, distinguished on the basis of color, tone, texture, and depositional setting, were mapped on clear acetate overlays. Where clouds obscured the land surface, other Landsat TM scenes from other dates or RADARSAT scenes were used as collateral information. In a few areas where cloud-free Landsat images were not available, map-unit boundaries were approximated. Boundaries defined on other images were transferred to the base map using a zoom transfer scope. Map lines were manually digitized, and a plot of digitized polygons was hand colored to define map units. All polygons in the hand-colored map were coded in GIS. Full-color GIS plots were checked for accuracy and completeness.

Geo-Environmental Map Units of the Northwest Delta

More than 20 map units were defined and delineated through integrated visual, statistical, and field analysis (table 11 and pl. 2). Map units were grouped into five major depositional environments: (1) marine-influenced coastal environments, (2) marine-influenced distributary-channel and island systems, (3) fluvial/marine transitional environments, (4) distributary-channel systems, and (5) interdistributary basins (table 11). The most extensive systems are the interdistributary basins and distributary-channel systems, which comprise areas of 2,950 km^2 and 980 km^2, respectively (table 12 and pl. 2).

Marine-influenced coastal environments

Marine-influenced coastal environments occur on the lower delta plain and compose the seawardmost system in the map area. Map units include mangrove-covered coastal facies, landward of which are forested and/or herbaceous swamps. Except for a narrow beach and berm along the shoreline, environments in this system are perennially flooded or waterlogged. Most are strongly affected by diurnal tides.

The mangrove-covered coastal facies, along the seaward margin of the map area, is characterized by marine-deposited muddy substrates, where three species of red mangroves (*Rhizophora* spp.) (Dr. Valois González, personal communication, 1998), as well as black mangroves (*Avicennia germinans*) and white mangroves (*Laguncularia racemosa*), are dominant. The mangrove community typically grades landward into a fresher water assemblage of forested or herbaceous swamps characterized by thick organic deposits or raised peats. A good example of the forested swamp is located between Caño Macareo and Isla Cocuina (pl. 2).

Typical forest species include *Symphonia globulifera, Tabebuia insignis* var. *monophylla, Euterpe* sp., and *Virola surinamensis* (Geohidra Consultores, C.A., 1997a, b; Dr. Valois González, personal communication, 1998). Two small anomalous areas of coconut palms near Capure and Pedernales were included in this forest category.

Herbaceous swamps form a broad coast-parallel belt between Isla Cocuina and Capure, seaward of Caño Angostura. This area was mapped as permanently inundated open savanna by Canales (1985). Although these herbaceous swamps are permanently flooded, areas with low elevations are the sites of standing water that produce dark signatures on the Landsat imagery. These environments were delineated separately as topographically low herbaceous swamp to define areas more susceptible to prolonged and deep inundation. Such sites, which may indicate higher rates of subsidence, could eventually become coastal lagoons and open water.

Thick peat deposits characterize herbaceous swamp substrates. Vegetation includes *Lagenocarpus guianensis, Blechnum serrulatum,* and *Rhynchospora gigantea.* Scattered trees include *Mauritia flexuosa* and *Tabebuia insignis* var. *monophylla* (Geohidra Consultores, C.A., 1997a, b; Dr. Valois González, personal communication, 1998). In some areas, such as east of Capure, herbaceous species include *Eleocharis* sp., *Typha* sp., and *Cyperus articulatus,* among others.

Herbaceous swamps are periodically subject to burning during the dry season, producing complex patterns on the imagery as a result of plant succession. These areas consist of herbaceous vegetation with varying concentrations of shrubs and trees that are rather difficult and meaningless to map separately because of their gradational and ephemeral nature as a result of periodic fires. Where herbaceous vegetation is dominant, these areas were mapped as herbaceous swamp. However, in some areas, complex configurations of herbaceous and forested vegetation were mapped together as mixed herbaceous and forested swamp. These areas generally coincide with areas mapped by Canales (1985) as savanna with trees and shrubs. Substrates are primarily peats in these permanently flooded environments (figs. 31 and 33). Predominant vegetation is similar to that listed earlier for forested and herbaceous swamps.

Marine-influenced distributary-channel and island system

The marine-influenced distributary-channel and island system is defined in large part by mangroves that are the dominant vegetation on the islands and along the lower reaches of the caños (figs. 31 and 32b). This system has its broadest distribution near the mouths of Caño Manamo and Caño Pedernales, where Isla Manamo is the largest in a series of islands that have formed in this estuary. In more inland areas, the influence of salt and brackish water declines, as does the abundance of mangroves. At Isla Tigre, ~45 km upstream from the mouth of Caño Pedernales along Caño Manamo, mangroves cover the seaward tip of the island but upstream integrate with and are replaced by forested swamp. Other major occurrences of this mangrove-dominated system are along Caño Pedernales, Caño Cocuina, and Caño Capure, where significant stands of mangroves visible on the imagery extend upstream along the channels ~45 to 50 km from the marine shoreline. Narrow stands of mangroves, too narrow to show on the map, occur along channels much farther upstream than indicated on plate 2.

Herbaceous swamps that are part of this system are located principally in the central part of Isla Manamo. On the basis of image interpretation and selected field surveys, water regimes appear to range from semipermanently to seasonally flooded. Substrates are predominantly clay and silt, with organics increasing away from the channels. The predominantly clastic, or mineral, composition of substrates in this system, which is in general agreement with soils mapped by CVG-TECMIN, C.A. (1991a though f), reflects the fluvial influence in these environments (figs. 31 and 33).

Mangroves in this system include *Rhizophora* spp., *Avicennia germinans*, *Laguncularia racemosa*. Dominant species in forested swamps generally include *Mauritia flexuosa*, *Symphonia globulifera*, *Pterocarpus officinalis*, *Tabebuia* spp., *Euterpe* spp., *Virola surinamensis*, *Ficus* spp., *Machaerium lunatum*, *Manicaria saccifera*, *Bactris* spp., and *Clusia* sp., among others. Scattered mangroves occur in the forested swamps in many areas. The forested swamp community is similar to the mixed swamp forest and palm swamp of Muller (1959).

Herbaceous swamp vegetation consists of species similar to those listed in the preceding section of marine-influenced coastal environments, including *Lagenocarpus guianensis*, *Blechnum serrulatum*, and *Rhynchospora gigantea*, with local occurrences of *Montrichardia arborescens*, *Mauritia flexuosa*, and *Tabebuia insignis* var. *monophylla*.

Fluvial/marine transitional environments

Fluvial/marine transitional environments are generally located in a coast-parallel zone landward of the marine coastal environments. Although mapped areas probably include relict marine features, these environments are influenced by a combination of fluvial and marine processes (figs. 31, 32b, 45). The most important environments are herbaceous swamps with thick peat substrates, possibly peat mounds, that appear to be topographically higher than adjacent areas but nevertheless are permanently flooded. The most extensive herbaceous swamp in this system (~200 km^2 in area) occurs east of Caño Pedernales (pl. 2). This area was mapped as permanently inundated open savanna by Canales (1985). It is part of a chain of herbaceous swamps that extends to the southeast parallel to the modern coast. In some areas along this trend, mixed herbaceous and forested swamps were mapped.

Typical vegetation in these herbaceous swamps, as in those of the marine-influenced herbaceous swamps, includes *Lagenocarpus guianensis*, *Blechnum serrulatum*, and *Rhynchospora gigantea*. Mixtures of forested swamp vegetation include *Mauritia flexuosa*, *Tabebuia insignis* var. *monophylla*, *Symphonia globulifera*, *Pterocarpus officinalis*, *Euterpe* spp., *Virola surinamensis*, *Ficus* spp., *Machaerium lunatum*, *Manicaria saccifera*, and *Bactris* spp., among others.

Distributary-channel systems

The distributary-channel system consists principally of channels, channel banks, levees, and crevasse splays but also includes abandoned channels, tidal creeks, and forested levee-flank environments. In many areas, the levee map unit is broad and includes adjacent forested belts that are significantly affected by overbank flooding and sedimentation. Among the more prominent levees and tidally induced splays are those along and between Caños Manamo, Pedernales and Macareo. The flood basin between these caños has been partially filled by tidal splays, the most seaward of which is marine influenced and has numerous bifurcating tidal channels that are lined with mangroves (pl. 2). In the map area to the east, numerous smaller channels are lined with narrow levees, and adjacent forested belts also appear to be channel related.

Substrates appear to be predominantly mud and muddy sand or sandy mud, with increasing amounts of organics toward the flood basins. In general, mapped levees and crevasse and tidal splays coincide with mineral soils delineated by CVG-TECMIN, C.A. (1991a through f).

The distributary-channel system varies from the lower to middle to upper delta plain. On the upper delta plain, levees have higher elevations and are less frequently flooded as compared with the middle and lower delta. Vegetation communities on upper-delta-plain levees are similar to that of the rain forest described by Muller (1959) and semideciduous forest of La Salle (1996). Species include *Ceiba pentandra*, *Ficus* spp., *Spondias mombin*, *Inga* spp., *Erythrina* spp., *Vismia macrophylla*, *Cecropia peltata*, *Tabebuia insignis* var. *monophylla*, *Sapium* sp., *Macrolobium bifolium*, and *Gynerium sagittatum*, with increasing abundance of species such as *Pterocarpus officinalis* and *Mauritia flexuosa* on lower delta levees. Along channels in the middle and lower delta *Rhizophora* spp. and *Machaerium lunatum* are common.

In the southwest corner of the map area, near Caño Manamo, are several tidal crevasse splays that are vegetated primarily by *Mauritia flexuosa*. These areas were classified and mapped separately as tidal creek/crevasse spays (pl. 2). The adjacent flood basins have been cleared for agricultural purposes, which accentuates the moriche palms along the channels. These features were mapped by Canales (1985) as seasonally flooded dense forest of medium height. Substrates are predominantly mud and sandy mud deposited primarily by Caño Manamo (fig. 33).

Interdistributary flood basins

The interdistributary-basin system is the most widely distributed system in the map area (pl. 2). Mapped environments include three forested swamps, two herbaceous swamps, and one mixed herbaceous and forested swamp (table 11). Topographically high, intermediate, and low forested swamps were delineated on the basis of variations in imagery reflectance, which are influenced by relative heights of the land surface (topographic setting), flood regime, and associated vegetation. Topographically low forested swamps appear to be permanently flooded, intermediate swamps permanently to semipermanently flooded, and high swamps semipermanently to seasonally flooded. Low and intermediate swamps have their broadest distribution (1) in flood basins between Caño Manamo and Caño Pedernales, (2) in the area immediately east of Caños Pedernales and Cocuina, and (3) in the lower delta near the marine-influenced environments. High forested swamps are more widely distributed in the central part of the map area from Caño Pedernales eastward toward Caño Macareo.

Differentiation of topographically high and low herbaceous swamps in flood basins was based primarily on interpreted hydrologic regimes, or duration of flooding, as indicated on the imagery. The most extensive herbaceous swamps occur in the southwest portion of the map area, where higher elevations associated with the upper delta plain are apparently suited for agricultural purposes. Much of this area, which was probably forested in the past, has been cleared and is periodically burned to establish and maintain herbaceous vegetation for grazing.

Substrates are predominantly mud on the upper delta plain, and they have increasing amounts of organics and peats toward the centers of basins (figs. 31 and 33). Substrates are predominantly peat and organics in the middle and lower delta plain, where they can be several meters thick. Low forested swamps immediately east of Caño Manamo near Isla Tigre (pl. 2) were mapped by Danielo (1976b) as peat-flat with dense morichal (palms) and by Canales (1985) as permanently inundated dense, low forests and dense palm forests with organic soils. As mapped by CVG-TECMIN, C.A. (1991a through f), topographically low and intermediate flood basins roughly coincide with organic soils, and high flood basins with mineral soils.

Forested swamp vegetation in the flood basins includes *Mauritia flexuosa, Manicaria saccifera, Euterpe oleracea, Tabebuia insignis* var. *monophylla, Erythrina glauca, Pterocarpus officinalis, Bactris* spp., *Symphonia globulifera, Montrichardia arborescens*, and others. Herbaceous swamp vegetation includes *Rhynchospora gigantea, Thalia* sp., *Ludwigia* spp., *Cyperus articulatus, Cyperus* spp., *Eleocharis* spp., *Nymphoides indica, Paspalum repens, Paspalum* sp., *Andropogon* sp., *Hydrocotyle umbellata, Gynerium sagittatum*, and others, with local occurrences of *Montrichardia arborescens* and *Mauritia flexuosa.*

Geo-Environmental Map of Southwestern Delta—Tucupita Area

A preliminary computer-assisted classification was performed on the northwest (Aslan and others, 1998, their fig. 18) and southwest parts (pl. 3) of the Orinoco Delta using 1996 and 1997 Landsat TM scenes. For the computer classification, geo-environmental map units were simplified as compared with those shown in plate 2, which was based on visual interpretation of Landsat scenes and on-site verification and refinement. The geo-environmental map of the southwest delta (pl. 3) was completed after the programmed 1999 field activities of the project were cancelled as a result of the budget reduction, and therefore the mapped units were not field checked. Thus, the classification of geo-environmental units in this area is provisional.

Computer-Classification Methodology

A supervised maximum-likelihood classification was used to classify environments. The bands selected as inputs to the classifier include TM 3 (red) , TM 4 (near-infrared), TM 5 (near-infrared), and TM 7 (mid-infrared). These bands appear to be the best combination for discriminating vegetation. It is likely that in future classifications, which will include radar data, a more sophisticated methodology for band selection and pixel classification, possibly implemented within a hierarchical structure, will result in a more detailed and accurate computer-classification approach. Previous research on classification of coastal environments indicates that neural network approaches and Bayesian classifiers based on mixture models are likely to provide superior results (Crawford and others, in review). This approach was used in addition to the maximum-likelihood classification in the southwest part of the delta (Tucupita area). Results from these two classification methods were comparable, each having strengths in selected classes and areas. We decided to use the maximum-likelihood classification, which is discussed later.

Classification algorithms are broadly grouped as unsupervised or supervised approaches. Unsupervised techniques do not require input training information and thereby use the pixel values in conjunction with similarity measures to determine which pixels should be grouped into "classes" in the spectral space. Typically, unsupervised algorithms are used for preliminary analysis of imagery, for areas where no prior knowledge of the land cover exists, or for situations where the signature that is being isolated is very different from the remainder of the image.

Clouds, which occlude the underlying vegetation and landscape, are a persistent and significant problem in most imagery of the delta. An unsupervised approach was used for the cloud-detection phase of the classification procedure because the signatures of cumulus clouds are unique in the image. The Isodata clustering algorithm implemented in the PCI software package (Richards, 1993) was used as the unsupervised classification method for identification of the clouds. The algorithm is initiated by randomly selecting a prespecified number of cluster centers in the multidimensional input data space. For the cloud-detection phase, 50 cluster centers were specified. Each pixel is then grouped into a candidate cluster on the basis of the minimization of a distance function between that pixel and the cluster centers. After each iteration, the cluster means are updated, then individual clusters are evaluated for homogeneity. The resulting clusters are then split or merged depending on the size and spread of the data points in the clusters. Operations are repeated for a user-specified number of iterations (20 in this case) or until the algorithm converges. Clusters that correspond to cloud signatures were aggregated and isolated for cloud removal. Using the results from the cloud identification, we digitized the neighboring cloud shadows manually because they are nearly impossible to identify automatically. A logical NOT was utilized to create a mask that includes all pixels except those that were labeled as cloud or cloud shadow. This cloud-screening method, although time consuming, is effective in the removal of cumulus clouds. However, in areas where water vapor and other thin clouds exist, the underlying vegetation is still identifiable but results in an attenuation of the signal, which could lead to a misclassification. Unfortunately, this typically occurs in small, localized areas. Thus, applying a uniform atmospheric correction across the scene would not improve this condition. Where necessary, postprocessing after statistical classification will be used to correct these errors.

For supervised techniques, a priori knowledge of the image content is required. Groups of pixels that are representative of the response of each class are extracted, and their values are provided for "training" the classifier. For statistical classification algorithms, this involves computing statistics that represent the distribution, such as the mean and covariance matrix of the multivariate Gaussian distribution. Similarly, neural networks "learn" the patterns of spectral responses for each class in the training phase. After the training phase, the resulting algorithm then labels the pixels in the image being classified.

Maximum-likelihood classification (ML) assuming a Gaussian distribution of the data is the most common supervised classification technique and, as such, is implemented in some form in all commercial packages. For ML classification, pixels are assigned to the preselected classes, whose values have been used to train the classifier on the basis of a decision rule that maximizes the likelihood of having obtained the observed values, given the overall assignment of classes to the image. The ultimate goal is to assign each pixel to the class that has greatest probability of occurrence, given the observed data. The ML algorithm implemented in PCI used to classify the Landsat data over the Orinoco Delta uses a Gaussian distribution where vector of variables is not independent but assumes spatial independence between pixels. Application to the project of an extended version of this algorithm developed at CSR, which considers the contextual information (class of neighboring pixels), will be investigated in possible future developments of the project, to obtain more refined land-cover maps.

Computer-Classification Results

Twelve land-cover classes and water features were identified in the TM imagery (table 13) with reference to existing maps and field surveys. Overall the maximum-likelihood classification seemed to perform well as a preliminary classification approach as listed in table 14. However, the classifier does have difficulties near Pedernales, where thin cloud cover has distorted the signal, resulting in misclassification of mangrove forest as palm. Statistically, the maximum-likelihood classifier seemed to have difficulty in accurately identifying class 8 (low herbaceous swamp) and class 10 (moriche palm), although quantitative interpretation of the classified imagery shows that the classifier did a better job at identifying these classes than the numbers indicate. Units classified in the southwest part of the delta are shown in table 15 and plate 3.

Comparison of Visual and Computer Classifications

In the northwest part of the delta, more than 20 map units were visually delineated, compared with 11 (excluding water) using computer-assisted methods. There are obvious similarities between the major map units and their distribution. Visual interpretation of imagery, however, allowed a more selective differentiation of environments on the basis of geographic distribution and an understanding of the geomorphic systems. For example, mangrove forests occurring in the marine-influenced coastal environments were mapped separately from mangrove forests occurring in the marine-influenced distributary-channel and island environments (table 12 and pl. 2). Because coastal and inland mangrove forests have a similar "signature," or reflectance pattern, on the imagery, they were classified as a single unit in the computer classification (table 12). In another example, herbaceous swamps in interdistributary basins on the upper delta plain were visually differentiated from herbaceous swamps in marine-influenced coastal environments on the lower delta (pl. 2). These areas were combined into a single herbaceous swamp class in the computer classification.

Additional units could have been classified using computer methods, and, in fact, the classification may be revised, expanded, and employed more fully in the future. There are obvious advantages in computer analysis, including increased efficiency and reduction in time and cost for such tasks as manual digitization. In addition, a more detailed subdivision of complex areas is presented in computer-classified maps. For instance, along the mangrove-covered distal end of the crevasse splay between Caños Manamo and Pedernales, a more complex system composed of smaller polygons is shown by the computer-classified map as compared with the visually classified map (pl. 2). The differentiation of units in such complex areas provides additional useful information about land and water resources and provides a sound basis for change analysis. It also provides collateral data for visual classifications. On the other hand, problems such as cloud cover and atmospheric haze that obscure or produce subtle variations in landscape reflectance seem to be more difficult to resolve through computer analysis than through visual analysis.

Shoreline Change and Shoreline Type West of Boca De Araguao

Introduction

The geometry, position, and type of shoreline of the Orinoco Delta are a result of geologic setting, sediment supply, and fluvial and oceanic processes. Figure 1 and plate 1 reveal two principal sectors: the southeastern quarter of the coast along Boca Grande and Boca de Araguao, where the shoreline geometry is complex, and the northwestern three-fourths, where the shoreline geometry is much less complex and mudcapes, such as Punta Pescadores, are prominent features.

Previous studies (Van Andel and Postma, 1954; Van Andel and Sachs, 1964; Van Andel, 1967; Coleman, 1981; Herrera and others, 1981) demonstrate that the broad shallow shelf and lack of high-intensity storms (such as hurricanes) result in a low- to moderate-energy wave regime along the Orinoco coast. The position of the delta in the Intratropical Convergence Zone makes it subject to wind and waves from the east and northeast (fig. 24). Mean diurnal tides range from ~1.6 to 2.0 m. Tidal ranges are higher in the southeastern (Boca Grande) and northwestern (Boca de Guanipa) estuaries and relatively lower along the central delta coast. The coast is also strongly affected by the Guayana Current (fig. 24), a primarily northwest-directed littoral current with velocities of 50 to 75 cm/s in the spring and 25 to 40 cm in the autumn (Van Andel, 1967). The Guayana Current transports Amazon sediment northwestward, providing ~50 percent of the sediment deposited along the Orinoco Delta shelf and coast (Meade and others, 1983).

More than 75 percent of Orinoco River discharge is through Boca Grande. The high-volume river discharge and diurnal tides are principal processes in forming the complex coastline in the southeastern quarter of the delta. The Guayana Current is the principal process acting on the regional configuration of the northwestern three-fourths of the delta (fig. 40a). This last observation is substantiated by examining the shoreline geometry of the Suriname coastal plain, which is characterized by small rivers and mudcape development (Roeleveld and van Loon, 1978) and appears remarkably similar to the northwestern three-fourths of the Orinoco Delta. Both the northern Orinoco Delta coast and Suriname coast are controlled by a relatively weak wave regime, relatively minor river discharge, and a strong littoral current that supplies large volumes of sediment from the southeast.

Within this regional context, Bureau efforts focused on developing a preliminary classification system that describes Orinoco Delta coastal features and processes. The study area included the central and northwestern Orinoco Delta between Boca de Guanipa and Boca de Araguao. The classification scheme is specifically for the Orinoco Delta shoreline. Identifying and mapping distinct shoreline types increase understanding of the patterns of shoreline change and can help reconstruct the recent history of the lower delta so that future trends can be inferred. Once refined, the resulting shoreline classification map will also be useful for oil-spill contingency planning and design of coastal infrastructure.

Devising a comprehensive shoreline classification involves determining those features of a coast that are indicative of the important ongoing processes and geologic settings. For the Orinoco Delta coast, the following characteristics are considered: (1) sediment grain size; (2) vegetation type; (3) stability (accretional/erosional/stable); (4) shoreline form (that is, many indentations or relatively smooth shoreline); (5) geomorphic process (for example, prograding spit); (6) landward, beach, and nearshore elevation profile; (7) energy level of tidal and oceanic currents, and (8) exposure to wave energy.

Methods

The preliminary shoreline-type map was devised from (1) visual observations and oblique aerial photographs taken during low-altitude (less than 300 m above ground level) flights, (2) ground- and boat-based shoreline visits, and (3) analyses of radar and Landsat remote-sensing imagery. During 1998, we conducted six low-altitude flights over the delta (fig. 6a). The entire shoreline on the outer coast was observed at least once during these flights, and hundreds of photographs were taken. Kinematic GPS positions recorded during the flights allowed precise positioning of the photographs. Much of the shoreline within the coastal bays was also photographed. In addition, we made ground and boat excursions to shorelines on the northwest portion of the delta west of Punta Pescadores (fig. 39). While devising the preliminary classification scheme and map, we determined the type of coastal data, described earlier, required to complete the classification.

Preliminary Assessment of Shoreline Types

Following is the preliminary shoreline-type classification for the Orinoco Delta.

1. Mangrove
    - 1.1 Advancing
        - 1.1.1 Dentate (shoreline indentations of 100 to hundreds of meters)
        - 1.1.2 Straight with fronting tidal flat
        - 1.1.3 Prograding mudcape or river-mouth bar
    - 1.2 Retreating
        - 1.2.1 Ragged (shoreline-form roughness on a scale of tens to hundreds of meters)
        - 1.2.2 Straight with fringing sand beach
        - 1.2.3 Straight without fringing sand beach
    - 1.3 Stable
2. Sandy
    - 2.1 Advancing
        - 2.1.1 Prograding spit
        - 2.1.2 Pocket beach
        - 2.1.3 Straight (not prograding spit) with beach ridges
    - 2.2 Retreating
        - 2.2.1 Fringing low (topographically) swamp
        - 2.2.2 Fringing high (topographically) swamp
    - 2.3 Stable

3. Mixed mud, sand, and gravel
4. Vegetated, nonmangrove
    4.1 Advancing
    4.2 Retreating

The classification's primary distinctions, the presence of mangroves, nonmangrove vegetation, and sediment grain size, are obviously significant biologically and physically. The secondary division concerns shoreline stability, which refers to the relative rate of retreat or advance of shoreline position over the past several decades. This distinction is important because of the implications regarding predominant coastal processes, sediment supply, geologic setting, and biological habitats. Furthermore, an eroding shoreline of a particular type will have a morphology different from its accreting or stable counterpart. A shoreline-change distinction is also important for oil-spill contingency planning. A particular situation may call for scarce oil-spill-response resources to be directed toward an accreting shoreline where the oil may become buried, rather than an eroding one where it would naturally disperse. If the rates of shoreline change were determined more quantitatively, the shoreline-type mapping could be refined.

Initial observations indicate that shoreline form varies significantly along the coast and should be included in the classification. Form refers to the shape of the line that the shoreline describes. If the shoreline has no significant reentrants repeated within about a kilometer along shore, it is referred to as "straight." Shorelines with reentrants on the order of hundreds of meters or more that are repeated over several hundreds of meters alongshore are referred to as "dentate." Shorelines with relatively small-scale roughness are referred to as "ragged," which describes their irregular appearance. Also included in the preliminary classification are the terms "prograding spit" and "prograding mudcape." These are morphogenetic terms that describe a shape (spit/cape) and a process (prograding). It may be useful to include more morphogenetic terms in a final classification.

Advancing Mangrove Shorelines

Advancing mangrove shorelines have extensive tidal flats fronting them and ongoing mangrove colonization. Where shore-normal tidal currents prevail, a dentate form develops such as in western Boca de Guanipa (figs. 35c and 39). Shore-parallel currents combined with an abundant fine-grained sediment supply produce straight, advancing mangrove shorelines such as in the center of Boca de Guanipa (fig. 39). Even along straight, advancing shorelines, tidal creeks are present, but the mouths of the tidal creeks are much smaller than the indentations that create a dentate shoreline. Advancing, ragged shorelines may form as a result of mudcape or river-mouth-bar progradation such as in the center of Boca de Macareo (figs. 10b, 35g, and 39). Here, the terminations of accretionary ridges create an irregular shoreline.

Retreating Mangrove Shorelines

Fallen mature mangroves in the surf zone typify retreating mangrove shorelines. Unlike advancing mangrove shorelines, wide tidal flats do not occur seaward of retreating mangrove shorelines. These eroding shorelines may intersect small tidal creeks that are probably remnants from a time of earlier mangrove advancement. East of Punta Tolete, blackwaters issuing from small creeks contrast with turbid water in the surf zone. Where these creeks are larger, they may cause an interruption in the littoral drift and create small deltas. Retreating mangrove shorelines are typically straight where there is a high rate of littoral drift. Reworked sand from the eroding mangrove substrate or from updrift sources may form a fringing sand beach. A typical mangrove shoreline that is retreating and straight occurs east of Punta Tolete (figs. 35e and 39). Differential shoreline erosion caused by variations in topography and sediment type may cause a ragged form. Retreating mangrove shorelines that have a ragged form typically occur in areas where there is a relatively low rate of littoral drift, such as west of Barra de Cocuina (fig. 39).

Stable Mangrove Shorelines

There are mangrove shorelines with neither fallen mangroves in the surf zone nor ongoing mangrove colonization. Mangroves are mature, and shorelines are relatively straight and without broad tidal flats. These shorelines are probably relatively stable and commonly occur in wave-sheltered areas where tidal or fluvial currents do not allow sediment accumulation or where sediment supply is low.

Sandy Shorelines

Sand veneers occur over long sections of eroding, muddy mangrove shorelines west of Punta Pescadores, but beaches where sand is the dominant sediment type are rare in this area. The lack of sandy shorelines reflects the predominance of mud-rich source material and low-energy wave climate. Sand beaches, however, increase in abundance southeast of Punta Pescadores. Advancing sandy shorelines may take the form of a prograding spit such as the spit, apparently formed by flood-tidal currents in the Boca de Guanipa area (fig. 39). Depositional sandy pocket beaches may form in ragged mangrove shorelines or other reentrants along the coast. These beaches are too small to note on the preliminary shoreline-type map. Multiple modern beach ridges may also indicate an advancing or stable shoreline, such as northwest of Boca de Araguao (fig. 35a). Retreating sandy shorelines are typified by washover terraces, low dunes or no dunes, and possibly peat or mud outcrops on the lower beachface.

Mixed Mud, Sand, and Gravel Shorelines

These poorly sorted shorelines are associated with mud diapirs or mud volcanoes and only have been observed locally in the Boca de Guanipa area (fig. 39). Waves erode a bank of poorly sorted sediment uplifted by mud diapirism. Sand and gravel eroded from the cliff form a veneer on mud. These shorelines are not extensive.

Vegetated, Nonmangrove Shorelines

Only retreating shorelines of this type have been observed along the Orinoco Delta coast. These shorelines are present where herbaceous or forested swamps are being eroded but where there is no fringing sand beach or substantial mangrove colonization. An area between Boca de Mariusita and Barra de Güiniquina includes this type of shoreline.

Patterns of Shoreline Change and Type: Preliminary Observations West of Boca de Araguao

The following initial observations are qualitative or semiquantitative because rigorous comparisons between photographs and imagery have not been performed. It is evident, however, that there is a large variation in the rates and direction (advance or retreat) of shoreline change. Variation in sediment supply, exposure to waves and currents, and the geologic setting of the landward environment cause this variation. Below, the coastline is described progressively from Boca de Guanipa east to Boca de Araguao.

Over the last several decades, there has been extensive mud-flat accretion and mangrove island growth and formation in the Boca de Guanipa area, as discussed elsewhere in this report. Comparison of a 1977 Side-Looking Airborne Radar (SLAR) image and a 1996 Radarsat radar image shows that approximately 30 km^2 of intertidal mangrove forests were added to the bay during this 19-yr period. In contrast to the rapid deposition occurring within Boca de Guanipa, erosion is prevalent on the outer coast between Punta Tolete and Barra de Cocuina (fig. 39). Overall erosion along this section of coast is evident by fallen mangroves in the surf zone along the western two-thirds (fig. 35e) and eastern end of the section (fig. 39). Between these mangrove areas, erosion is indicated by (1) narrow sandy beaches with washover terraces, (2) no modern beach-ridge development, (3) low dunes, and (4) peat outcrops on the beach.

The shoreline between Punta Tolete and Barra de Cocuina has several large-scale undulations caused by varying rates of shoreline retreat. Sections of the coast where the shoreline has intersected areas on the delta that are relatively low in elevation have higher retreat rates and form erosional embayments (fig. 39). Broad erosional promontories form between these embayments. Low coastal areas in which embayments form are evident on the 1996 Landsat (figs. 39 and 5 for more detail) and Radarsat (pl. 2) images as being darker than surrounding areas owing to ponding water. There are two erosional embayments approximately 5 km west of Punta Blanca, where the shoreline intersects environments classified as low (topographically) herbaceous swamps (fig. 39 and pl. 2). Between these embayments is a small section of mangroves that forms a small promontory. To the west of the two embayments is a broad erosional promontory of mangrove shoreline, and to the east a promontory is formed along a high (topographically) herbaceous swamp environment.

There are two other small erosional embayments between Punta Tolete and Barra de Cocuina that are probably formed in topographically low environments but have not been classified differently from adjacent areas. About 10 km east of Punta Tolete, a 2.5-km-long embayment has formed along the mangrove shoreline. The Landsat and Radarsat images show ponds 400 m landward of the shoreline and subtle contrasts with adjacent mangroves in the area between the ponds and the shoreline. Oblique aerial photographs show that the mangroves are shorter in the embayment than they are to each side. Another embayment is present 8 km east of Punta Blanca. Here, a narrow (<300-m-wide) mangrove strip fringes a high (topographically) herbaceous swamp environment, which also forms the promontory to the west. Even though the landward environment in the embayment is not classified differently from the adjacent promontory, the darker tones in the Landsat imagery indicate wetter conditions and, hence, lower elevations in the embayment.

The mangrove shoreline on the south and east side of Barra de Cocuina appears to be relatively stable (not advancing or retreating). There are no fallen mangroves in the surf zone that would indicate retreat, nor are there new mangroves colonizing tidal flats that would indicate advance. Shoals evident in the Landsat imagery show that the east shoreline is probably dominated by ebb-directed tidal flow and that the south side is flood dominated. Shore-parallel tidal currents probably keep this shoreline straight and stable by sweeping fine-grained sediments out of the bay. The sheltered setting prevents wave erosion.

To the east of Barra de Cocuina the mangrove shoreline appears relatively stable or slightly erosional for about 9 km. At that point the shoreline becomes erosional (fallen mangroves in the surf zone) and ragged in form for about 9 km to Boca de Macareo. This apparently erosional shoreline is perplexing because it appears to be in a more wave sheltered environment than the 9 km of stable shoreline to the west. Longshore currents do not appear to be important because of the ragged shape. The erosional shoreline encounters an area that shows slightly different colors and tone in the Landsat imagery (figs. 39 and 5) than those shown along the stable shoreline. Furthermore, the erosional shoreline intersects a shore-normal pattern with about a 700-m wavelength that is subtly displayed in the Landsat imagery. This pattern corresponds to undulations in the shoreline. Therefore, the differing lithologies of the preexisting deltaic environment that the shoreline is intersecting may be the dominant factor controlling the shape and rate of change of the shoreline.

Along the south side of Boca de Macareo the mangrove shoreline appears stable. A mangrove-covered levee is in the center of the bay (fig. 35g). This levee prograded (lengthened) about 2 km from 1977 to 1996, as determined by comparing the SLAR and Radarsat radar images. Along the north side of the levee and across Caño Macareo to the south side of Punta Pescadores, the mangrove shoreline appears relatively stable. The stability and straightness of the shoreline is probably a function of longshore tidal currents and sheltering from wave activity, which is the same setting as described for the south and east sides of Barra de Cocuina. Ebb-tidal currents are causing tidal-flat progradation across a small bay on the south side of Punta Pescadores. Mangroves are colonizing these flats in this wave-sheltered setting. Farther to the northwest the mangrove shoreline becomes relatively stable.

The northwestern outer coast of Punta Pescadores has several erosional embayments that create a "bumpy" morphology on a scale of 1.5 to 5 km (fig. 39). On a smaller scale, however, the shoreline is relatively straight. This entire section of coastline consists of eroding mangroves, but unlike the eroding mangrove shoreline east of Punta Tolete, there appears to be no sand veneer. Close inspection of Landsat and Radarsat images reveals that the embayments are formed in areas with signatures slightly different from those of the adjacent promontories. These signatures may indicate slightly lower topography in the embayments, suggesting that the shoreline shape may be related to variations in the geomorphology of landward environments intersecting the coast. A broad erosional embayment has formed in the area southwest of the tip of Punta Mariusa. This embayment is accentuated by the relatively stable shoreline to the southeast, which is sheltered by Punta Mariusa.

Punta Mariusa is a mudcape that prograded along the coast about 12 km from 1977 to 1996 (fig. 39). The landward side of the tip of this mudcape is a relatively straight, advancing mangrove shoreline with a muddy tidal flat. The outer coast is also an advancing mangrove shoreline but with an irregular dentate morphology that increases in scale from 100 m on the northwest tip to hundreds of meters to the southeast. This dentate morphology exists even though there is a significant northwesterly longshore current as evidenced by the progradation of the mudcape and a northwest-prograding sandy spit to the southeast (fig. 39). The dentate morphology extends to the landward side of the cape south of the tip. This morphology is the result of the form of the accreting sediment banks during the progradation of the mudcape. The indentations probably are the remnants of channels that were once present between the banks.

Halfway between Punta Mariusa and Boca de Mariusita the shoreline is eroding and forming a broad erosional embayment. Retreating mangroves with a fringing sand beach form the shoreline, and inspection of Landsat imagery reveals that this may be a relatively wet and topographically low area. To the southeast toward Boca de Mariusita the mangrove shoreline becomes stable and then becomes a sandy shoreline with modern beach ridges forming a depositional promontory (fig. 39).

On the western shore of Boca de Mariusita the mangrove shoreline is stable. On the eastern side a sandy shoreline exists that may be fed by eroding outer-coast shorelines to the east. East of Boca de Mariusita the mangrove shoreline is retreating in a ragged form. It is suspected that more thorough mapping would reveal sandy pocket beaches, but none were observed during preliminary observations. About halfway between Boca de Mariusita and Barra de Güiniquina (fig. 39) a small depositional embayment is present. This embayment eroded in a topographically low area but has now become sheltered from waves and tidal-flat deposition and mangrove colonization is occurring. Farther to the east, the shoreline protrudes but is punctuated by erosional embayments and promontories on a scale of 1 to 2 km. Here the shoreline is eroding herbaceous and forested swamps, and fringing sand beaches are present in places. An eroding to stable mangrove shoreline to the east forms an erosional promontory.

East of Boca de Güiniquina the mangrove shoreline is stable to slightly eroding, but at about 10 mi east, a prominent sandy spit is prograding to the northwest. East of the spit the mangrove shoreline appears relatively stable. Toward Boca de Araguao the shoreline is sandy and multiple, and modern beach ridges form a depositional promontory (figs. 39 and 35a). Compared with the western delta, wave energy and sand supply are higher here and have prevented mangrove colonization.

Conclusions

Sediment supply and fluvial and tidal currents are the primary control on the types and stability of shorelines in the coastal bays of Boca de Guanipa, Barra de Cocuina, and Boca de Macareo. On the outer coast, the relative intensity of longshore currents and wave energy, which is primarily controlled by local wave shadowing by mudcapes or exposure to the Atlantic Ocean, is important in determining shoreline change and type. However, the deltaic environment intersecting the coast may be the dominant control on the character of the erosional outer coast, at least for the part of the Orinoco Delta west of Barra de Güiniquina. Erosional embayments form in what apparently are topographically lower environments that are remnants from a time of earlier deltaic progradation. The difference in topography between erosional embayments and adjacent erosional promontories is probably very slight, possibly less than 1 m. The higher erosion rates in the lower topographic areas may simply be a result of tides and wave action reaching farther up the profile and more effectively eroding sediment. On the other hand, there may be areas, such as the first embayment east of Punta Tolete (fig. 39), where the shoreline is not lower topographically, although runoff from ponds that formed in a low area a few hundred meters behind the beach hastens erosion. Sediment type or amount of sediment compaction that may or may not be correlated with topography may also cause differential shoreline erosion. This situation may contribute to creating the ragged shoreline west of Boca de Macareo (fig. 39).

An important note is that apparently small variations in topography cause significant increases in the rate of shoreline erosion. These topographic variations may be an expression of the remnant depositional environment, but subsidence may also cause or enhance the variation. Faulting, natural sediment compaction, or sediment compaction enhanced by fluid extraction may cause subsidence. Knowing detailed topography and the relative rates of shoreline change along the coast may allow us to infer future changes if subsidence increases or decreases. Detailed studies of coastal processes at select locations are necessary to test the hypotheses presented here. These studies will help provide an understanding of the mechanisms of shoreline change, which will further our ability to understand the past and to predict the future at the Orinoco Delta coast.

Evolution of the Modern Orinoco Delta

We now review the Holocene history of the delta to more fully establish relationships between physical processes, geoenvironments, and ecosystems. Moreover, analysis of Holocene delta evolution is the most effective means for evaluating the response of delta geoenvironments and related ecosystems to changes in physical processes such as hydrology and climate.

The Orinoco Delta Holocene history remains unclear for several reasons. First, differential subsidence is a major control on the age and distribution of surficial deposits across the delta plain, complicating the relationship between landform distribution and geomorphic history. Second, peat deposits up to 6 m thick mantle a large portion of the middle and lower delta plain (figs. 33 and 51d), obscuring relict landforms (cheniers, abandoned channels, mudcapes) that record earlier phases of delta progradation. Third, there are very few boring logs and samples that document the late Pleistocene and Holocene section in the delta, and those currently available are very general or only record the upper Holocene section. High-resolution, shallow seismic data are not yet available for the delta-plain area. Hence, there are currently insufficient subsurface data to generate a time-space framework of delta evolution.

Previous Studies

In a study of the pyritic clays of the Tucupita area, Dost and Pons (1971) presented a schematic cross section that extends from the delta apex to the coast (fig. 54). The cross section indicates that marine clays underlie the entire northwestern delta and that a seaward-thickening prism of peat blankets the marine clays. The seaward-thickening peat suggests that subsidence rates are progressively greater toward the coast. The abrupt transition between the marine clay and peat suggests a widespread and sudden change in the physical environment across that greatly reduced terrigenous sediment input and accumulation across the delta plain, which provided the opportunity for widespread accumulation of peat.

Danielo (1976a) utilized aerial photography to interpret the middle and late Holocene history of the Orinoco Delta. Danielo (1976a) defined three principal phases of Orinoco Delta evolution:

(1) widespread deposition of silty muds formed a complex of estuarine islands and tidal channels that are now partially or completely infilled and covered with upper-delta forests (Danielo, 1976b). The seaward extent of this phase demarcates the maximum extent of the Flanderian transgression. Peats began to develop as the rate of sea-level rise slowed and shoreline positions stabilized.

(2) The second phase began at the end of development of the most ancient peat deposits to the south and west of the current delta. This phase is characterized by widespread development of mangrove forests as the delta prograded seaward and ended with establishment of fluvial and/or pluvial conditions in these areas and consequent decline of the mangroves.

(3) The third phase is characterized by development of extensive forested and nonforested littoral-peat swamps. Beach-ridge complexes (cheniers) also developed during this phase. The littoral-peat phase apparently ended as thick mangroves were reestablished along the coast, resulting in entrapment and deposition of mud deposits.

Danielo (1976a), primarily on the basis of mapping of the landward extent of ancient tidal channels, delimited the maximum landward extent of the late Pleistocene-early Holocene (Flanderian) transgression. Danielo (1976a), because of regional differences in subsidence rates and intensity of fluvial processes, was not able to correlate evolutionary phases of the Orinoco with those defined for the Guiana coastal region to the southeast and the Gulf of Paria to the northwest (Van Andel and Postma, 1954; Brinkman and Pons, 1968). Danielo (1976a) concluded that the delta subsurface model presented by Dost and Pons (1971) is an oversimplification of a fluvial, deltaic, and coastal system that varied both in time and space. Mendez-Baamonde (1997a, b) provided a summary of the Quaternary geology and history of Venezuela, including the Orinoco Delta region.

Factors Controlling Holocene Delta Development

Sea-level change, subsidence, neotectonism, and climate are the major factors controlling delta evolution. Climate and climate change in turn largely control major factors such as river discharge and marine hydrodynamics.

Sediment-Accumulation and Subsidence Rates

Subsidence-rate measurements are essential not only for determining delta history but also for developing effective structural and environmental designs and for predicting the effects of human activity in the delta. By subsidence we refer to 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 land-surface lowering associated with both sediment compaction and tectonic lowering.

Nota (1958) identified a series of reeflike mounds along the shelf edge of the Guiana and Orinoco Delta region (figs. 42 and 43). On the basis of ^{14}C dating of fossil corals from these mounds, he determined that these were shallow water reefs that accumulated during the latest Pleistocene sea-level lowstand ~11,500 to 17,500 yr B.P. By plotting the depths of these reefal lithosomes below sea level, Nota (1958; his fig. 37) calculated Holocene differential subsidence rates. His calculations demonstrate that the shelf edge seaward of Orinoco Delta at Boca Grande has subsided ~25 m more than the relatively stable passive-margin shelf edge farther south in the Guiana region. Brinkman and Pons (1968), using radiocarbon-dated sediment borings, identified a strong increase in subsidence rates in northwestern Guyana, toward the Venezuelan border. The near-parallel, northeast-southwest alignment of caños and tidal channels in the central delta (fig. 26) is largely the result of differential subsidence of the middle and lower delta plain to the northeast (compare Danielo 1976a).

In addition to calculating subsidence rates, it is worthwhile to calculate sediment-accumulation rates because fewer assumptions are required. In particular, long-term sediment-accumulation-rate calculations do not require assumptions regarding water depths across the delta at the time of initial delta deposition. Besides, sediment-accumulation rates provide information regarding major trends in sedimentation in time and space.

In the present study, sediment-accumulation and subsidence rates were determined for areas of the delta where subsurface information is available. These rates have been calculated from two sources of subsurface data: (1) existing subsurface information (geotechnical boring logs) and (2) radiocarbon dates from shallow core samples taken by BEG (figs. 6b and 41). Data used to generate the sediment-accumulation rates are summarized in table 16. Sediment-accumulation- and subsidence-rate calculations generated from the shallow BEG cores provide shorter term estimates but are based on radiocarbon dates from samples of in situ peat or large wood fragments. The deeper geotechnical boring logs are poorly constrained chronologically but provide insight into long-term trends in progradation and aggradation.

Sediment-Accumulation Rates

Sediment-accumulation-rate calculations in the deep geotechnical borings (fig. 44) are based on the assumption that (1) the base of the Holocene is a distinct and abrupt transition from: (a) dark-gray, plastic, Holocene mud, to (b) shelly upper Pleistocene to lower Holocene transgressive sand (may or may not be present), to (c) tan to brown, upper Pleistocene stiff mud and sandy mud; and (2) the base of the Holocene delta section is 7,500 yr B.P. (Stanley and Warne, 1993).

Sediment-accumulation-rate calculations are generated by dividing the depth of the dated horizon below the ground or (in the Gulf of Paria) water-sediment interface by the age of the dated horizon. For example, the sediment-accumulation rate for log A4 (table 16) is 45,400 mm ÷ 7,500 yr = 6.0 mm/yr. Calculated sediment-accumulation rates are:

0.8 to 1.0 mm/yr in the upper delta,
0.8 to 2.0 mm/yr in the middle delta,
10.1 to 13.3 mm/yr in the lower delta Punta Pescadores area,
0 to 8.0 mm/yr in the northwestern delta, and
6.0 to 8.9 mm/yr in the Gulf of Paria (table 16).

Van Andel and Postma (1954) estimated Holocene sediment-accumulation rates for the Gulf of Paria to range from 0.6 to 10 mm/yr .

Analysis of radiocarbon-dated samples from shallow borings collected from the upper, central, and lower Holocene delta plain (figs. 6b and 55) shows that rates of clastic and organic sediment accumulation locally range between 0.25 and 6.0 mm/yr. This large range of values reflects a combination of local environmental influences on sedimentation rates and regional-scale patterns of delta progradation and subsidence. The most rapid rates of sediment accumulation (~5.0–6.0 mm/yr) are associated with an upper-delta crevasse splay along Caño Macareo (fig. 49c) and shallow bay-fill deposits along the southwest margin of Boca de Guanipa (fig. 51c).

Excluding areas of local rapid sedimentation, rates of sediment accumulation generally increase from ~0.25-1.5 mm/yr in the upper delta to ~1.0-3.0 mm/yr in the lower delta (fig. 55). This pattern reflects a combination of increased subsidence toward the coast and delta progradation. Radiocarbon ages of shallow (<4 m below the land surface) peats from the upper delta near Tucupita range in age from ~ 5,500 to 4,500 yr B.P. In contrast, basal peat samples in the central and lower delta range in age from ~3,600 to 2,800 yr B.P. and ~1,500 to 200 yr B.P., respectively (fig. 56). Decreasing ages of basal peat samples toward the coast can be interpreted as a possible indication of at least local, northward, late Holocene delta progradation. Because it is likely that the lower delta-plain peats formed near sea level, age-depth relationships for these peats suggest that subsidence near Boca de Guanipa has been as much as ~3 to 4 mm/yr over the past ~1,000 yr. However, local deformation, such as the Pedernales anticline (fig. 17), has complicated sediment accumulation (and subsidence) history in several delta sectors.

Radiocarbon ages of upper delta-plain deposits near Tucupita also suggest that rates of sediment accumulation have decreased in this region during the Holocene (fig. 55). Prior to ~5,000 yr B.P., rates of sediment accumulation were ~1 mm/yr and decreased to ~0.25 to 0.50 mm/yr over the last 5,000 yr. Decreasing rates of Holocene sedimentation near Tucupita are represented in cores by the widespread occurrence of peat. This decrease in sedimentation rates probably reflects the development of sea-level highstand conditions and delta progradation, infilling of available accommodation space, and consequent sediment bypassing in the upper delta.

Subsidence Rates

To calculate subsidence rates, the same assumptions regarding stratigraphic position and age of basal Holocene deltaic deposits were used to generate sediment-accumulation rates. In addition, the following assumptions are made: (1) 7,500 yr B.P. sea level was 5 m lower than it is at present (fig. 11); (2) water depths (accommodation space) in the Gulf of Paria and Punta Pescadores area were 50 m at the beginning of Holocene delta deposition; (3) water depths (accommodation space) were 30 m in the central delta and Boca de Guanipa areas at the beginning of Holocene delta deposition; and (4) water depths were negligible in the upper delta at the beginning of Holocene delta deposition.

To calculate subsidence rates using shallow, radiocarbon-dated borings, the following assumptions were made: (1) elevation at the boring site has not changed since the time of deposition of the dated material; (2) sea level has been steady since the time of deposition of the dated material; (3) the dated material was buried in situ, immediately after dying (that is, it is not older material imported from upstream).

Subsidence-rate calculations are generated by: (1) accounting for other factors influencing the depth of the dated horizon by adding amount of sea-level change since the time of the dated horizon (for example, 5 m since 7,500 yr B.P.) plus the water depth at the site at the time that the dated horizon was deposited (for example, 50 m in the Gulf of Paria), (2) estimating the elevation of the depositional surface at the time of the dated horizon by subtracting the sum in (a) from the depth of the dated horizon below present and then (c) estimating subsidence by dividing the elevation of the depositional surface (b) by the age of the dated horizon. For example, the calculated subsidence rate for log A4 is [71,500 mm – (5,000 mm + 50000 mm)] ÷ 7,500 yr = 2.2 mm/yr (table 16).

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 16).

Subsidence rates show a clear increase from the upper to the lower delta. The variable subsidence rates in the Boca de Guanipa and Punta Pescadores areas are related to active folds in these areas (fig. 17). Subsidence rates in the Gulf of Paria are similar to those of the lower delta plain. Unfortunately, we have no subsurface data from the Río Grande and Boca Grande region where we suspect that subsidence rates are greater than in the delta to the west (largely because of the position of Río Grande and Boca Grande).

Although these sediment accumulation and subsidence-rate calculations required a number of assumptions, they are similar to rates calculated for the Mississippi, Nile, and Rhine-Muese Deltas, where more radiocarbon-dated subsurface information is available (Stanley and Warne, 1993; Törnqvist, and others, 1993). However, a series of radiocarbon-dated cores that sample the entire Holocene and upper Pleistocene section across the delta plain are needed to determine this critical parameter.

Sea Level

Pleistocene and possibly Holocene sea-level changes had a profound influence on delta evolution, particularly maintenance of the marine flow through Boca de Serpientes, which in turn had a profound influence on coastal and littoral hydrodynamics along the Orinoco Delta coast. We refer to sea-level change in this report as the change in the ocean-water surface relative to a topographic datum rather than relative sea-level change, which typically refers to the combined influence of sea-level change and subsidence.

Sea-level studies along the coast of Suriname (Roeleveld and van Loon, 1978) and the Caribbean region (Lighty and others, 1982; Pirazzoli, 1991) show rising sea levels during the early Holocene followed by decelerating sea-level rise or the establishment of present-day sea level during the late Holocene. None of the curves show evidence of significant sea-level fluctuations or sea levels significantly higher than those at present during the late Holocene. On the basis of ^{14}C dates from the Guiana coastal plain, Brinkman and Pons (1968) and Roeleveld and van Loon (1978) generated a sea-level curve for the region (fig. 11).

Subsurface data from the Orinoco Delta indicate that the late Pleistocene to Recent sea-level history can be summarized as follows (compare Kidwell and Hunt, 1958; Van Andel, 1967; Stanley and Warne, 1993): at approximately 18,000 yr B.P., during the glacial maximum, sea level was low such that the shoreline was located near the present shelf edge, and the delta was forming along the continental slope (fig. 23a). From ~18,000 to 10,500 yr B.P., glaciers melted causing sea level to rapidly rise, and the shoreline to migrate landward across the shelf, reworking alluvial-plain deposits that covered the shelf, producing a blanket transgressive sand locally punctuated by incised valley fill (fig. 23b). A radiocarbon date of 9,500 yr B.P. at the top of the transgressive sand in the Pedernales area served to bracket the sea-level history in the region (Kidwell and Hunt, 1958). By ~7,500 yr B.P. the rate of sea-level rise decelerated such that the rate of sediment input from the Orinoco River and by longshore transport along the Guiana coast was sufficient for delta accumulation to begin. By ~6,000 yr B.P., sea level had reached its present level, fostering conditions conducive to delta progradation. The increase of montmorillonite with respect to illite with increasing depth in boreholes in the Pedernales area provides evidence that the deeper samples were deposited at a considerable distance offshore and that the delta gradually advanced to its present position (Van Andel and Postma, 1954; Kidwell and Hunt, 1958).

Nota (1958) identified several terraces on the western Guyana shelf that he related to pauses in the overall late Pleistocene to early Holocene sea-level rise. He identified an especially conspicuous feature at 22 m depth. On the basis of shallow geophysical data on the shelf, Butenko and Barbot (1984) identified three phases to the Holocene transgression. They identified interruptions in the transgression at 80 to 87, 42 to 62, and 20 to 37 m bmsl. The younger-Drayas event at ~11,000 yr B.P. (Fairbanks, 1989; Roberts, 1998) is widely recognized as causing a pause or reversal in the overall rapid rate of sea-level rise and may be associated with the terrace at 22 m.

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 oceanic water entered the Gulf of Paria through Boca de Dragón ~13,000 yr B.P. but did not begin to flow through Boca de Serpientes until sea level reached 45 m below present stand, approximately 9,500 yr B.P. They proposed that flow through Boca de Serpientes was interrupted for an undefined period of time by a minor sea-level drop until ~1,500 yr B.P., when sea level rose and the hydraulic connection between the Atlantic shelf and Gulf of Paria was reestablished. Geohidra Consultores, C.A. (1997b), proposed that there was a major change in the coastal current regime ~3,000 yr B.P. Geohidra Consultores, C.A. (1997b), determined that circulation through Boca de

Serpientes was reestablished ~1,000 yr B.P., promoting littoral current processes along the Orinoco coast and development of mudcapes.

Neotectonism

Currently the Orinoco Delta is seismically quiescent. The only recorded seismic activity of consequence was in 1940 along the boundary of the Guayana Shield, when a magnitude-6.0 (Richter) earthquake occurred. In the Gulf of Paria region, on the other hand, reports of magnitude-6.0 (Richter) earthquakes are widespread and common (INTEVEP, 1978; Case and Holcombe, 1980; Geohidra Consultores, C.A., 1997b).

Principal structural features in the delta, mostly identified by geophysical surveys, include the diapiric Pedernales anticline and associated mud volcanoes (compare Kidwell and Hunt, 1958; Aslan and others, app. 2) and the Sabeneta syncline and Macareo anticline along the central delta coast (fig. 17). Faulting in the lower Orinoco River determines the course of the main channel and defines the boundary between the Guayana Shield and the EVB. Robertson and Burke (1989) proposed that branches of the Urica (EVB) and Soldado (Gulf of Paria) faults extend across the delta.

Three regional structural trends influence the delta: (1) northeast-trending normal faults and lineaments near Tucupita that may reflect deep-seated Precambrian basement faults related to those of the Guayana Shield, (2) northeast-trending and southeast-verging thrust faults of the Monagas region (for example, San Juan fault), Gulf of Paria, and Trinidad, and (3) northwest-trending right-lateral transform faults of the Monagas region and Gulf of Paria (for example, Soldado and Los Bajos faults) (fig. 17). The latter two structural elements are related to transpressional stresses along the South American–Caribbean plate boundary. Collectively these structures probably influence the locations and orientations of many of the delta's channels.

Shallow geophysical surveys on the Orinoco Delta shelf indicate that most of the Pleistocene strata beneath the shelf is uniformly dipping ~8 to 23 m/km to the north or northwest or is flat lying (McClelland Engineers, 1979). McClelland Engineers (1979) reported gently folded strata east of Boca Araguao and toward the middle and outer shelf. Most of the folding on the middle and outer shelf appears to be related to a series of subparallel, northwest-trending faults that cross much of outer shelf (McClelland Engineers, 1979). Many of these faults have seafloor expressions in the form of scarps and linear seafloor troughs and appear to be active. Local seafloor relief across these faults ranges from 1 to ~48 m. Several faults are 10 to 20 km in length, and one is 60 km. Most appear to be normal, but several reverse faults have been recognized (McClelland Engineers, 1979). These faults are generally attributed to oversteepening and rotational slumping of Quaternary delta deposits rather than basement-controlled faulting (fig. 22a). Regional earthquakes may incite movement of these faults.

Several lineaments, which we interpret to be fault related, appear to influence the location and orientation of several delta distributaries, as well as the overall geomorphology and hydrology of the delta. In particular, we recognize three prominent northwest-southeast-oriented lineaments (fig. 57). The southwesternmost of these three lineaments extends northwest from the upper reaches of Brazo Imataca, crosses the head of Caño Macareo, passes by the Volcán dam, and parallels the western boundary of the Holocene delta plain. It is near the upper-lower delta transition zone and was recognized by Pees and others (1968). To the west-northwest of the delta, this lineament is coincident with the contact between the upland area known as the Mesas and the swampy Holocene coastal plain (figs. 18 and 57). A large number of lakes are located immediately northeast of the lineament and could reflect differential subsidence on the downthrown side of a fault. Low sinuosities of distributaries, such as Caños Macareo and Araguao northeast of the lineament, could reflect low channel gradients on the downthrown fault block.

The second, central lineament is nearly coincident with a large portion of Caño Manamo and marks the northeast limit of the widespread interdistributary lakes. Southwest of this lineament, the major distributary channels are oriented in a radiating pattern, whereas to the northeast these channels are remarkably parallel and oriented to the northeast. This lineament marks a major deflection in Caño Macareo and the fork of the Río Grande and Caño Merejina.

The northeasternmost of the three northwest-southeast-oriented lineaments is generally coincident with the boundary between the upper and middle delta plain and major change in orientation of Caño Manamo and the Río Grande. This lineament apparently is a branch of the Soldado fault (figs. 17 and 57).

In addition to these three northwest-southeast-oriented lineaments, a generally east-west-oriented lineament is coincident with the boundary between the geomorphically and hydrologically distinct southeast (Río Grande) and the central and northwest delta. This lineament appears to be related to an extension of the Urica fault (figs. 17 and 57). This lineament and associated hydrogeomorphic boundary may also be influenced by an extension of the El Pao fault of the Guayana Shield (fig. 17).

Extension of the rather straight Punta Pescadores mudcape into Boca Serpientes, despite the strong northwest-directed Guayana Current, is attributed to differential uplift along the Macareo anticline (Pees and others, 1968; Geohidra Consultores, C.A., 1997b). In addition, numerous gas seeps and one petroleum seep along Punta Pescadores suggest concentration and upward migration of hydrocarbons along tectonically induced fissures and vents (Geohidra Consultores, C.A., 1997b).

Late Pleistocene to Holocene Climate

Largely on the basis of identification, mapping, and analysis of extensive, relict dune fields in northeastern South America, several authors have determined that a large part of the Orinoco River basin was more arid during the late Pleistocene, ~11,100 to 12,300 yr B.P., and that extremely arid conditions prevailed in the Llanos region (Tricart, 1974a, b; Roa, 1979; Schubert, 1988). Schubert (1988) proposed that the drier Pleistocene climate promoted expansion of savannas across northeastern South America such that the tropical rain forests that characterize the modern uplands were restricted to enclaves (probably areas with a high ground-water table). Analysis of South Atlantic deep-sea cores reveals the widespread occurrence of upper Pleistocene (upper Wisconsin; ~19,000 to 11,500 yr B.P.) arkosic sand layers in the abyssal plains adjacent to the mouths of the Amazon and Orinoco Rivers, indicating regional semiarid to arid conditions during that time (Damuth and Fairbridge, 1970). Damuth and Fairbridge (1970) and Latrubesse and

Ramonell (1994) discussed the oceanic and barometric conditions that produce semiarid to arid conditions during glacial and tropical conditions during interglacial periods.

Peats in the high plateaus of the Guayana Shield (Schubert, 1988) and forest vegetation in the Lake Valencia Basin (Leyden, 1985) began to develop ~8,000 yr B.P., providing evidence that humid tropical conditions were established in northeastern South America during the early Holocene. Meggers (1979) identified a generally cooler and drier period in northeastern South America between ~4,000 and ~2,000 yr B.P., which was sufficient to induce widespread changes in forest biota. Eisma and others (1991) and Sommerfield and others (1995) correlated sequences of late Holocene deposition/nondeposition along the northeastern South America coast with 100- to 1,000-yr scale wet/dry periods in the Amazon and Orinoco basins. Trade-wind dynamics also influence long-term deposition and erosion cycles along the Guiana coast (Rine and Ginsberg, 1985; Wells and Coleman, 1981b; Eisma and others, 1991). Eisma and others (1991) proposed that dry periods in the Colombian Andes from 200 to 400 yr B.P., from 600 to 900 yr B.P., and a fluctuation at ~1,300 yr B.P. reduced sediment discharge from the Amazon River, promoting development of cheniers along the Guiana coast (figs. 7, 8, and 58). Eisma and others (1991) concluded that during wet periods, large volumes of mud discharged from the Amazon and Orinoco Rivers and were deposited along the Amazon, Guiana, and Orinoco inner shelf and coast. During drier periods, mud discharge from the Amazon and Orinoco Rivers is reduced and the mud supplied by migrating mudbanks becomes more important to littoral transport of sediment to the Orinoco Delta coast. The dual processes of transport and supply of littoral sediment—advection by littoral current along the shelf and mudbanks along the coast—tend to modulate supply of Amazon sediment to the Orinoco coast during climatic oscillations. Eisma and others (1991) concluded that the Orinoco Delta is currently in a wet, depositional phase that began ~700 yr B.P. (fig. 58).

Arid conditions that dominated the early Pleistocene produced a poorly defined drainage network across large portions of the Orinoco basin. For example, the Orinoco/Río Negro headwater region (fig. 13) of the Orinoco/Amazon basin drainage divide remains poorly defined, such that surface water sometimes flows to the Amazon and other times to the Orinoco. The drainage network in the partly reworked eolian deposits of the Llanos is poorly developed, such that removal of local rainfall is insufficient and widespread flooding is common during the wet season. The drainage network in turn influences the magnitude and duration of water and sediment discharge to the delta.

Largely because subsidence has buried earlier Holocene deposits, the Holocene history derived from analysis of the Guiana coast is not readily apparent in the Orinoco Delta. Wells and Coleman (1981b), Rine and Ginsberg, (1985), and Eisma and others (1991) demonstrated that climate directly influences physical processes, which in turn are recorded in the sedimentary record along the Amazon, Guiana, and Orinoco coast. Most researchers concur that, at any given time during the Holocene, climate was relatively uniform across northeastern South America. Hence, the climatic oscillations outlined in figure 58 should provide a template for analysis of the Holocene stratigraphy of the Orinoco Delta as more subsurface information becomes available.

Summary of Modern Orinoco Delta Evolution

Late Pleistocene (~18,000 yr B.P.)

The climate was much more arid in the late Pleistocene than at present, the region was largely covered with dryland savanna vegetation, and eolian dune formation was widespread (Tricart, 1974a, b; 1985; Roa, 1979; Schubert, 1988). Sea level was as much as 120 m lower than the present stand. As a result, the coastline was positioned along the present shelf edge, and deltas were forming along the upper slope (fig. 23a). Inland, the sea-level lowstand induced downcutting of the river channels to form relatively narrow, deep, incised river valleys, and large volumes of coarse sediment were transported to the coast. Offshore submarine canyons and deep-sea fans developed.

Because the climate was semiarid to arid, there was little vegetation to hold sediments and the Orinoco River was characterized by coarse, braided-stream deposits. River discharge was much lower and more erratic than at present, but snowmelt from the Andes provided a perennial source of discharge through the semiarid to arid region. The river was restricted to a narrow, incised valley west of the present-day delta apex but expanded into a broad braid plain across the coastal plain (present-day shelf). We infer that sediment was delivered to the coast through a number of braided river channels whose position changed over time. Therefore, the coast comprised a series of coalesced depocenters distributed across a broad region of the coast. The shelf was narrow and, therefore, waves and littoral currents reached the coast without being attenuated. These coastal-marine processes performed substantial geomorphic work along the coast, reworking coarse material in the nearshore and transporting finer material offshore. Because the shelf was narrow and steep, a significant portion of the sediment was transported to the deep ocean by density-current processes. Furthermore, incised valleys locally debouched onto the slope and broad, coalesced, deep-sea fans developed. Therefore, widespread deposition of sand occurred in the abyssal plain. A number of coral reefs formed near the coast during this period, indicating that, at least along portions of the coast, suspended sediment concentrations in the marine surface water were low. The Gulf of Paria was a closed inland basin during this time, with an evaporite (gypsiferous) lake at its center.

Late Pleistocene to Holocene (11,000 to 9,500 yr B.P.)

During this period, melting of continental glaciers induced a rapid, eustatic sea-level rise. Climate was probably transitional between arid and tropical, with substantial, short-term oscillations that are typical of glacial-interglacial transition periods (Heusser, 1993; Roberts, 1998). The rapid rise in sea level caused the shoreline to migrate landward from the shelf edge. By ~9,500 yr B.P. the coastline was landward of its present position (fig. 23b). The overall rise in sea level was interrupted by short-term pauses or reversals (Bard and others, 1996; Roberts, 1998), resulting in development of terraces along the present-day shelf.

In the Orinoco drainage basin, the majority of the sediment transported to the channel system was incorporated into the alluvial valley to adjust river-base level to the higher sea-level stand. Hence, initially, relatively little river sediment was delivered to the coast during this period, and estuaries formed at the mouths of the incised rivers.

As the late Pleistocene to Holocene sea level rapidly rose and the shoreline migrated landward, the incised river valleys filled with fluvial and transgressive sediments, and preexisting coastal-plain deposits were reworked by coastal and shallow marine waves and currents to form a widespread, relatively thin (<10 m) layer of sand and minor silt and much thicker incised valley fills. By ~9,500 yr B.P., sea level was ~30 m below present (fig. 11), the hydraulic connection between the Atlantic shelf and the Gulf of Paria was established, and the area of the present-day Orinoco delta plain and shelf was covered by shallow sea. 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.

Early Holocene (~6,500 yr B.P.)

By the early Holocene (~6,500 yr B.P.) the climate was generally warm and wet, much like it is at present. However, millennial-, centennial-scale, and decadal-scale climatic (wet-dry) oscillations characterized the region (fig. 58). The early Holocene sea-level rise had terminated by this time, sea level was near its present elevation, and coastline positions were stabilized. Because the northeastern South America climate was similar to that at present, the Orinoco River wet/dry season discharge cycle resembled the current cycle.

The modern Orinoco Delta was well established by 6,500 yr B.P. (fig. 23c). The delta plain was relatively small, although the volumes of Orinoco River water and sediment delivered to the delta were the same as at present, and so the delta plain and coast were more strongly river dominated than at present. Moreover, the large volumes of erodible sediments that were generated and stored within the drainage basin during the arid late Pleistocene were entrained and transported to the delta. This period of high sediment influx to the delta occurred after sediments were no longer needed to adjust river base to the modern sea level and before tropical vegetation cover and soil development greatly reduced the supply of sediment to the delta. The high sediment discharge induced elevated sediment accumulation rates and rapid infilling of the deep-water portions of the depocenter. High early Holocene sediment discharge further enhanced the riverine influence across the delta plain during this time, resulting in typical river-dominated delta-plain and coastal features, such as well-developed levees and sand-rich bar promontories at the mouths of major distributaries. There were several active distributaries during this period (although the number and locations are uncertain). Individual distributary-channel discharge and position varied as the delta-plain slope varied during the progradation.

Because climate and sea level were similar to those at present, regional marine wave and current regimes were also similar to those at present. However, the Orinoco coast was considerably west of the present shoreline (fig. 23c) so that (1) the delta was located in a broad embayment and therefore shallow marine processes were less dominated by the strong Guayana littoral current and (2) there was not the constriction of littoral flow through Boca de Serpientes at that time, and therefore nearshore littoral flow was not as focused along the central delta coast as it is at present. Tides were probably one of the principal marine coastal process at that time, because the area was still and embayment and therefore waves were attenuated.

Middle Holocene (~4,000 yr B.P.)

The climate continued to be generally warm and wet, with millennial-, centennial-scale, and decadal-scale climatic (wet-dry) oscillations (fig. 23d). The delta-plain area continued to expand so that riverine influence diminished relative to tide and direct rainfall. As a result, promontories at the mouths of distributaries diminished and estuaries began to develop. In addition, peat plains became common in the interdistributary basins.

The delta continued to prograde eastward, infilling the EVB embayment and narrowing the constriction at Boca de Serpientes, which progressively increased the influence of littoral currents on coastal evolution, such that locally chenier plains developed. However, tides and river discharge continued to be the predominant coastal processes. There were several active distributaries during this period (although the number and locations are uncertain). Individual distributary-channel discharge and position varied as the delta-plain slope varied during the progradation.

Late Holocene (~2,000 yr B.P.)

After the relatively cool and dry period between 4,000 and 2,000 yr B.P., the climate became generally warm and wet, with relatively well documented millennial-, centennial-scale, and decadal-scale climatic (wet-dry) oscillations (fig. 58).

River hydrology assumed its modern character of large, highly seasonal water discharge (fig. 16; table 3). 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 the dominant processes. Because there was little accommodation space in the upper delta plain, lateral sedimentation/erosion processes were predominant, whereas in the middle and lower delta, where subsidence rates were higher, vertical accretion processes predominated in the interdistributary basins. However, distributary-channel development, abandonment, and infilling processes were important processes throughout the delta.

Interpretation of remote-sensing images and geologic/geo-environmental mapping and stratigraphic analysis of radiocarbon-dated shallow borings provide evidence that major distributaries comparable in size to Caños Manamo and Macareo evolved, avulsed, and infilled on a regular basis during the late Holocene (fig. 36) (Van Andel, 1967). Many of the blackwater distributaries, such as Caños Pedernales, Cocuina, Tucupita, and Guayaro, are interpreted as underfit streams that occupy abandoned-channel systems formed by larger distributaries, probably comparable in size to Caño Manamo. Several of the small northeast-flowing blackwater distributaries also probably represent underfit streams that occupy abandoned-channel systems of coastal-plain rivers, such as Río Morichal Largo and Río Tigre, that were active in the northwestern delta prior to establishment of Caño Manamo (Van Andel, 1967).

Evolution of the Western Delta

Evidence of late Holocene distributary avulsion

The clearest evidence of avulsion by major distributaries in the western delta is their bifurcation pattern (fig. 59). Minor distributaries branch off from major distributaries such as Caños Manamo and Macareo and flow along separate courses to the Atlantic Ocean. For example, Caño Tucupita branches off of Caño Manamo at Tucupita and flows northeast toward Boca de Macareo, whereas Caño Manamo discharges into Boca de Guanipa. Similarly, Caño Cocuina diverges from Caño Manamo at Tucupita and flows to Barra de Cocuina. Caño Pedernales branches from Caño Cocuina several kilometers north (downstream) of Tucupita at La Horqueta and flows to Boca de Guanipa along a course that generally parallels Caño Manamo (fig. 59).

Similarities in meander sizes and wavelengths among several of the major and minor distributaries support the idea of episodic distributary avulsion. For instance, not only do Caños Pedernales and Manamo follow parallel routes to Boca de Guanipa, but their similar meander dimensions suggest that the discharge of Caño Pedernales may have formerly been comparable to that of Caño Manamo.

Additional evidence of distributary avulsion is provided by detailed mapping near the mouths of Caños Cocuina, Capure, and Pedernales. Mapping shows that the modern channels have natural levee-flank depressions that separate mangrove and transitional forests along channel margins from more distal interdistributary forested swamps. Field observations demonstrate that the levee-flank environments are slightly lower in elevation than are proximal areas of the interdistributary forested swamps, and remote sensing images show that these depressions parallel modern channels near the coast. These relationships suggest that the levee-flank depressions represent the margins of abandoned channels that were 1 to 2 km wide, substantially wider than the present-day channels and similar to the dimensions of the lower reaches of modern Caño Manamo.

Caños Manamo-Pedernales-Cocuina-Tucupita channel systems

We infer that avulsion among the Caño Manamo-Pedernales-Cocuina-Tucupita channel systems occurred frequently in the western delta during the late Holocene. Channel systems such as Caño Manamo have probably experienced more than one episode of Holocene abandonment and reoccupation, complicating the reconstruction of an accurate chronology of fluvial activity in the region and suggesting significant implications for developing hydrologic and sediment models for the region.

The delta-plain stratigraphy northwest of Tucupita partially constrains the timing of recent fluvial activity and provides evidence of important environmental changes in the western delta during the late Holocene (fig. 60). Delta-plain deposits separating Caños Manamito and Cocuina consist of three units: (1) basal bioturbated muds, (2) overlying vegetal-rich deposits including clayey peat, and (3) a shallow veneer of mottled muds and muddy sands. The lowermost bioturbated muds are up to 5 m thick and contain abundant plant remains and authigenic pyrite. Grass fibers, weakly expressed laminations, and organic fragments of probable charcoal are locally present. Overlying this unit are 1 to 2 m of organic-rich deposits that include dark-brown peat and clayey peat, as well as gray to dark-gray organic muds (fig. 60). The peat is 0.5 to 1.0 m thick, fibrous, and extends laterally for up to several kilometers. Dark-gray organic muds overlie the peat and at several sampling sites, a very dark brown (10YR 3/2-3/1) organic mud is present at depths of 0.75 to 1.00 m. This deposit is darker and presumably more organic rich than the underlying sediments and probably represents a buried A horizon of a wetland soil. The youngest unit consists of a thin veneer of gray mottled muds and wedges of brown mottled muddy sands (fig. 60). The wedges of brown muddy sand thin from a maximum thickness of ~3 m near channel margins to less than 0.5 m over distances of 1 to 2 km within flood basins. The brown muddy sands have common root pores with gray reduction haloes and are extensively bioturbated. The gray mottled muds are typically <1 m thick and locally veneer the brown muddy sands adjacent to Caño Cocuina. The gray muds contain few to many yellow-brown mottles and iron-oxide stains along root traces. Small iron-oxide nodules are also common and pyrite is rare in the gray muds. The muds are less plastic and have a firmer consistency than do the underlying organic-rich muds.

The muddy texture and abundance of organic remains and pyrite indicate that the lower gray to dark-gray bioturbated muds accumulated in perennially saturated reducing environments, such as poorly drained marshes. Although previous studies have suggested that these pyrite-rich muds are marine and reflect the widespread incursion of saltwater as far inland as Tucupita, authigenic pyrite is a common constituent of reducing freshwater and brackish environments, including the floodplain and delta plain of the Mississippi (Ho and Coleman, 1969; Krinitsky, 1969). Furthermore, marine-shell material was never found in any of the upper or central delta-plain deposits. Grass fibers in some upper Holocene intervals near Tucupita provide evidence of wetland marsh environments, whereas the bioturbated muds, which contain few grass fibers and many large plant fragments, could represent marsh or transitional forested swamp environments. Radiocarbon dating of these deposits suggests that they are older than ~5,000 yr B.P. and were accumulating by at least 6.5 yr B.P. (fig. 61). On the basis of a limited number of radiocarbon dates, we infer that these sediments accumulated in fresh- to brackish-water environments at a relatively rapid rate of 2 to 3 mm/yr. Peat deposits overlying the bioturbated muds represent a dramatic decrease in clastic input to the basin, which, along with high water levels, led to peat formation and widespread organic sedimentation. Radiocarbon dates show that the basal ages of the peat range from 4,920+40 yr B.P. to 5,300+90 yr B.P., and the youngest ages from the upper peat section range from 3,700+50 yr B.P. to 3,880+80 yr B.P. One sample provided a date of 3,050+50 yr B.P. On the basis of these data, we interpret the peat as a period of low clastic input and slow (~0.5 mm/yr) but widespread organic sedimentation that spanned ~2,000 yr (~3,000–5,000 yr B.P.). Organic muds overlying the peat represent a period of renewed clastic sedimentation in the Tucupita area, but this period of clastic input was again interrupted by a second episode of organic sedimentation, which produced the very dark gray organic mud. A single radiocarbon date of 1,410+70 yr B.P. was acquired from this deposit. The youngest deposits represented by the brown muddy sands and gray mottled muds are interpreted as natural-levee and flood-basin deposits associated with overbank flooding of Caños Manamito and Pedernales.

Peat and organic mud buried beneath natural-levee deposits of Caños Manamito, Cocuina, and Tucupita near Tucupita provide maximum-age estimates for the establishment of the channel systems. The radiocarbon ages for the peat near Tucupita clearly show that the Caño Manamo/Manamito and Cocuina channel systems were not established until after 3,000 to 4,000 yr B.P. (fig. 60). Because Caño Pedernales diverges from Caño Cocuina downstream of the stratigraphic cross section, these maximum-age estimates also apply to Caño Pedernales. A single radiocarbon date of 4,780+80 yr B.P. was determined on a thin clayey peat buried by gray mottled muds and sandy muds located along the outer bend of a large meander of Caño Tucupita near Tucupita (fig. 61). The muds and sandy muds are interpreted as flood-basin overbank and distal natural-levee deposits, respectively. The radiocarbon age date is remarkably consistent with radiocarbon ages of peats elsewhere in the Tucupita region and lends support to the idea that the period 3,000 to 5,000 yr B.P. represents an episode of widespread peat development in the western upper delta. This period of peat formation also predates the establishment of major channel systems, such as Caños Manamo and Pedernales. This interpretation, however, does not imply that older channel systems were never present in the Tucupita area. The age and stratigraphy of the peat simply suggest that the deposits of older early Holocene channel systems are buried.

We infer a maximum age of ~1,500 yr for the Caño Manamo-Manamito channel system on the basis of a radiocarbon-dated sample (1,410+70 yr B.P.) from the organic-rich mud (buried A horizon) that overlies the peat and passes laterally beneath natural-levee deposits of Caño Manamito (fig. 60).

Several radiocarbon ages from core samples elsewhere in the western delta support the inference of recent establishment of the Caño Manamo-Manamito and Pedernales channel systems. Along the banks of Caños Pedernales and Manamo cores show 1 to 2 m of mottled muddy sands and sandy muds that we interpret as natural-levee deposits (figs. 61b, c and 62). Radiocarbon ages of plant remains in dark-gray muds located beneath the natural-levee deposits range from 1,620+40 yr B.P. to 1,940+50 yr B.P. These ages support the interpretation that the Caño Manamo-Manamito and Caño Pedernales channel systems were established by ~1,500 yr B.P., similar to the interpretations based on the radiocarbon data from the Tucupita area. Whereas the size difference between the modern channels of Caños Manamo and Pedernales shows that the discharge of Caño Manamo has been historically greater than that of Caño Pedernales, this relationship may have been reversed periodically over the past ~1,500 yr.

Coastal-plain channel systems

Remote-sensing images show that present-day Caños Manamo and Pedernales flow northwest and crosscut older and smaller channel systems that flowed northeast across the western delta (fig. 62). The small size of meanders and orientation of the channel courses that include Caños Capure, Caijarina, Güinamorena, and Simoina suggest that they are abandoned-channel courses of coastal-plain rivers such as the Río Morichal Largo and Río Tigre. These coastal-plain rivers presumably flowed northeast across the delta to Barra de Cocuina. These observations support Van Andel's (1967) interpretation that coastal-plain rivers have contributed significantly to the development of the northwestern delta and that avulsion of Caño Manamo to its present-day location transformed the Río Morichal Largo and Río Tigre from coastal-plain rivers that debouched directly into the Atlantic Ocean or Gulf of Paria.

Sands, muddy sands, and interbedded sands and muds located ~4 m below the land surface in cores acquired on channel margins of Caños Manamo and Pedernales (figs. 61b, c and 62) are interpreted as buried channel deposits of the coastal-plain rivers. Radiocarbon dates of 2,520+50 yr B.P. from wood fragments in muddy sands near the base of the Caño Pedernales core and 1,940+50 yr B.P. on plant material in muds overlying channel deposits in the Caño

Manamo core suggest that these channels were abandoned ~2,000 to 2,500 yr B.P. (fig. 61b, c). Several peat deposits overlying gray muds in the central delta have basal ages that range between 2,800 and 3,290 yr B.P., which suggests that clastic sedimentation in this region ended ~3,000 yr B.P., an age generally consistent with the abandonment of the coastal-plain river channel systems. Conversely, the muds underlying the central-delta peats probably represent clastic overbank deposits associated with the coastal-plain rivers and suggest that these channels were active prior to ~3,000 yr B.P.

Caño Macareo-Caño Guayaro channel system

Similar to that of Caño Manamo, the Caño Macareo channel system also appears to have been established recently, probably since ~1,000 yr B.P. Remote-sensing data indicate that prior to the establishment of the modern course of Caño Macareo, this channel flowed northeast from the delta apex to Boca Mariusa through Caños Guayaro and Caño Caiguara (figs. 36a, 59, and 63a). The presence of several minor distributaries connecting Caños Guayaro and Mariusa further suggests that this older channel system may have included precursors of the modern Caño Mariusa channel system.

Caño Macareo established its present course by avulsing from Caño Guayaro and reoccupying a portion of the Caño Tucupita channel system, which merges with the modern course ~30 km inland from the coast (fig. 63). This avulsion would have dramatically reduced fluvial discharge to Boca de Mariusa and may have allowed northwest-directed littoral currents to prograde the Punta Mariusa mudcape and partially fill the bay (fig. 63b). Mudcape progradation and bay filling continues today (fig. 52). Conversely, establishment of the modern course of Caño Macareo and increased fluvial discharge to Boca de Macareo could explain why the Punta Pescadores mudcape has not prograded across the bay. Although the timing of the Caño Macareo avulsion is not well constrained, a radiocarbon age of peat buried by crevasse splay deposits of Caño Macareo upstream of the Caño Macareo-Guayaro diversion provides a minimum age of 930+40 yr B.P. (fig. 49c).

We infer that both Caño Manamo and Caño Macareo avulsed westward across the delta plain during the Holocene. Recent westward shifting of major distributaries is also supported by differences in the types of interdistributary flood basins that are located between Caños Macareo and Manamo. Topographically high flood basins are abundant near Caños Macareo and Cocuina, and proportions of topographically low flood basins increase to the west. This change indicates that western flood basins are in an early stage of infilling related to the recent establishment of the Caño Manamo channel belt. In contrast, eastern flood basins have filled more completely because of previous episodes of channel activity and overbank sedimentation associated with older channel belts.

Late Holocene Evolution of the Northwest Delta Coast

Geologic mapping and stratigraphic relations suggest that the northwestern delta consists of a series of Holocene mudcapes and bays that partially or completely filled as the delta prograded during sea-level highstand. Evidence of former bays includes large areas of mangrove swamp near the coast that are flanked by transitional forests and herbaceous swamps such as along the lower reaches of caños entering present-day Barra de Cocuina and Boca de Guanipa. Mangrove forest developed in depressions that outline margins of former shallow bays and lower reaches of distributaries that flowed across herbaceous swamps and contributed to bay filling. Caños that converge south of present-day Barra de Cocuina, including Caños Caijarina, Capure, Cocuina, Cocuinita, and Guarina, also suggest that this area was a shallow bay similar in size and shape to Boca de Guanipa (fig. 36a).

The orientation of the coastal-plain river and Orinoco distributary-channel systems suggests that Boca de Guanipa was not the only major discharge point for the delta's distributaries. Additional geomorphic evidence of the presence of former bays along the northwest coast of the delta includes complex networks of dendritic channels along the upper reaches of Caños Cocuina, Cocuinita, and Caño Manamo (for example, Caño Guamal) (fig. 64). The geometry of these channel networks strongly resembles that of tidal channels. At present these channels are partially filled with dense aquatic vegetation and show little evidence of fluvial or tidal current activity. However, their presence indicates that they are relict tidal channels that were probably active when the precursors to Barra de Cocuina and Boca de Guanipa existed and the shoreline was at least 10 km landward of its present-day position.

Large arcuate-shaped herbaceous swamps on the northwestern delta plain are interpreted as old mudcapes (fig. 36a). These features, similar in size and shape to modern mudcapes, deflect the lower reaches of major and minor distributaries to the northwest (fig. 59). Whereas modern coastal mudcapes are covered by mangrove forest and are affected by marine processes, the herbaceous swamps are located as much as 30 km inland and contain abundant freshwater peat. We infer that the old mudcapes may have been upper Holocene shoreline features that were abandoned as the delta prograded seaward (fig. 54). Shoreline progradation progressively removed mudcapes from marine influences, including clastic sedimentation; continued subsidence would have transformed these areas into shallow, sediment-starved flood basins. Vertical accretion of organic sediments accompanied by little or no clastic sedimentation probably created acidic and nutrient-poor conditions, which allowed herbaceous vegetation to replace mangrove forests. Perennial saturation and subsidence promoted widespread peat accumulation. Danielo (1976a, b) noted that peat deposits also overlie mangrove sediments in several areas elsewhere in the delta, and similar vertical successions of herbaceous swamp peats and mangrove clays attributed to shoreline progradation are reported from tropical peat swamps in Indonesia (Anderson, 1964; Anderson and Muller, 1975).

We infer that this period of early delta progradation and the development of broad shallow bays located slightly landward of present-day Barra de Cocuina and Boca de Guanipa occurred 3,000 to 5,000 yr B.P. During this time, major Orinoco distributaries and coastal-plain rivers flowed into Barra de Cocuina, rather than Boca de Guanipa (fig. 36a). Some time after ~3,000 yr B.P., distributary avulsions established the Caño Manamo and Pedernales channel systems, which flowed into Boca de Guanipa (fig. 36b). Avulsion of Orinoco distributaries to the west would have captured the flow of coastal-plain rivers and greatly reduced fluvial discharge to Barra de Cocuina. In the absence of fluvial currents, northwest-directed littoral currents led to mudcape development and progradation and partial filling of the bay (fig. 36b). As the mudcape prograded across the former Barra de Cocuina, it deflected the course of Caño Cocuina northwest.

Continued discharge into Boca de Guanipa and the establishment of Caño Macareo within the last ~1,000 yr contributed to sedimentation in Boca de Guanipa and Boca de Macareo, but the areal extent of Holocene mudcapes suggests that the majority of coastal progradation was accomplished by mudcape development and bay filling (fig. 36c; for example, Barra de Cocuina). The former Barra de Cocuina has almost completely filled because of a combination of avulsion of Orinoco distributaries westward and mudcape progradation (fig. 36c). Similar patterns of coastal progradation continue today in areas such as Punta Mariusa, where avulsion has significantly reduced fluvial discharge and mudcape growth is rapid.

Integration of the coastal and avulsion histories of the northwestern delta reveals that episodes of fluvial activity and shoreline change 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. Bay filling probably occurs through a combination of littoral-current activity and mudcape progradation. For example, while the late Holocene channel systems of Caños Cocuina, Cocuinita, Caijarina, Guarina, and Capure were active and discharged into Barra de Cocuina, the estuary was maintained by the combination of fluvial and tidal currents similar to the situation in present-day Boca de Guanipa. Following avulsion and channel-system abandonment, Barra de Cocuina filled as a mudcape prograded northwest across the bay. Note that in the Orinoco Delta, coastal progradation occurs following avulsion and distributary abandonment. In contrast, coastal progradation in systems such as the Mississippi and Rhone Deltas are associated with active distributary-channel mouths (Coleman, 1982; Coleman and others, 1998; Roberts, 1998). In these systems, avulsion and distributary abandonment typically result in subsidence and widespread land loss. The key difference in the Orinoco Delta is that littoral currents supply large volumes of (both Amazon and Orinoco) suspended sediment that lead to mudcape development and coastal progradation in the absence of significant fluvial-sediment input.

Historical Sedimentation in Boca de Guanipa

Rapid sedimentation in Boca de Guanipa during the past ~40 yr is similar to patterns of coastal sedimentation that occur following an avulsion (fig. 65). Completion of the Volcán dam has significantly reduced discharge and sediment transport along Caño Manamo, and seasonal high flows no longer move sediments across the shallow bay and deposit them in deeper waters. Consequently, the bay is filling rapidly with sediment, as demonstrated by the historic development of large islands in the bay. This situation is similar to what occurs following an avulsion and is also analogous to the episode of bay filling that occurred in the former Barra de Cocuina. Because rivers such as Río Guanipa, Río Tigre, and Río Morichal Largo carry little sediment, most of the recent sedimentation in Boca de Guanipa is probably associated with littoral and tidal currents that are moving sediments into the bay. During periods of rising tide, waters from the mouth of Caño Manamo to Tucupita carry abundant suspended sediment, much of which probably accumulates within the channel now that seasonal flooding and sediment transport by fluvial currents has been dramatically reduced because of the construction of the Volcán dam on Caño Manamo. Rapid sedimentation in this area should continue until either the bay completely fills or discharge on Caño Manamo increases.

Human-Induced Changes in the Orinoco Delta

Deltas are transitional aqueous/terrestrial ecosystems that are the product of interaction and balance of numerous atmospheric, geologic, hydrologic, and biologic processes. Therefore, human activity has profound impacts on the ecosystem integrity of these river/coastal-plain environmental systems. Construction of the Volcán dam at Caño Manamo has significantly influenced the hydrology and ecology of the northwestern Orinoco Delta. In addition, clearing of forests for agriculture, grazing, and human habitation in the upper delta has also significantly impacted delta ecosystems.

The Volcán dam: the Volcán dam was constructed across Caño Manamo (fig. 2) in 1966 and 1967 to (1) protect Tucupita from flooding, (2) expand agriculture in the delta by controlling flood regimes and provide the opportunity for drainage of soils, and (3) raise water levels in the Río Grande to enhance commercial navigation (Colonnello and Medina, 1998). 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 and others, 1998; Colonnello, 1998). Sediment discharge through upper Caño Manamo has been essentially reduced to zero, so that the only sediment discharging from the lower distributary channel is supplied by upland streams flowing from the west, such as Río Morichal Largo and Río Tigre.

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, which, when drained, transforms into sulfuric acid, making the soils inhospitable for agriculture and even native plants.

There are many impacts associated with modification of the natural water and sediment discharge regime by the Volcán dam. Because the delta is a transitional aquatic/terrestrial environment, ecosystems and processes are strongly interrelated, and, therefore, the impacts of the Volcán dam tend to cascade from one set of processes and ecosystem to another. The impacts of the Volcán dam water regulation include:

- Upstream incursion of estuarine (brackish) water has induced a marked increase in upstream tidal flow of marine waters. 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). Moreover, expansion of mangroves has significantly increased rates of sediment entrapment, which in turn has accelerated expansion of channel islands in the lower Manamo and infilling of Boca de Guanipa (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 (fig. 27o). Moreover, upon dying, the floating vegetation settles to the bottom of caños, greatly accelerating infilling and loss of sandy channel-bottom habitat for fish and invertebrates.

The marked reduction in sediment discharge to the northwestern delta 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). However, bioaccumulation associated with peat development in the Orinoco Delta may be offset by the reduction in mineral sediment influx. Peat marshes, however, support different ecosystems than do wetlands with terrigenous soils. In addition, the hydrology, nutrient base, and water chemistry of the wetlands will be markedly different.

Water and sediment discharge through Caño Macareo has doubled as the result of dam construction, going 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 undoubtedly has increased overbank discharge of freshwater and suspended sediment into the adjacent interdistributary basin. The well-developed crevasse splays along upper Caño Macareo (figs. 27q, 34, and 47b) are at least in part the result of increased discharge. The effects of enhanced discharge on Caño Macareo, the adjacent interdistributary basins, and Boca de Macereo have not been studied.

Large portions of the upper delta have been cleared for grazing, agriculture, and habitation (figs. 4 and 27p). Clearing is concentrated downstream from the Volcán dam and along the elevated, well-drained levees. However, neither the extent nor impacts associated with human-induced clearing and burning in the delta have been systematically studied.

The Guri dam: a major dam was constructed across Rio Caroní at the site of the former Necuima waterfall (fig. 12). The reservoir, which has the world's fourth-largest capacity for hydroelectricity, stretches along 212 km of the lower Caroní and covers 4,260 km^2. The Caroní River accounts for 11 percent of Orinoco River discharge (Lewis, 1988), and the dam has had a modest but significant effect on discharge to the delta, reducing peak, and increasing low, discharge (fig. 66). Approximately 50 percent of the suspended sediment entering the Guri reservoir is retained (Lewis and Saunders, 1990). Changes in sediment discharge associated with the dam have not been determined, but because Rio Caroní historically had very low sediment concentrations and contributed <3 percent of sediment input to the delta, and therefore we infer that the impact of Guri dam on Orinoco Delta sediment budget is small.

SYNTHESIS OF WATER AND SEDIMENT DYNAMICS OF THE ORINOCO DELTA REGION

Surface-water and sediment dynamics (including rates of inflow, throughflow, and outflow, as well as the timing, frequency, and duration of inundation and/or saturation) are the controlling factors in delta-ecosystem composition and long-term stability. Because deltas are transitional terrestrial/marine systems, it is essential to evaluate, integrate, and interpret regional water and sediment dynamics associated with both river and coastal systems. Evaluation and interpretation of river and coastal systems, and their interaction on the delta plain and coast, are essential for determining the influence of physical processes on delta-ecosystem integrity and for developing models to predict the impacts of changes in water and sediment flow on delta ecosystems.

The Orinoco River basin maintains a very high discharge:drainage basin-area ratio (table 3) largely because of high rainfall, the impermeable crystalline substrate of the Guayana Shield, and perennially high ground-water levels of the Llanos region. This high ratio promotes large seasonal fluctuations in annual stage and discharge and consistently low suspended-sediment concentrations in the tributaries, river, and delta (figs. 14 and 16; table 10). Large seasonal-discharge oscillations are also promoted by the location of the Orinoco basin in the northern portion of the ITPZ; seasonal rainfall distribution varies uniformly across the drainage basin so that peak (and low) discharge occurs simultaneously in all major tributaries. Wet/dry season oscillation in discharge in the lower Orinoco is significantly greater than in most major river systems and induces almost complete (freshwater) inundation of the delta for 2 to 3 months each year. Orinoco River discharge volumes, which rank third among world rivers, promote perennial inundation of ~80 percent of the delta plain, although tides, direct rainfall, and subsidence are also major factors in maintaining this vast wetland ecosystem complex.

Differential subsidence toward the coast promotes marine influence and vertical accretion processes in the lower delta. We infer that a secondary component of differential subsidence in the southern delta is a major determinant in the position of the Río Grande and has induced formation of the large estuary at Boca Grande (Nota, 1958). Neotectonic activity associated with features such as the Pedernales and Sebeneta anticline and Macereo syncline (fig. 17) significantly influences water and sediment dynamics of the coastal region. Diurnal tides, which influence the entire delta plain (fig. 24), enhance ecosystem variability by creating a spectrum of fresh to saline surface-water conditions, especially in the lower delta. The large rainfall volumes, which vary across the delta (fig. 28a), also contribute to hydrologic and ecosystem variability and are a principal water source in the central portions of the larger interdistributary basins.

Approximately half of the 1.5 to 2.1×10^8 tons/yr of Orinoco sediment is deposited on the delta plain (Meade, 1994). We infer that flood discharge is capable of transporting sand bedload within the principal distributary channels. Suspended load is mostly limited to silt and clay, and once overbank discharge begins, the transport capacity of the floodwater away from the channel diminishes and floodwaters are only capable of maintaining clay in suspension. According to Meade and others (1990), peak river-sediment discharge is not coincident with peak water discharge, which would diminish terrigenous-sediment transport to interdistributary-basin centers rather than promote the formation of broad mounds around the basin perimeters that further inhibit influx of sediments to the central basin areas. River-sediment concentrations are relatively low, even during flooding, and, therefore, many of the interdistributary basins in the middle and lower delta plain are sediment starved and sites of ombrogenous peat development. Because the Río Grande transports more than 85 percent of the sediment through the delta, the northwestern delta is especially sediment starved and supports extensive peat basins (fig. 33). This situation has been amplified by construction of the Volcán dam on upper Caño Manamo (fig. 25) (Bracho and others, 1998; Colonnello, 1998).

Flood discharge induces distributary-channel formation, but diurnal tides perform the majority of geomorphic work within the Orinoco channel network (Geohidra Consultores, C.A., 1997a, b; FUNINDES USB, 1998). Differences in distributary-channel geometry and resistance to flow result in significant differences in the timing of diurnal tide oscillations among channels. These out-of-phase tidal oscillations result in significant differences in water-surface elevations between adjacent channels, which induce development of the cross-channel network of caños that characterizes the delta plain (fig. 26). The channel network is dynamic, and evidence of the progressive channel avulsion, hydraulic isolation, and infilling are common across the delta (figs. 27b, d, and 36). Preliminary analysis of radiocarbon-dated sedimentary cores demonstrates that major distributaries, such as Manamo and Cocuina, are no more than 1,000 yr old. Historical aerial photographs of the Boca de Guanipa area demonstrate significant expansion of estuarine islands (that is, infilling of the estuary) during the past 45 yr (fig. 65). Analysis of the Guiana coast (Brinkman and Pons, 1968; Roeleveld and van Loon, 1978) indicates that large volumes of Amazon sediments have been transported northwestward along the northeast South American coast throughout the Holocene.

Sediment-accumulation rates appear to be greater in the early Holocene than in the middle and late Holocene (table 16); the higher rates probably reflect available accommodation space below effective wave and littoral current base or perhaps a less intense littoral current regime, rather than significant changes in rates of sediment input, sea-level rise, or subsidence. Similarly, because there was more accommodation space (deeper water) in the lower delta than in the middle and upper delta region during the early and middle Holocene, the (higher) rates of sediment accumulation in the lower delta reflect both the rates of infilling of deep-water areas as well as rates of subsidence. The arid climate during the late Pleistocene may have produced large volumes of easily erodible sediment in the Orinoco drainage basin, which was delivered to the delta as the climate became more humid in the early Holocene. As Boca de Serpientes has become more constricted, causing acceleration and intensification of littoral currents along the Orinoco Delta coast, mudcape development has increased, although the overall rate of delta progradation has decreased.

Approximately 50 percent of the sediment deposited along the Orinoco coast is derived from the Amazon River, 1,600 km to the south (fig. 67). The Amazon is an important sediment source, not only in terms of volume, but also in terms of its sediment supply (by longshore transport), tending to be constant throughout the year (as opposed to the highly seasonal Orinoco sediment discharge).

More than 85 percent of Orinoco discharge to the coast is through Boca Grande (fig. 25), and suspended sediment concentrations of Orinoco River water are very low, even during flood season. On the other hand, littoral marine waters flowing from the Guiana coast into Boca Grande contain high concentrations of suspended Amazon mud (Eisma and others, 1991). We infer that a buoyant, freshwater plume develops as the Orinoco River water encounters the dense, muddy marine waters (fig. 40b). Although development of freshwater plumes at the mouths of delta distributaries is common (Orton and Reading, 1993; Nemec, 1995). We infer that the buoyant suspension (or hyperpycnal) layer is especially well developed along the Orinoco coast because of the large density difference in the dilute river and sediment-rich marine water (figs. 40 and 67).

Largely on the basis of remote-sensing analysis (for example, fig. 40a), we infer that the buoyant Orinoco River plume is transported northwestward along the shelf and coast by the Guayana Current and eventually mixes with marine waters (Van Andel and Postma, 1954; Koldewijn, 1958; Nota, 1958). We infer that Orinoco and Amazon sediments mix just northwest of Boca Grande and are (1) transported landward by waves and tides and deposited along the Orinoco coast and shelf (McClelland, 1979), (2) transported through Boca de Serpientes and into the Gulf of Paria (Fugro Gulf, Inc., 1979; INTEVEP, 1981), or (3) transported northeastward along the south coast of Trinidad and then northward along the east margin of Trinidad (Koldewijn, 1958; fig. 67). Largely on the basis of volume estimates of Holocene sediments on the Atlantic shelf and Gulf of Paria, we infer that approximately half of the Orinoco/Amazon sediment is deposited as delta-front and prodelta deposits on the Atlantic shelf, half is transported through Boca de Serpientes and deposited in the Gulf of Paria, and a small percentage is transported along the eastern Trinidad coast and beyond into the Barbados Accretionary Complex and Caribbean Basin (fig. 67a).

Although tidal mud flats and mudcapes are principal features along the Orinoco coast, fluid mud layers, mudbanks, and extensive mud flats that characterize the Guiana coast are less developed along the Orinoco coast. We propose that discharge of large volumes of dilute freshwater at Boca Grande disperses fluid muds and thereby inhibits development of mudbanks along the Orinoco coast. We infer that disruption and fragmentation of the Guayana Current along the Orinoco shelf also inhibit development of mudbanks. It is of note that Danielo (1976) recognized mudbanks along the coast of Corocoro Island (mudcape) just southeast of Boca Grande but did not document them along the Orinoco Delta coast.

Although fluid muds are not prevalent along the Orinoco coast, field observations indicate that nearshore waters are muddy (figs. 35c, d, e, f, and 40a) and that the suspended sediment concentrations of 11 mg/L that have been documented along the coast (Monente, 1989/1990) are probably lower than what commonly occurs. Field observations and analysis of satellite imagery indicate that the central delta coast (between Boca de Araguao and Punta Pescadores) is prograding rapidly (figs. 40a and 67). We infer that development of the buoyant suspension plume along Boca Grande inhibits deposition and consequent delta progradation in the southeastern delta. In addition, we infer that progressive constriction of Boca de Serpientes as the Orinoco Delta has prograded eastward and has concentrated and accelerated littoral-current flow, which in turn has increasingly inhibited prodelta, delta-front, and delta-plain progradation along the northwestern delta. The relatively deep Boca de Serpientes channel (fig. 42) provides evidence of the strength of the littoral current as it accelerates through Boca de Serpientes.

The Gulf of Paria is a major depositional area for the Orinoco Delta. Subsurface data demonstrate that up to 70 m of Holocene sediment has been deposited in the basin (Van Andel and Postma, 1954; Fugro Gulf, Inc., 1979; INTEVEP, 1981). Water and sediment regulation at the Volcán dam has undoubtedly affected freshwater and sediment influx into the Gulf of Paria (fig. 25). Milliman and others (1982) estimated that approximately 2 percent of the Orinoco/Amazon sediment passes through Boca de Dragón and is deposited on the continental shelf and upper slope north of the Paria Peninsula (fig. 67a, b, c). Bowles and Fleischer (1985) identified Orinoco sediment as far north as the central Caribbean basin.

Although the Orinoco Delta is a largely pristine system, the building of the Volcán dam and the clearing of the upper delta have significantly influenced delta hydrology and ecosystems. Together, the dams at Tucupita and Guri tend to accentuate the estuarine character of the Orinoco Delta (FUNINDES USB, 1998). Continued subsidence will further accentuate the estuarine character of the northwestern delta.

RECOMMENDATIONS FOR FUTURE RESEARCH

A major goal of this report is to identify areas of research that will significantly enhance understanding of the sediment and water dynamics of the Orinoco Delta and the influence of these processes on ecosystem integrity. By being regional in perspective and comprehensive in approach this report provides a basis for identifying areas of research needed to (1) develop an environmental baseline that characterizes the current, natural delta ecosystem complex; (2) evaluate the influence of human-induced changes; and (3) generate engineering designs that will minimize negative environmental impacts associated with development.

Base Maps

Georeferenced, High-Resolution Satellite Image

BEG has significantly enhanced the potential for systematic analysis of the Orinoco Delta by generating a georeferenced Radarsat mosaic that has horizontal accuracy of <100 m, and spatial resolution of 30 m (fig. 1). We recommend generating a georeferenced Radarsat mosaic with 10-m horizontal accuracy and spatial resolution of less than 10 m. This image will be invaluable for geomorphic mapping and monitoring change in caños and along the coast. DGPS surveys used to georeference the high-resolution satellite image should be designed so that historical aerial photographs can also be georeferenced.

Georeferenced, High-Resolution Digital Terrain and Bathymetric Model

The delta plain is very low relief, and, therefore, existing topographic maps (10-m vertical resolution) are of limited value in evaluating delta geomorphology, hydrology, and ecology. Because of their importance to characterizing the environmental setting of the delta, recent environmental impact studies (Geohidra Consultores, C.A., 1997a, b; ENSR Venezuela, 1998; FUNINDES USB, 1998) have generated detailed bathymetric data of selected areas of the coast and distributary channels. However, these bathymetric studies cover only a small fraction of the delta and are not readily available in standardized digital format. Evaluation and, ultimately, protection of the Orinoco Delta ecosystem complex will be greatly enhanced by generating a comprehensive, high-resolution (5 m or less contour interval) digital-terrain and bathymetric model of the delta. The model can be used for

- geomorphic and geoenvironmental mapping and analysis, monitoring and analysis of geomorphic and ecological change (Warne and others, in press)
- defining distributary and tidal channel network more accurately

- defining and delineating ecosystems across the delta more accurately by draping satellite imagery on elevation data

- accurately extrapolating point-location data, such as shallow ground-water and surface-water monitoring information to other areas with similar landscape settings and elevation ranges, thereby enhancing the development of a comprehensive hydrologic model of the delta

- identifying tectonically induced topographic anomalies such as mud volcanoes, folds, and lineaments

- locating and defining former coast positions (for example, relict beach ridges) that will improve understanding of recent delta evolution

- evaluating coastal processes, including mud-flat, mudcape, and river mouth-bar development

- identifying areas of coastal progradation and erosion, as well as determining rates of shoreline, estuarine, and shallow-shelf change

- providing baseline data for development of hydrological and geomorphic models of the delta

- providing a base map for engineering and other projects in the delta.

We recommend that the digital-terrain and bathymetric model incorporate elevation data from the entire delta plain, major caños, estuaries, and shallow shelf.

Topographic mapping of the Orinoco Delta could be done in the context of an upgrading of the Venezuelan geodetic network and cartographic infrastructure. The technologies that are most suitable for topographic mapping in a remote area are GPS, airborne interferometric synthetic aperture radar (INSAR), and airborne laser terrain mapping (ALTM), also known as airborne LIDAR. The following steps are recommended:

1. Establish a fundamental network of integrated GPS satellite receiver stations for the nation. It would be composed of several (four to six) GPS stations distributed throughout the country, operating 24 h a day, remotely linked to a GPS-processing center in Cartografía Nacional. The processing center would contain computers, software, and data-archiving devices. Trained personnel would process the data on a daily basis. This network would support national and private development and scientific research.

2. Create a GPS station at Tucupita in order to conduct LIDAR surveys in the delta. Once operating, two state-of-the-art tide gauges could be established along the delta coast. These GPS stations would be self-supporting and would need to be linked through geo-stationary satellites to Cartografía Nacional. The tide gauges would be surveyed by GPS, using Tucupita as the base station. These tide gauges would provide estimates of mean sea

level. Over time, they would provide information about, among other things, subsidence rates in the delta.

3. Map critical areas (coastline, rivers) by using ALTM. This would provide detailed elevation and geomorphologic information for hydrology, geology, ecosystem-integrity management, and engineering applications.

4. Evaluate airborne INSAR for mapping the entire delta. If INSAR is not accurate enough, consider using ALTM in a multiyear program.

Historical Aerial Photography

The analysis of historic change along the estuary and coast presented in this report (figs. 39, 52, and 65) is preliminary. A more systematic and comprehensive analysis of historic rates of major delta processes (for example, distributary-channel migration, avulsion and infilling, and coastal accretion and erosion) will be invaluable for identifying the types of change taking place in the full spectrum of delta environments and evaluating natural rates of change. Systematic analysis of georeferenced historical photographs will be particularly useful in evaluating the impacts of Volcán dam, the type and rates of human-induced changes in the upper delta plain, and coastal changes and the processes that induced these changes.

We recommend a systematic review of all available historical aerial photographs. Essential information describing each available data set should be recorded and compiled. This information can then be used as a basis for selecting data sets for a systematic and comprehensive analysis. We recommend that the selected sets of aerial photographs be digitally scanned, georeferenced, and entered into a GIS for analysis. The georeferenced aerial photograph mosaics will have a number of historic mapping applications for geomorphology, hydrology, vegetation, and utilization of the delta by indigenous populations.

Hydrology/Sediment Dynamics

Delta Plain

Currently very little is known about the timing and duration of water levels and discharge, as well as water inputs and outflows, associated with the different delta-plain geomorphic settings and geoenvironments (table 8). Yet, as in all wetland environments, the hydrology of these environments is the fundamental process controlling physical and geochemical processes, and subtle changes in the timing and depth of water levels have profound influences on wetland ecology. Therefore, we recommend an integrated, comprehensive program to characterize the hydrodynamics of the delta plain. This program should relate rainfall discharge, tide levels, and interdistributary-basin water levels. The comprehensive review of geomorphic settings and related processes in this report provides a sound basis for developing a program to characterize delta hydrology. We also recommend a monitoring program that characterizes both hydrologic and sediment dynamic characteristics of caños and interdistributary basins. We recommend that parameters collected and compiled from the caños include discharge, stage, velocity, and direction, suspended-sediment concentration, and standard water-quality parameters such as Eh, pH, salinity, total organic content, and dissolved-solid concentration. We recommend that parameters collected and compiled from the interdistributary basins include stage, suspended-sediment concentration, and standard water-quality parameters such as Eh, pH, salinity, total organic content, and dissolved solid concentration. We recommend that a variety of caños and interdistributary basins be monitored so that a comprehensive framework of delta hydrology is developed so that accurate hydrologic and geomorphic models can be produced. We recommend using a combination of portable monitoring equipment that can be used by a monitoring team at a large number of sites, in combination with selected longer-term stations. With modern technology, this sampling strategy is most appropriate in this vast region.

It is essential to relate the results of hydrologic assessments to regional meteorological conditions (Sprecher and Warne, in press). Therefore, we recommend establishing or reestablishing a series of four to five meteorological gauge sites across the delta (fig. 28d). These should be long-term sites that collect data on a daily basis. FUNINDES USB (1999) has also recognized the need for these data and has been collecting data of a number of sites across the delta.

Coast and Shelf

Currently little is known about the water and sediment dynamics along the Orinoco coast. There have been a few short-term studies in the Gulf of Paria and along the coasts (Van Andel and Postma, 1954; Koldewijn, 1958; Nota, 1958; INTEVEP, 1981; Geohidra Consultores, C.A., 1997b), but these do not incorporate seasonal changes, nor do they systematically cover the spectrum of Orinoco coastal and shallow-shelf environments. The summary of marine environments provided in this report provides a basis for determining a coast- and shelf-monitoring program. We recommend a systematic wave-, tide-, and current-monitoring program that covers the spectrum of marine-delta environments from south of Boca Grande to north of Boca de Guanipa. We recommend that several long-term stations be established that will collect data for several years. We also recommend that these data be supplemented by short-term surveys at a variety of sites by means of portable equipment. Sites chosen for short-term surveys should be revisited and monitored several times at different times of the year. The monitoring program should include a component to evaluate the relationship between marine hydrodynamics and coast and shelf erosion, transport, and sedimentation processes.

Our initial analysis of the Orinoco coast at Boca Grande has identified that the difference in density between the rather dilute Orinoco River water and muddy coastal waters advected along the coast of Guyana and into the Boca Grande shelf by the Guayana Current creates conditions for a buoyant freshwater plume (fig. 40b). This freshwater plume appears to be a major factor in Orinoco and northeastern South America coastal-sediment dynamics. However, no data currently exist that characterize the nature and extent of this Orinoco freshwater plume. We recommend that special attention be given to defining and evaluating this freshwater plume and its effect on Orinoco coast and shelf-sediment dynamics.

Our analysis has also revealed that sediment dynamics along the Guyana and Surinam coast are markedly different. In particular, fluid muds and associated mudbanks that characterize the nearshore and coast from the Amazon Delta to the northeastern Guyana are not present along the Orinoco coast. Yet mudcapes similar to those along the Guiana coast appear to be developing along the Orinoco coast. We recommend conducting sedimentologic studies similar to those conducted along the coast of Surinam and Guyana (Wells and Coleman, 1981a, b; Rine and Ginsberg, 1985; Eisma and others, 1991; Allison and others, in press) in conjunction with shoreline-profile surveys to determine the sediment dynamics along the Orinoco coast.

It is widely recognized that Amazon sediments are a major contributor to the Orinoco coastal deposition system. Yet the volume of Amazon sediment entering the Orinoco coast is poorly constrained. Accurate appraisal of Amazon sediment is essential for developing sediment dynamics and sand-impact-assessment models of the Orinoco Delta, and we therefore recommend that oceanographic surveys include a component for evaluating longshore flux of Amazon sediment just south of Boca Grande, as well as assessing sediment dynamics as the Amazon sediment enters the Rio Grande freshwater plume. For reasonable evaluation of sediment influx, it will be necessary to measure longshore-transport conditions three to four times during the course of the year.

Systematic Coring of the Upper Pleistocene and Holocene Section

Very little is currently known about the Holocene history of the Orinoco Delta. Yet analysis of Holocene delta history provides critical information for identifying critical physical and biological processes that control delta ecology and for evaluating rates of change associated with these processes (compare Stanley and Warne, 1993). The subsurface information presented in this report covers only a small portion of the delta, penetrates only a small portion of the Holocene section, and/or lacks sufficient detail to identify specific environments of deposition (Nittrouer and others, 1986; DeLaune and Pezeshki , 1994; Stanley and Warne, 1998).

The radiocarbon-dated samples from short cores (to 8 m) collected and analyzed for this study provide a preliminary assessment of sediment accumulation and subsidence rates in the northwestern delta (fig. 55; table 16). However, as discussed in the text, these short cores commonly record variations associated with local conditions or specific environments of deposition, rather than actual long-term rates of sediment accumulation and subsidence. We therefore recommend collecting longer cores that include the complete Holocene section in order to accurately determine sediment-accumulation and subsidence rates across the delta. On the basis of geomorphic evidence, we infer that subsidence rates are greater in the southeastern delta and that systematic coring is needed to determine subsidence rates across the entire delta plain.

Preliminary analyses indicate that widespread peat formation in the middle and lower delta plain is a rather recent phenomenon. Subsurface analysis would clarify (1) conditions that initiated development of peat accumulation and (2) whether they represent the natural progression in tropical delta-plain development or widespread change in delta hydrology and/or sedimentology that induced widespread accumulation of peat. This information will be important in predicting impacts associated with natural and human-induced changes in the delta.

Studies along the Guiana coast have identified millennial- to centennial-scale changes in Holocene climate, which had significant influence on the coastal wave and current and, hence, sedimentary regime (Eisma and others, 1991). Because the Orinoco Delta provides a more extensive sedimentary record than does the Guiana coast (because the delta is subsiding at a much higher rate than the Guiana coast), analyses of Orinoco cores would be invaluable in evaluating the Holocene climatic history of northeastern South America. The Orinoco Delta is the repository for both Amazon and Orinoco basin sediments, which enhances its usefulness as a utility to decipher the Holocene history of the region.

Systematic Documentation of the Relation between Physical Settings and Ecosystem Composition

Many studies highlight the importance of sediment and water dynamics to the physical and biological characteristics of ecosystems (Stanley and Warne, 1998; Warne and others, in press). In order to generate a predictive model for the Orinoco Delta, we recommend development of a multidisciplinary program to systematically document hydrological, sedimentological, pedological, biogeochemical, faunal, and floral characteristics of delta environments. This information can then be used to identify those physical processes that are essential to ecosystem integrity. Not only will this be the essential environmental baseline data, it will also be the source for developing accurate process/response models to predict the effects of human manipulation of delta environments.

SUMMARY AND CONCLUSIONS

Deltas are dynamic, transitional, terrestrial/marine environments that are maintained by interaction among climatic, upland, riverine, and marine processes, together with longer-term processes, such as subsidence and sea level. The ecosystem integrity of large coastal-plain deltas is a function of the dynamic balance among inputs and outputs of these Earth systems, and, therefore, even modest changes in water and sediment inflow and throughflow may induce marked ecosystem change. Moreover, ecosystems within deltas are strongly linked, and so changes are prone to cascade into other delta ecosystems. Therefore, environmentally responsible and sustainable development of the relatively pristine Orinoco Delta requires comprehensive analysis of major physical processes and their influence on ecosystem integrity.

We have generated a summary of major coastal-plain, shallow-marine, and river systems of northeastern South America to identify and evaluate the primary sources and controls of water and sediment flow into, through, and out of the Orinoco Delta (fig. 67). In addition, regional analysis of major geologic, climatologic, oceanographic, and hydrologic features and processes of northeastern South America provides a framework for evaluating the timing, frequency, and rates of water and sediment input to the delta (figs. 14, 16, 24, 25, and 67) and for determining major coastal processes and resultant landforms (figs. 9, 10, 24, 35). Among many findings, the regional analysis highlights the importance of the freshwater plume seaward of Boca Grande (fig. 40) in controlling water and sediment dynamics along the Orinoco coast. As part of this regional analysis, we generated a comprehensive bibliography of available scientific information that pertains to the Orinoco Delta (app. 3); this bibliography will be an invaluable resource for future Orinoco Delta researchers by eliminating the need for time-consuming literature searches.

We conducted a comprehensive geomorphic analysis of the Orinoco delta plain to clearly define the spectrum of physical environments that are currently present in the delta plain (figs. 26, 31; tables 8, 9). Moreover, we conducted the geomorphic analysis to characterize the flow of water and sediment within the delta and to evaluate the effect of water and sediment dynamics on delta physiography, substrate characteristics, and geoenvironments (figs. 25, 30 through 33; pls. 2, 3).

We generated a preliminary geoenvironmental classification and set of geoenvironmental maps of the western Orinoco Delta (tables 12 through 14; pls. 2, 3) to begin to define relationships between physical and biological environments in the delta plain. As part of the geoenvironmental classification and mapping, we generated a photographic record of commonly occurring Orinoco Delta vegetation to facilitate future botanical and ecological investigations in the delta and promote interest among nonspecialists.

We generated a preliminary shoreline classification of the Orinoco Delta from Boca de Araguao to Boca de Guanipa (fig. 39). This classification and mapping serve (1) as a definition of major coastal habitats; (2) as a definition of the relationship between coastal water and sediment dynamics and resultant coastal form, substrate composition, and habitats; and (3) as a planning and design resource that defines major areas of coastal erosion, stability, and progradation, as well as the principal processes controlling coastal dynamics.

We evaluated major long-term processes that influence Orinoco Delta evolution (including Holocene sea-level change [fig. 11], sediment-accumulation and subsidence rates [table 16], neotectonism [figs. 17, 57], and Holocene climate change [fig. 58]) to determine the influence of these major delta processes on ecosystem distribution and integrity. Analysis of neotectonism and subsidence is particularly important for development of effective, environmentally responsible engineering-design criteria.

We present a preliminary analysis of the Holocene evolution of the Orinoco Delta to determine the nature and rates of natural change of delta-plain and coastal environments (figs. 44, 49, 51, 60, 61, 62, 64, 65). Analysis of Holocene delta evolution shows that the delta has undergone some fundamental changes over the past 2,000 yr, both in terms of delta-plain environments as well as major processes controlling delta-plain development (figs. 23, 36). Narrowing of Boca de Serpientes and development of Caño Manamo have been especially significant in late Holocene delta evolution. Analysis of the northwestern delta also reveals the cycle and associated rates of (1) distributary-channel evolution, avulsion, and infilling (figs. 36, 63); (2) estuary evolution and eventual infilling (figs. 36, 63, 65); and (3) mudcape development and extinction (fig. 36). Combined with careful definition of current delta-plain and coastal processes (figs. 10, 16, 17, 24, 25, 28, 30, 31, 32, 39, 40) and characterization of long-term controls (figs. 11, 17, 57, 58), analysis of Holocene delta evolution provides a means of evaluating how changes in major physical processes and delta configuration influence delta-plain geoenvironments and ecosystems.

We generated an Internet website that summarizes our research and observations on the Orinoco Delta (on the CD that accompanies this report). The website is designed to serve as a resource for future Orinoco Delta researchers and to stimulate interest and excitement among nonspecialists interested in preserving this unique and diverse ecosystem complex.

The inferences presented in this report are based on preliminary remote-sensing analysis, a modest set of field observations (see data bases on the CD that accompanies this report), and limited data available from scientific literature and other sources within Venezuela. Hence, a major objective of this comprehensive analysis was to identify and define critical areas of research needed to ensure environmentally responsible development of the delta. Major areas of research that are needed to generate environmental baseline data include topographic surveys to more clearly define delta geomorphology, to provide baseline information for development of hydrologic and geomorphic models, and to serve as a basis for development of environmentally responsible engineering plans; hydrologic and sedimentologic monitoring programs to define delta-plain water and sediment dynamics; oceanographic surveys to verify, define, and evaluate the freshwater plume seaward of Boca Grande and determine the volume of Amazon sediment entering the Orinoco coastal system; coastal and oceanographic surveys to determine water and sediment dynamics along the Orinoco coast, through Boca de Serpientes, and in the Gulf of Paria; subsurface analysis of the delta-plain region using radiocarbon-dated sediment cores to determine subsidence rates and delta history; and multidisciplinary analysis of the spectrum of delta environments to define relationships among physical setting, biological composition, and ecological integrity.

The Orinoco Delta is one of the world's most diverse, unaltered ecosystem complexes. Further baseline surveys of the physical processes controlling ecosystem integrity are essential to the protection of this valuable resource. The present report provides a sound basis for development of an effective research program to better define delta environments, critical physical processes, and relationships between physical setting and ecosystem composition.

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Figures

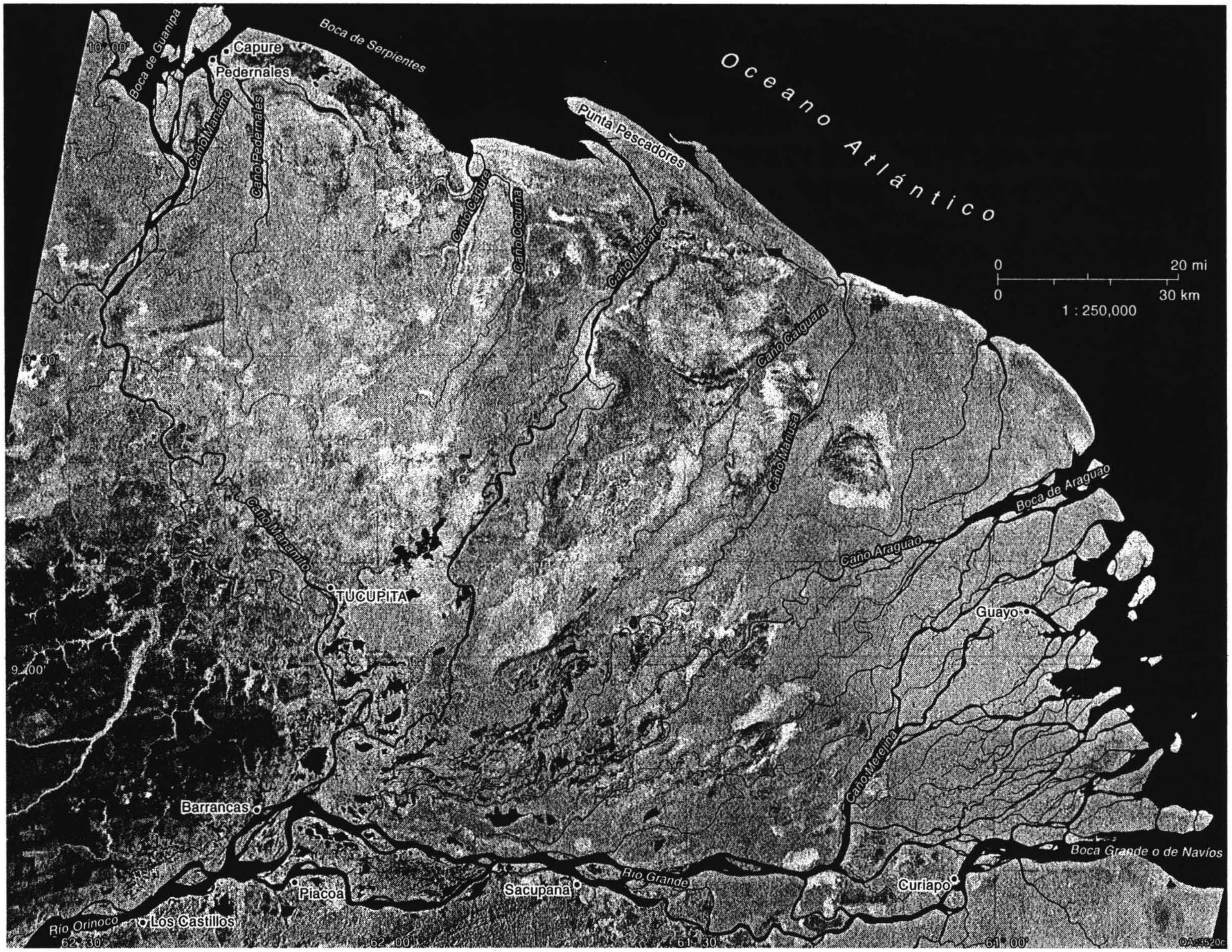


Figure 1. Radarsat satellite mosaic of the Orinoco Delta, Venezuela. The images were acquired in November and December 1996.

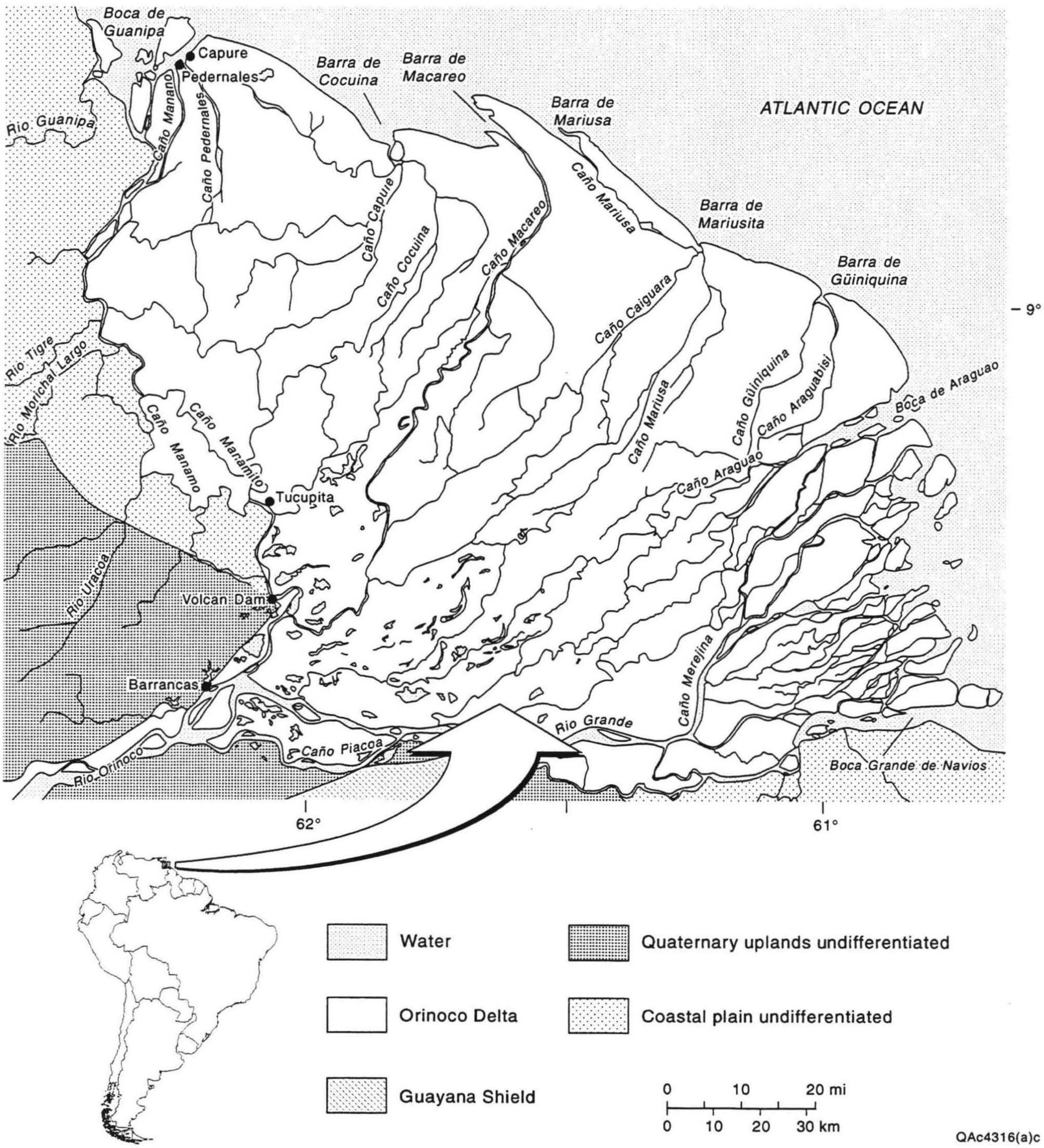


Figure 2. Geographic features of the Orinoco Delta. Note location of Volcán dam in southwestern delta.

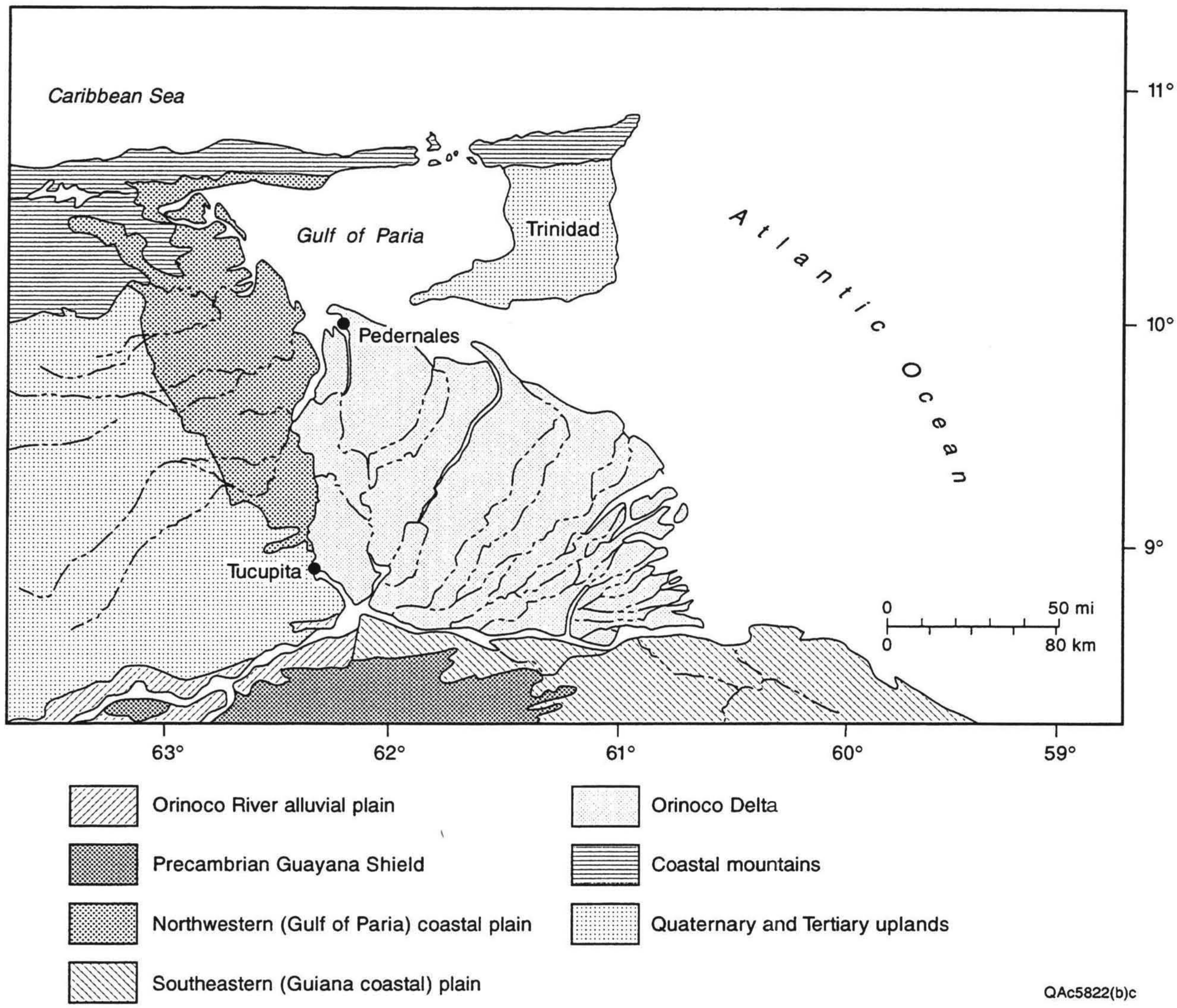


Figure 3. The three principal coastal-plain regions of northeastern Venezuela.

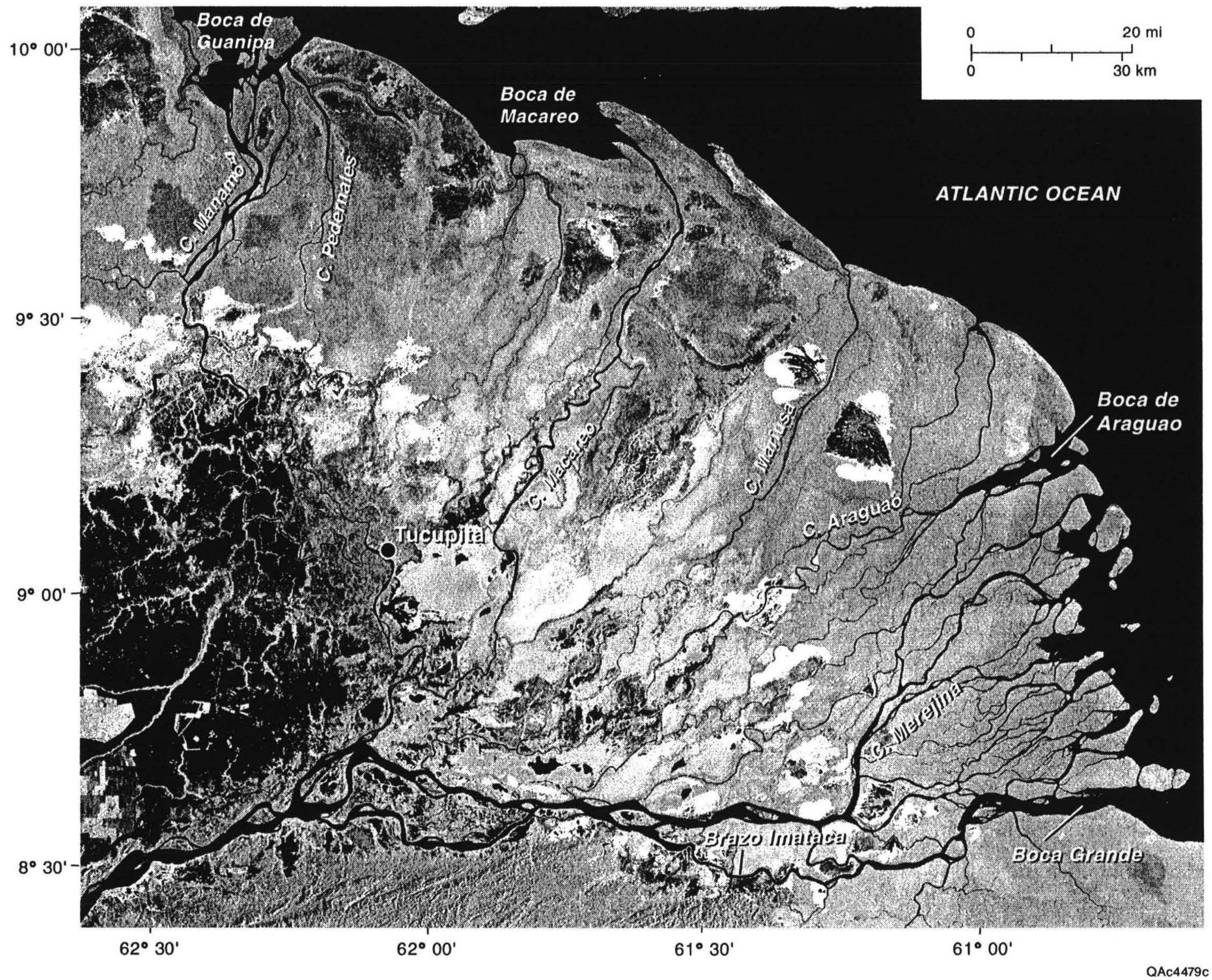


Figure 4. JERS image and principal geographic features of the Orinoco Delta. The six images in the mosaic were acquired September to December 1995. Note that most of the lower courses of delta distributaries are deflected northwestward along the coast and locally converge.

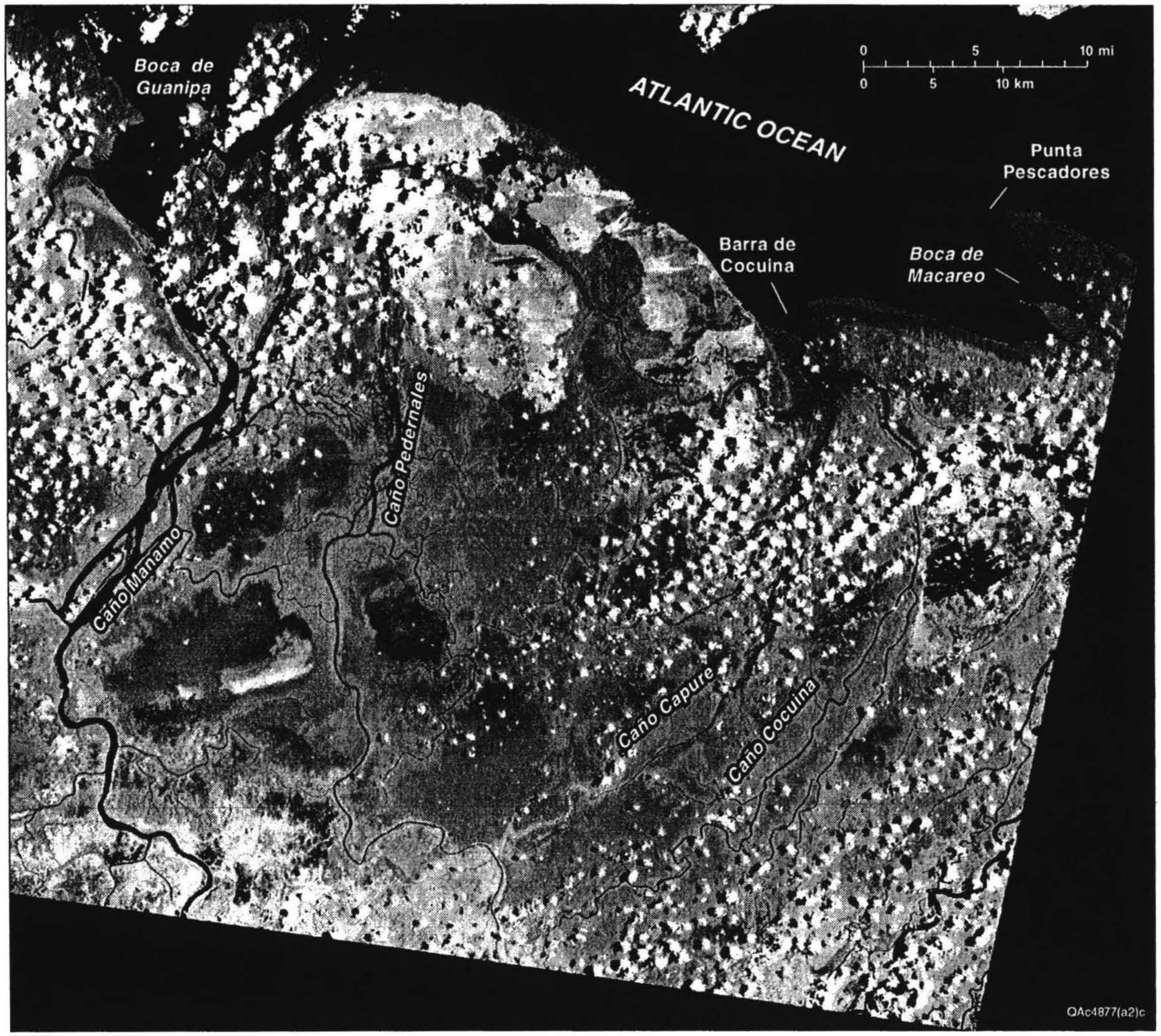


Figure 5. Landsat image of the northwestern Orinoco Delta. The image was acquired in August 1996 (table 1) and processed using bands 4, 5, and 7 and then converted to a gray-tone image. Processing differentiates levee areas from forested and herbaceous interdistributary basins. Significant cloud cover, which appears as small, irregular white areas with adjacent shadows, is nearly always present across the delta plain.

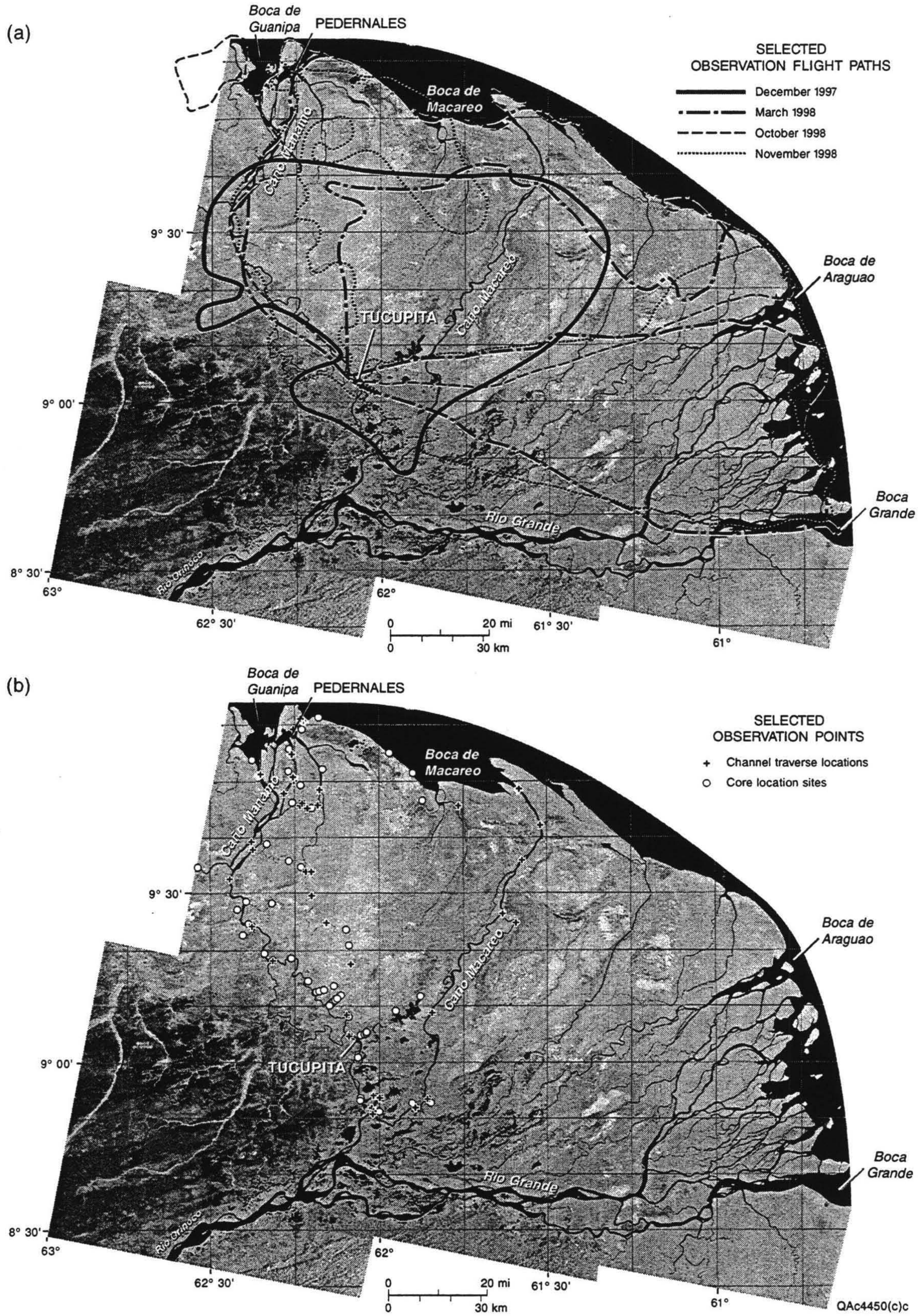


Figure 6. Field sites of BEG studies. (a) Flight paths of airplane flyovers. (b) Channel traverse and core-sampling locations. Detailed core and core site descriptions and channel-transect data are available in a data base on the CD that accompanies the report.

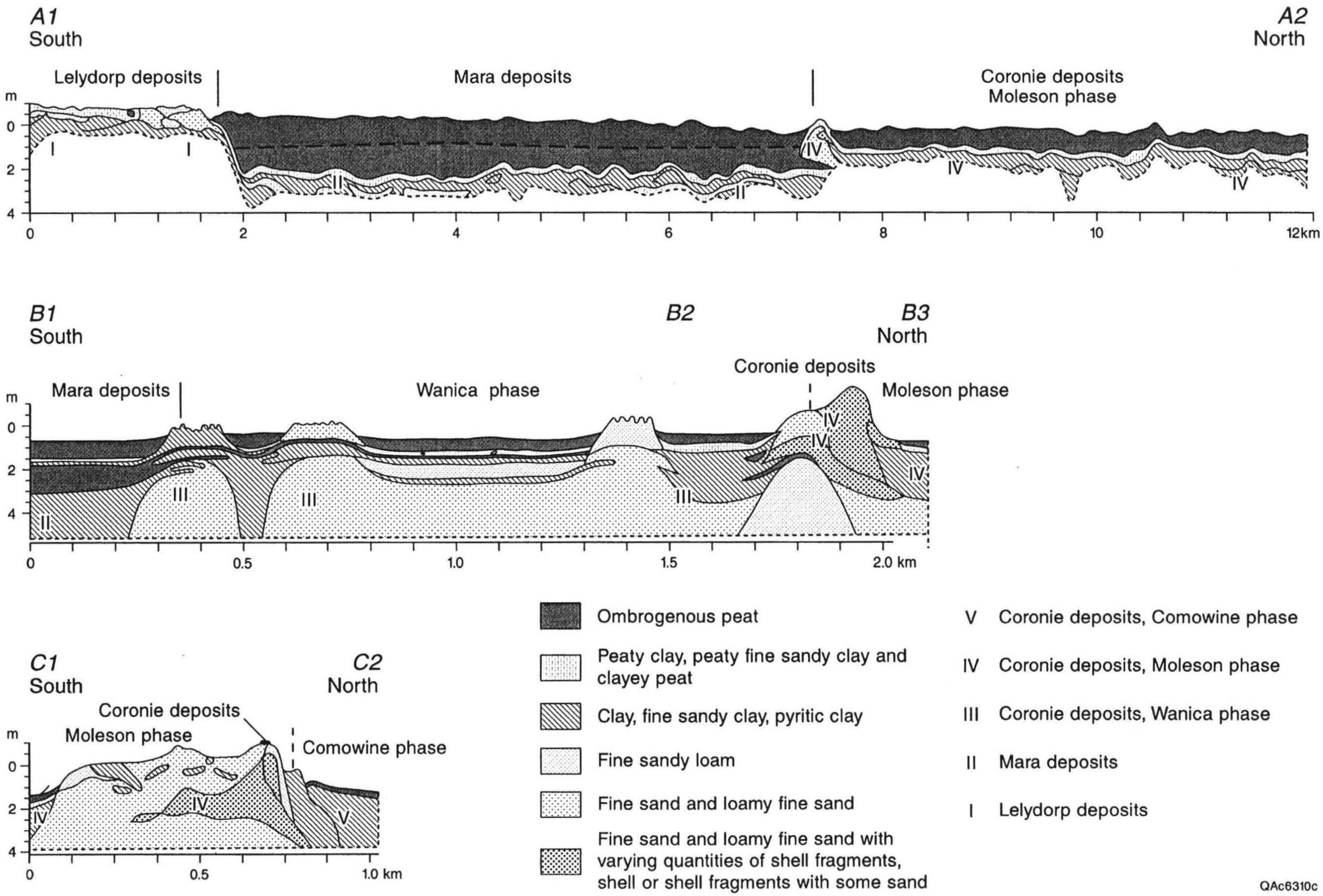


Figure 8. Cross sections of the eastern sector of the Coronie district, Surinam. Cross-section locations shown in figure 7c. Modified from Brinkman and Pons (1968).

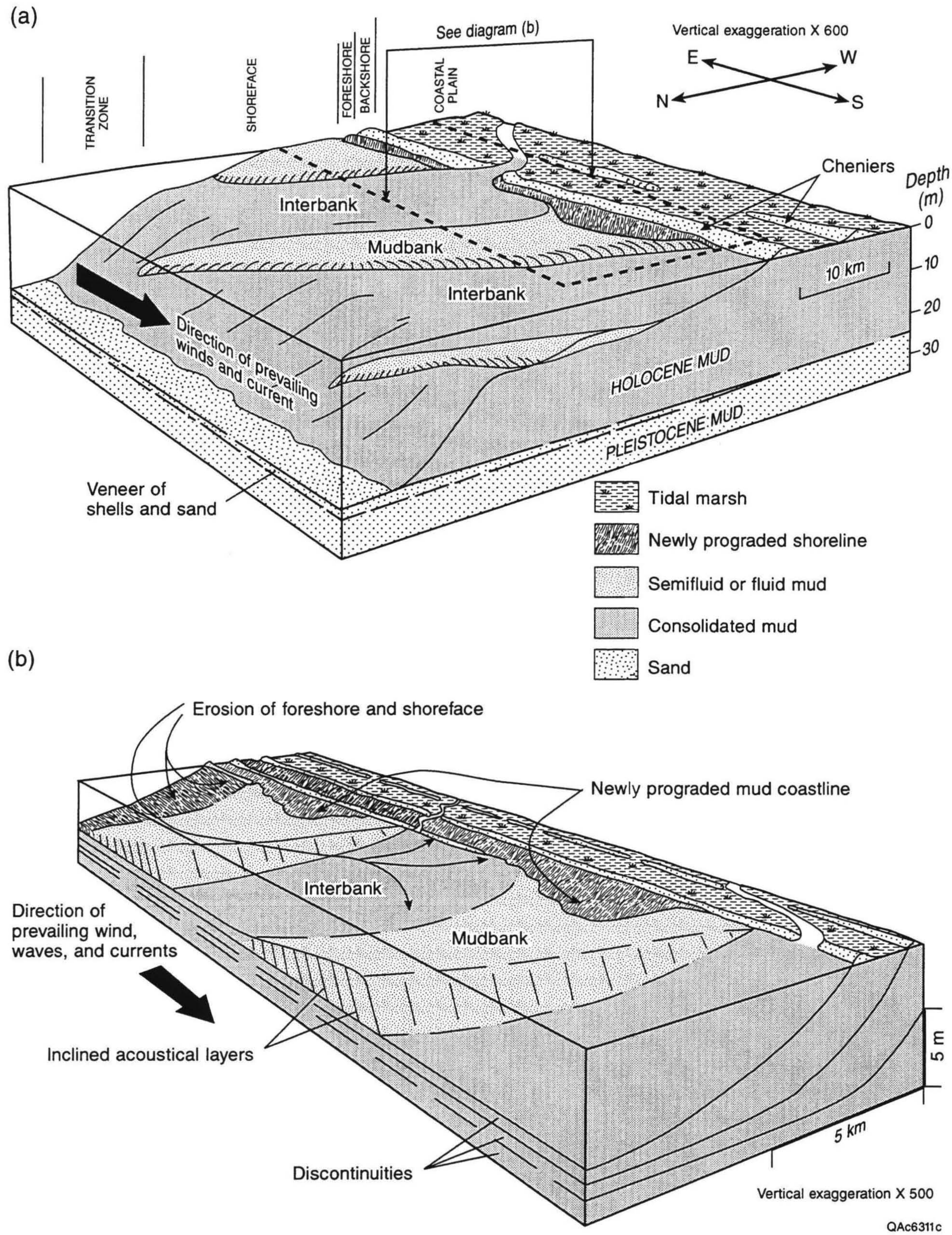
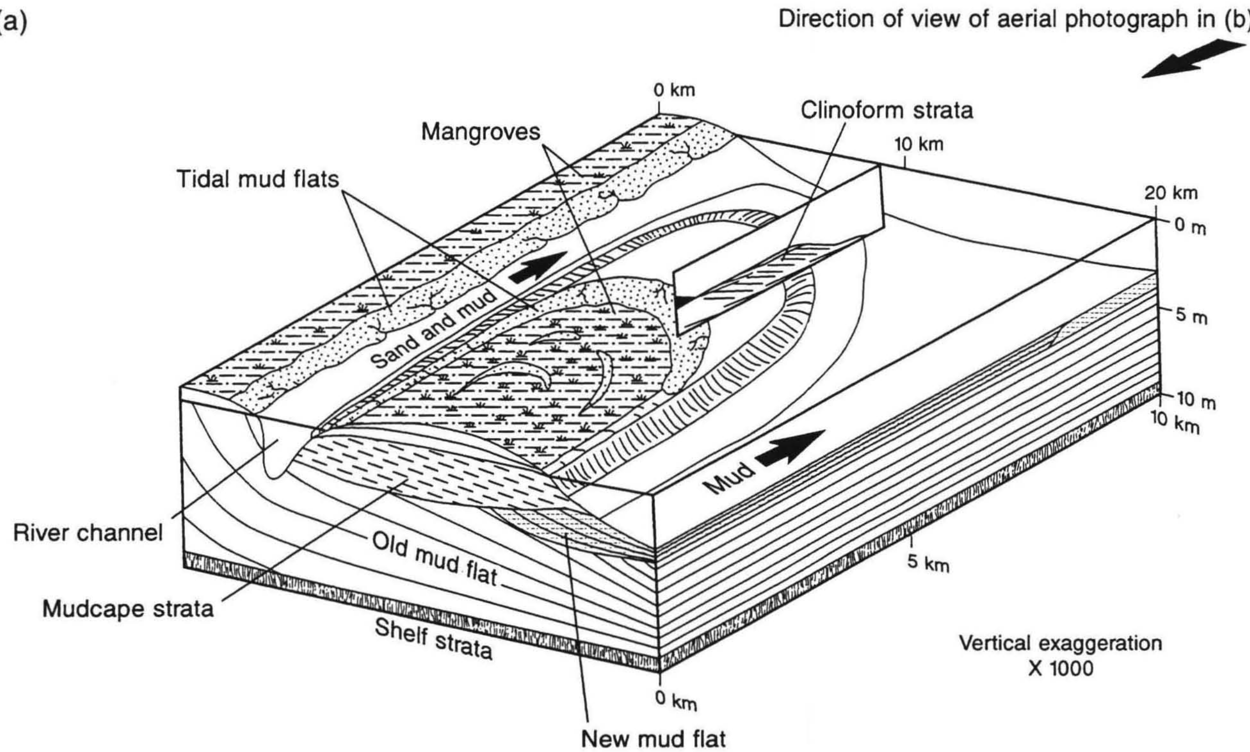


Figure 9. Model of Guiana coast mudbank development. (a) Disposition of mudbanks along the shelf and locations of depositional and erosional coastal zones relative to mudbank position. Modified from Rine and Ginsberg (1985); (b) Stacking of sediments from migrating mudbanks creates a shoreface vertical sequence of laminated and massive muds with discontinuities and a coastal-plain horizontal sequence of mud marshes and sand cheniers. Modified from Rine and Ginsberg (1985).

Figure 10. Examples of mudcape development. (a) Mudcapes primarily develop by alongshore (downdrift) accretion of a succession of (4 to 6 m thick) clinoform strata, mangrove muds, and supratidal facies (freshwater, seasonally inundated swamp). The primary source for downdrift accretion of mudcapes is from along the shelf, with only a minor contribution of sand and mud from the local river. Offshore, seaward mud-flat accretion takes place along the outer flank of the mudcape after passage of the rapidly accreting mudcape point. The mudcape and new tidal mud flat are deposited above old tidal-flat deposits that accumulated along the flank of a previous generation of mudcapes and are incised by the local river mouth. Shoreface muds are offlapping relict inner-shelf muds. Modified from Allison and others (1995). (b) Small mudcape along the Caño Mariusa mudcape, demonstrating that mudcapes develop at a variety of scales. Note extensive mangrove forest, which is common along the Orinoco coast. Location of mudcape shown in figure 35h.

(a)



Direction of view of aerial photograph in (b)
0 km
Clinoform strata
Mangroves
10 km
Tidal mud flats
20 km
0 m
Sand and mud
5 m
10 m
10 km
Mud
River channel
Old mud flat
5 km
Mudcape strata
Shelf strata
Vertical exaggeration
X 1000
0 km
New mud flat

(b)

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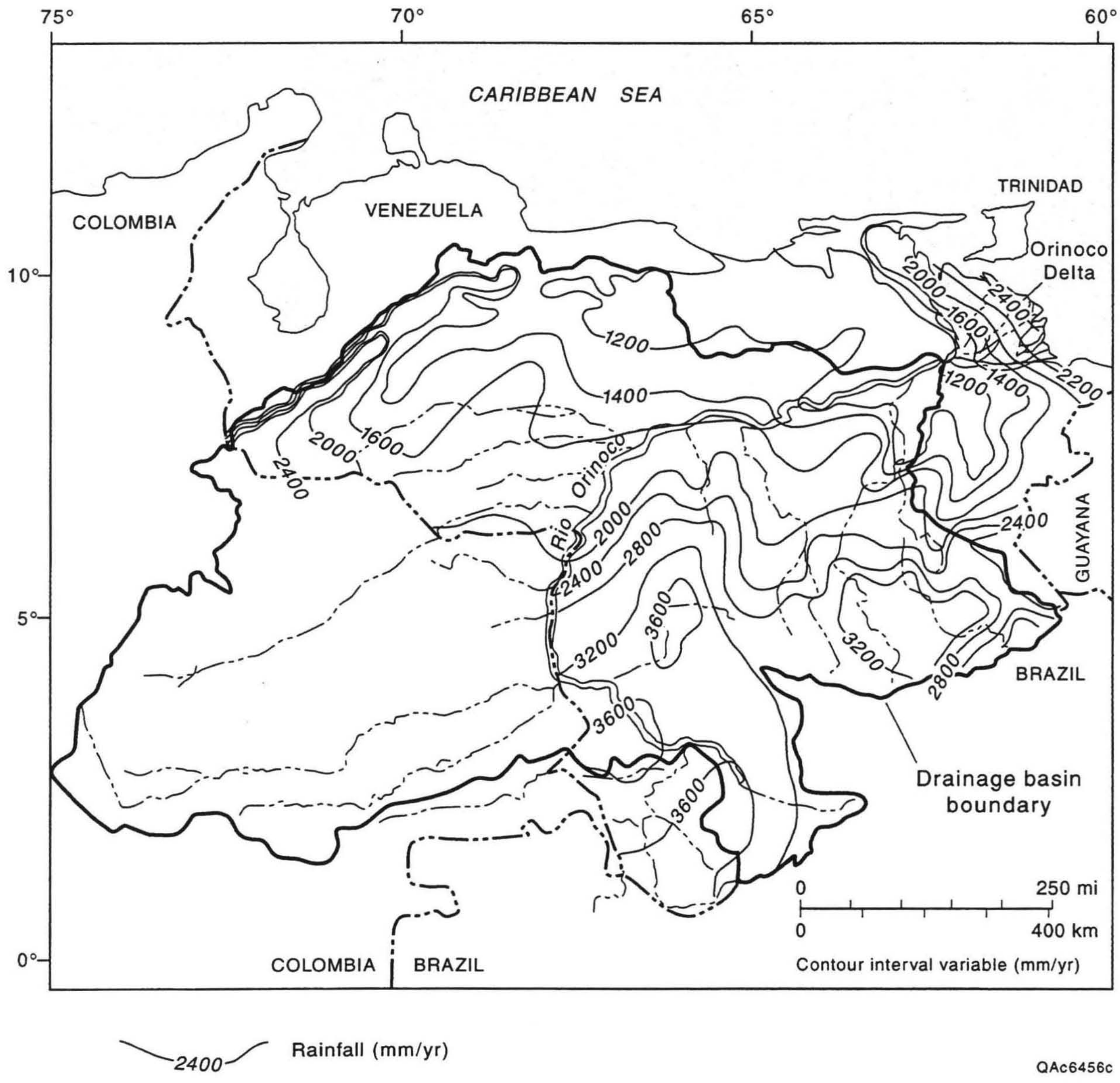


Figure 13. Rainfall distribution in the Orinoco drainage basin. Modified from Vásquez and Wilbert (1992).

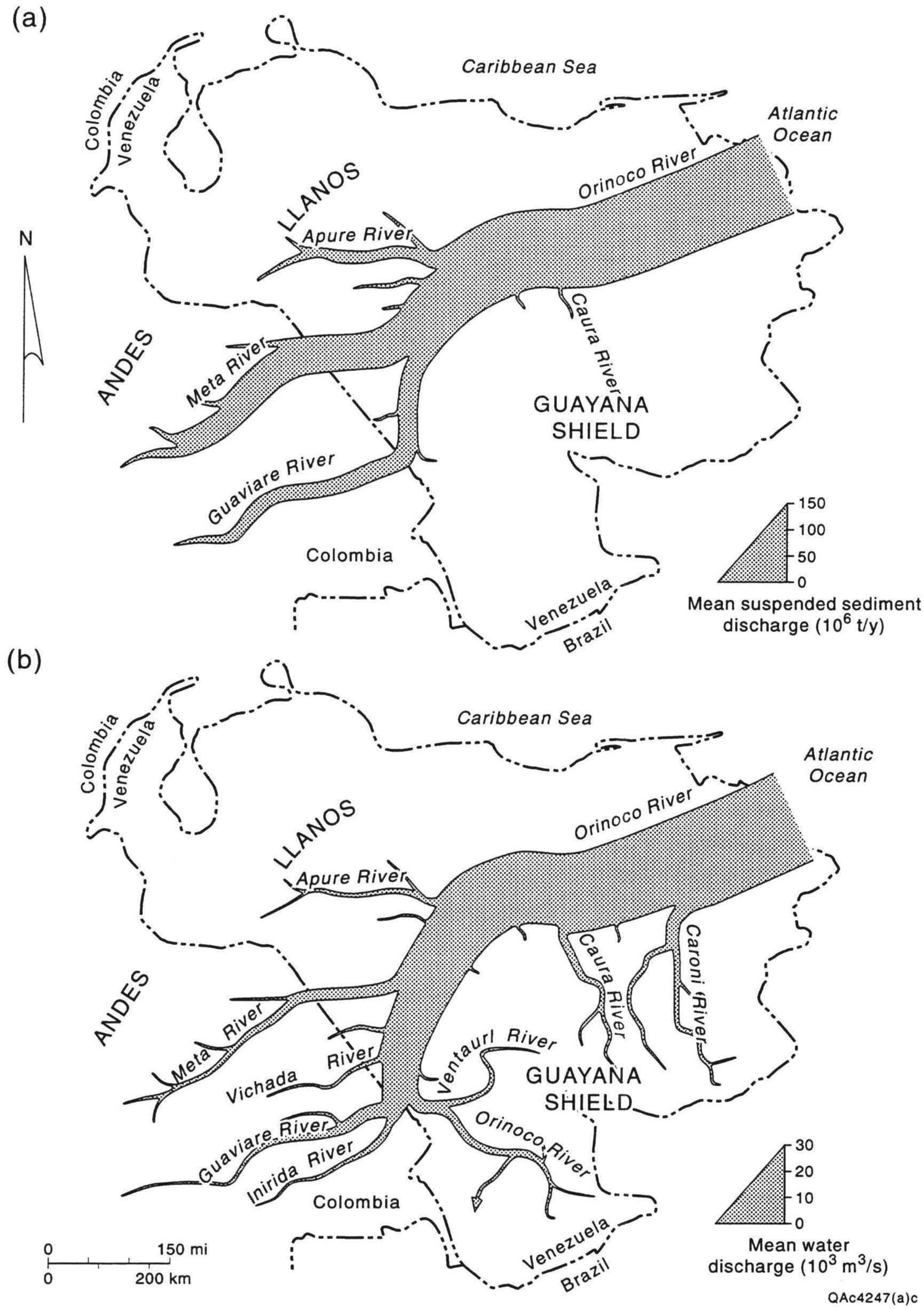


Figure 14. Water and sediment discharge of major Orinoco River tributaries. Modified from Meade and others (1990).

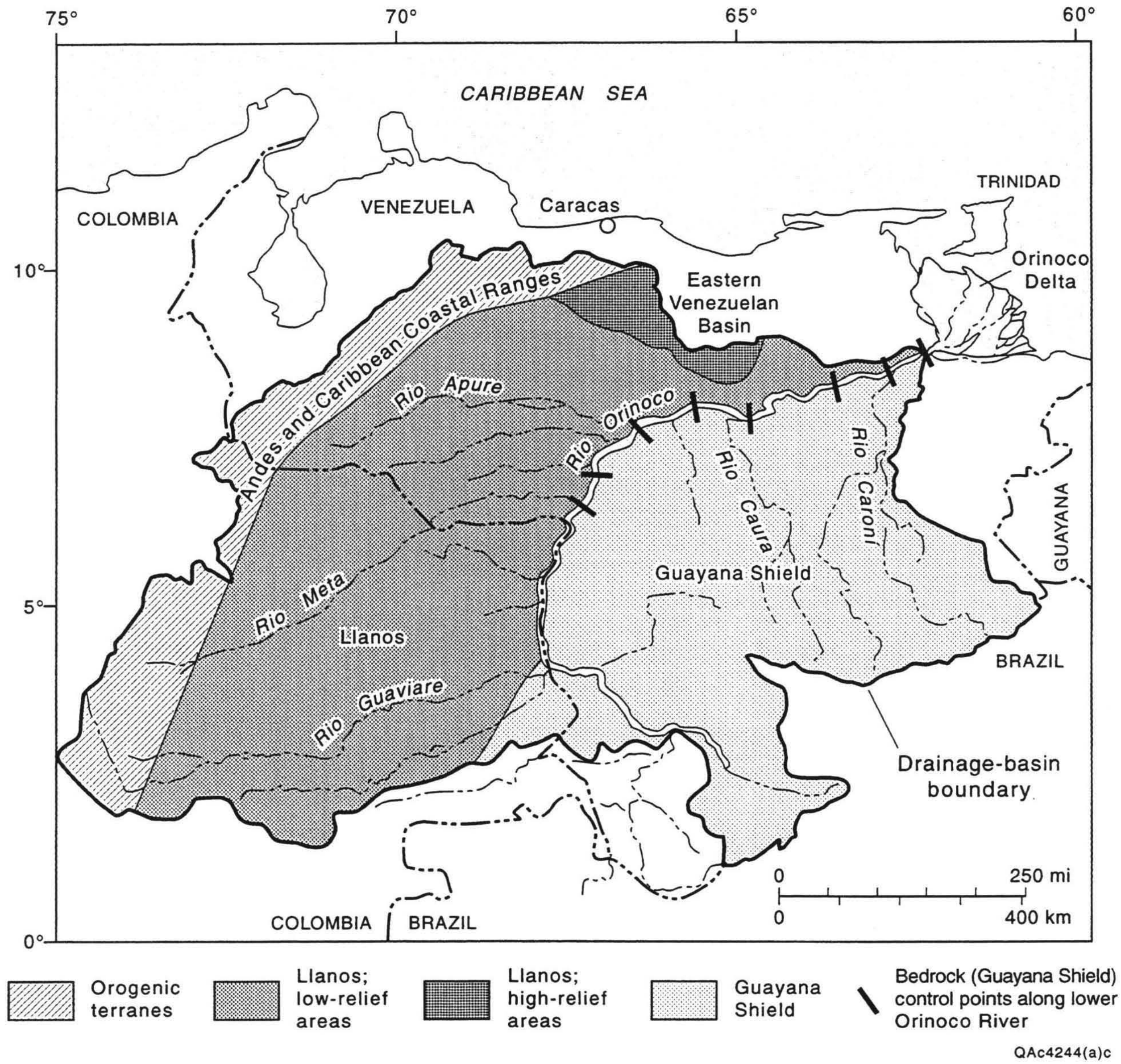


Figure 15. Morphotectonic provinces in the Orinoco drainage basin, location of Eastern Venezuela Basin (EVB), and major control points (bedrock constrictions that control Orinoco river flow).

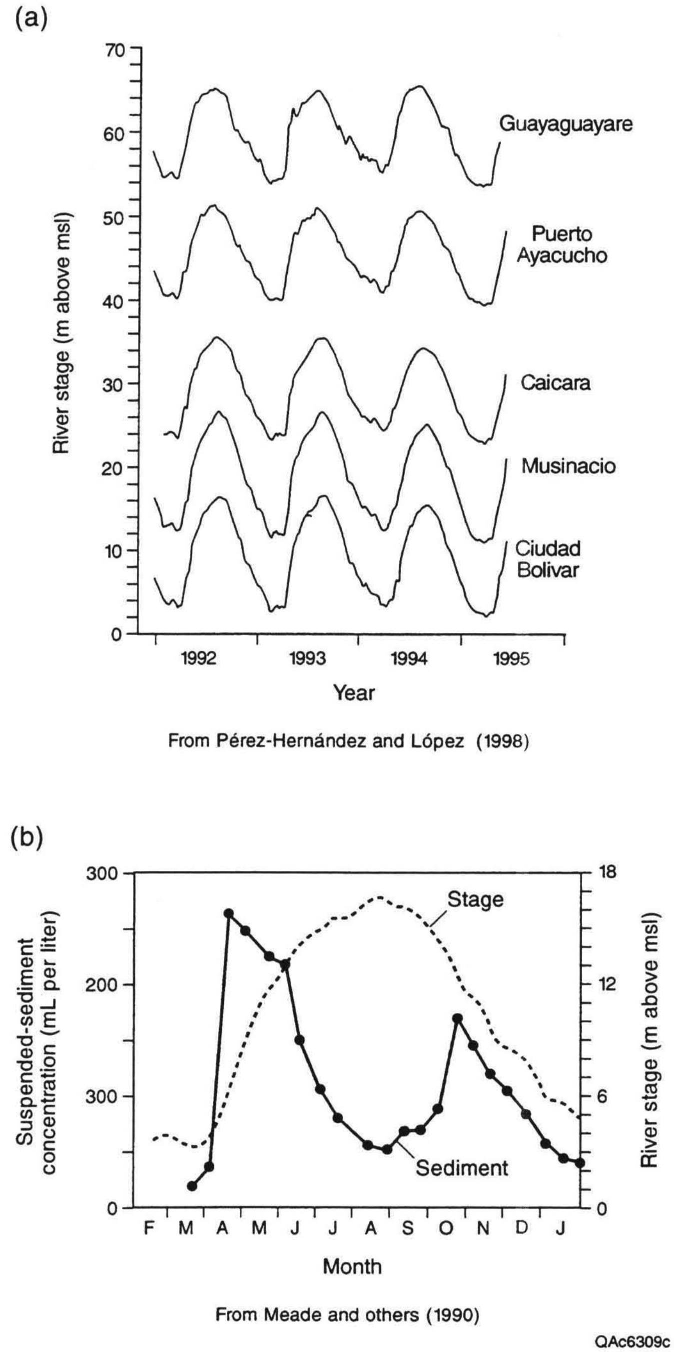


Figure 16. Hydrology of the Orinoco River. (a) Stage at several stations along the lower Orinoco River (see fig. 12 for locations of gauging sites). Note the near-simultaneous peak discharge along the river, which reflects the change from wet to dry to wet season across the entire drainage basin. Modified from Pérez-Hernández and López (1998). (b) Monthly sediment and water discharge in the lower Orinoco River (Ciudad Bolívar). Modified from Meade and others (1990).

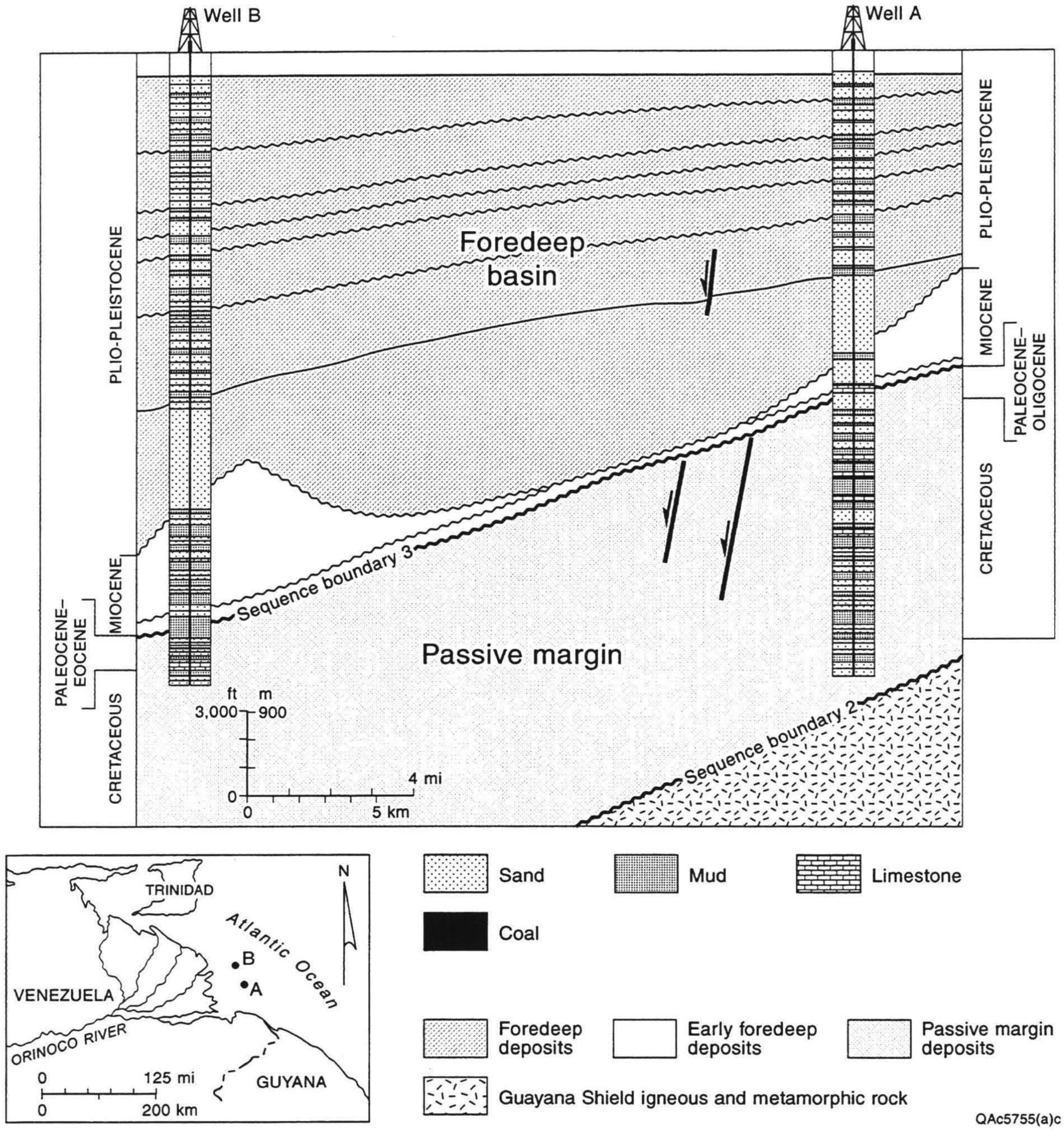


Figure 19. Generalized, shore-parallel cross section of Cretaceous through Recent sediments on the Orinoco shelf. The strata can be subdivided into a lower passive margin and upper foredeep basin sequence. The passive-margin sequence was induced by opening of the Atlantic Ocean. Development of foredeep accommodation space was induced by differential motion between the Caribbean and South American plates. The foredeep sequence is largely composed of Orinoco Delta sediments. The unconformities in the foredeep sequence are largely caused by major eustatic sea-level changes. Modified from Di Croce and others (1999).

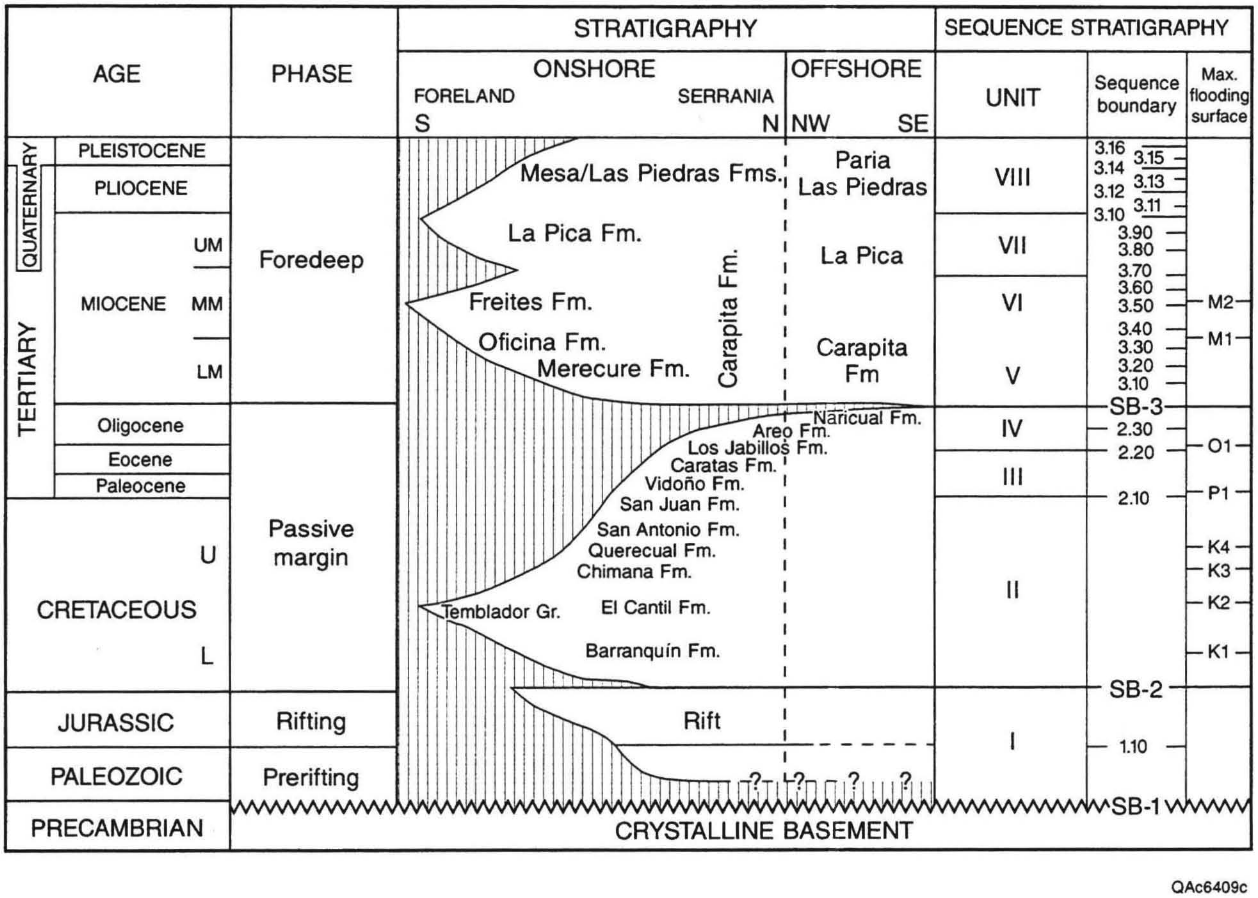


Figure 20. Stratigraphic chart summarizing the chronostratigraphy, tectonic phases, formations, and major sequence stratigraphic boundaries. Modified from Di Croce and others (1999).

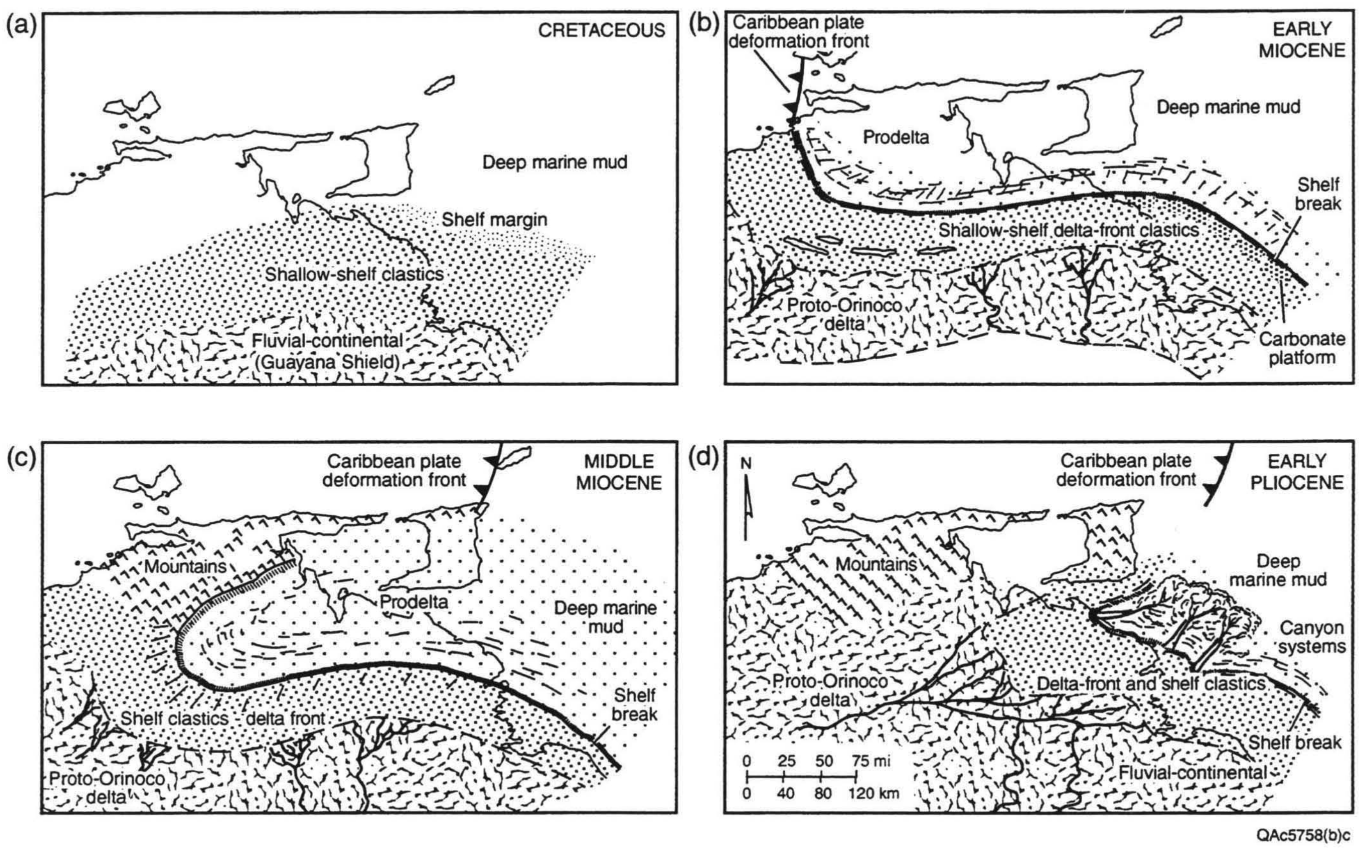


Figure 21. Cretaceous-Tertiary paleogeography of the EVB. (a) Upper Cretaceous; (b) upper Oligocene; (c) middle Miocene; (d) lower Pliocene.

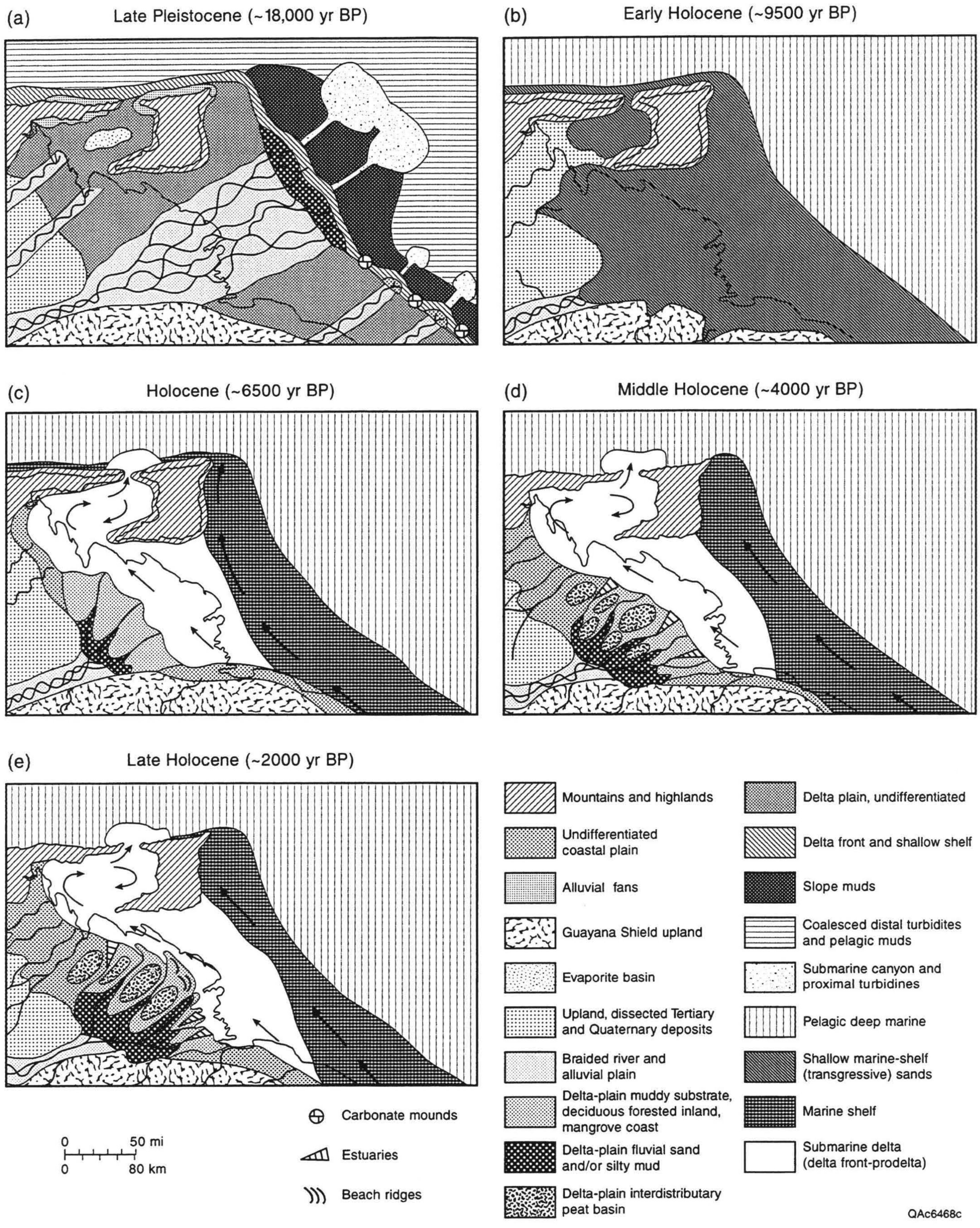


Figure 23. Late Pleistocene to Recent paleogeography of the Orinoco Delta. (a) Late Pleistocene (~18,000 yr B.P.); (b) late Pleistocene, early Holocene (9,500 yr B.P.); (c) middle Holocene (6,000 yr B.P.); (d) middle Holocene (4,000 yr B.P.); and (e) late Holocene (2,000 yr B.P.).

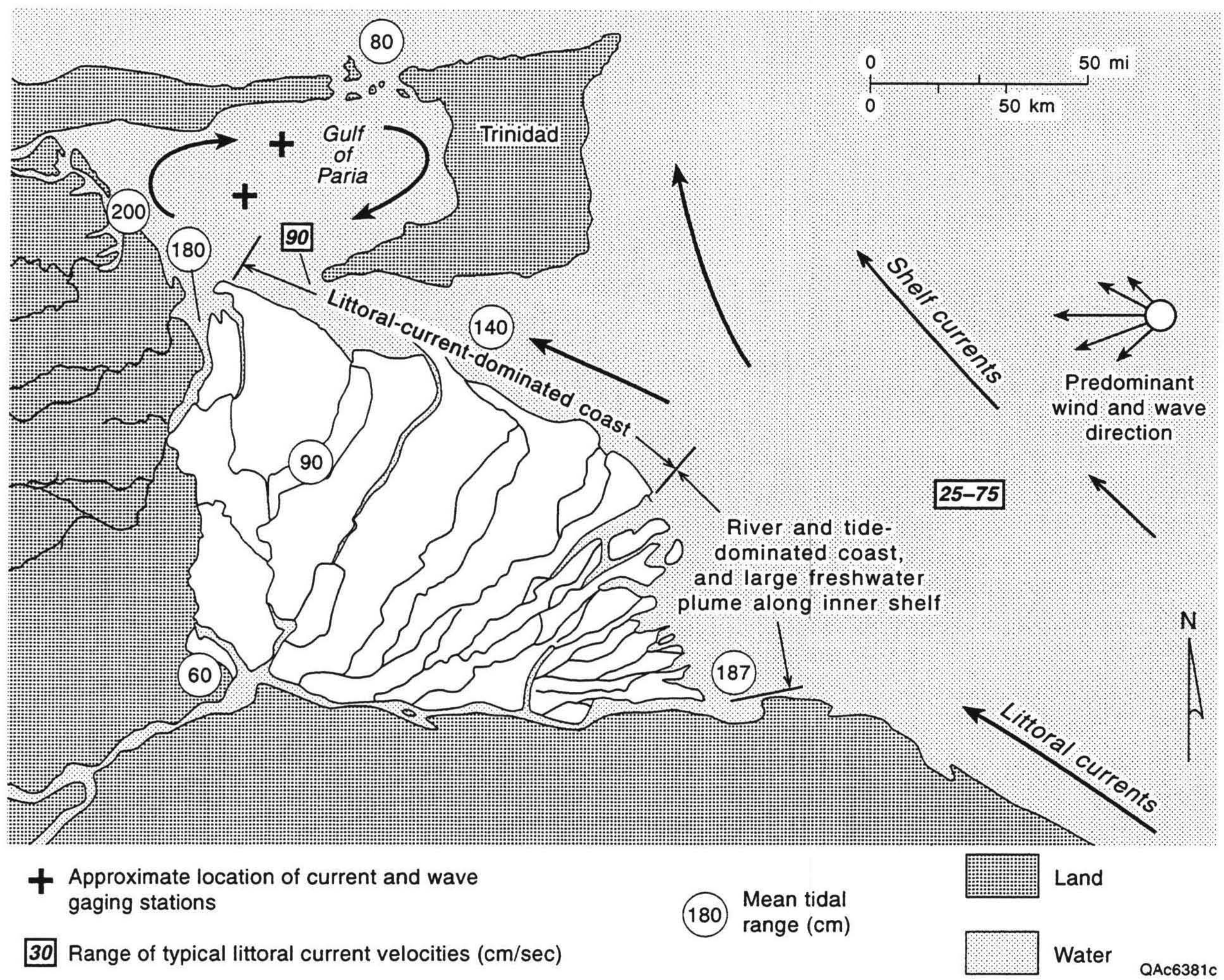


Figure 24. Summary of marine hydrodynamics along the Orinoco Delta coast. Note the location of the two temporary (December 1979 and May to August 1979) wave and current meter stations in central Gulf of Paria. Data generated from these sites are used to characterize the marine hydrodynamics of the Orinoco coast (Geohidra Consultores, C.A., 1997b; ENSR Venezuela, 1998). Atlantic littoral current and tide data from Nota (1958), Koldewijn (1958), and Van Andel (1967).

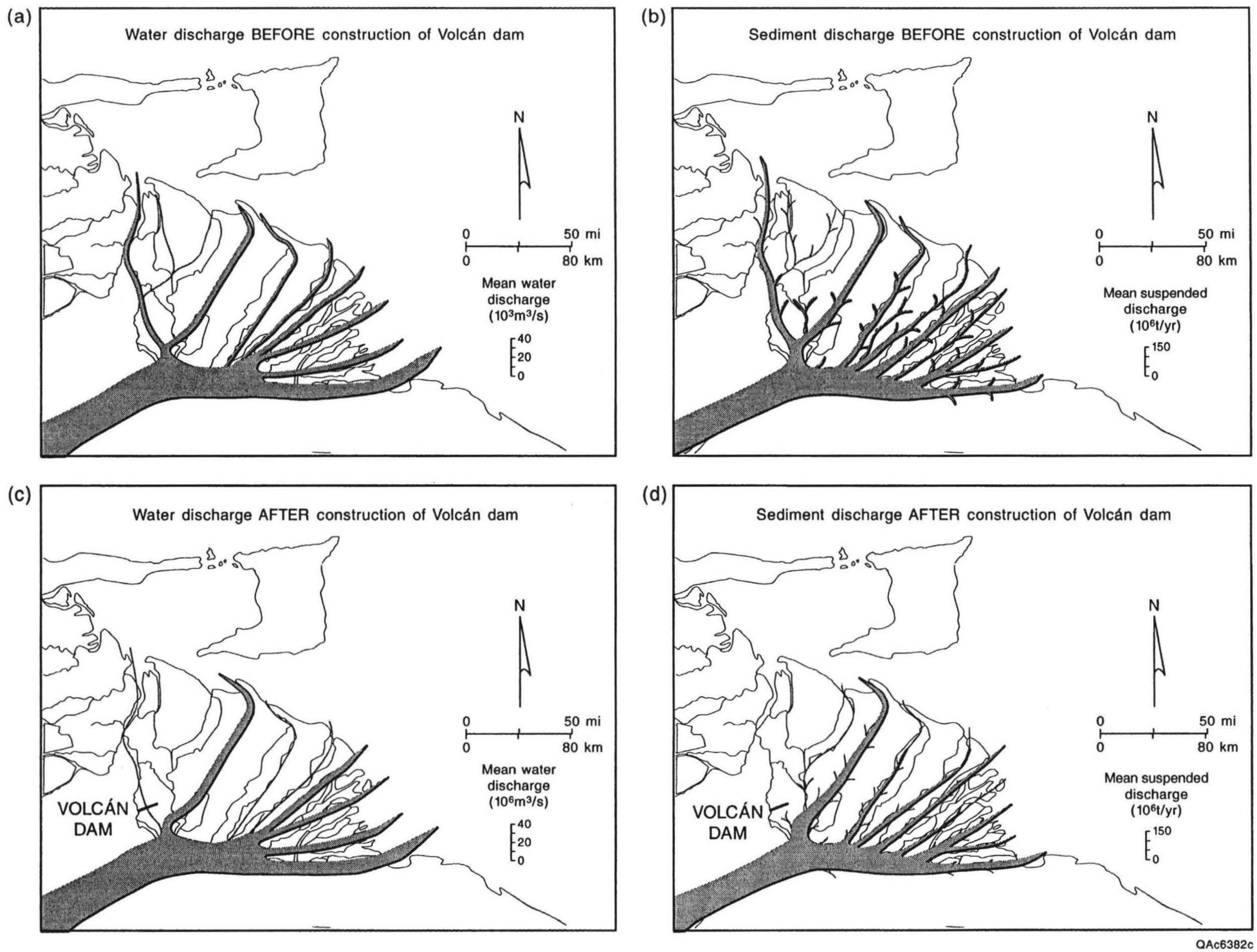


Figure 25. Distribution of water and sediment discharge in the Orinoco delta before (a), (b) and after (c), (d) construction of Volcán dam.

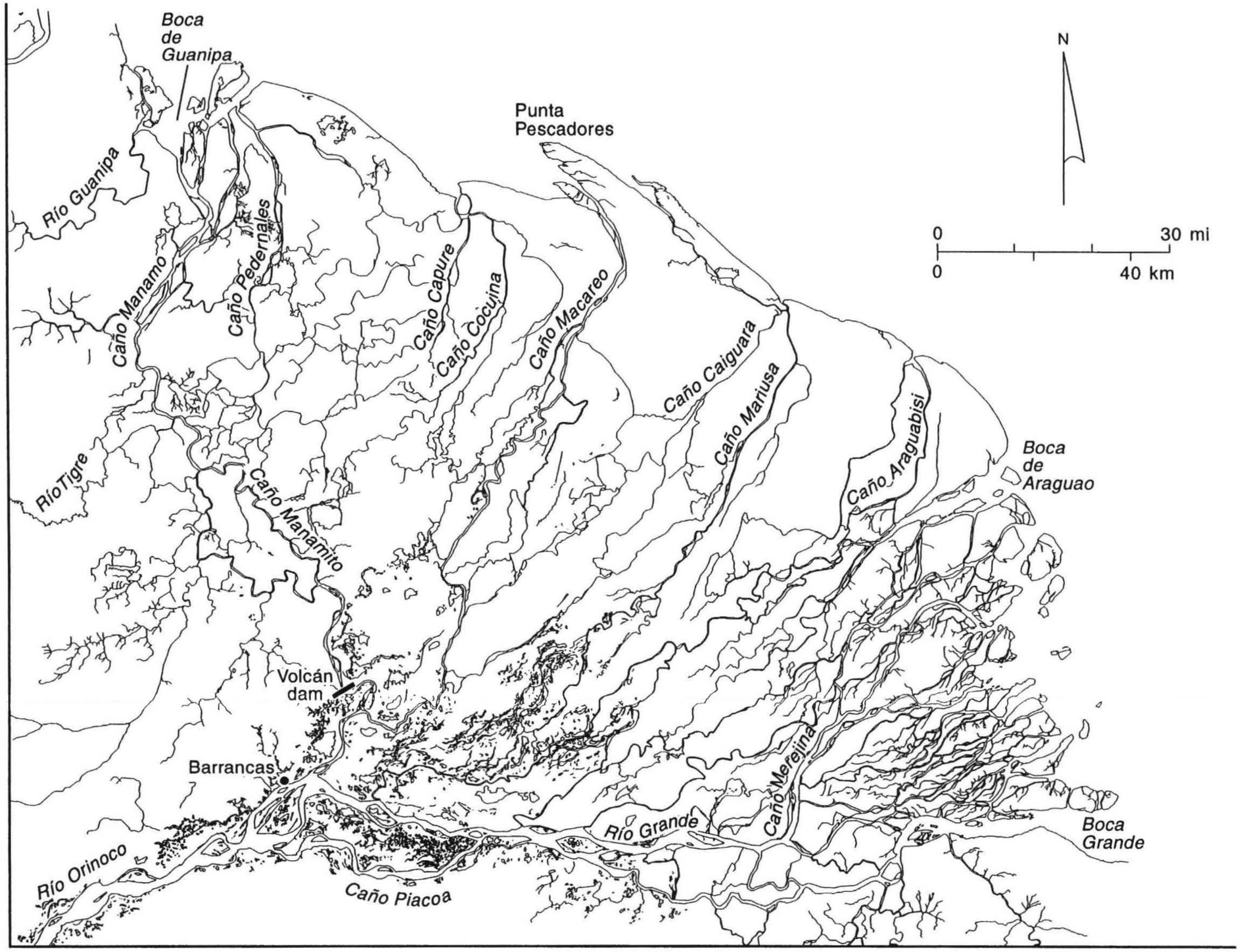
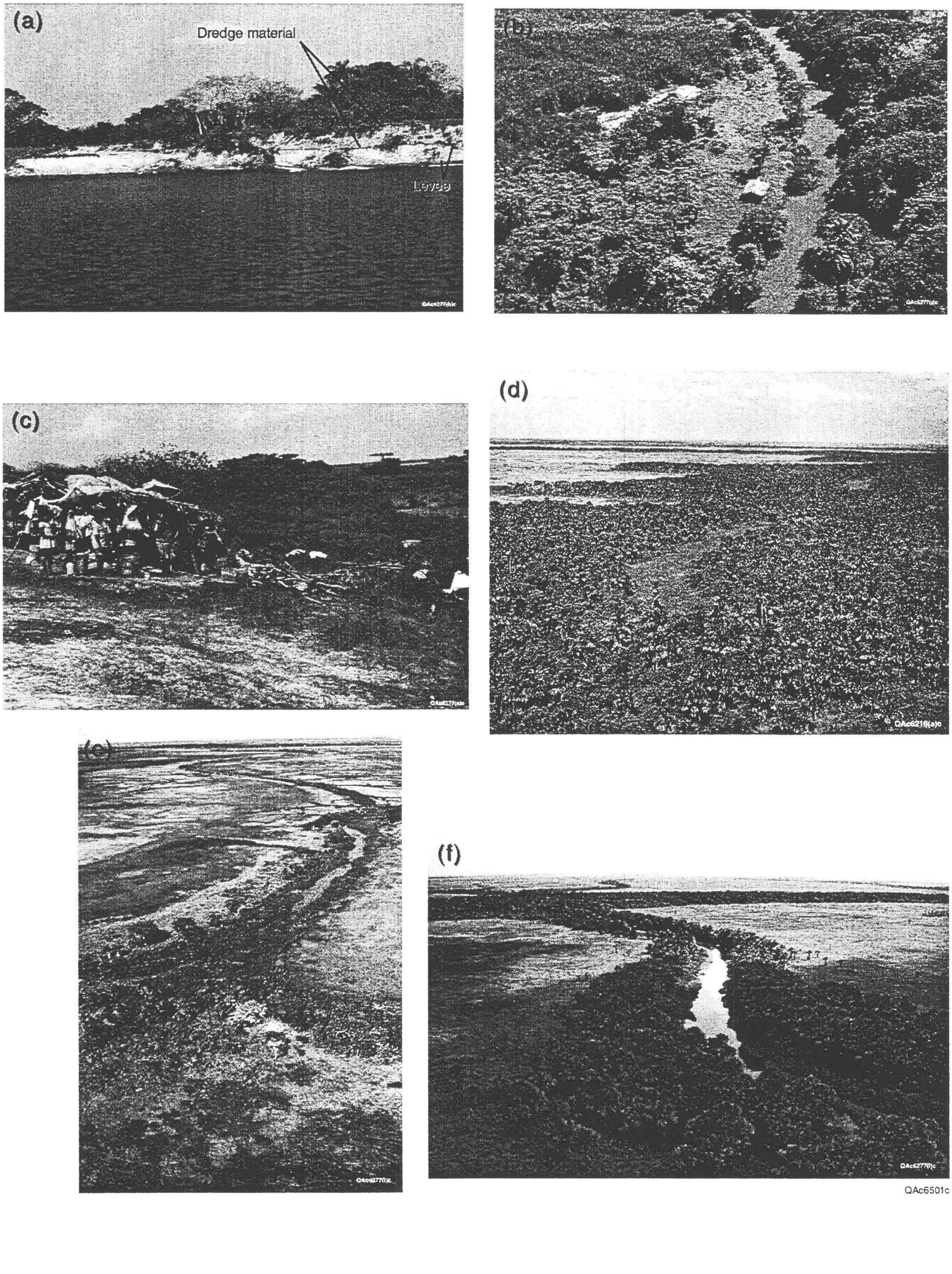


Figure 26. Channel network of the Orinoco Delta. These channels were digitized from the November–December 1996 RADARSAT mosaic (fig. 1). Flood-basin lakes are also shown. A digital version is on the CD that accompanies this report.

Figure 27. Photographs of the Orinoco Delta plain. (a) Levee bank along upper Caño Macareo. This reach contains the best-developed levees in the delta. The uppermost layer along the bank is dredge material. Caño Macareo is currently not being dredged. Photograph taken March 1998. (b) Northwest delta plain showing partially infilled caño. Indigenous dwelling and associated clearing on levee. Infilling by vegetation is accelerated by construction of Volcán dam and consequent loss of flood discharge through the caño. Photograph taken March 1998. (c) Basinward side of levee in the upper delta. Levee has been cleared for human activity. Large interdistributary basin in background. Photograph taken March 1998. (d) Central delta and an abandoned, partially infilled caño. Note transition from forested (palm) to herbaceous interdistributary basin are the distance. Inactive and/or abandoned caños. Photograph taken in November 1998. (e) Partially developed or partially abandoned caño in the central delta. Evidence of a partially developed caño includes the lack of forested vegetation along the channel banks, which usually occurs along established caños (see fig. 27f). Photograph taken March 1998 (f) Well-established third- or fourth-order caño in the central delta. The forested levee and extensive, herbaceous interior basin are common in many parts of the central delta. Photograph taken in November 1998. (g) 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. Photograph taken in October 1998. (h) Central delta showing complexity of vegetation in herbaceous interdistributary basin. Photograph taken March 1998. (i) Upper delta and complexity of vegetation in herbaceous interdistributary basin. Note forested levee along Caño Macareo in distance. Photograph taken March 1998. (j) Widespread tree mortality in a central delta-plain interdistributary basin. Widespread tree mortality is commonly induced by increased depth and/or duration of inundation and demonstrates the dynamic nature of delta-plain ecosystems. Note the vast forested delta plain in the distance. Photograph taken in March 1998. (k) Central delta-plain interdistributary basin showing the transition from a forested (mixed palm and deciduous) to herbaceous wetland. This photograph portrays the vastness of these interdistributary basins. Photograph taken March 1998. (l) Central delta plain showing an example of a mixed herbaceous and palm interdistributary basin. Photograph taken in March 1998. (m) Floodplain lakes in the upper delta near the Río Grande. Photograph taken March 1998. (n) Floodplain lakes in the upper delta near Río Grande. Note that the caño water in this portion of the delta has much higher suspended concentrations than in the northwestern delta (fig. 28g). Note the obvious gradation from abandoned channels and floodplain lakes. Photograph taken March 1998. (o) Caño Tucupita (upper delta near Tucupita), which has been almost completely infilled with vegetation as a direct result of elimination of flood discharge since construction of Volcán dam. Photograph taken March 1998. A program is currently under way to artificially clear the caño of vegetation. (p) Cleared and partially drained upper delta floodplain. Note that despite the well-developed drainage system, there is abundant standing water. Photograph taken March 1998. (q) Crevasse splay along upper Caño Macareo. Photograph taken November 1998.



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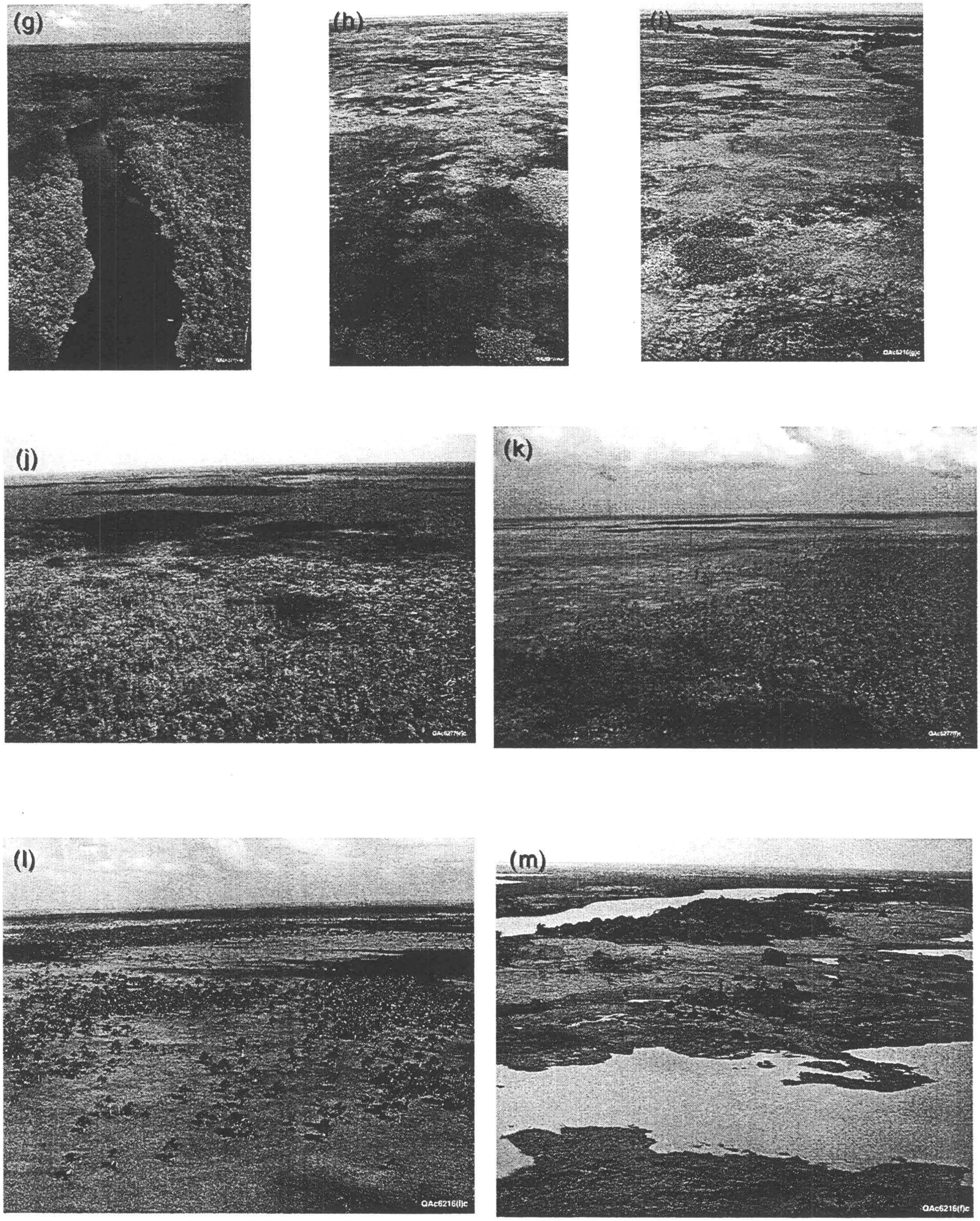

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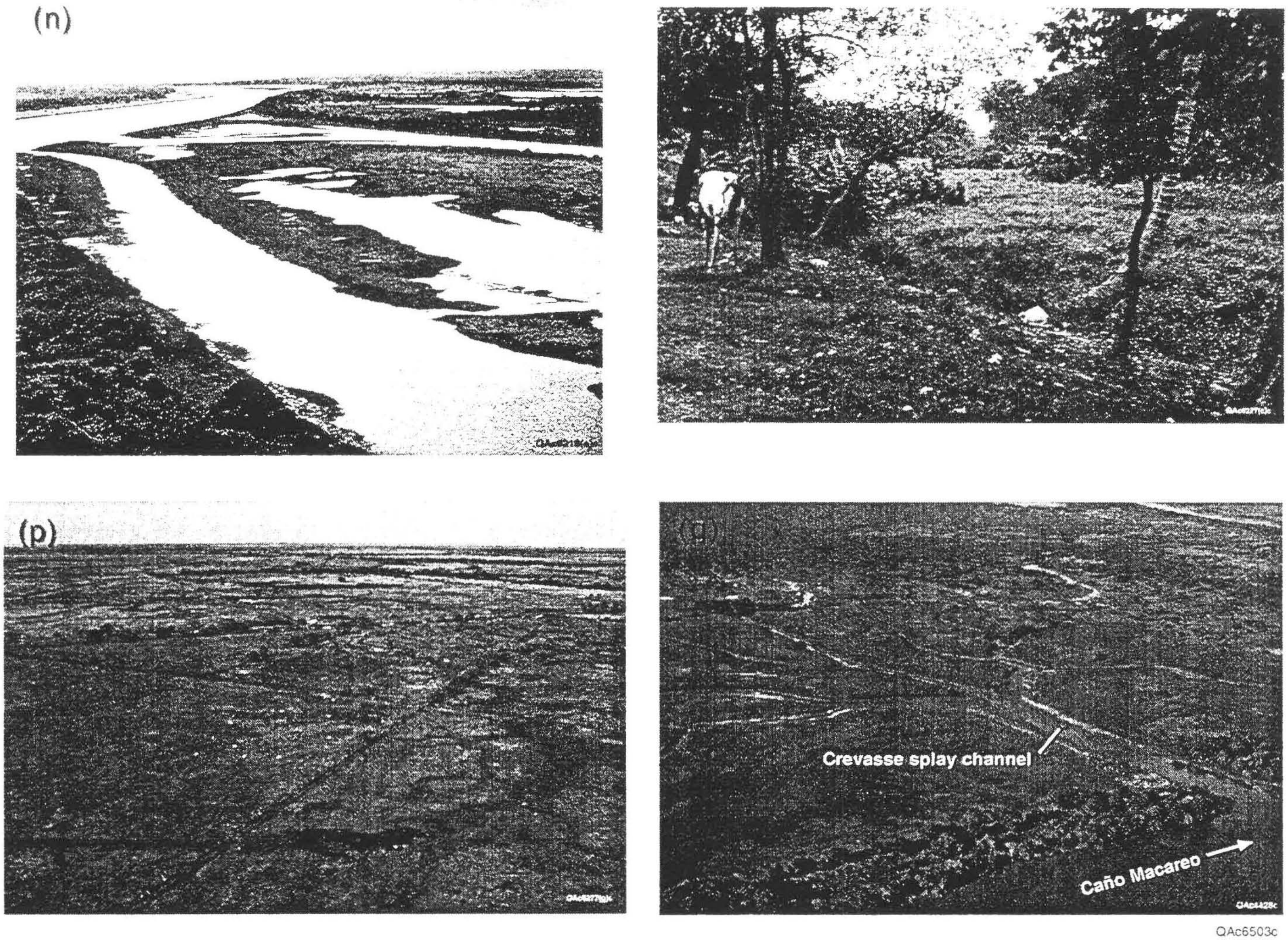
(n)
(p)
Crevasse splay channel
Caño Macareo
QAc6503c

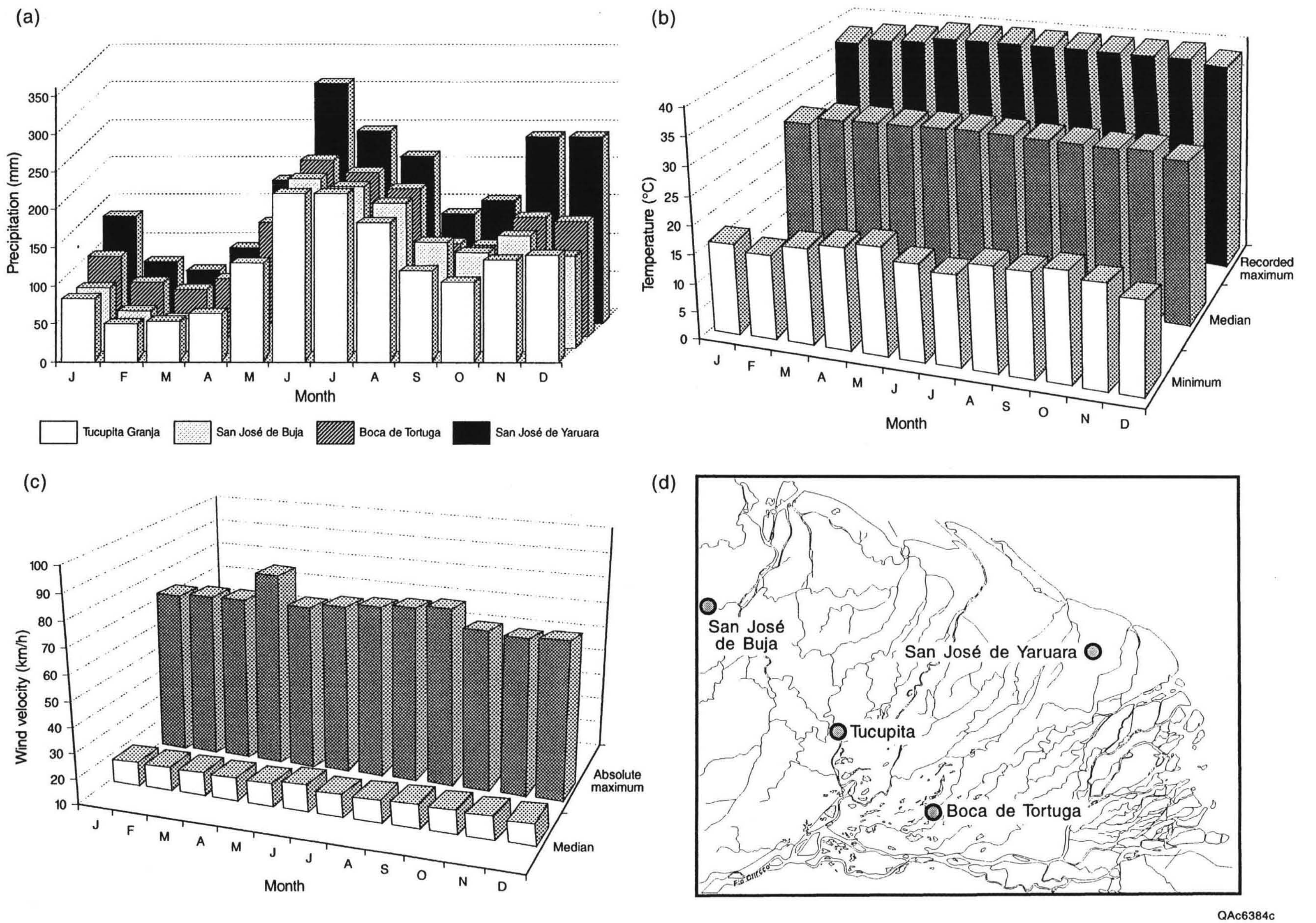

Figure 28. Climatic conditions across the Orinoco Delta. (a) Rainfall records across the delta, generally spanning from 1970 to 1990 (FUNINDES USB, 1998; their table [Cuadro] IV-1). (b) Temperature at Tucupita, 1970–1995 (FUNINDES USB, 1998). (c) Wind at Tucupita, 1970–1995 (FUNINDES USB, 1998). (d). Locations of meteorology stations.

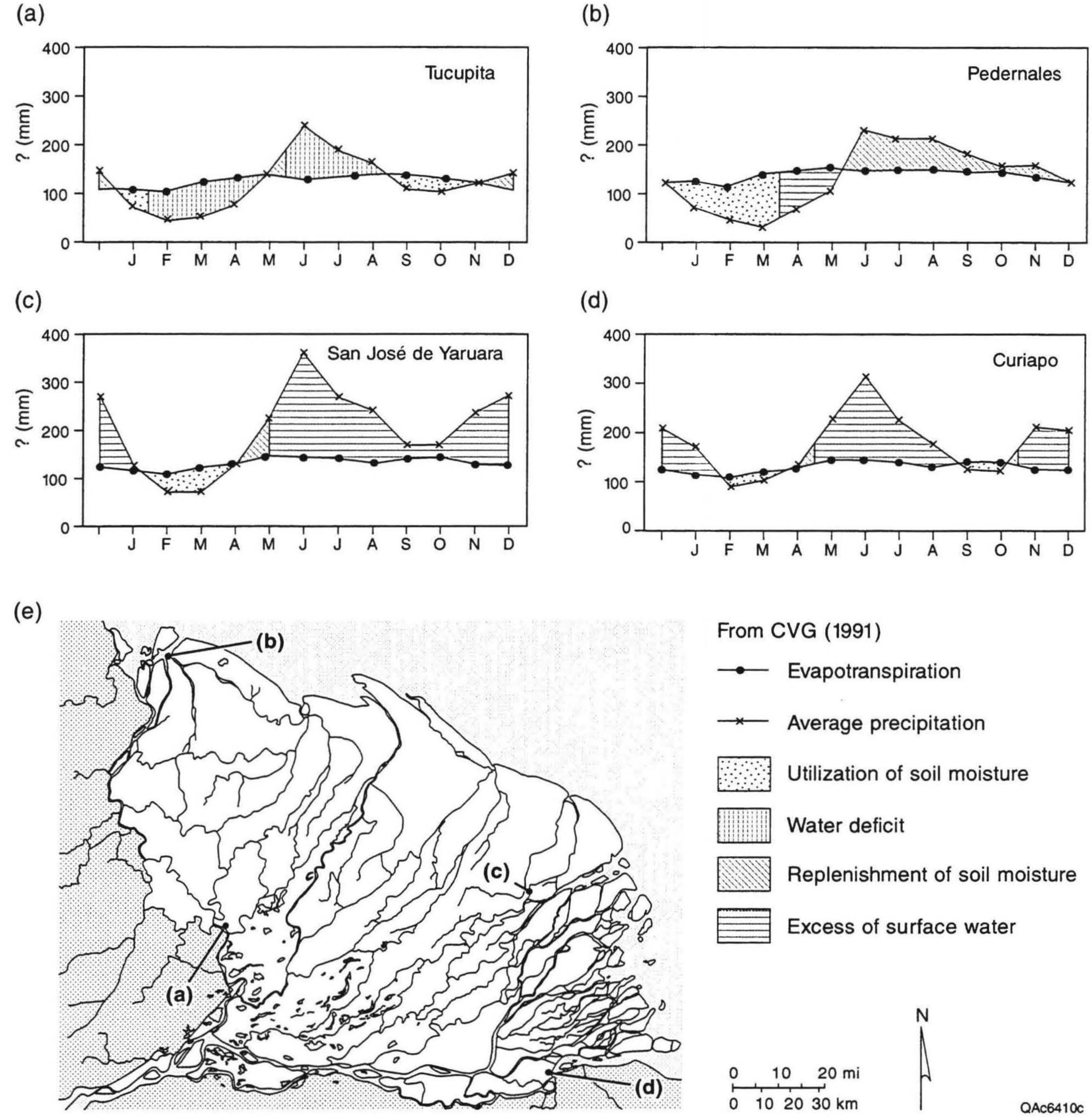

Figure 29. Water budgets calculated for the Orinoco Delta using the method outlined in Mather (1978). Compiled from CVG-TECMIN, C.A. (1991a through f).

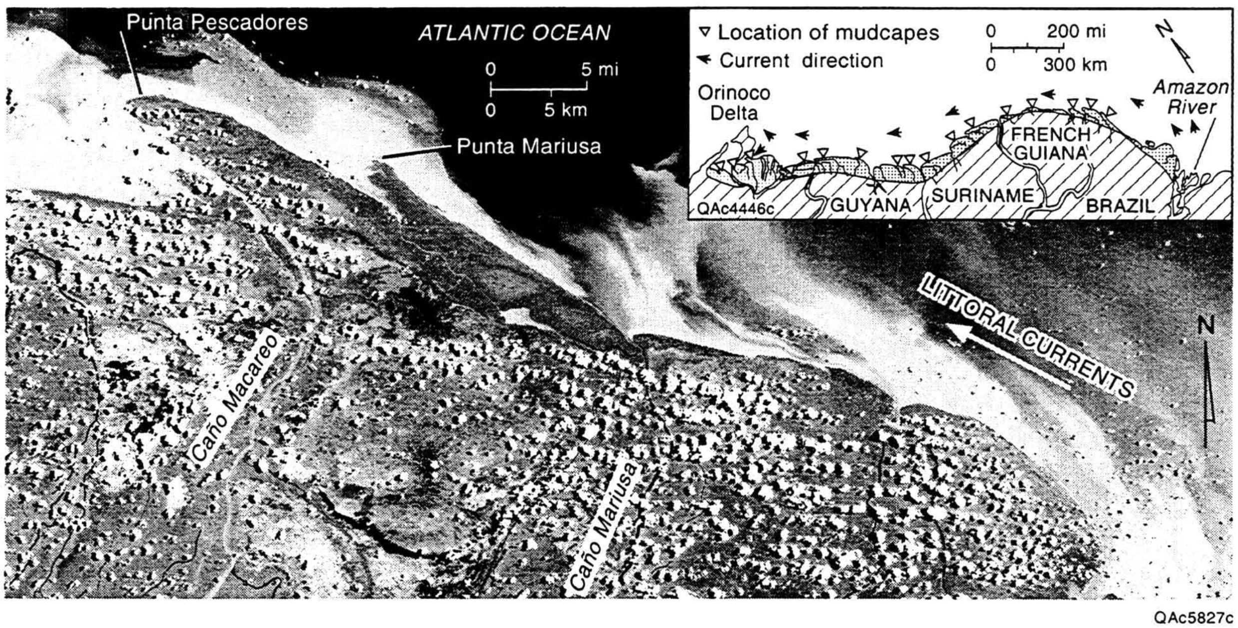

Figure 30. Landsat TM image (bands 2, 4, 7; August 1996) showing a portion of the north coast of the Orinoco Delta and turbidity patterns in the Atlantic Ocean. The turbidity plume shows east-west sediment transport. Mudcape progradation by longshore drift is the primary process of coastal progradation in this region. Inset map showing the distribution of mudcapes and Holocene coastal-plain and deltaic deposits along the northeast coast of South America. Arrows show the northwestward movement of longshore currents along the shelf, and triangles mark the location of coastal mudcapes. Modified from Allison and others (1995).

	Principal hydrologic agent	Setting/surface compostion	Drainage class	ID code	Associated landforms
	Tides	Littoral	Inundated	Pd3-43	Mud flats, mangrove swamp, cheniers
	Tides	Forested peat plain	Inundated	Pd3-33A	Tidal peat swamp
	Tides	Herbaceous peat plain	Inundated	Pd3-33B	Tidal peat marsh
	Tides	Mud plain	Inundated	Pd3-23	Tidal marsh, mud flat, cheniers
	River and tides	Littoral estuary	Inundated	Pd2-43	Tidal swamp, estuary margin, estuary islands
	River and (lesser) tides	Forested peat swamp	Inundated	Pd2-33A	Forested interdistributary tidal peat basin
	River and (lesser) tides	Herbaceous peat marsh	Inundated	Pd2-33B	Herbaceous interdistributary tidal peat basin
	River and tides	Mud and peat plain	Inundated	Pd2-33/43	Tidal swamp or bog
	River	Mud plain	Inundated	Pd2-23	Interdistributary tidal basin
	River with lesser tides	Mud plain	Deficient drainage	Pd2-22	Very poorly drained inter-distributary tidal basin
	River	Alluvial	Inundated	Pd2-13	Distal levee, flood basin
	River with lesser tides	Alluvial	Deficient drainage	Pd2-12	Very poorly drained distal levee and flood basin
	River	Alluvial	Inundated	Pd1-13	Distal levee and flood basin
	River	Alluvial	Deficient drainage	Pd1-12	Levee and crevasse splay

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Figure 31. Geomorphology of the Orinoco Delta plain. See table 8 for description of the map units. Modified from CVG-TECMIN, C.A. (1991a through f).

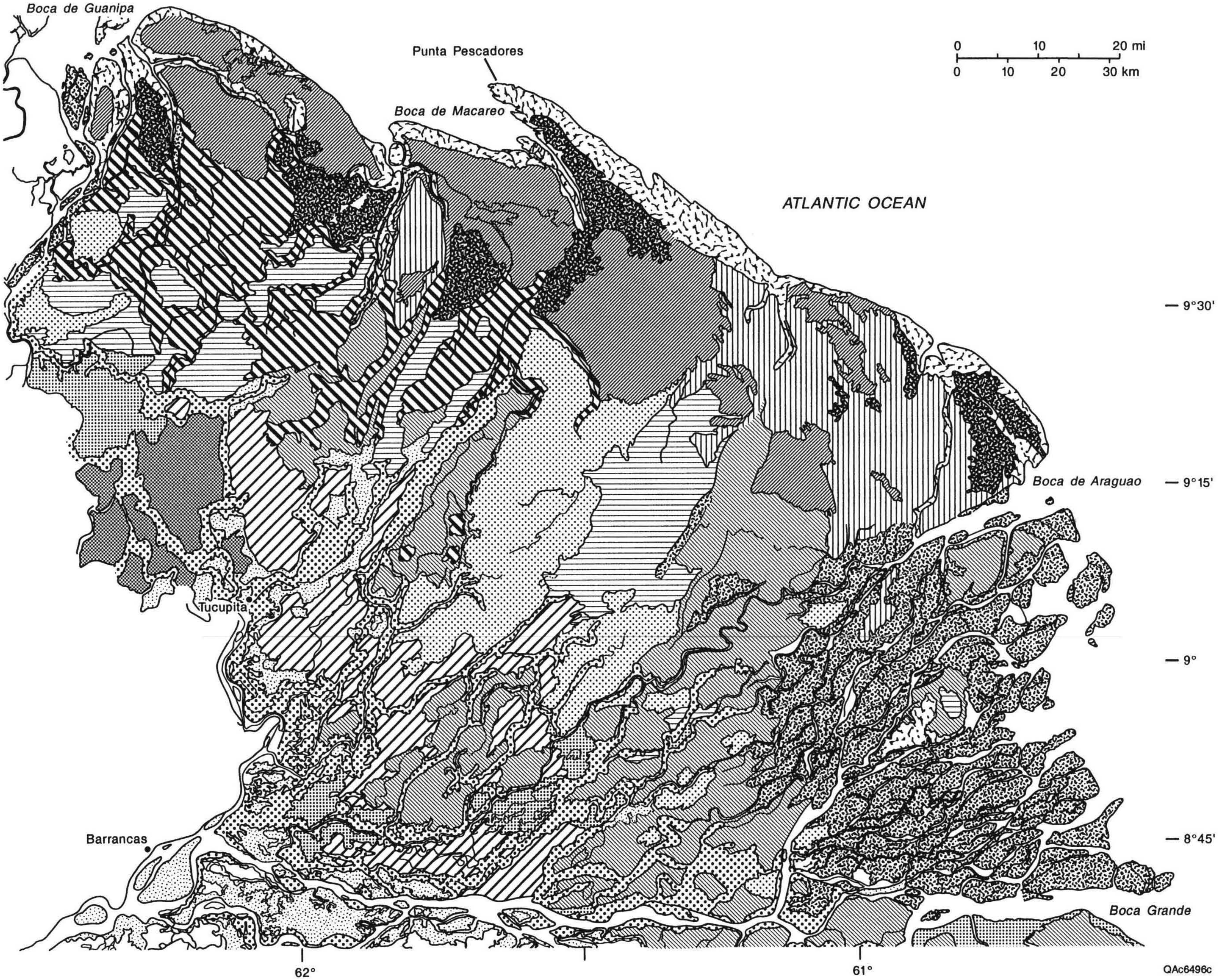
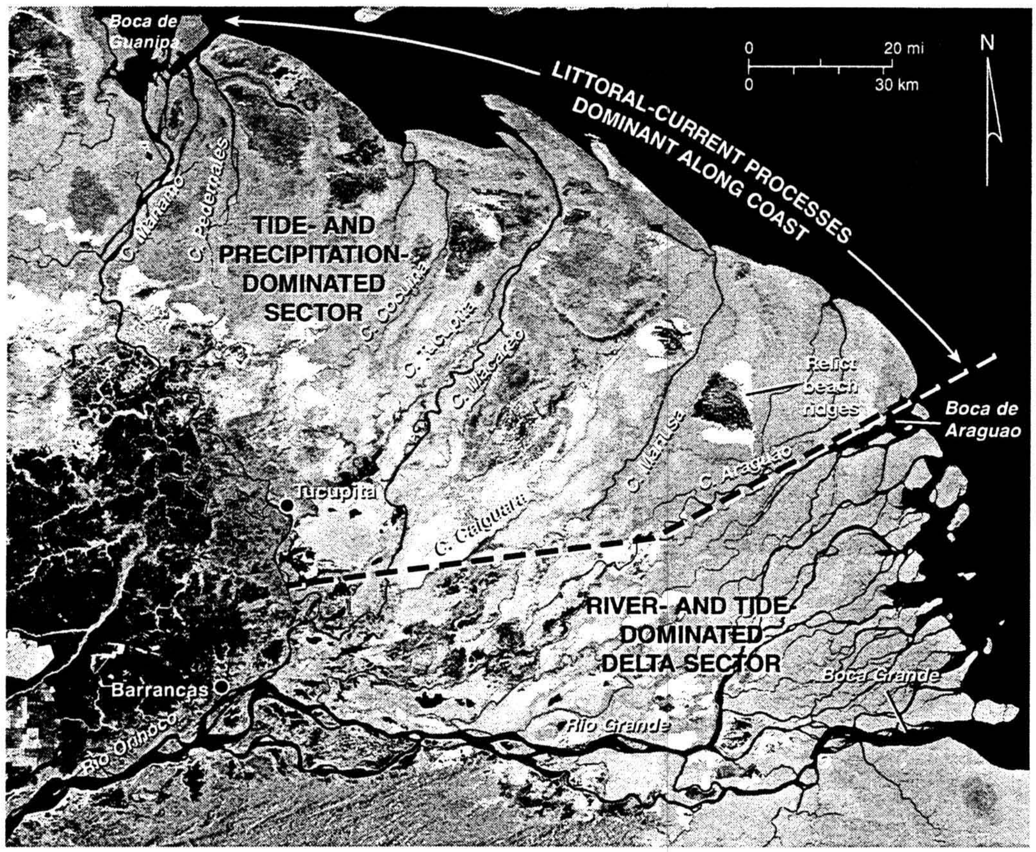

Boca de Guanipa
Punta Pescadores
Boca de Macareo
ATLANTIC OCEAN
0 10 20 mi
0 10 20 30 km
9°30'
9°15'
Boca de Araguao
9°
Tucupita
8°45'
Barrancas
Boca Grande
62°
61°
QAc6496c

Figure 32. Orinoco Delta hydrodynamics. (a) The river- and tidal-dominated southeast versus the pluvial- and tidal-dominated central and northwestern sector. These regimes may be controlled by differential subsidence in the southeastern sector. (b) Upper (fluvial-influenced), middle (fluvial- and marine-influenced), and lower (marine-influenced) delta. This tripartite, generally coast-parallel hydrologic regime is typical of tide-dominated deltas.

(a)



(b)

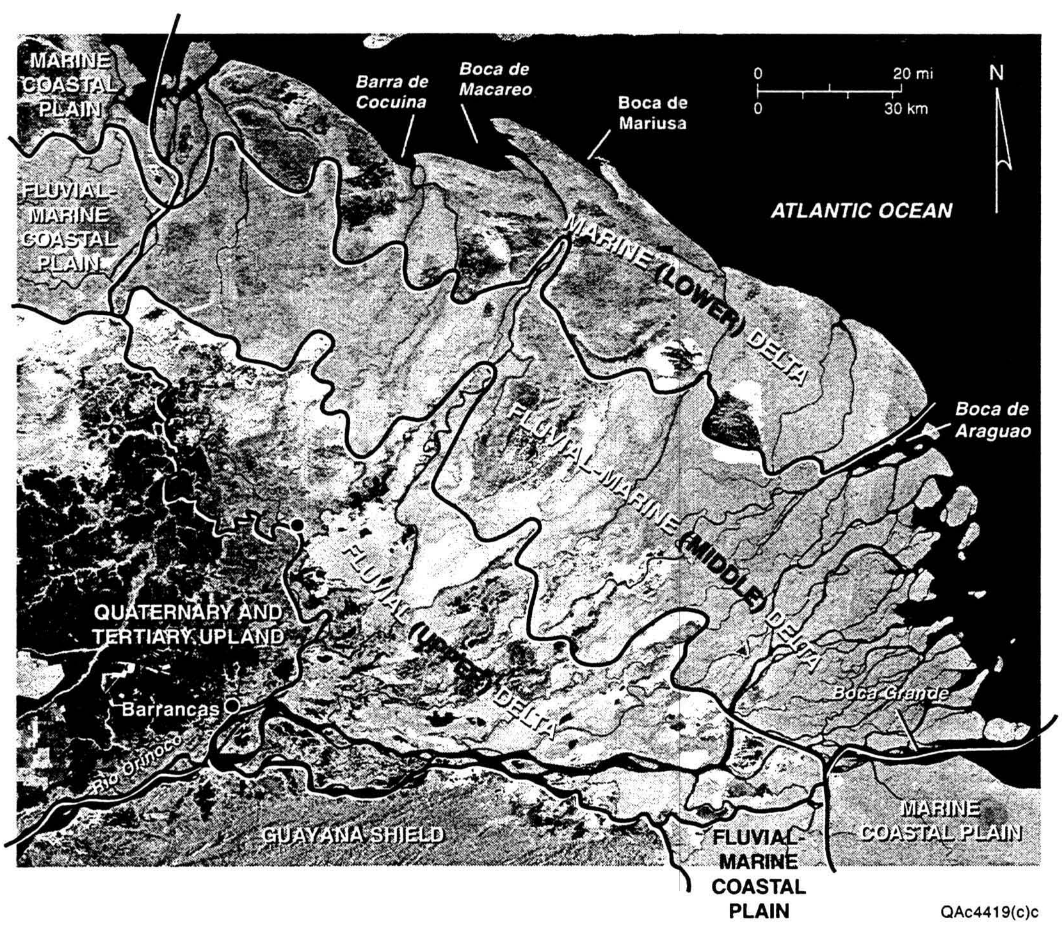


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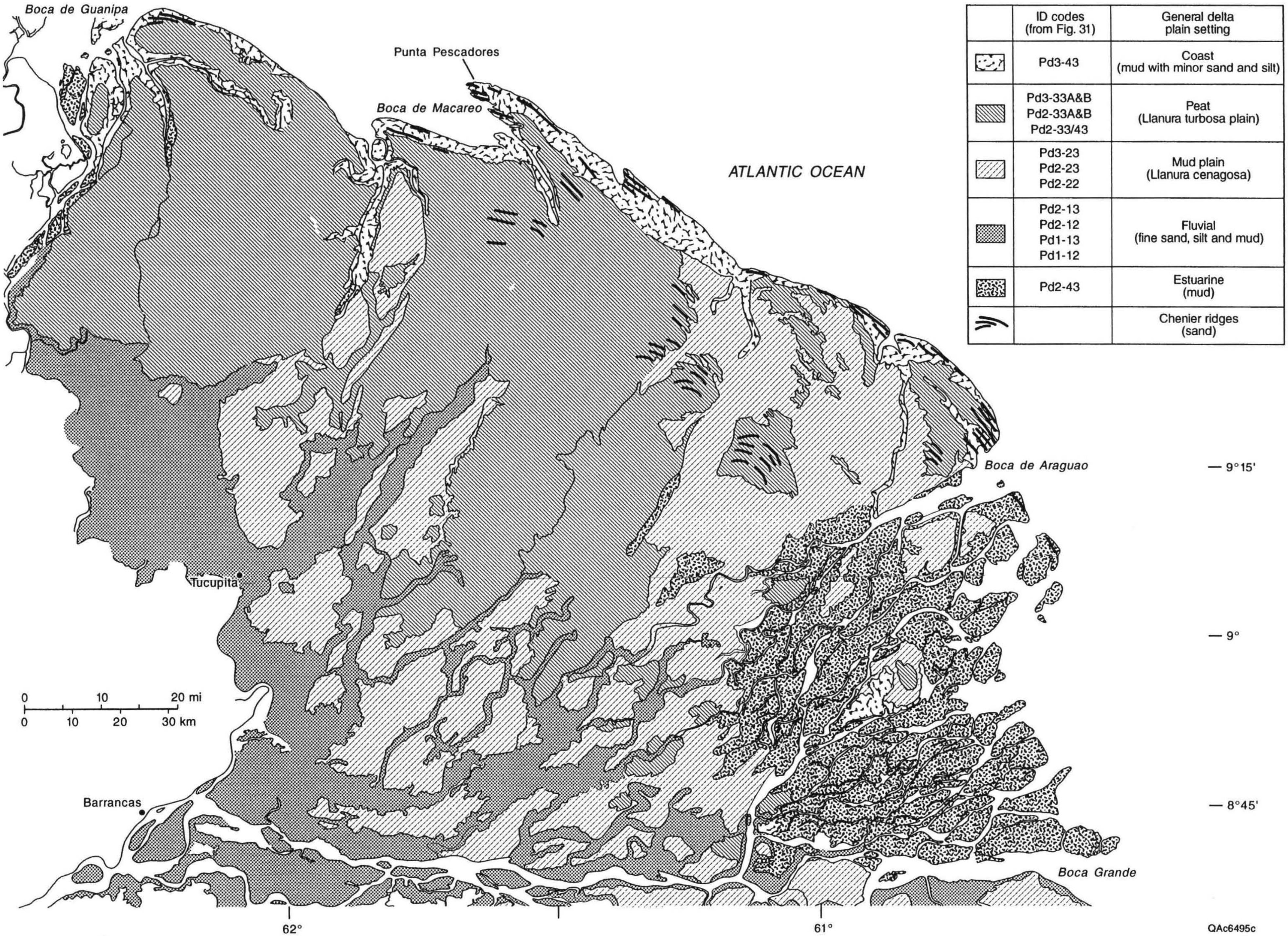
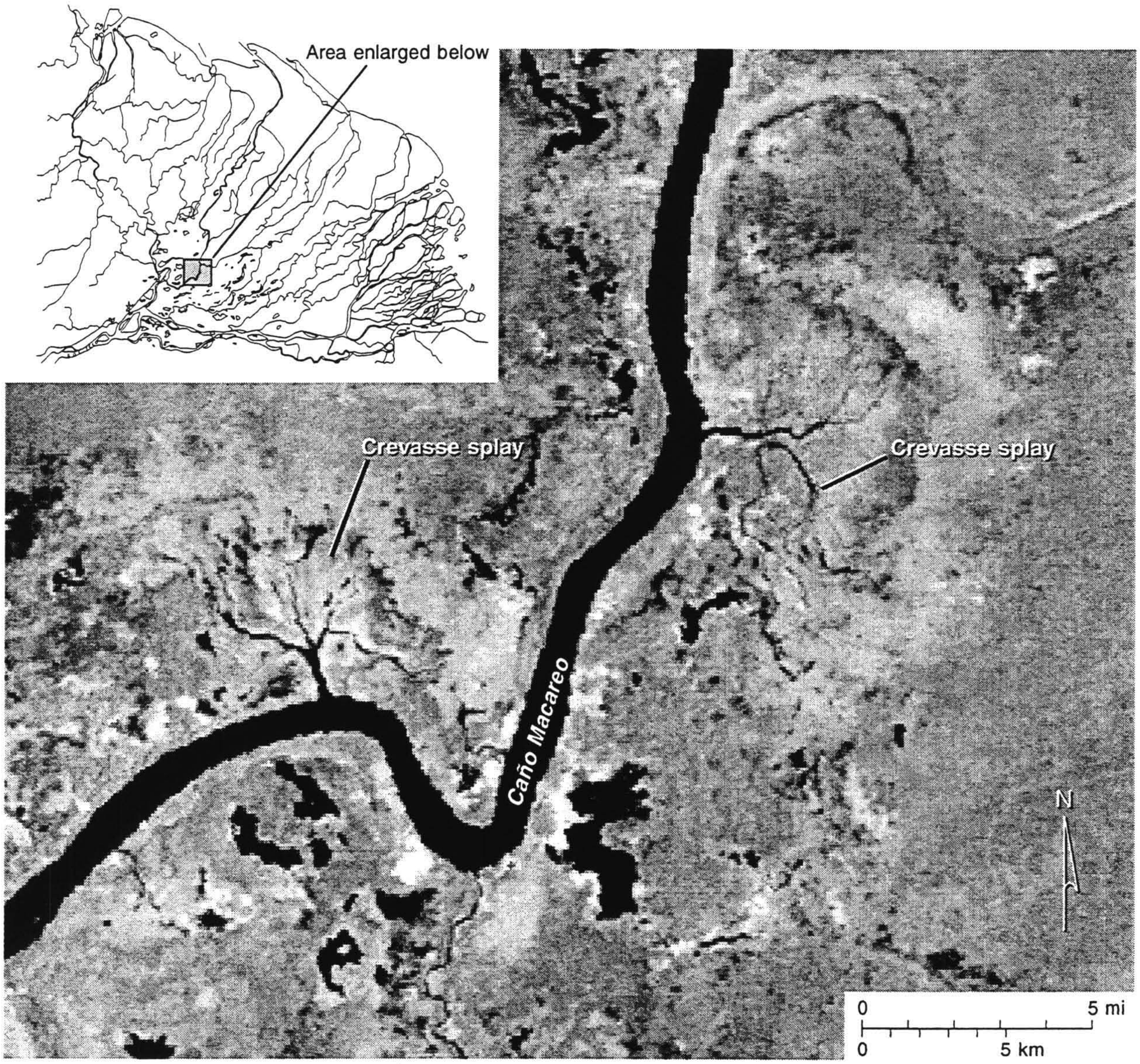
Figure 33. Substrate characteristics of the Orinoco Delta. These subdivisions were derived by combining the geomorphic units outlined in figure 31 and table 8. Note that the interdistributary basins with mud substrates are predominantly in the south and southeast, reflecting the importance of the Río Grande as a source of terrigenous sediment in the delta. The vast areas of the central and northwestern delta reflect that most of the Orinoco Delta plain receives little or no terrigenous sediment despite the high stages associated with the wet season and despite the extensive channel network.



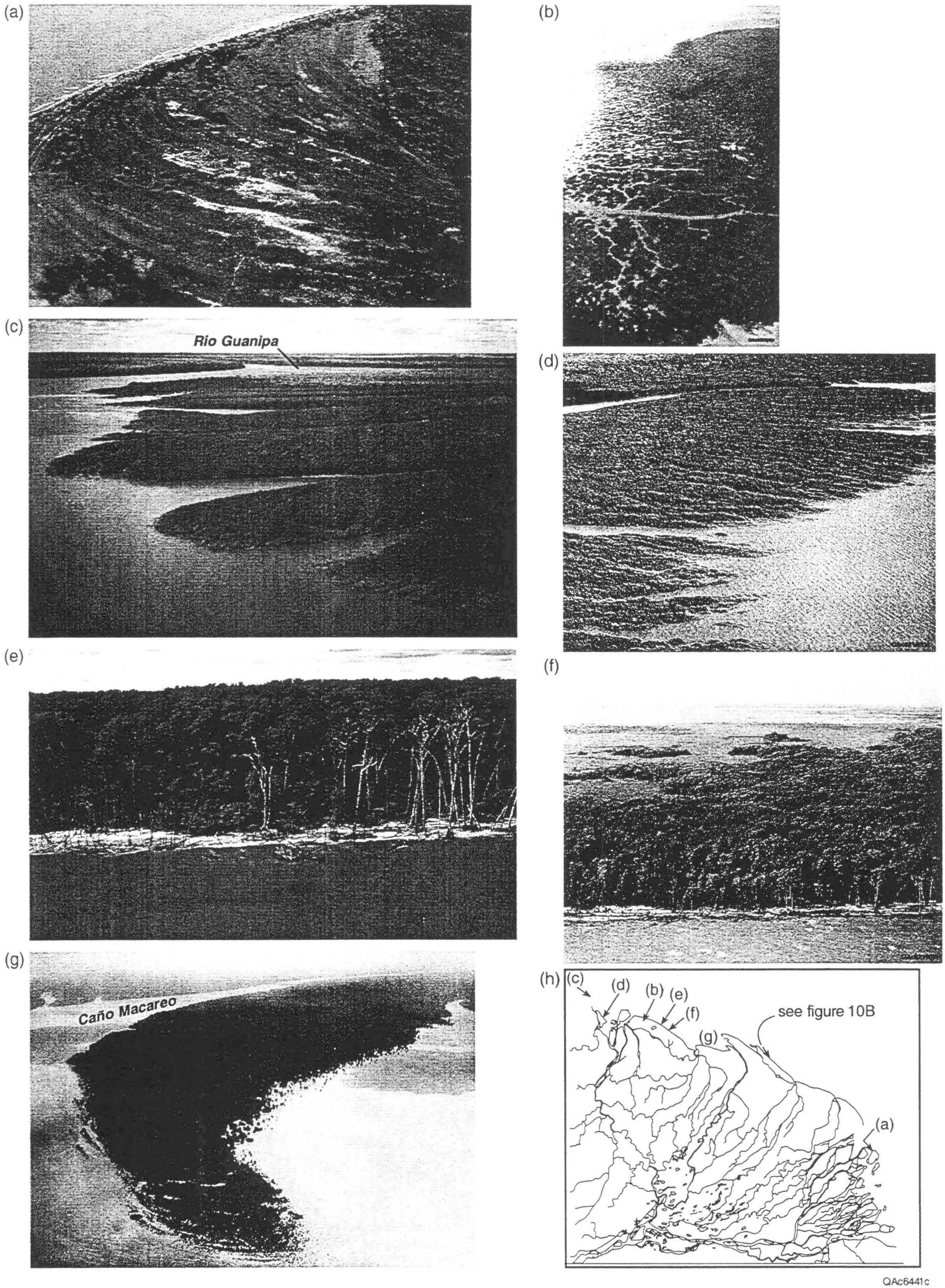
Boca de Guanipa
Punta Pescadores
Boca de Macareo
ATLANTIC OCEAN
Boca de Araguao
Tucupita
Barrancas
Boca Grande
— 9°15'
— 9°
— 8°45'
62°
61°
0 10 20 mi
0 10 20 30 km
ID codes (from Fig. 31)
General delta plain setting
Pd3-43
Coast (mud with minor sand and silt)
Pd3-33A&B
Pd2-33A&B
Pd2-33/43
Peat (Llanura turbosa plain)
Pd3-23
Pd2-23
Pd2-22
Mud plain (Llanura cenagosa)
Pd2-13
Pd2-12
Pd1-13
Pd1-12
Fluvial (fine sand, silt and mud)
Pd2-43
Estuarine (mud)
Chenier ridges (sand)
QAc6495c



QAc4427(a)c

Figure 34. Landsat TM image highlighting crevasse splays of Caño Macareo. Image was taken in September 1997 and is a gray tone of bands 4, 5, 7. Also see figure 27p.

Figure 35. Orinoco Delta coastal features. (a) Beach ridges (cheniers) near the mouth of Boca de Araguao. These relatively well-drained, sandy areas are cleared (by burning) to graze livestock. (b) Mud flats at low tide. (c) Estuarine islands at Boca de Guanipa. These are aggrading by lateral accretion of along seaward edge of mud flats and overstepping of mangroves onto the mud flat. (d) Aggradational shoreline in the Boca de Guanipa area. Aggradational process is similar as described for estuarine islands. The density of parallel tidal channels reflects the importance of tidal processes in coastal development in this area. (e) Static to erosional shoreline, as shown by slight beach development, straight profile, and paucity of dead mangrove. As is common along many stretches of the Orinoco Delta coast, the mangrove dominated coast is backed by extensive herbaceous marshes. (f) Erosional coastline as shown by thin beach and abundance of dead mangrove in the surf zone. (g) Rapidly accreting levee in Boca Macareo. View is to the southwest. Note concentric lines highlighted by mangroves at point, indicating rapid accretion. Photograph taken April 1998.



(a)
(b)
(c)
Rio Guanipa
(d)
(e)
(f)
(g)
Caño Macareo
(h)
(c)
(d)
(b)
(e)
(f)
(g)
see figure 10B
(a)
QAc6441c

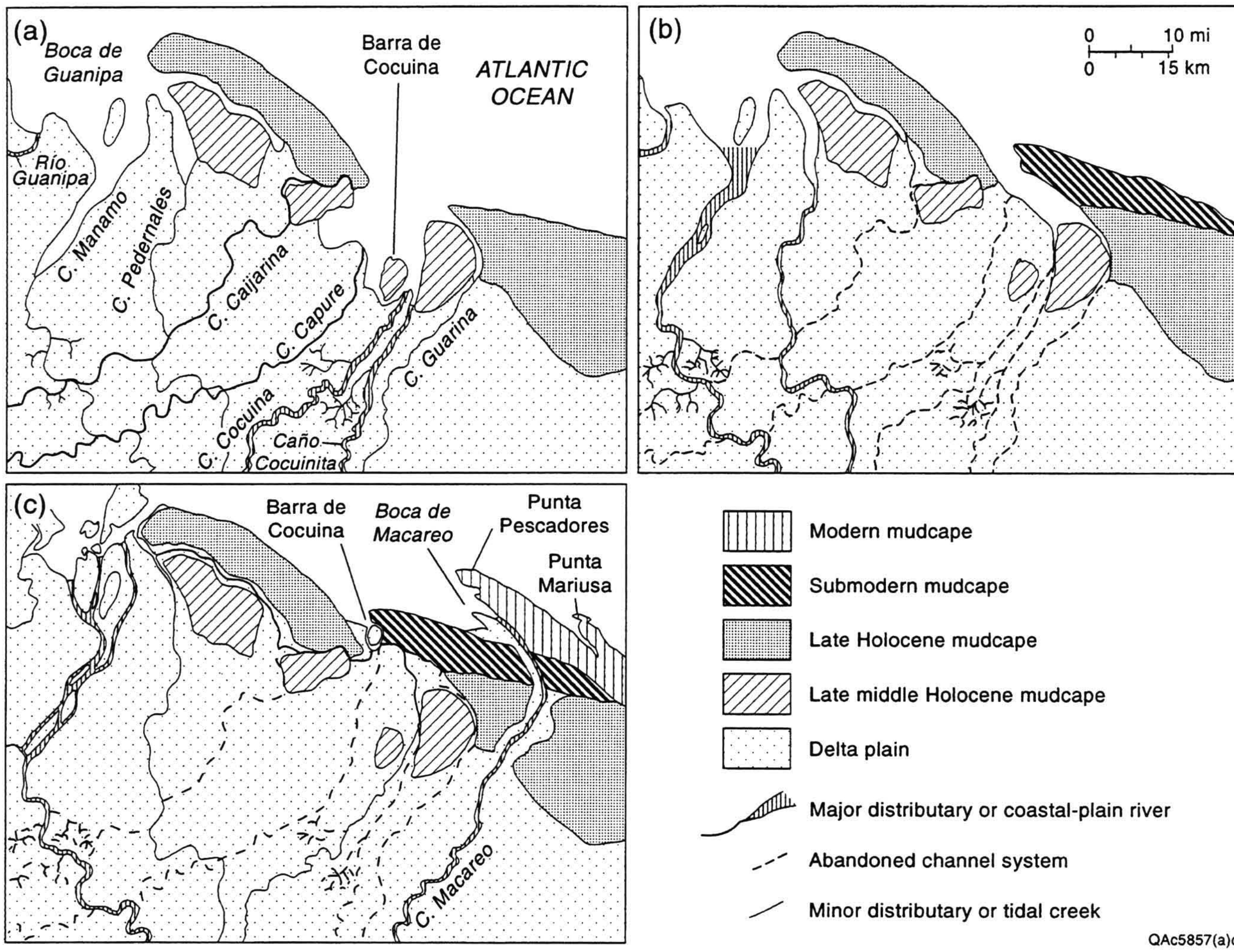


Figure 36. Paleogeographic maps showing our preliminary interpretation of the late Holocene evolution of the northwestern delta. The distribution of Holocene mudcapes and channel systems indicates that episodic avulsion and mudcape progradation have played a major role in the development of the delta in this region. Mudcape progradation has prograded the coastline as much as 20 to 30 km during the late Holocene. (a) From ~3,000 to 5,000 yr B.P., major Orinoco distributaries (for example, Caño Cocuina) and coastal-plain rivers (for example, Caño Caijarina and Capure channel systems) flowed northeast across the delta and discharged into Barra de Cocuina. The shoreline at this time was ~5 to 10 km landward of its present position, and tidal influences were strongly felt in the central delta, as demonstrated by the presence of dendritic tidal-channel networks. An estuary representing the precursor of Boca de Guanipa was also present at this time, but this bay was not the primary discharge point of Orinoco distributaries. (b) Some time after ~3,000 yr B.P. and perhaps as recently as ~1,500 yr B.P., avulsion of distributaries to the west shifted a significant portion of Orinoco flow to Boca de Guanipa. Because of reduced fluvial discharge following the avulsion and capture of coastal-plain river and/or other delta distributary flow by Caño Manamo, a mudcape partially filled Barra de Cocuina. (c) Present-day location of major and minor Orinoco distributaries, coastal-plain rivers, bays, and mudcapes.

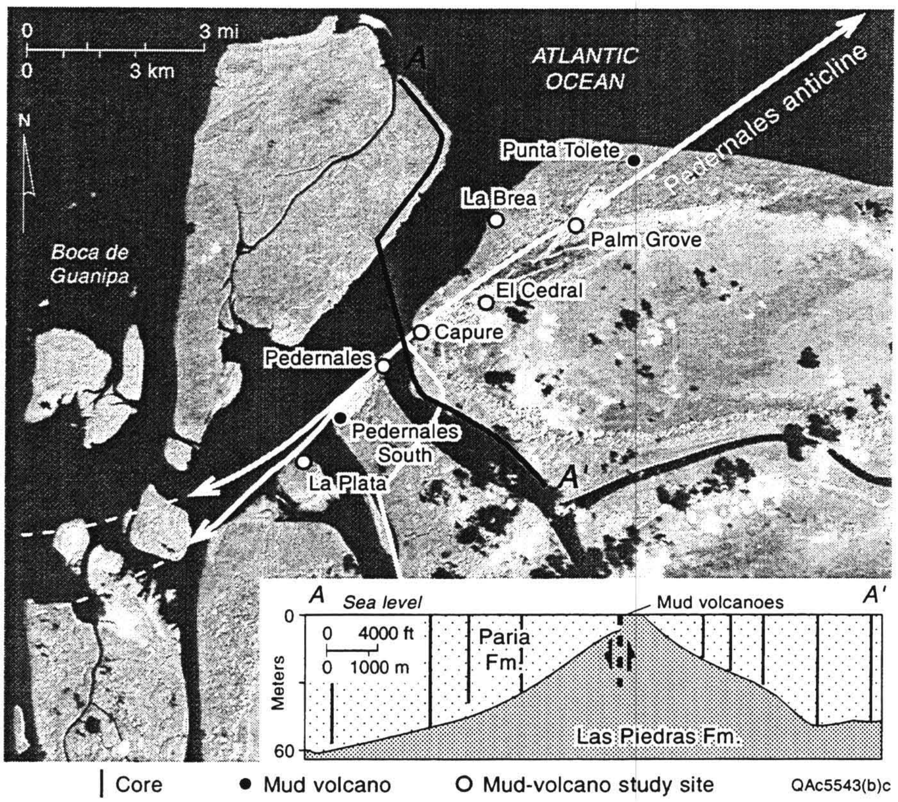


Figure 37. Distribution of Orinoco mud volcanoes along axis of Pedernales anticline. Background is a gray-tone Landsat TM image. Cross section in inset shows deformed Plio-Pleistocene strata of the Las Piedras Formation overlain by the Pleistocene Paria Formation.

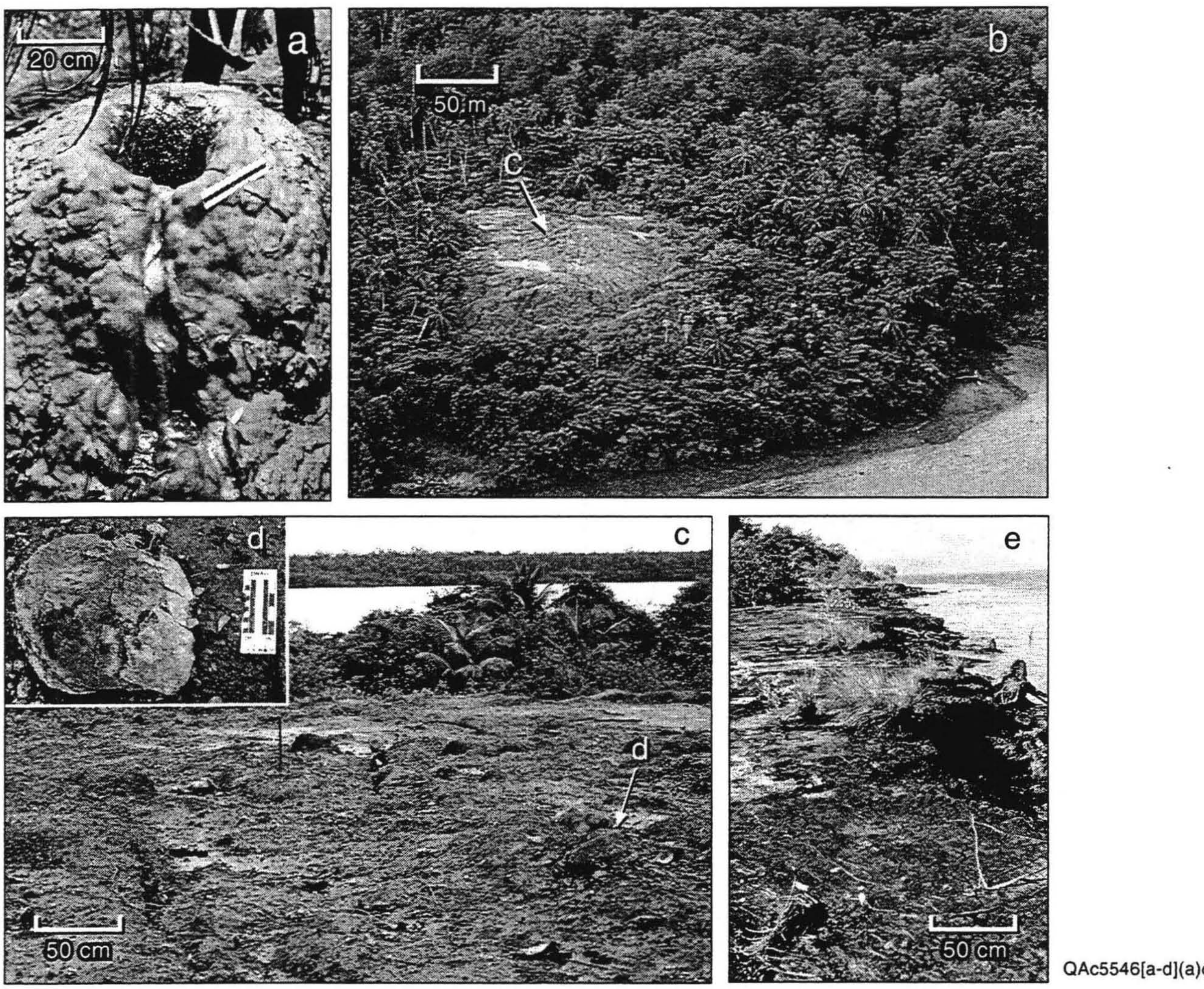


Figure 38. Photographs of Orinoco mud-volcano features. (a) Active vent of El Cedral mud volcano. (b) Oblique aerial photograph of La Plata mud volcano showing crest with little vegetation. View is to the southwest. (c) Surface of La Plata mud volcano showing the abundance of large clasts in the mud-flow deposits. View is to the northeast. (d) Rounded limestone clast with striations and pitting probably caused by acid etching during an eruption. (e) La Brea tar seep showing the tar-covered, wave-eroded mud flow and partly exhumed mangrove stumps. View is to the southwest. Photographs taken in November 1998.

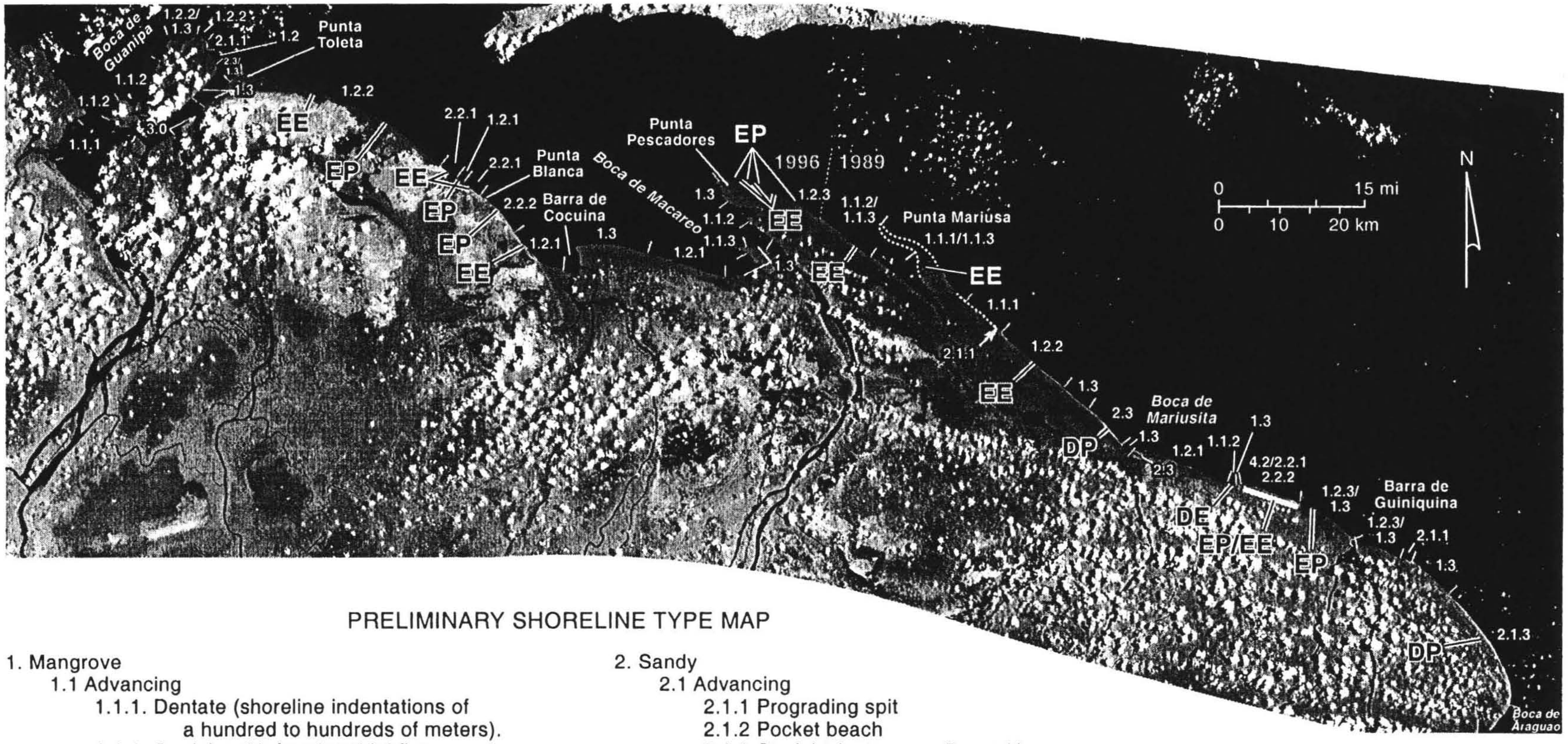


Figure 39. Preliminary map of shoreline types, northern coast of the Orinoco Delta. Base map is two Landsat images showing bands 4, 5, and 7. Image west of Punta Pescadores is from 1996, and the image east of Punta Pescadores is from 1989.

(a)

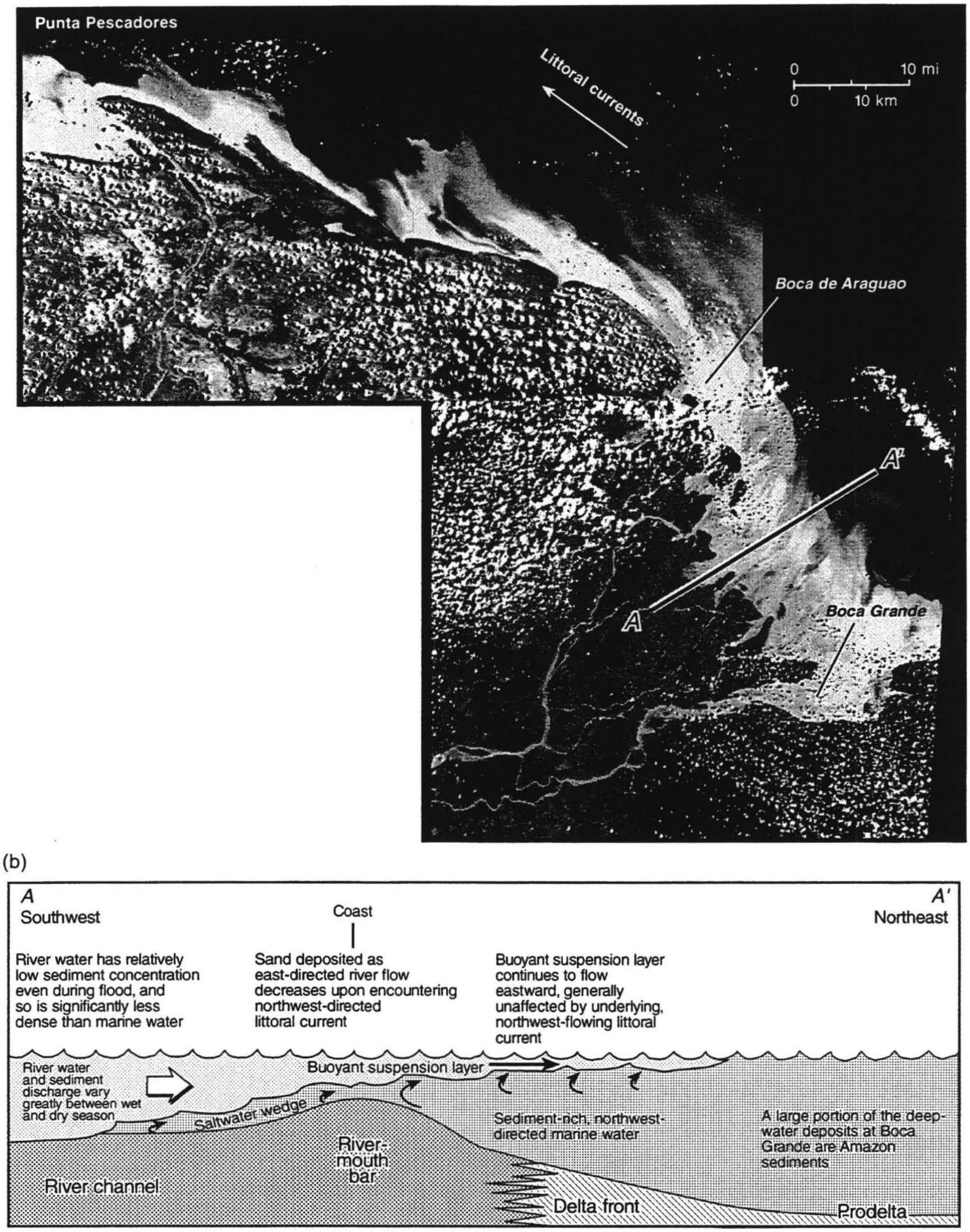


Figure 40. Sediment dynamics along Orinoco Delta coast. (a) Composite Landsat image of coast, processed using bands 4, 2 and 7 and then converted to gray tone. The northwestern half (Punta Pescadores area) was acquired in April 1989, and the southeast half (Boca Grande area) was acquired in November 1987. Cloud cover precluded the use of a single date. The mud plume seaward of Boca Grande appears to be moving orthogonal to coast. Only toward Boca Araguao are the effects of the northwest-directed Guyana current seen. Processes that induce the sharp delineation between high-sediment-concentration and low-sediment-concentration seawater is currently not understood. (b) Schematic cross section showing the hypopycnal plume that is maintained at Boca Grande.

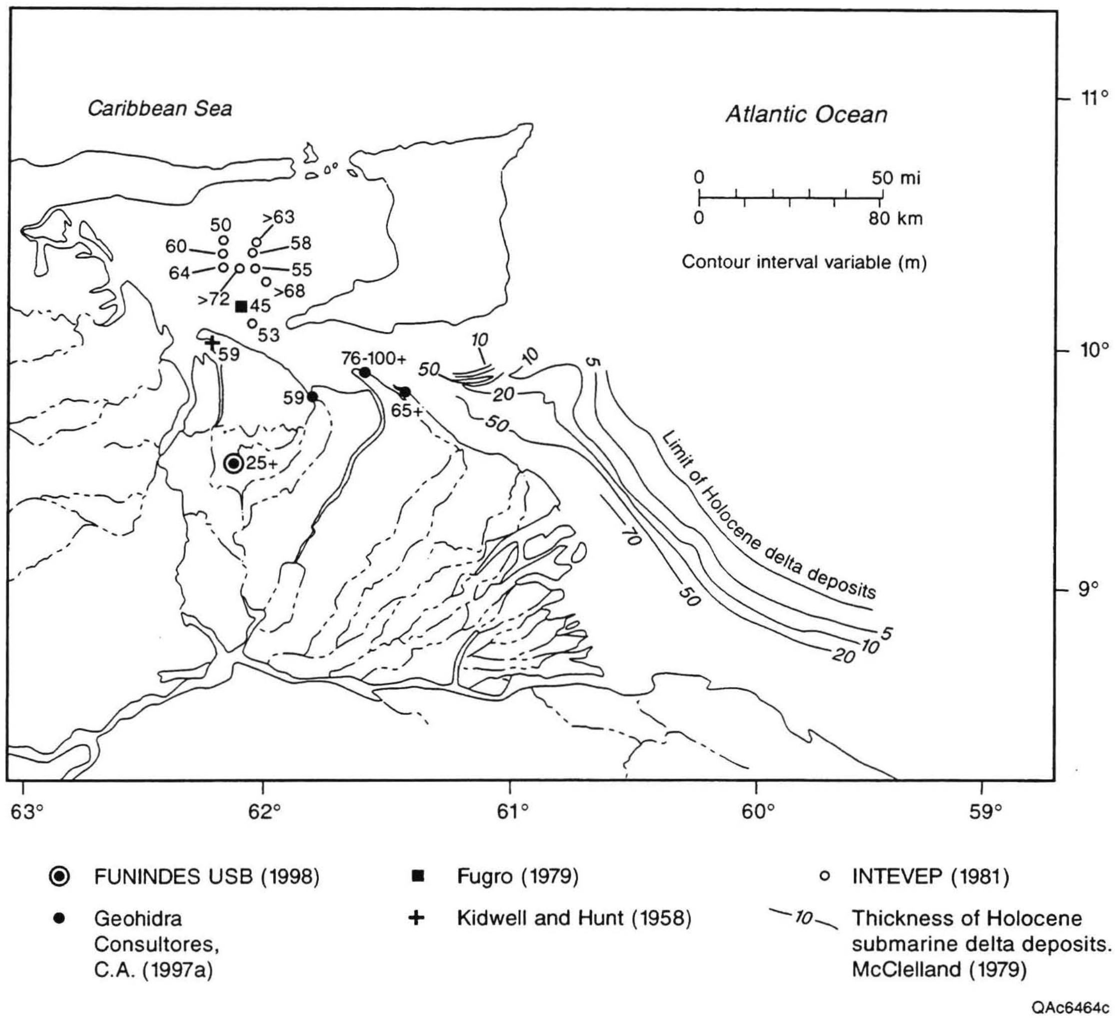


Figure 41. Preliminary assessment of the thickness of Holocene Orinoco Delta sediments. Data include geophysical surveys and boring (geotechnical) logs. Cross sections are presented in figure 44.

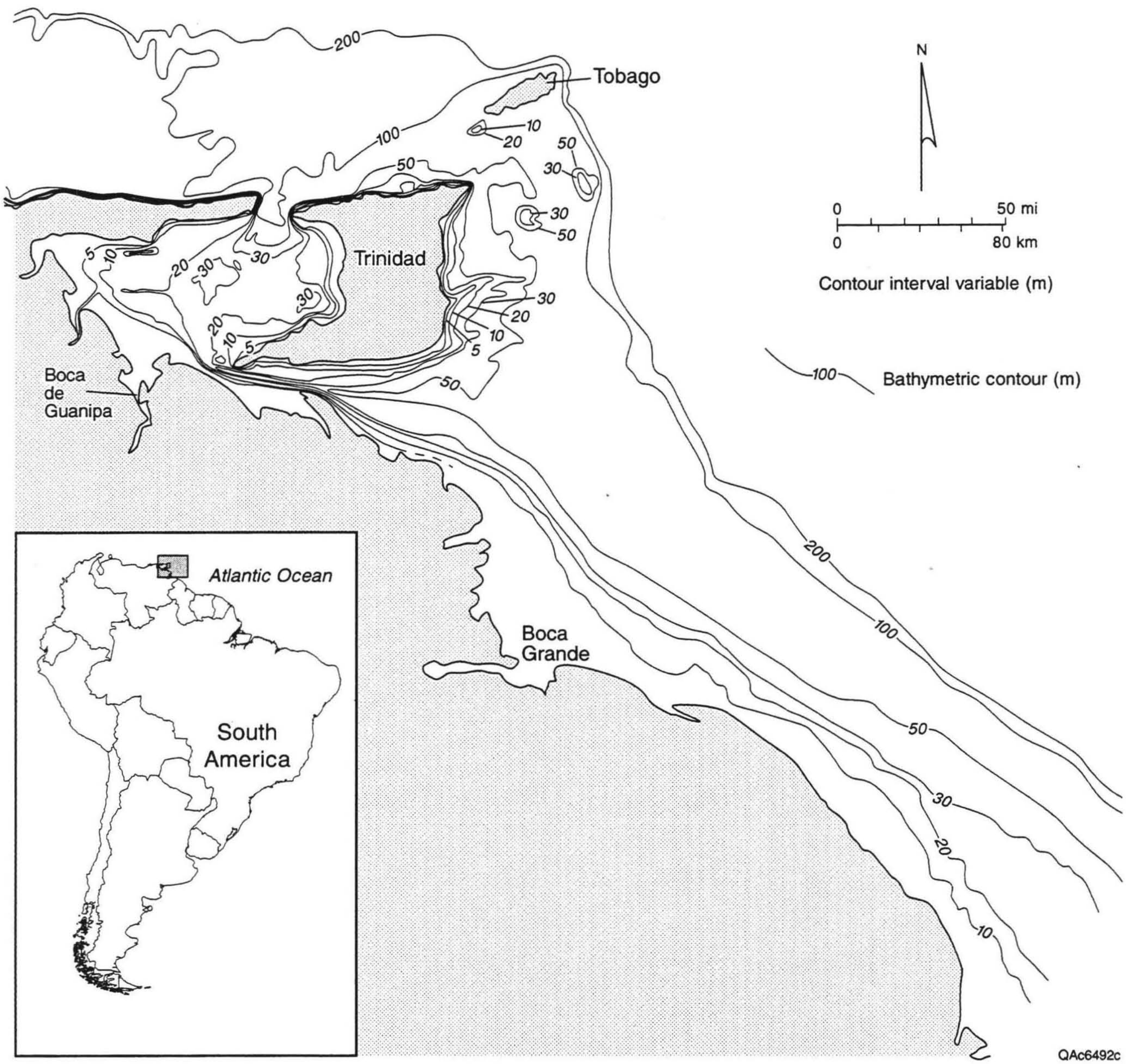


Figure 42. Bathymetry of the Orinoco shelf region. Information compiled from Van Andel and Postma (1954), Koldewijn (1958), and Nota (1958).

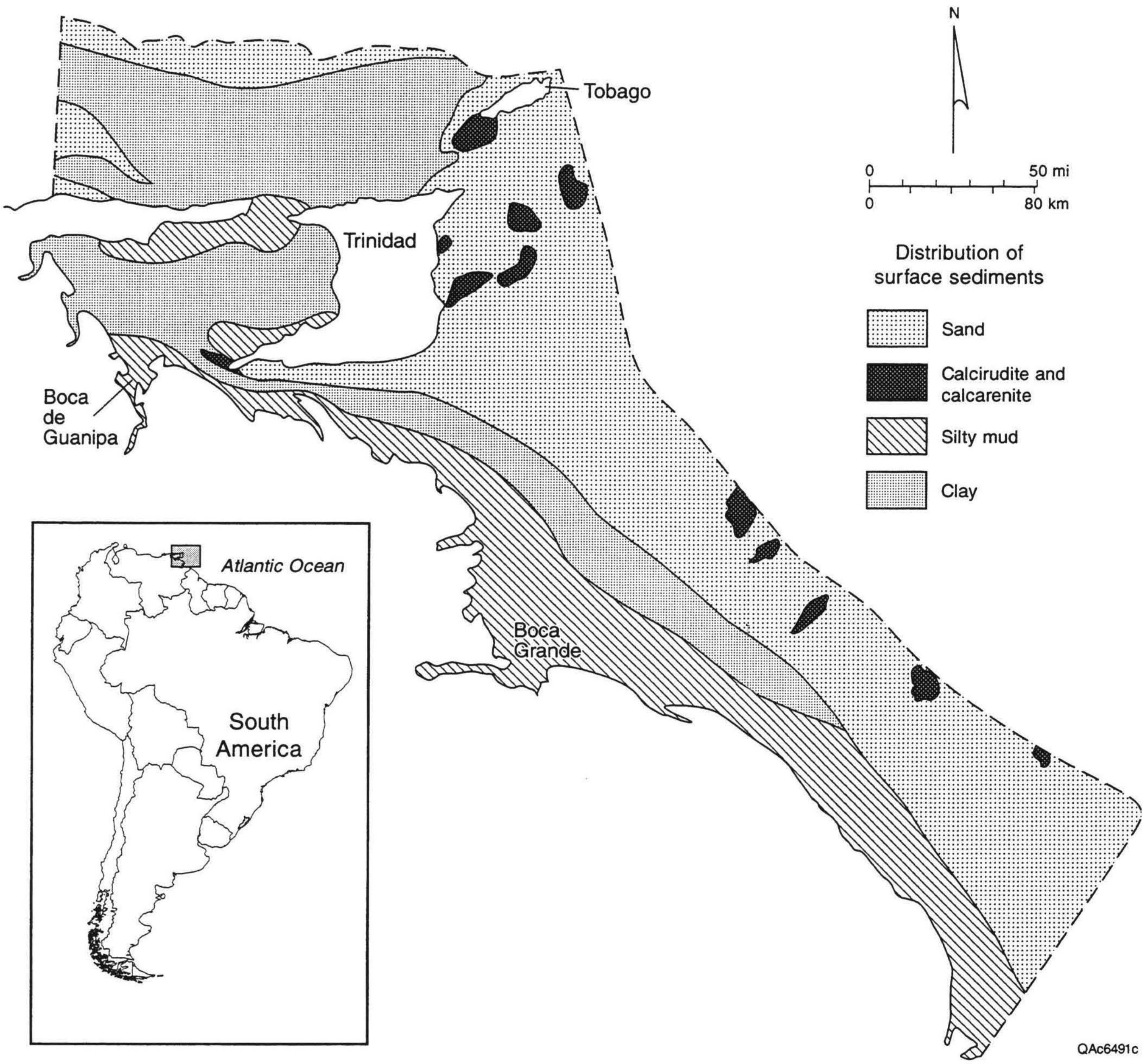
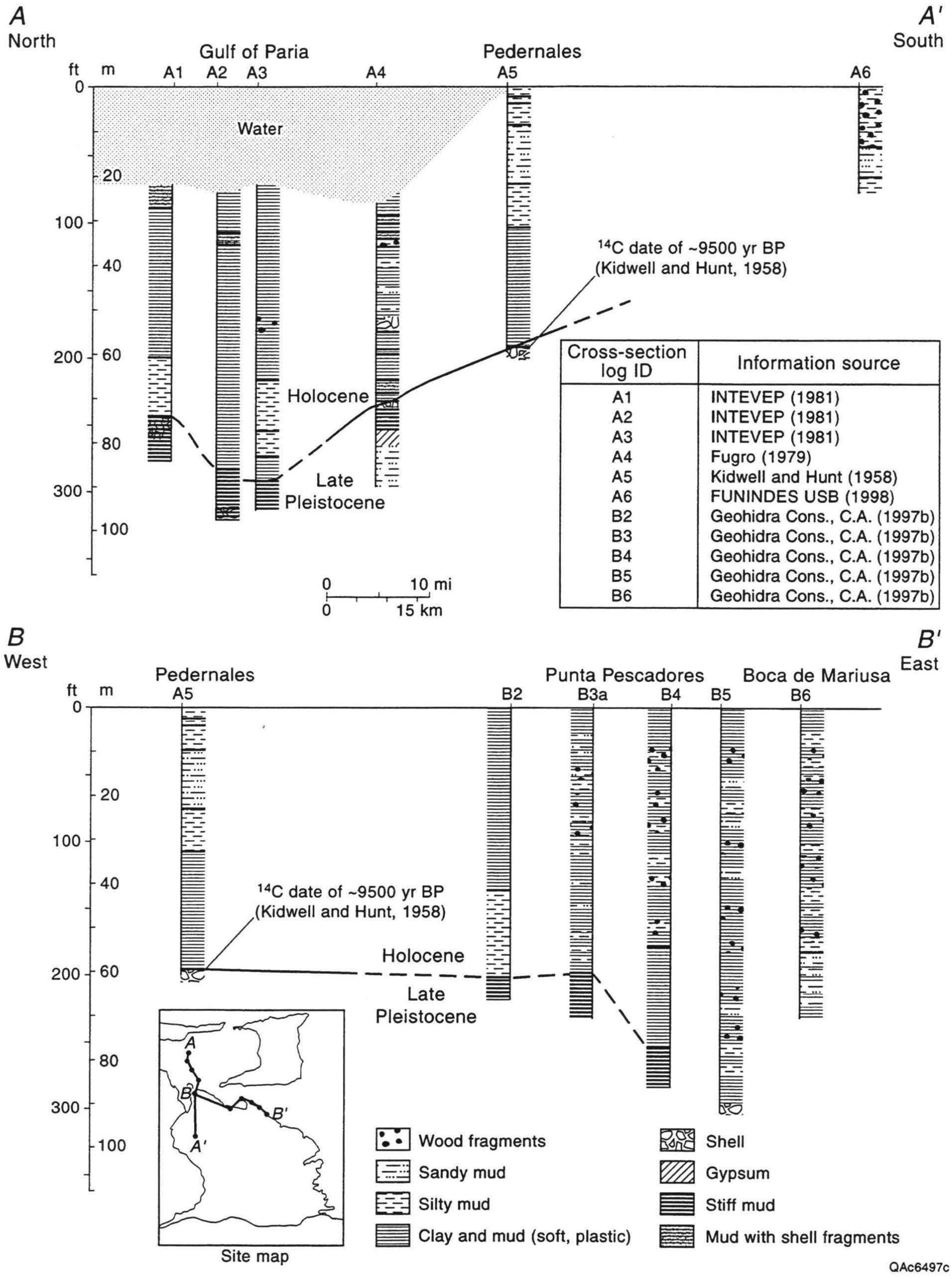


Figure 43. Sediment distribution and morphologic features of the Orinoco shelf. Compiled from Van Andel and Postma (1954); Nota (1958); Koldewijn (1958); McClelland (1979).



Cross-section log ID	Information source
A1	INTEVEP (1981)
A2	INTEVEP (1981)
A3	INTEVEP (1981)
A4	Fugro (1979)
A5	Kidwell and Hunt (1958)
A6	FUNINDES USB (1998)
B2	Geohidra Cons., C.A. (1997b)
B3	Geohidra Cons., C.A. (1997b)
B4	Geohidra Cons., C.A. (1997b)
B5	Geohidra Cons., C.A. (1997b)
B6	Geohidra Cons., C.A. (1997b)

Figure 44. 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 relatively soft, dark-gray to black, organic clays to sand or to stiff brown and yellow silty, sandy mud.

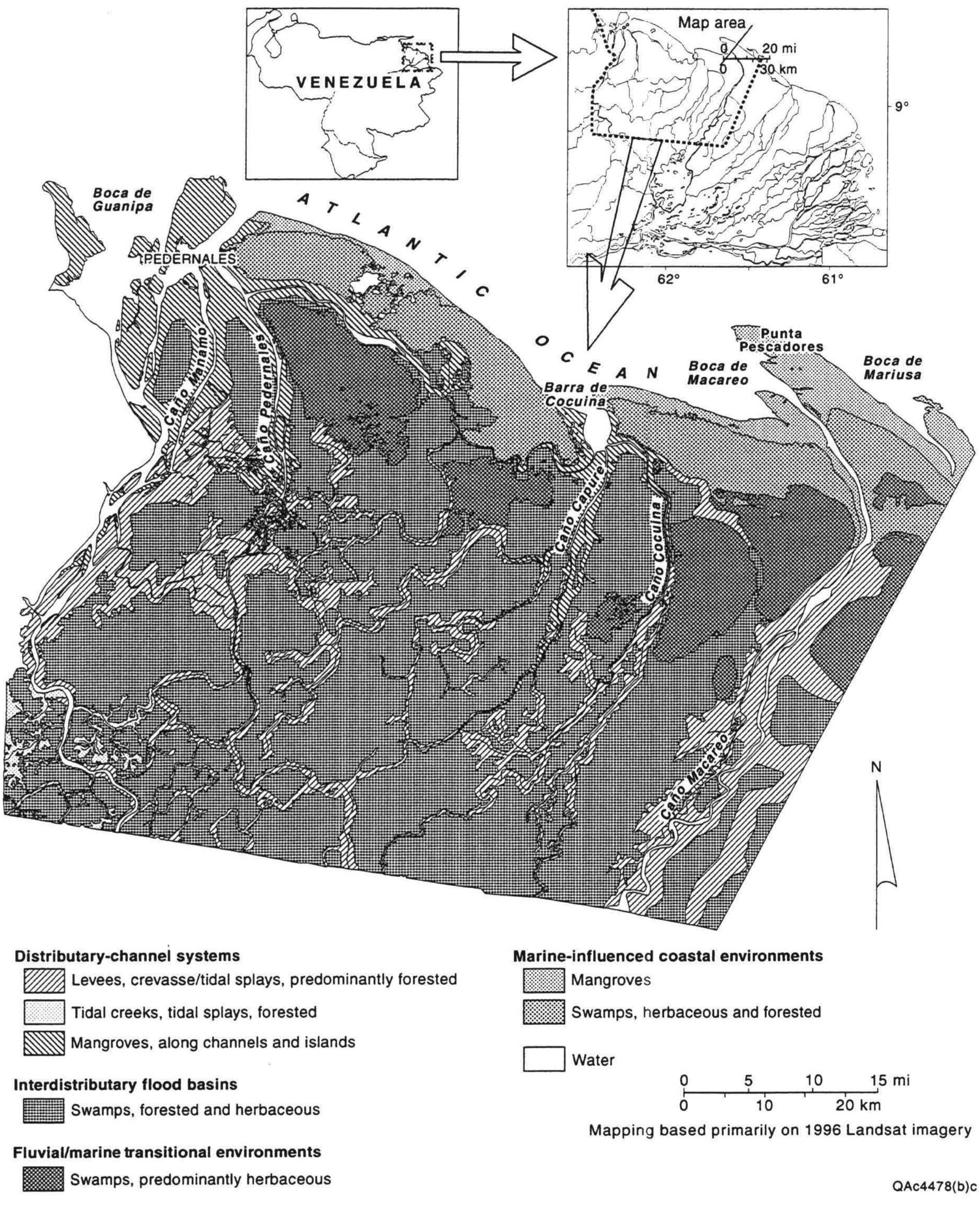


Figure 45. Generalized depositional systems map of the northwestern delta derived from geoenvironmental mapping in the area (pl. 2). This part of the delta is characterized by distributary channels and interdistributary flood basins that integrate seaward with swamps in fluvial/marine transitional environments and mangroves and swamps in marine-influenced coastal environments. Compare map with figure 31.

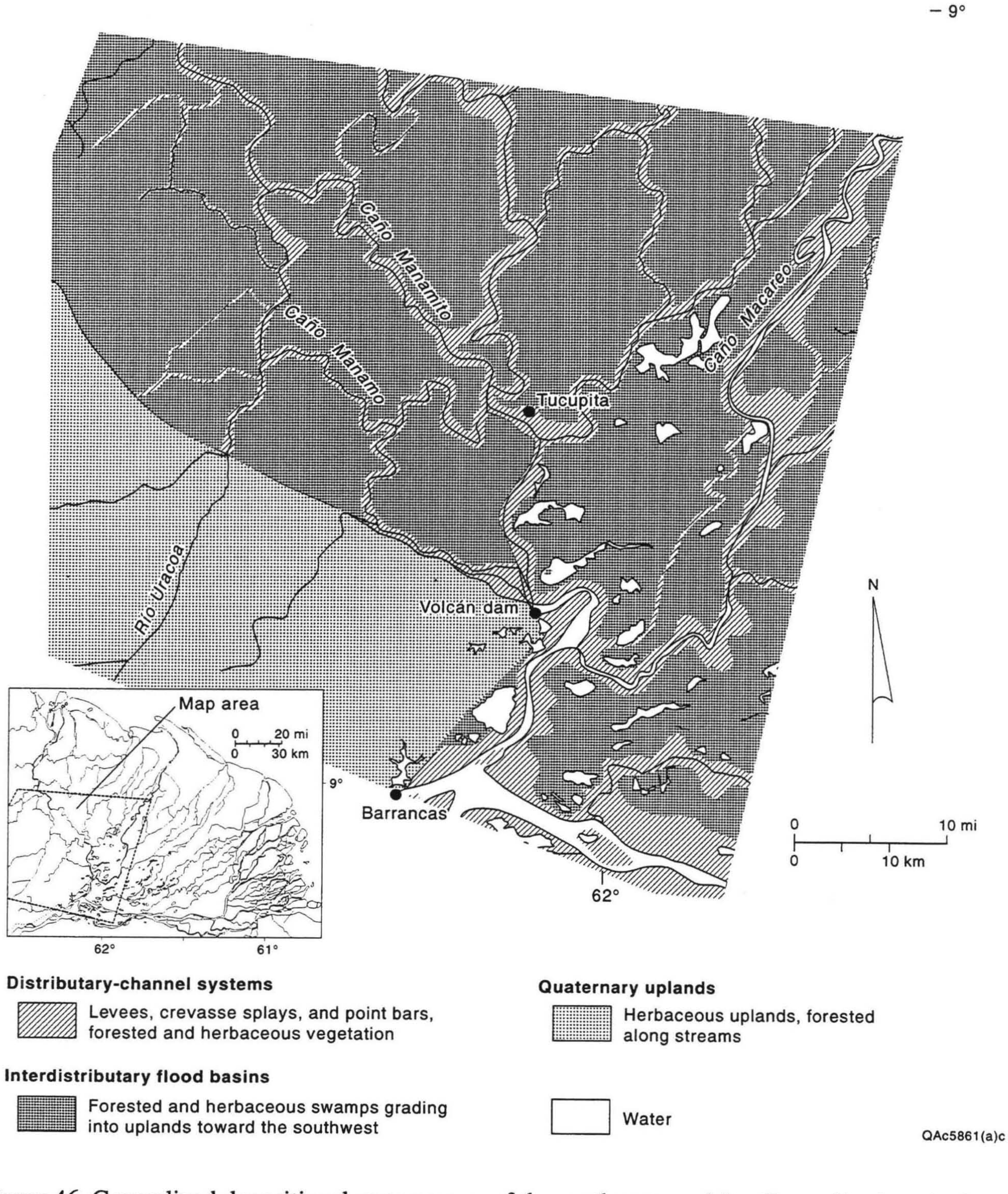


Figure 46. Generalized depositional systems map of the southwestern delta. Generalized geologic map of the southwestern delta, Tucupita area. This part of the delta is dominated by interdistributary flood basins characterized by forested and herbaceous swamps. Levees and crevasse splays along distributary channels provide topographically higher substrates on which forested and herbaceous vegetation occurs. These elevated areas are the site of local urban development such as at Tucupita. Compare map with figure 31.

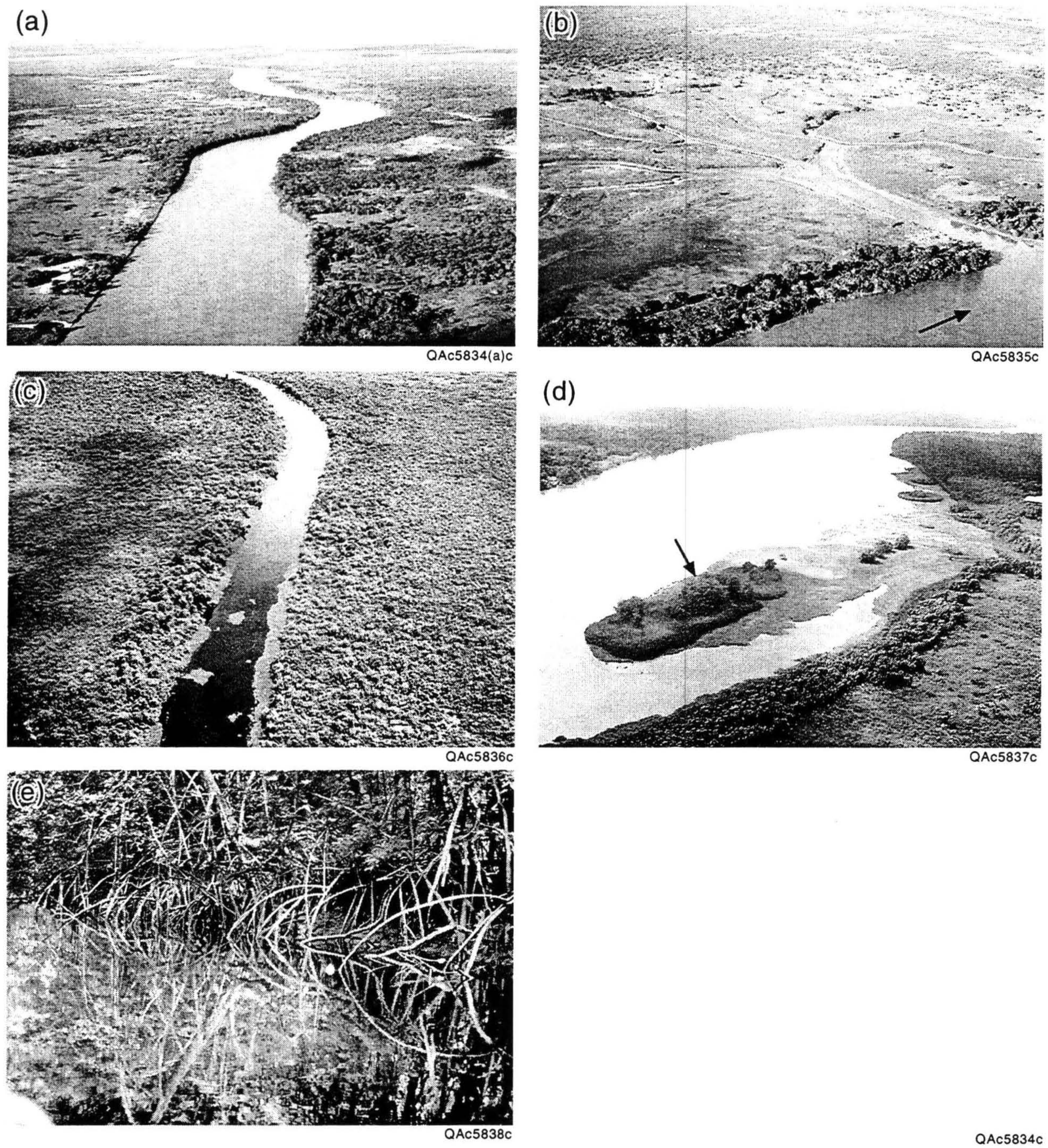


Figure 47. Photographs of distributary-channel-system environments. (a) Upper Caño Macareo. View is downstream. (b) Oblique aerial photograph of a crevasse splay of Caño Macareo. Photograph was taken in November 1998 during low-water conditions. Arrow shows flow direction. (c) Typical blackwater caño in the lower delta. Note the abundance of floating aquatic vegetation along the channel margins. View is downstream. (d) Aerial photograph showing small island of mangroves (arrow) and aquatic vegetation partially filling Caño Macareo. View is upstream. (e) Dense root network of mangroves (*Rhizophora*) along banks of blackwater distributary in the lower delta.

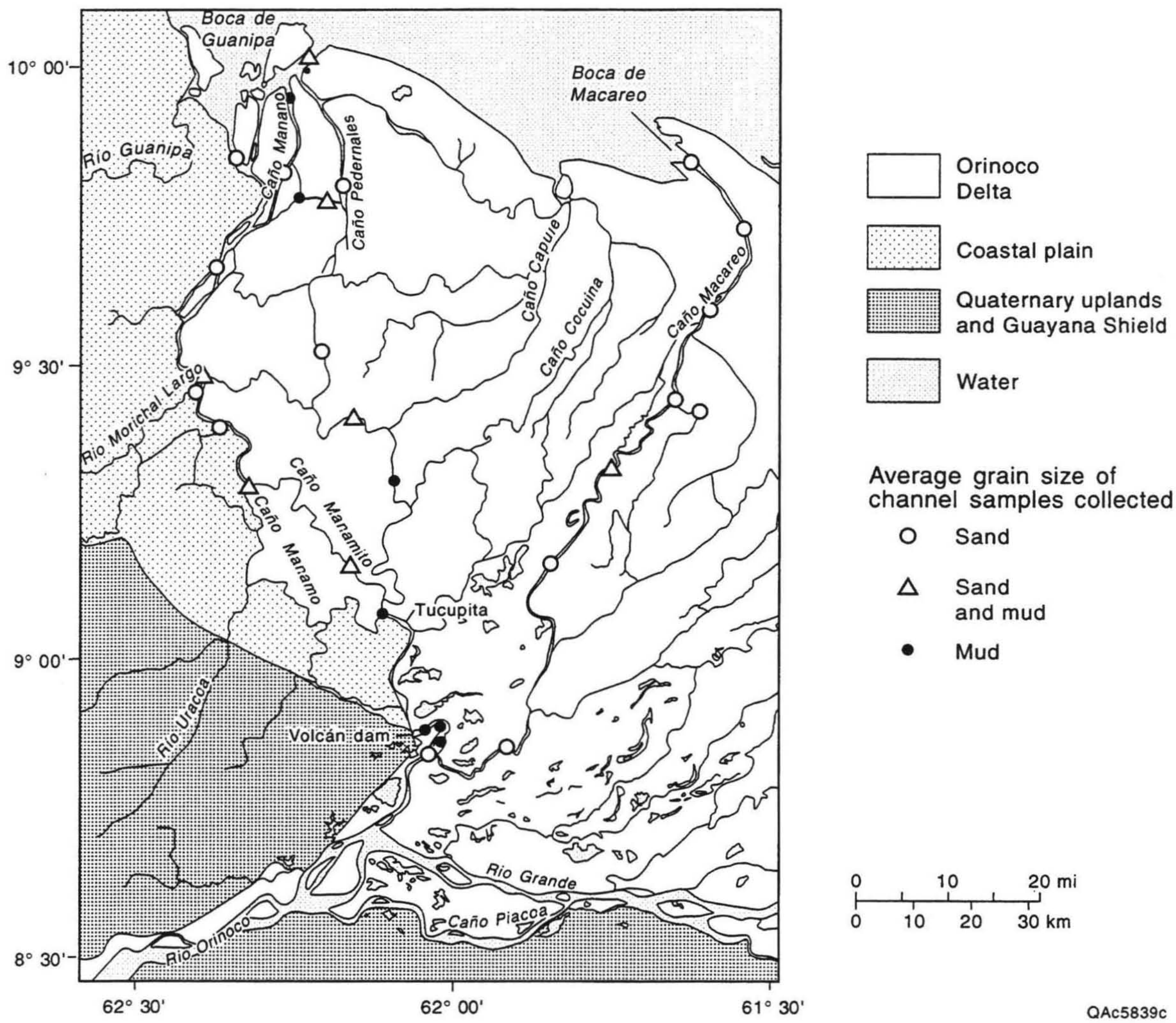


Figure 48. Western Orinoco Delta region showing the average grain size of channel-bed deposits within the major distributaries. Also see table 9.

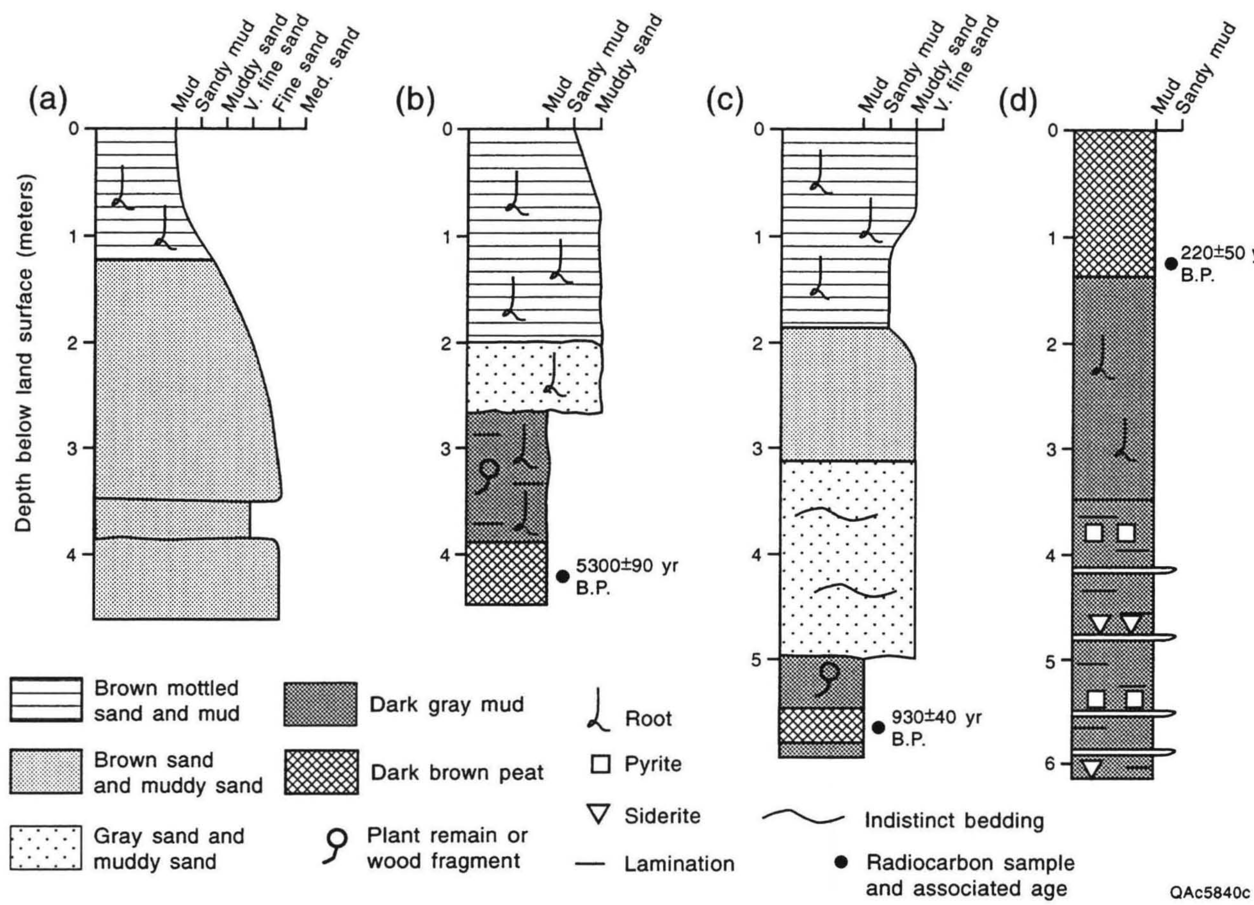


Figure 49. Lithologic profiles of cores from distributary-channel environments. (a) Upper-delta point-bar deposits of Caño Manamo located south of Tucupita. (b) Upper-delta natural-levee deposits of Caño Manamito located northwest of Tucupita. (c) Upper-delta crevasse splay deposits of Caño Macareo. (d) Lower-delta natural-levee deposits of Caño Pedernales south of Pedernales. Locations of logs are shown in figure 56. Detailed descriptions of the shallow cores are presented in a data base on the CD that accompanies this report.

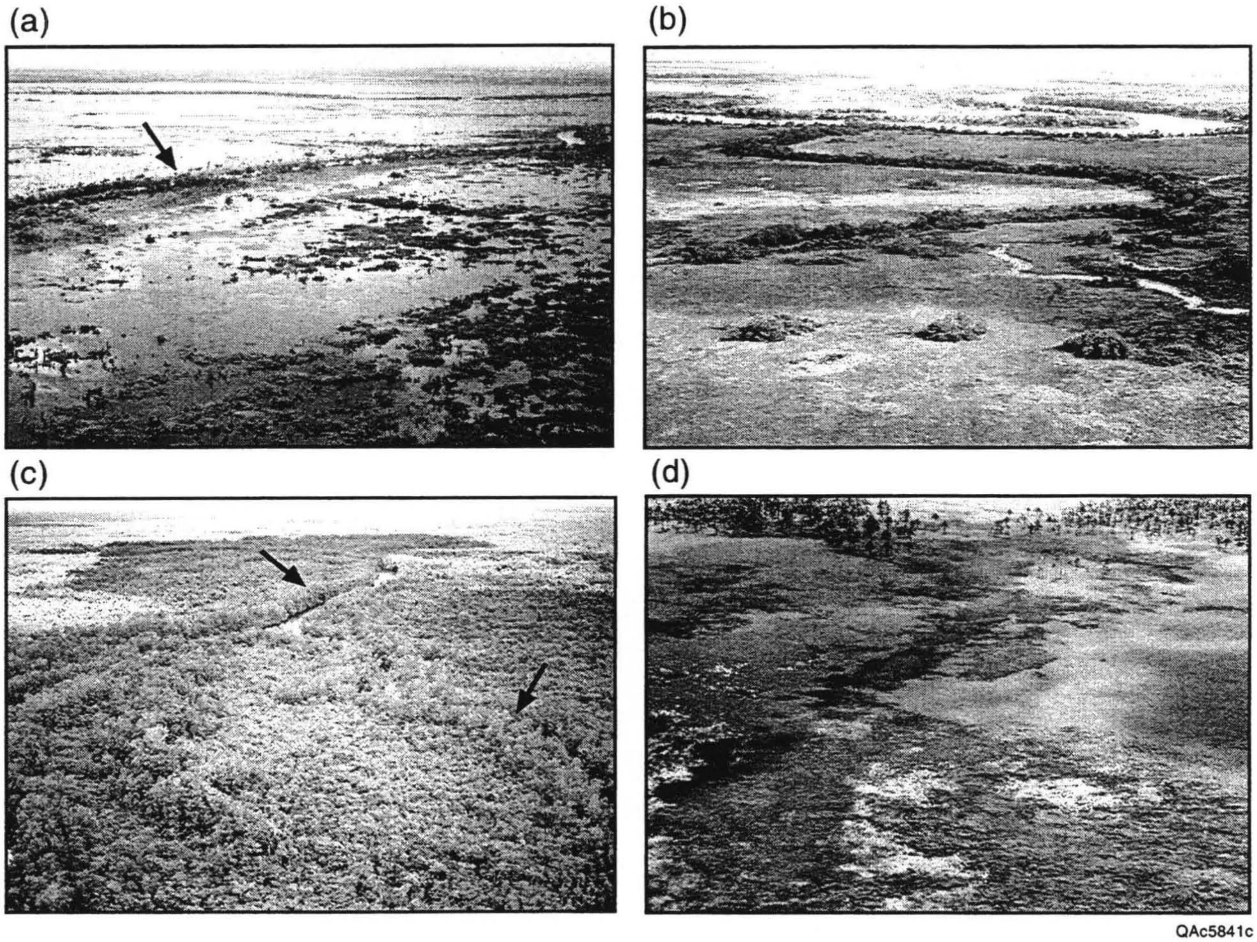


Figure 50. Photographs of interdistributary flood basins. (a) Widespread flooding in the upper delta east of Caño Macareo during November 1998. Note the alluvial ridge (arrow) representing the only portion of the delta plain that is not inundated in the photograph. View is south toward the Guayana Shield. (b) Herbaceous swamp with a shallow dendritic flood-basin stream along the western margin of Caño Macareo in the upper delta. (c) Forested swamp in a lower delta interdistributary basin located east of Caño Manamo. The forested swamp is crossed by a complex network of blackwater tidal channels (arrow). View is to the west. (d) Areas of standing water among herbaceous vegetation and moriche palms of a lower delta interdistributary basin located east of Cano Macareo. Photograph was taken in November 1998.

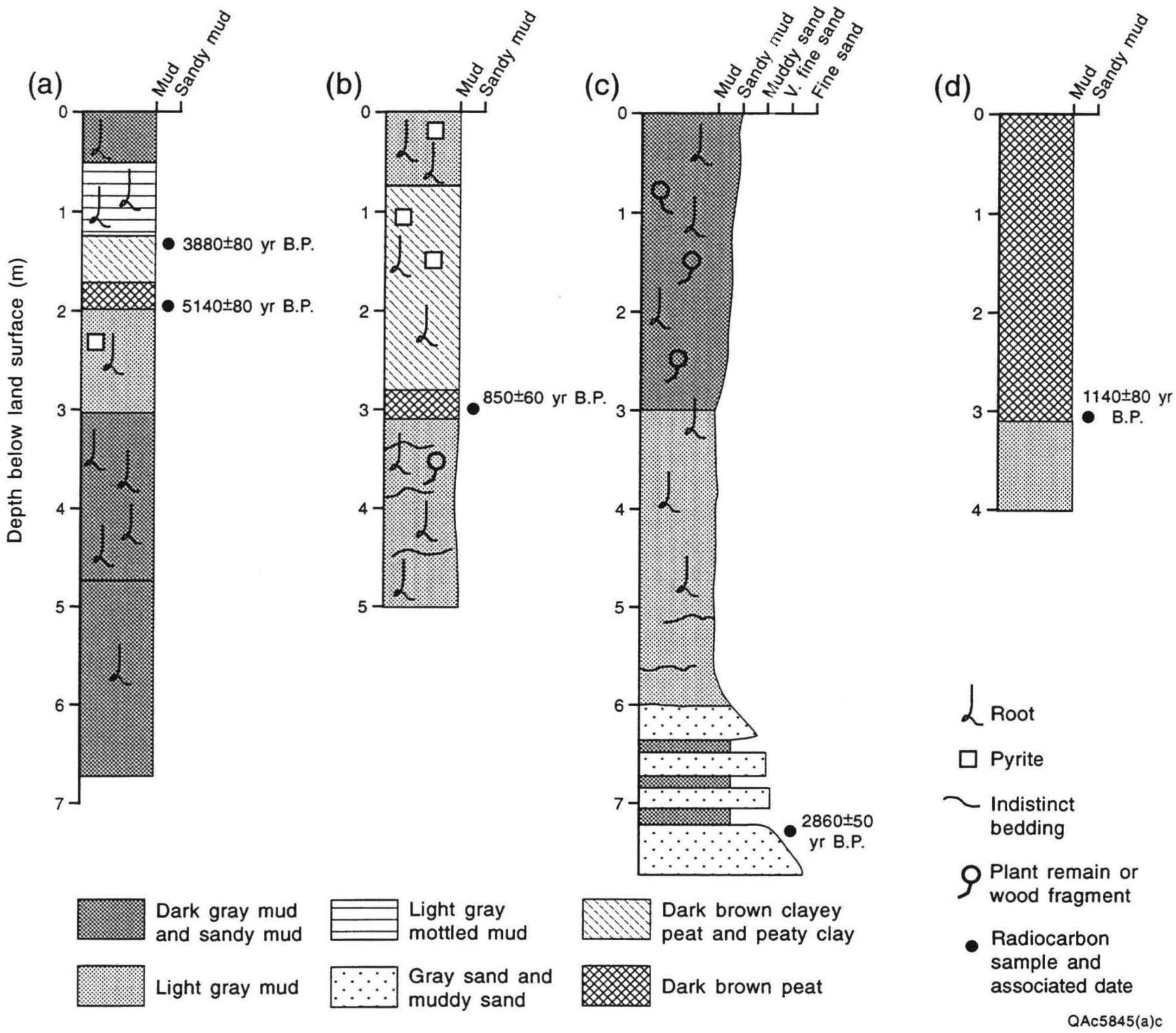


Figure 51. Lithologic profiles of cores from interdistributary flood basin and marine-influenced delta-plain environments. (a) Silicilastic-rich, upper-delta, interdistributary flood-basin deposits located between Caños Manamito and Cocuina northwest of Tucupita. (b) Organic-rich, lower-delta, distributary deposits within a densely forested interdistributary basin. (c) Sandy mud, mud, and muddy sand deposits along the southwest margin of Boca de Guanipa. (d) Lower-delta herbaceous swamp peat overlying older gray muds near the north coast of the delta at Punta Blanca. Locations of logs are shown in figure 56. Detailed descriptions of the shallow cores are presented in a data base on the CD that accompanies this report.

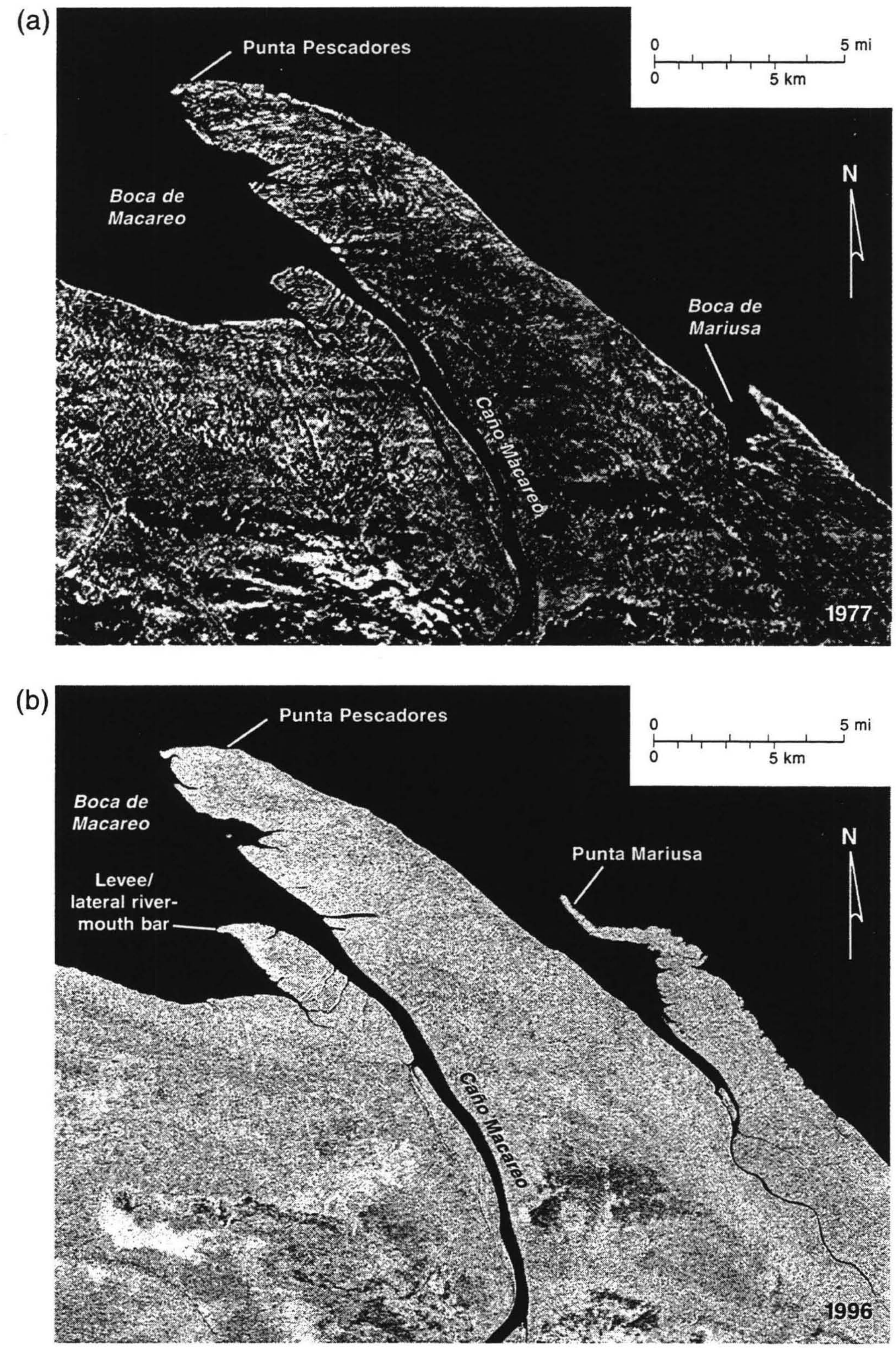


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Figure 52. Radar images from (a) 1977 (SLAR data) and (b) 1996 (Radarsat data). Comparison of the images shows significant historical progradation of the river-mouth bar in Boca de Macareo and as much as 10 km of progradation by the Punta Mariusa mudcape over the past 20 yr. Note that there has been modest erosion along Atlantic coast of Punta Pescadores.

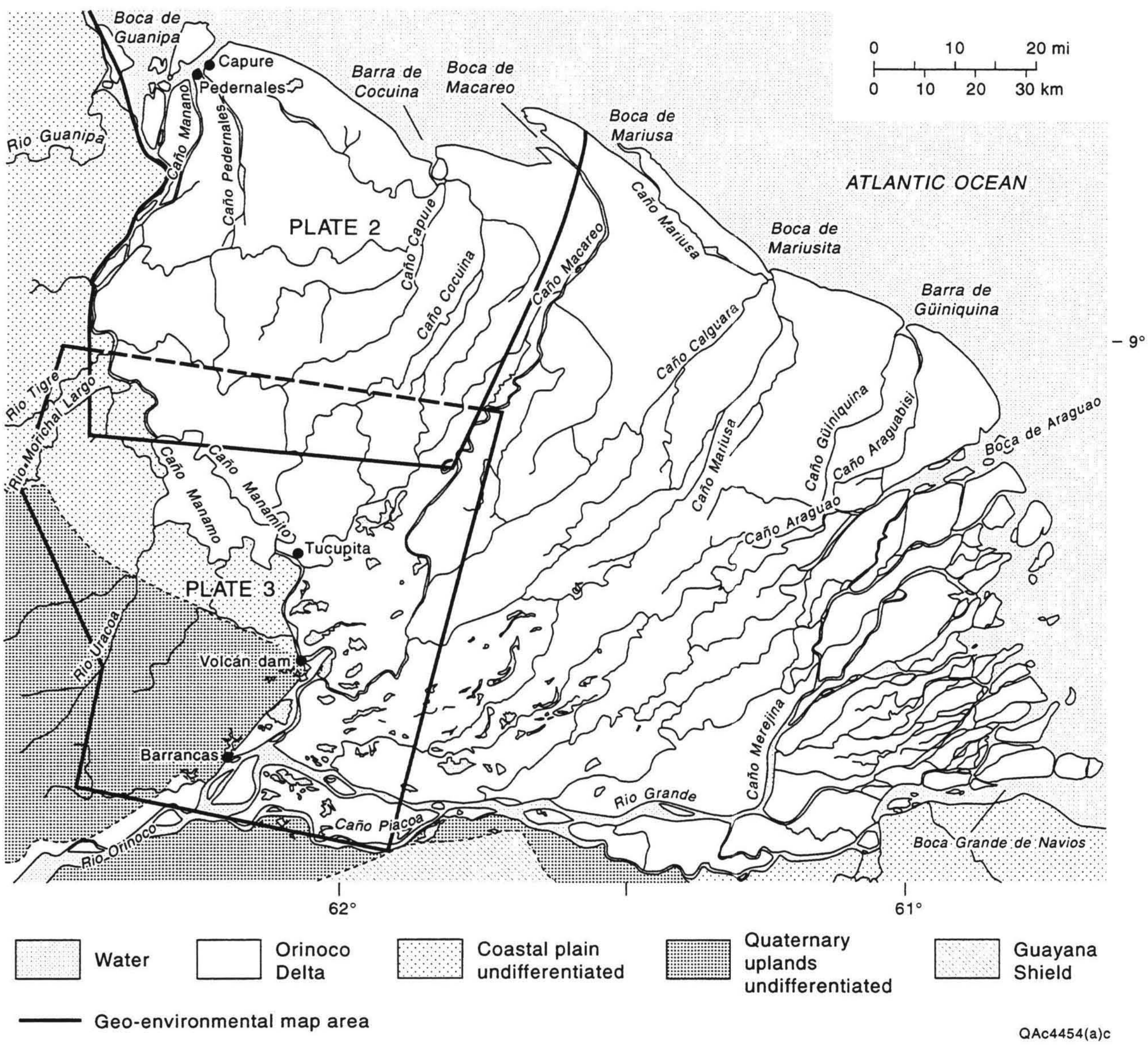

Figure 53. Index map of the geo-environmental maps.

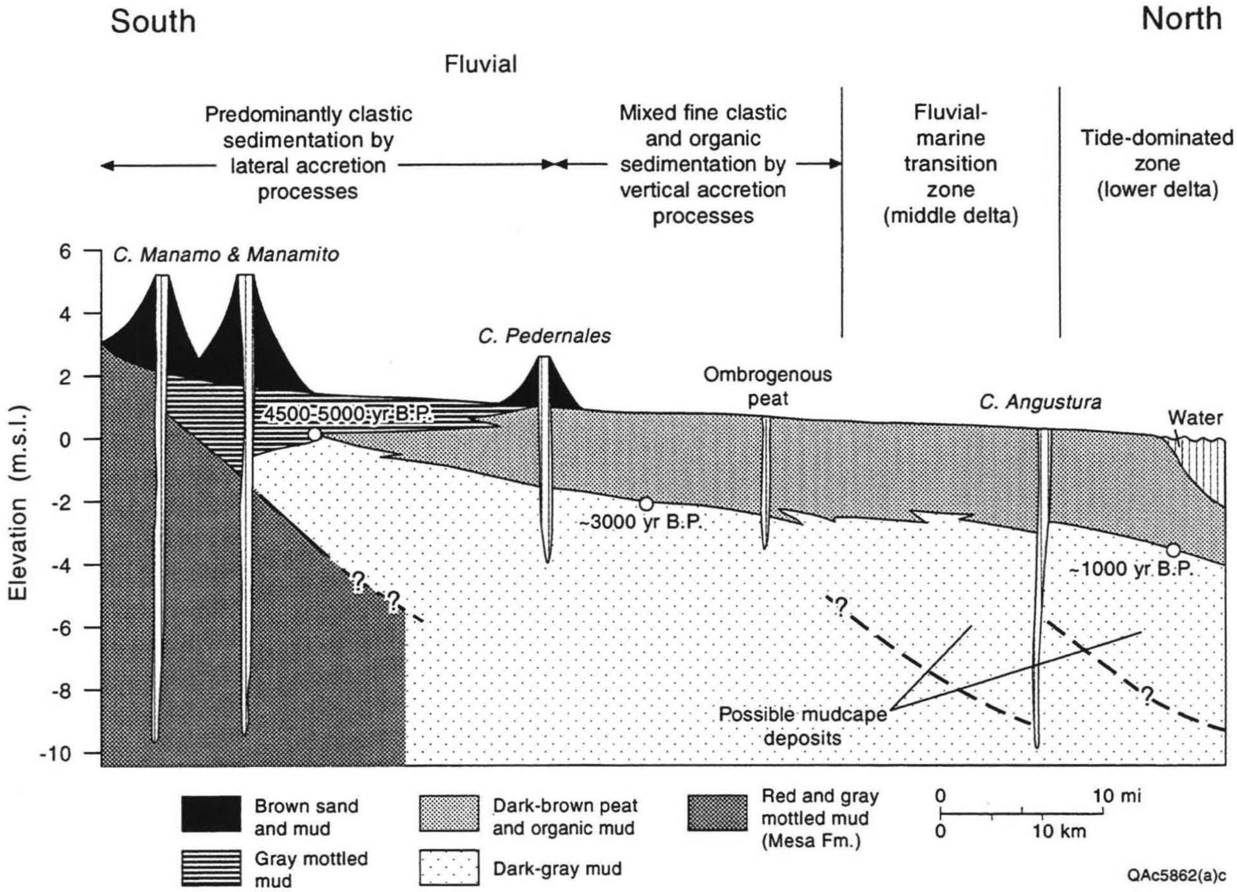

Figure 54. Schematic south-north stratigraphic cross section of the Orinoco Delta drawn from the delta apex near Tucupita to the north coast at Pedernales. The cross section shows that the Holocene delta-plain deposits form a wedge that veneers red Pleistocene deposits of the Mesa Formation near the delta apex and thickens substantially toward the coast. Brown sands and muds constitute prominent alluvial ridges of major distributaries in the upper delta, and these ridges decrease in height and become more mud-rich towards the coast. Mottled flood-basin muds in the upper delta reflect seasonal changes in water levels, whereas the abundance and thickness of peat and organic mud in the central and lower delta indicate perennial saturation. Note that peat and mud content varies across the delta. Dark-gray muds underlying the peat represent various deltaic environments, including mudcapes within the fluvial-marine and marine depositional systems. As the delta prograded basinward during the late Holocene, mudcapes were abandoned and incised by distributaries and became relatively isolated from marine influences. This transition resulted in the development of fresh and brackish-water herbaceous swamps and promoted substantial peat and organic-mud accumulation. Field observations indicate that these herbaceous swamps are at least locally ombrogenous. Modified from Dost and Pons (1971).

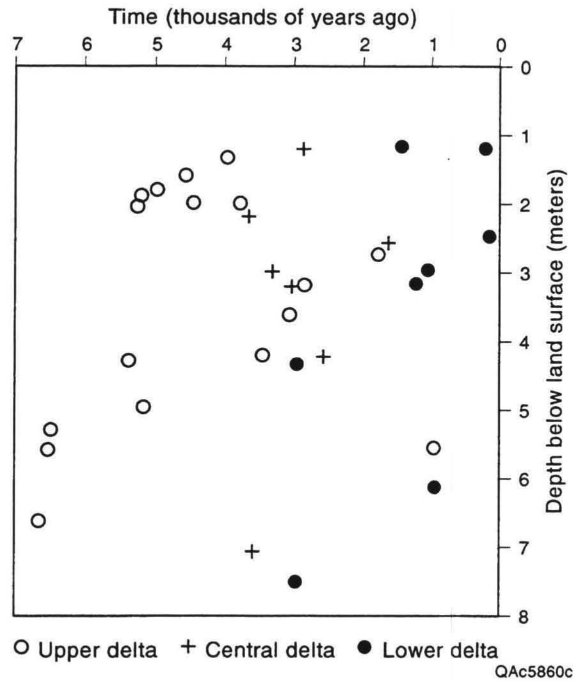

Figure 55. Scatter plot showing age-depth relationships of organic-rich deposits from the upper, central, and lower portions of the northwestern Orinoco Delta. The data reveal that rates of sediment accumulation generally increase from the upper delta toward the coast. The wide scatter of data reflects the importance of lateral erosion/sedimentation processes at sampling sites. Note that essentially all sampling sites were in the vicinity of major distributary channels, where lateral sedimentation/erosion processes predominate. Within interdistributary basins one would expect more consistent age–depth relationships. Details on the radiocarbon data and core samples are presented in data-base format on the CD that accompanies this report.

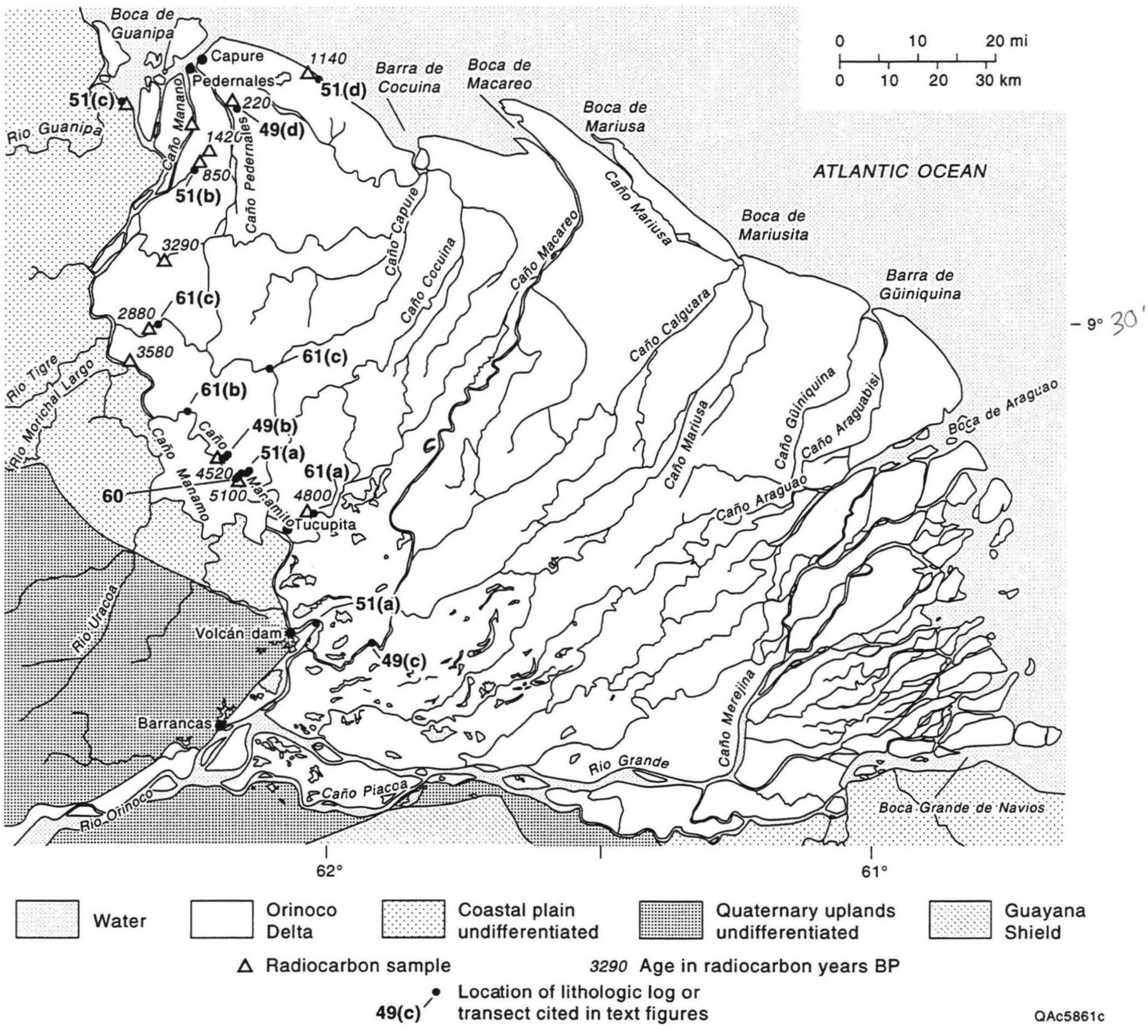

Figure 56. Radiocarbon ages of samples from the base of shallow (<4 m deep) peats and other organic material from the Orinoco Delta. The ages of basal peat samples decrease toward the coast and suggest that the Holocene has prograded northward significantly during the late Holocene. This figure also shows the locations of lithologic logs and transects shown in figures 49, 51, 60, and 61. More information on radiocarbon-dated samples is presented in a data base on the CD that accompanies this report.

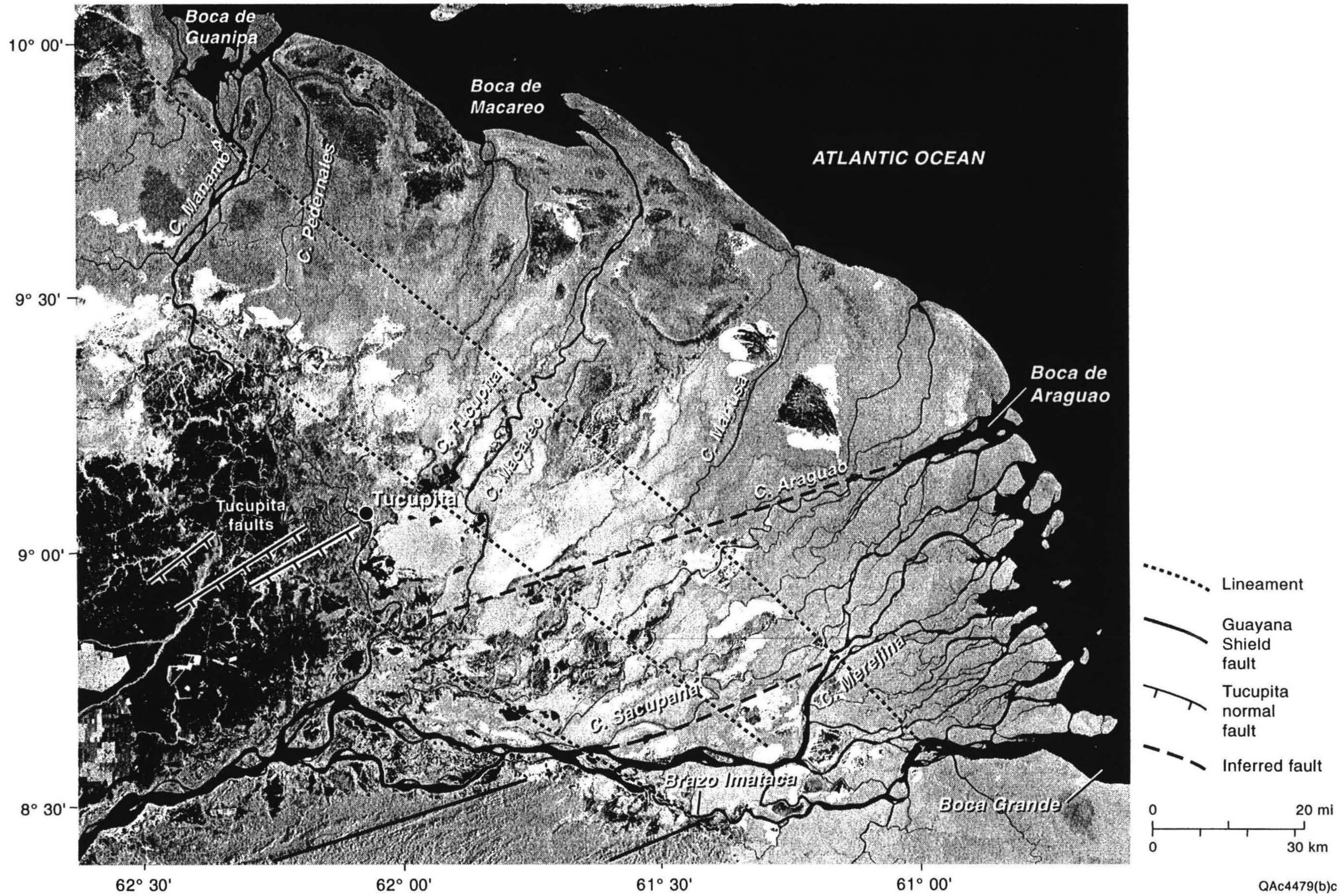

Figure 57. Tectonic lineaments that influence the geomorphology and hydrology of the Orinoco Delta plain. Note that many of these lineaments were initially identified on more regional-scale satellite images. JERS (1995) satellite image used as background.

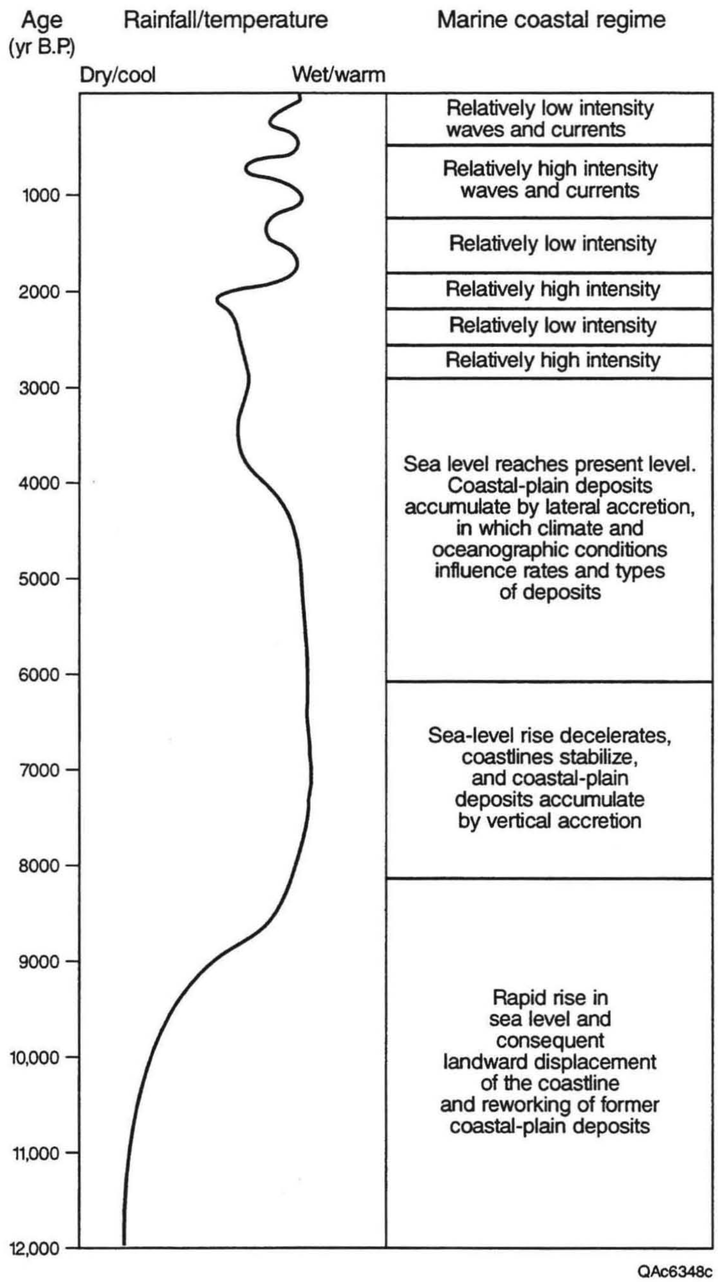

Figure 58. Preliminary summary of late Pleistocene and Holocene climatic changes in northeastern South America and their relationship to marine processes. Information derived from Meggers (1979), Leyden (1985), Eisma and others (1991), and Sommerfield and others (1995).

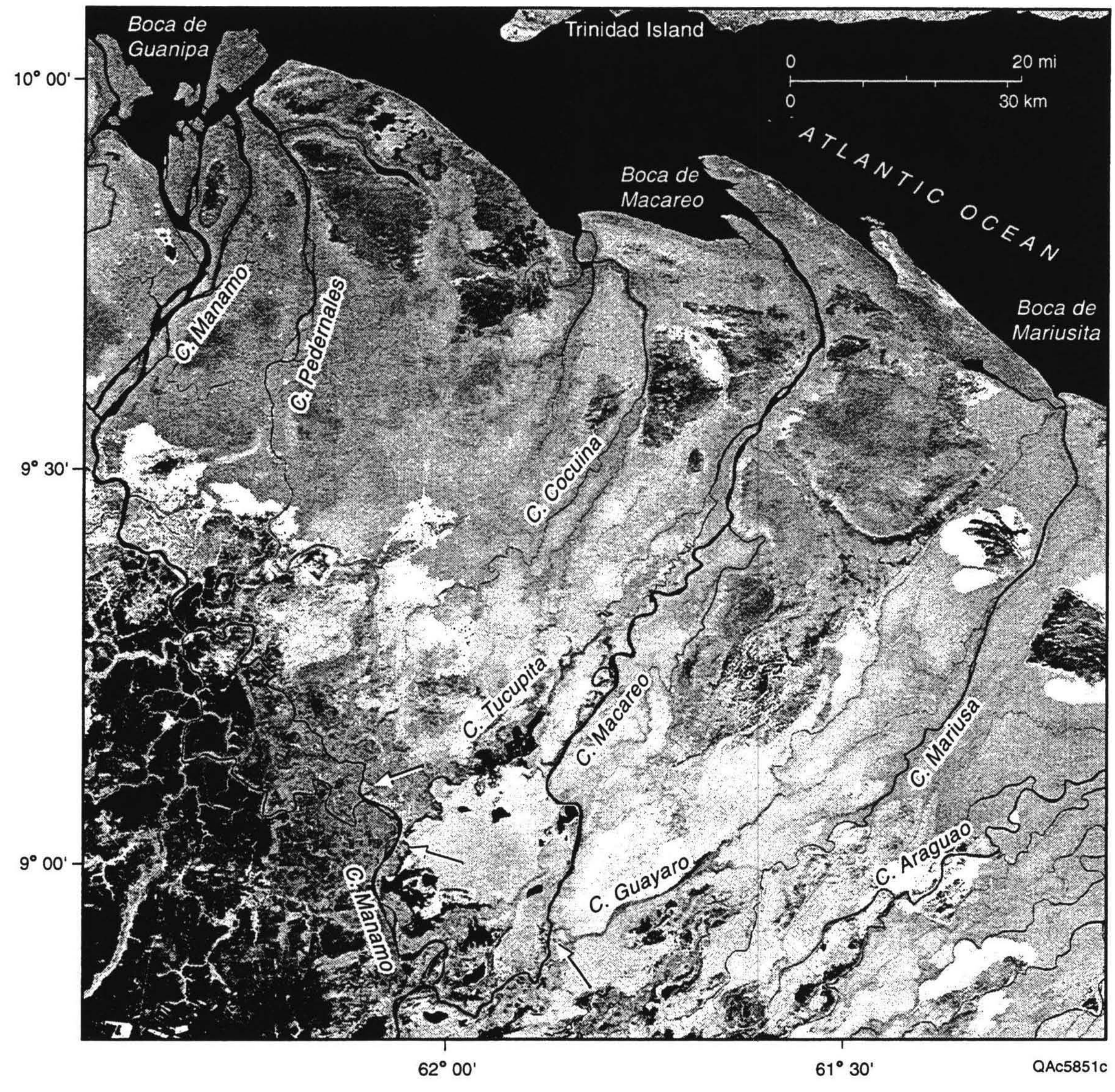

Figure 59. Radar image of the western delta plain showing major distributaries and the location of late Holocene avulsion nodes. JERS data, September–December 1995.

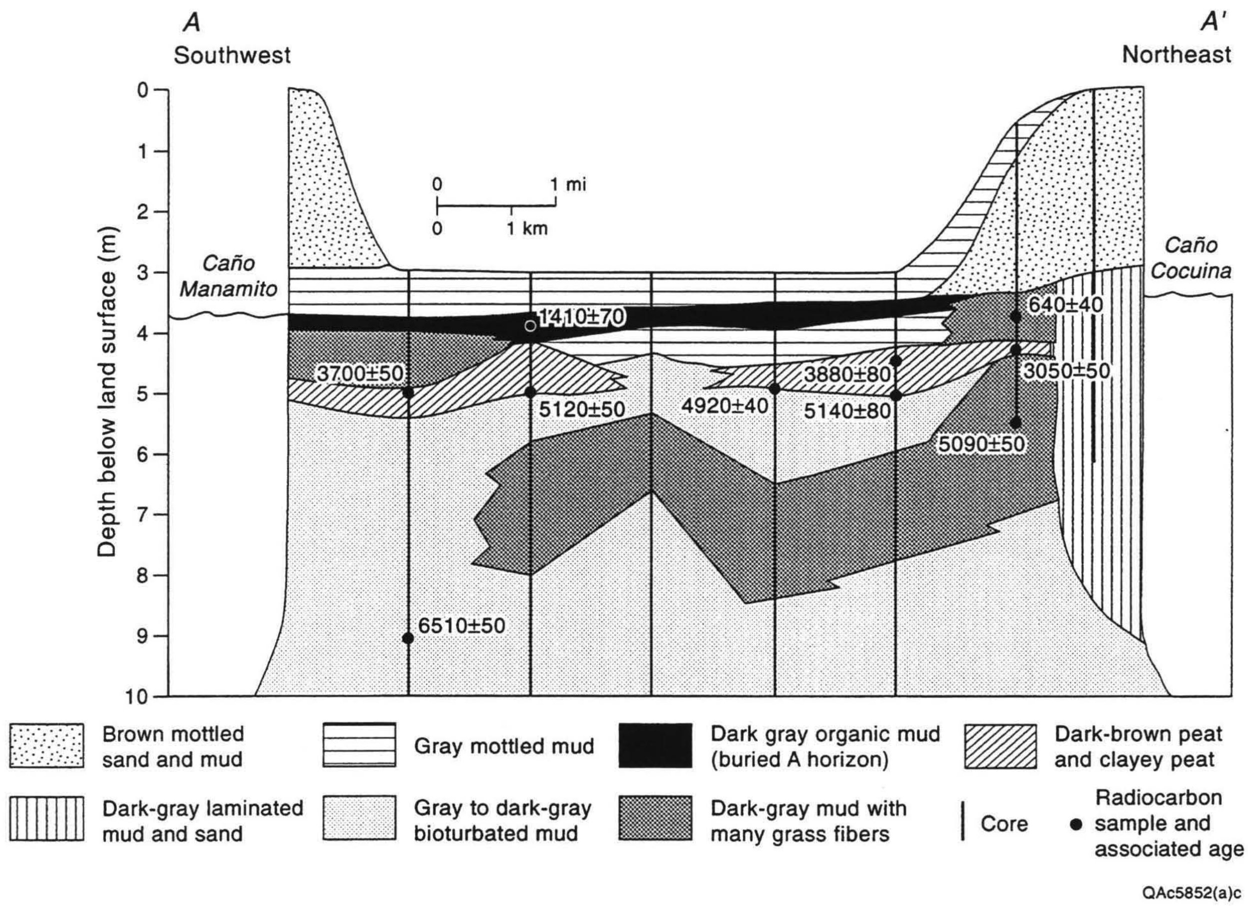

Figure 60. Stratigraphic cross section showing natural-levee and flood-basin deposits of Caños Manamito and Cocuina near Tucupita. Note that radiocarbon-dated peat buried by silty and sandy natural levee and muddy flood-basin deposits provides a maximum age of ~3 ka for these channel systems. A radiocarbon-dated organic flood-basin mud (buried A horizon?) passes beneath Caño Manamito natural-levee deposits and suggests that this channel system may be younger than ~1.5 ka. Location of transect is shown in figure 56. Detailed descriptions of the core sections are presented in a data base on the CD that accompanies this report.

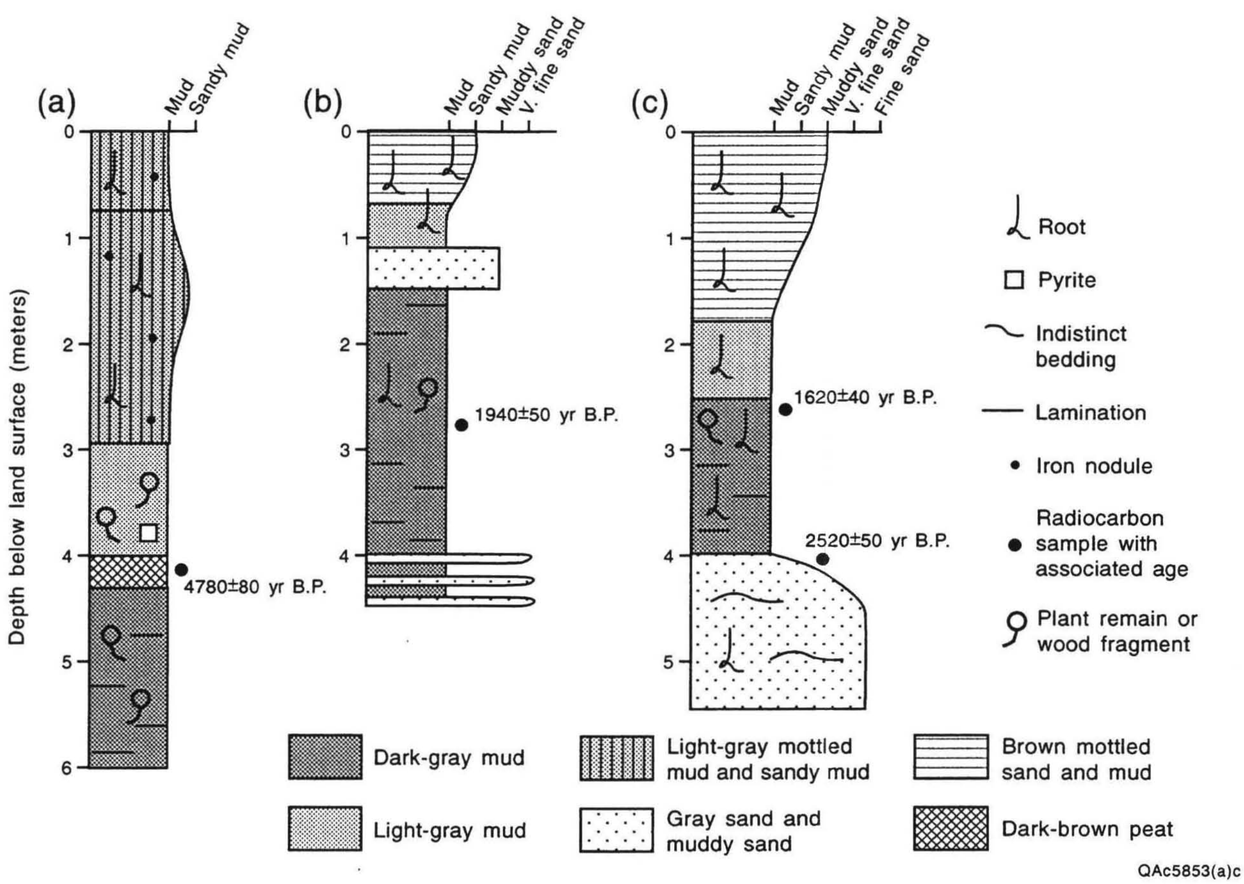

Figure 61. Lithologic profiles of cores from the upper and central delta with radiocarbon ages that constrain the timing of important fluvial events. (a) Upper-delta natural-levee and flood-basin deposits along Caño Tucupita north of La Florida and Tucupita. The radiocarbon date suggests that the Caño Tucupita channel system developed sometime after ~5 ka. (b) Upper-delta natural-levee sandy muds and flood-basin muds overlying interbedded sands and muds interpreted as channel deposits of a probable coastal-plain river. (c) Upper-delta natural-levee muddy sands and flood-basin muds overlying fine, sandy, channel deposits of a probable coastal-plain river. Radiocarbon dates indicate that the coastal-plain river was abandoned ~1.6 to 2.5 ky. Locations of lithologic logs are shown in figure 56.

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Figure 62. Radar image of a portion of the central delta plain along Caños Manamo and Pedernales. An abandoned-channel course of a northeast-flowing channel system interpreted as a coastal-plain river is shown (arrows). This abandoned-channel course merges with Caño Capure, which discharges into Barra de Cocuina. Modern Caños Manamo and Pedernales crosscut this abandoned-channel course and flow northwest to Boca de Guanipa. Also note the location of the cores shown in figure 61b, c. JERS data, September–December 1995.

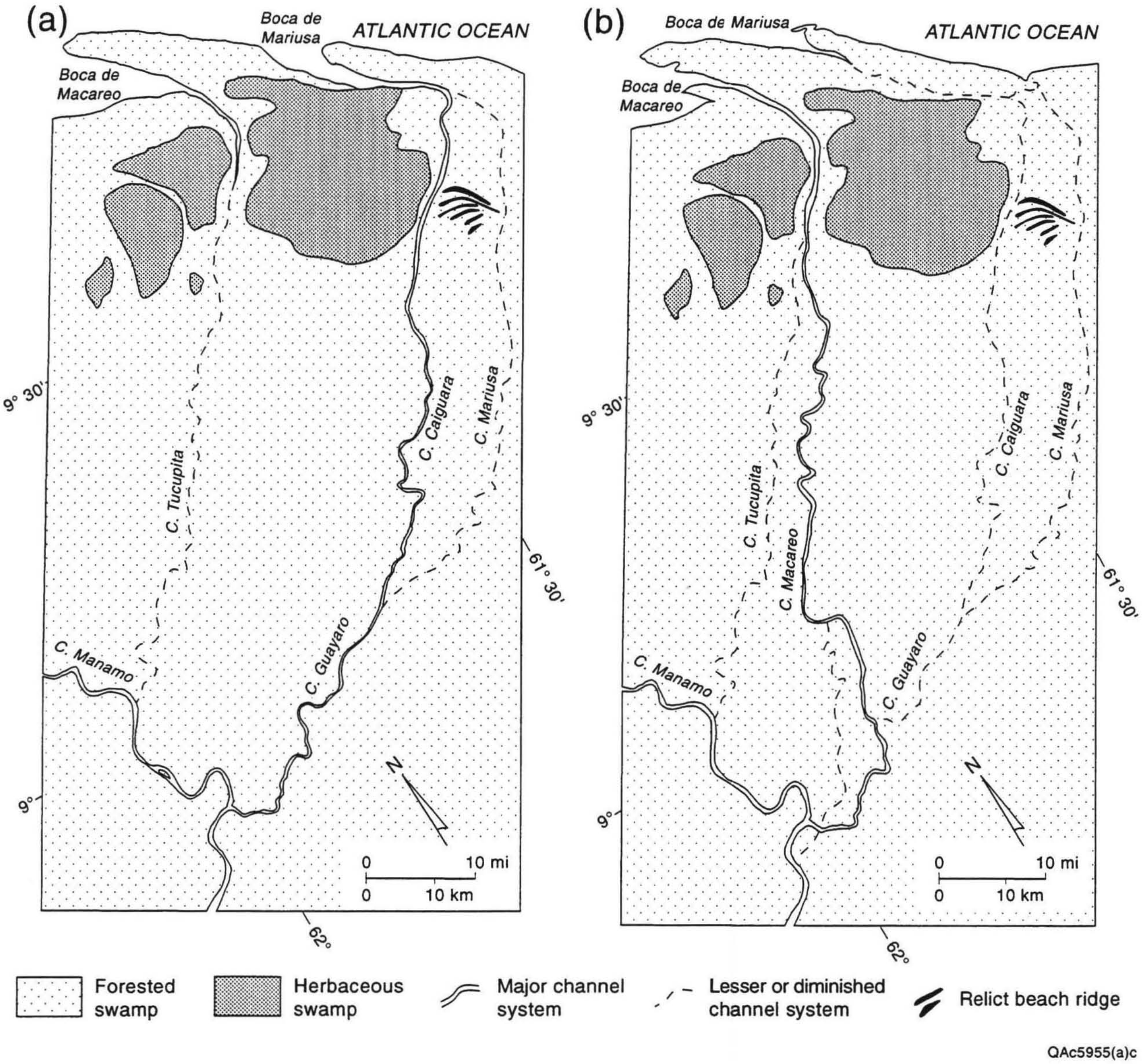


Figure 63. Schematic environmental maps showing the recent (<1 ky) evolution of Caños Macareo and Guayaro. Prior to the establishment of Caño Macareo's present course, Caños Guayaro and Caiguara transported water and sediment to the Atlantic Ocean through Boca de Mariusa. Following the avulsion of this channel system westward and the establishment of the modern Caño Macareo channel system, northwest progradation of the Punta Mariusa mudcape partially filled Boca de Mariusa.

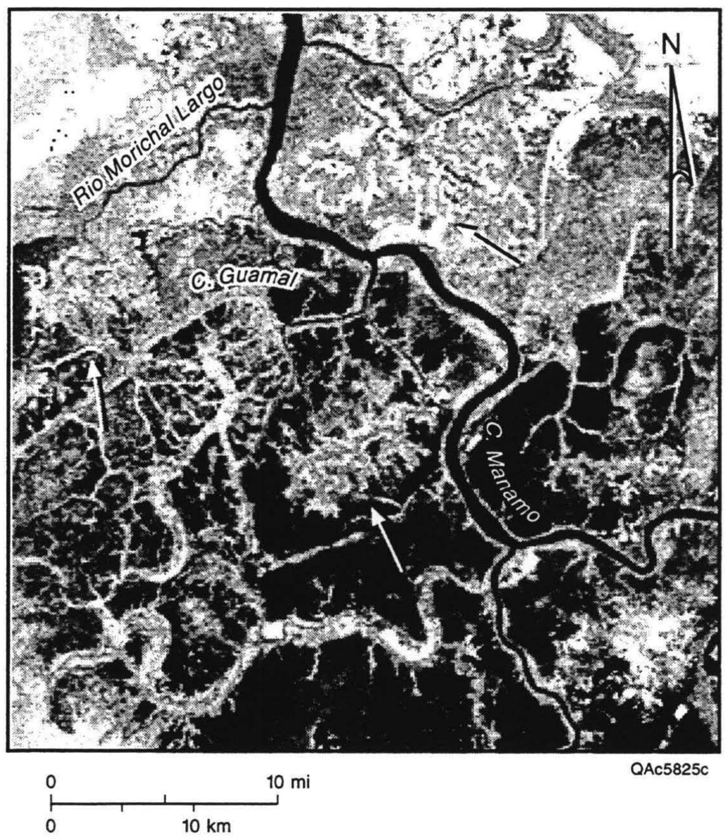


Figure 64. Radar image showing locations of relict tidal channels (arrows) along Caño Manamo in the central delta south of Río Morichal Largo. Danielo (1976a) also recognized relict tidal channels in this area. JERS data, November–December 1995.

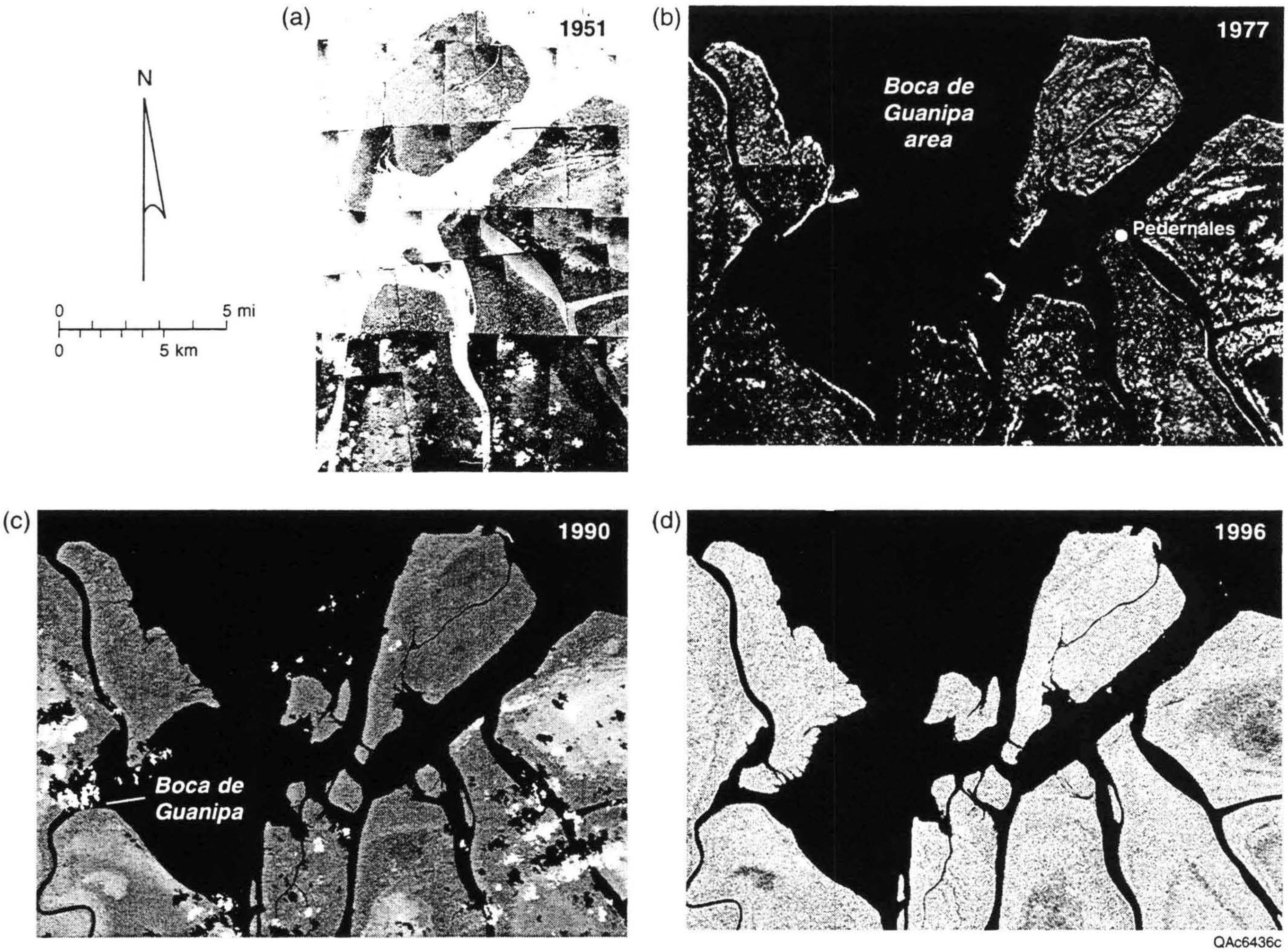


Figure 65. Historic changes in Boca de Guanipa region that are based on (a) 1951 aerial photograph mosaic, (b) 1977 SLAR image, (c) 1990 Landsat TM image, (d) 1996 Radarsat image. Note rapid shoreline progradation near mouth of Boca de Guanipa and formation of mangrove islands southwest of Pedernales.

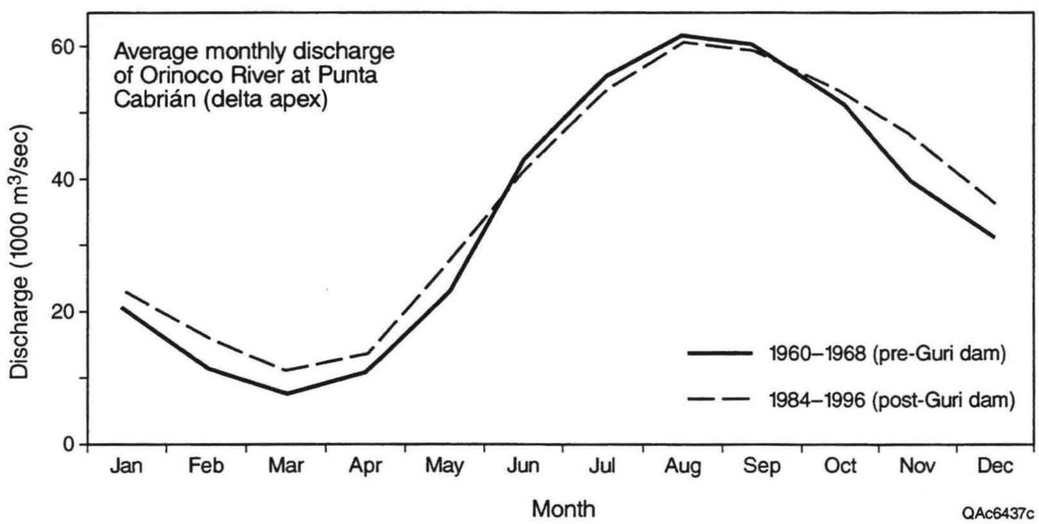
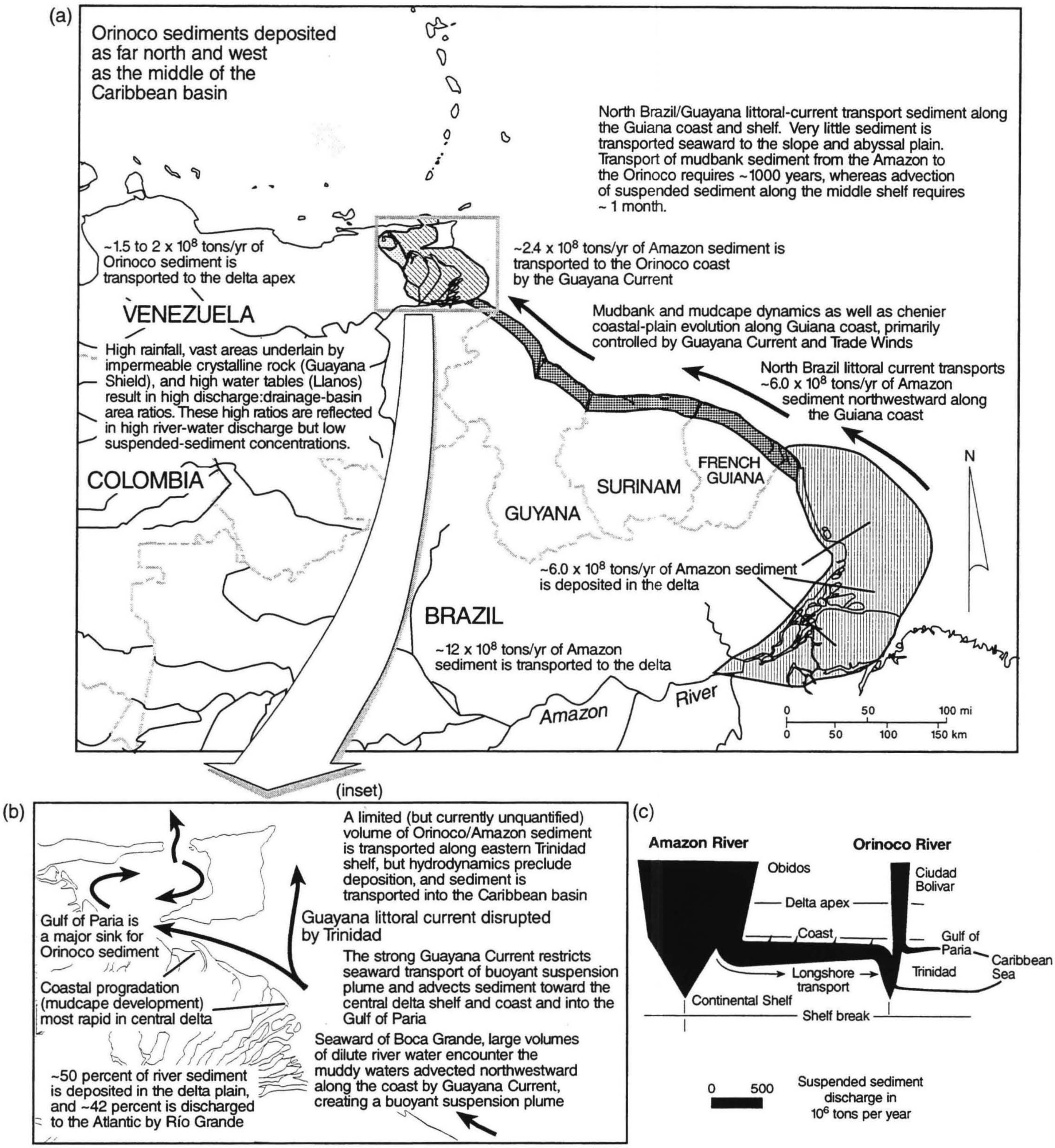


Figure 66. Influence of the Guri dam on Orinoco River discharge to the delta. Information derived from FUNINDES USB (1998).

Figure 67. Summary of major riverine and coastal processes influencing water and sediment dynamics in northeastern South America. (a) General characteristics; see text for further discussion. (b) Characteristics of the Orinoco Delta region. (c) Sediment budget for northeastern South America coastal region.



Amazon delta - tide and littoral current dominated. Despite the enormous volume of sediment discharged to the coast, current, tide, and wave energy has precluded development of a delta plain. The extensive subaqueous delta plain has a full suite of topset, foreset, and bottomset beds.

Orinoco delta - composed of vast, perennially inundated peat and mud plains subdivided by an extensive network of distributary and tidal channels. Along the coast, mudcapes develop at the mouths of smaller rivers, and estuaries at the mouths of larger rivers. Mudbanks do not develop along the coast, and beach ridges are not widespread.

Accreting muddy coastal plain of French Guiana, Surinam, and Guyana - the Holocene coastal plain is composed of coalesced beach ridges (cheniers). Mudcapes develop at the mouths of smaller rivers, and estuaries at the mouths of larger rivers. Mudbanks occur at regular intervals along the coast and migrate northwestward. Mudbank and mudcape migration and expansion induce lateral shoreline accretion.

Gulf of Paria coastal plain - in many respects a northwest extension of the Orinoco delta with peat and mud plains.

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Tables

Table 1. Summary of satellite-based remote-sensing data available for the Orinoco Delta.[1]

General location	Imagery type	Date of satellite acquisition of data	Path/row or identification number
Pedernales/Gulf of Paria	Landsat TM	March 24, 1986	1/53
Pedernales/Gulf of Paria	Landsat TM	December 24, 1990	1/53
Pedernales/Gulf of Paria	Landsat TM	July 12, 1991	1/53
Pedernales/Gulf of Paria	Landsat TM	August 26, 1996	1/53
Lower Orinoco River/delta apex	Landsat TM	January 6, 1997	1/54
Lower Orinoco River/delta apex	Landsat TM	September 30, 1997	1/54
Punta Pescadores	Landsat TM	December 30, 1986	233/53
Punta Pescadores	Landsat TM	August 24, 1989	233/53
Río Grande	Landsat TM	December 30, 1986	233/54
Río Grande	Landsat TM	November 23, 1987	233/54
Río Grande	Landsat TM	February 14, 1992	233/54
Pedernales/Gulf of Paria	Landsat MSS	April 25, 1986	1/53
Punta Pescadores	Landsat MSS	May 4, 1986	233/53
NW Orinoco Delta	RADARSAT	November 30, 1996	m0094457
South-Central Orinoco Delta	RADARSAT	November 30, 1996	m0094458
North-Central Orinoco Delta	RADARSAT	December 7, 1996	m0094707
SW Orinoco Delta	RADARSAT	December 7, 1996	m0094708
NE Orinoco Delta	RADARSAT	December 21, 1996	m0097113
SE Orinoco Delta	RADARSAT	December 21, 1996	m0097114
NW Venezuela coast including Paria Peninsula	SLAR	December 1977	NC20-7
NW Orinoco Delta	SLAR	December 1977	NC20-11
NE Orinoco Delta	SLAR	December 1977	NC20-12
SW Orinoco Delta	SLAR	December 1977	NC20-15
SE Orinoco Delta	SLAR	December 1977	NC20-16
Orinoco Delta	NASDA JERS-1 SAR	September/December 1995 January 1997	AM-2A-101
SW Orinoco Delta	ERS[2]	December 22, 1997	

[1]Bureau has digital files of images listed
[2]Earth Resources Satellite

Table 2. Aerial photomosaics of the Orinoco Delta used in this study.[1]

Area of coverage	Date of flight	Scale	Number of individual photographs in photomosaic	Photomosaic identification number
Pedernales	October 1951	1:75,000	51	C50
Caño Merejina–Río Grande	August 1983	1: 200,000	121	040544
Isla Guara	April 1978	1: 20,000	11	040532
Caño Capure–Caño Cocuina–Caño Macareo	August 1983	1: 200,000	154	040544
Caño Manamo–Pedernales	January 1983	1:100,000	77	040543
Caño Güiniquina–Caño Araguabisi	January 1983	1:100,000	57	040543
Delta Amacuro–Monagas	August 1951	1:75,000	43	C50
Caño Manamo–Isla Tigre–Caño Capure	April 1974	1:200,000	117	040526
Río Amacuro	April 1974	1:200,000	38	040526
Barrancas	1969–1970	1:80,000	124	040524
Tucupita	1969–1970	1:80,000	149	040524
Caño Manamito	1969–1970	1:80,000	134	040524
Caño Manamo	1969–1970	1:80,000	127	040524
Caño Manamo–Boca de Guanipa	1969–1970	1:80,000	176	040524
Boca de Guanipa	1969–1970	1:80,000	66	040526
Caño Macareo–Barra Mariusita–Punta Pescadores	April 1974	1:200,000	81	040526
Caño Manamo–Caño Tucupita–Barrancas	April 1974	1:200,000	107	040526
Boca de Araguao–Boca Lorán	April 1974	1:200,000	99	040526
Río Orinoco–Isla Matamata	April 1974	1:200,000	121	040526
Brazo Imataca–Isla Curiapo	April 1974	1:200,000	109	040526
Río Amacuro–Boca Grande	April 1974	1:200,000	38	040526

[1]Available through Cartografía Nacional de Venezuela, Caracas

Table 3. Fundamental characteristics of the Orinoco and Amazon drainage basins, rivers, and deltas.

Characteristics	Orinoco	Amazon
Drainage basin area (10^6 km^2)	1.1[1]	5.9[2]
Main channel length (km)	~2,000[3]	4,000[4]
Main channel geomorphology	Straight and anastomosing[5]	Straight and anastomosing[4]
River flood-plain area, not including delta (km^2)	77,000[3]	170,000[3]
Valley length: fringing flood-plain area (km^2/km)	9.3	40[3]
Flood-plain lake coverage (% of total flood-plain area)	7[5]	11[5]
Typical river channel width and depth in lower reaches (m)	2,000, 10–25[5]	5,000, 20–50[5]
Annual water discharge (10^9 m^3/yr)	1,200[6]	6,300[6]
Time of peak water discharge	August–September[1] (fig. 16b)	May–July[7]
Annual amplitude of water level in lower reach (m)	12[5] (fig. 16)	9[5]
Ratio of peak to low water discharge	8:1 to 54:1, average of 26:1[8]	2:1 to 3:1[9]
Drainage basin specific discharge (mm/yr)	1,300[5]	1,200[5]
Annual sediment discharge (10^6 metric tons/yr)	150[1]	1,200[7]
Major sediment source	Andes (~90 percent)[1]	Andes (~90 percent)[7]
Time of peak sediment discharge	April–May, October–November[1] (fig. 16b)	February–April[7]
Average suspended solid concentration in lower reaches of river (mg/L)	80[5]	220[5]
Predominant grain size of sediment delivered to delta	~80 percent silt and clay (<0.1 mm)[8]	85 to 95 percent silt and clay[10]
Delta-plain area (km^2)	22,000	25,000[3]
Tidal range at coast	to 2.6 m	to 6 m[11]
Wave energy	Low	Low to moderate[11]
Littoral current velocity (cm/s)	25–75 on Atlantic shelf, to 100 in Boca Serpientes[12]	Commonly exceeding 50[11]
Influence of major tropical storms on coast	Low	Very low[11]
Thickness of Holocene delta (m)	>100[13] (fig. 41)	30[14]

Data sources: [1]Meade and others (1990); [2]Coleman (1982); [3]Hamilton and Lewis (1990); [4]Dunne and others (1998); [5]Lewis and others (1995); [6]Meade (1996); [7]Meade and others (1985); [8]Nordin and others (1994); [9]Kineke and Sternberg (1995); [10]Kuehl and others (1986); [11]Nittrouer and others (1986); [12]Van Andel (1967); [13]Geohidra Consultores, C.A. (1997b); [14]Sommerfield and others (1995)

Table 4. Characteristics of Orinoco River fringing floodplain.[1,2]

Total flood-plain area (km^2)	Channel length (km)	Left (north) bank		Right (south) bank		Interchannel islands	
		Area (km^2)	Percent of fringing flood plain	Area (km^2)	Percent of fringing flood plain	Area (km^2)	Percent of fringing flood plain
6,964	770	3,802	55	2,546	36	636	9

[1]Source: Hamilton and Lewis (1990)
[2]Includes flood plain from confluence with Meta River to delta apex at Barrancas

Table 5. Summary of the intensity, frequency, and duration of rainfall in the Orinoco Delta.[1]

Duration (hr)	Return frequency (yr)	Intensity[2] (mm/hr)	Amount[2]
1	2.33	70	70
2	2.33	42	84
12	2.33	9	108
24	2.33	3.5	96
1	10	90	90
2	10	58	118
12	10	11	132
24	10	6.3	152
1	100	100	100
2	100	65	130
12	100	15	180
24	100	9	216

[1] Source: FUNINDES USB (1998)

[2] Estimates are approximate because the available data are averages of Tucupita, Pedernales, and Curiapo weather station data and available copies of original graphs are of poor quality.

Table 6. Magnitude/frequency characteristics of waves, Gulf of Paria[1,2]

Recurrence interval (yr)	Maximum wave height (m)	Period (s)
10	3.8	5.8
25	4.6	6.3
50	5.2	6.7
100	5.8	7.1

[1]Source: ENSR Venezuela (1998)
[2]Waves are presumed to have been generated by hurricanes

Table 7. Summary of the hydrology of the caños of the central Orinoco Delta.[1]

Caño	Tidal amplitude	Discharge (m^3/s)	Flow velocity (seaward) during falling tide (m/s)	Flow velocity (landward) during rising tide (m/s)	Calculated ratio of tidal discharge:river discharge
Pedernales	2.0 to 0.9	60 to 250	0.19 to 0.27	0.18 to 0.25	15:1 to 11:1
Capure	2.0 to 0.7	60	0.33	0.17	3:1 to 8:1
Cocuina	1.1 to 0.7	140	0.5	0.3	3:1 to 8:1
Jarina	1.0	230	0.53	0.53	5:1

[1]Source: FUNINDES USB (1998)

Table 8. Geomorphology legend.

Principal hydro-logic agents[1,2]	Setting/ surface com-position[1]	Drainage class[1]	Identifi-cation code[1]	Associated landforms	General description[1]	Associated geomorphic terms used in Venezuela [3]	Hydrology	Landforming processes	Soils[3,4]	Geo-environ-mental class[5]
Tides	Littoral	Inundated	Pd3-43	Mud flats, mangrove swamp, cheniers, tidal channels, mudcapes	Plano-concave to plano-convex, irregular surface profiles. Microtopographic features include organic buildups at base of tree clusters, tidal channels of varying size (fig. 35d,e), beach-ridge complexes (locally). Vegetation predominantly mangrove. Largely composed of relict and active mudcapes (fig. 10b).	Marismas, llanuras cenagosas, litoral marino, cordones litorales	Almost completely controlled by tides and waves. Importance of storms is uncertain. Rainfall becomes increasingly important inland.	Transport and deposition of muddy sediment by the Guayana Current, tides, and relatively low wave energy promote development of tidal mud flats and mudcapes (fig. 10). Lateral accretion processes associated with mudcape development are currently the primary mode of delta progradtion. Mangroves prograde over mud flats and promote vertical mud accretion. Sandy beach ridges typically form near mouths of distributary channels.	Sulaquents, Sulfihemists	Marine-influenced coastal; marine-influenced distributary channel and island system, mangrove dominant
Tides	Forested peat plain	Inundated	Pd3-33A	Tidal peat swamp	Plano-concave. Perennially inundated and therefore poorly developed drainage pattern. Typically located at centers of relict mudcapes.	Planicie turbosa boscosa, cubeta de marea	Perennially inundated and/or saturated. Rainfall and tides are the principal source of water, with seasonal river input.	Areas with particularly high rainfall. Rapid subsidence rates and removal from direct tidal and riverine flow are key to their long-term development. Peats underlying forested areas tend to be relatively thin (< 3 m), providing evidence of moderate rates of vertical accretion of vegetal material.	Tropo-hemists, Tropofibrists	Fluvial-marine transitional; interdistribu-tary flood basins; herbaceous and forested swamp

Table 8, cont.

Principal hydro-logic agents[1,2]	Setting/ surface com-position[1]	Drainage class[1]	Identifi-cation code[1]	Associated landforms	General description[1]	Associated geomorphic terms used in Venezuela [3]	Hydrology	Landforming processes	Soils[3,4]	Geo-environ-mental class[5]
Tides	Herbace-ous peat plain	Inundated	Pd3-33B	Tidal peat marsh	Plano-concave. Perennially inundated. Poorly developed drainage pattern. Shallow, brackish lagoons common. Typically occupy interior portions of former mudcapes.	Planicie turbosa herbácea, cubeta de marea	Perennially inundated and/or saturated. Rainfall and tides are the principal source of water, with seasonal river input.	Areas with particularly high rainfall. Rapid subsidence rates and lack of direct tidal and riverine flow are key to their long-term development. Hydraulic isolation seems related to their position in interior of former mudcapes. Peats underlying herbaceous peat plains tend to be thick (>3 m), providing evidence of relatively rapid and widespread vertical accretion of vegetal material.	Tropo-hemists, Tropofibrists	Marine-influenced coastal; fluvial-marine transitional; herbaeous and forested swamp
Tides	Mud plain	Inundated	Pd3-23	Tidal marsh, mud plains, cheniers	Plano-concave and rather regular in profile. Located near major distributary channels. Drainage (tidal) channels common, so peats are rather poorly developed. May include cheniers. Generally forested near caños, herbaceous toward basin center (fig. 27f).	Llanura cenagosa, pantano de marea, cordones litorales	Hydrology controlled interaction of tides, rainfall, and river. Seasonally to perennially inundated or saturated.	Clay sediment imported by overbank flooding during summer floods and tidal channels. Because areas are depressional, sediment is retained and vertical accretion is relatively rapid. Cheniers record former areas of rapid lateral accretion near mouths of major interdistributary channels.	Hydra-quents, Tropo-fibrists, Sulfihemists	Interdistribu-tary flood basin; intermediate (topograph-ically) forested swamp.

Table 8, cont.

Principal hydro-logic agents[1,2]	Setting/ surface com-position[1]	Drainage class[1]	Identifi-cation code[1]	Associated landforms	General description[1]	Associated geomorphic terms used in Venezuela [3]	Hydrology	Landforming processes	Soils[3,4]	Geo-environ-mental class[5]
River and tides	Littoral estuary	Inundated	Pd2-43	Tidal swamp, estuary margin, estuary islands	Plano-convex, irregular surface profiles. Primarily comprise estuarine islands but also areas along the banks of lower caños (fig. 35d,e, f). Rapidly accreting. Well-developed tidal channel system. Mangrove cover.	Islas de barrera, napas en formación, pantano de marea	Influenced by strong riverine and tidal currents. The relative influence of rivers and tides varies strongly seasonally. Because these areas are located near major caños, they are more deeply inundated during floods.	Interaction of tides and river currents produce complex hydrody-namics and, therefore, dynamic sedimentation/ erosional environments. However, general attenuation of current energy associated with shoaling along mud banks results in overall lateral accretion, primarily through mud-flat deposition. Combined river input and wave reworking have produced broad sandy shoal areas, including beach ridges, along seaward portions of some large esturaine islands.	Perennially saturated, so soil develop-ment poor. Sulfur bearing. Hydra-quents	Marine-influenced distributary and island system; mangrove; forested swamp; locally, transitional between mangrove and forested swamp
River and (to a lesser degree) tides	Forested peat swamp	Inundated	Pd2-33A	Forested interdis-tributary tidal peat basin	Plano-convex, somewhat irregular profile. Poorly developed surface drainage system. These tend to occur adjacent to blackwater (sediment-poor) caños (fig. 27g) forming a broad rim around interior basin. Vegetation cover primarily consists of deciduous and palm trees.	Planicie turbosa boscosa	Perennially inundated and/or saturated, and record the interaction of rainfall, tide, and river input.	Persistent wet conditions promote peat accumulation. Thin (2 to 3 m) peat substrates support forests; thick (to 6 m) peat substrates support herbaceous flora. Vertical peat accumulation may cause broad mounds to develop in basin centers.	Tropo-hemists, Tropo-fibrists.	Interdistribu-tary flood basin; primarily low to intermediate (topograph-ically) forested swamp.

Table 8, cont.

Principal hydro-logic agents[1,2]	Setting/ surface com-position[1]	Drainage class[1]	Identifi-cation code[1]	Associated landforms	General description[1]	Associated geomorphic terms used in Venezuela [3]	Hydrology	Landforming processes	Soils[3,4]	Geo-environ-mental class[5]
River and (to a lesser degree) tides	Herbace-ous peat marsh	Inundated	Pd2-33B	Herbaceous interdis-tributary peat basin	Plano-convex, somewhat irregular profile. Poorly developed surface drainage system, although existing caños import clay, particularly from the coast. Interior portions contain small tidal basins filled with peat deposits. Commonly featureless except changes in vegetation. Stands of dead trees common (fig. 27j). Typically comprise the interior portions of interdistributary basins.	Planicie turbosa herbácea	Perennially inundated and/or saturated, and record the interaction of rainfall, tide, and river input. Somewhat wetter than adjacent forested peat swamp.	Continuously wet conditions promote peat accumulation. Forests are associated with thin (2 to 3 m) peat substrates, and herbaceous wetlands with thick (to 6 m) peat substrates.	Tropo-hemists, Tropo-fibrists.	Interdistribu-tary flood basins' mixed herbaceous and forested swamp.
River and tide	Mud and peat plain	Inundated	Pd2-33/43	Tidal swamp or bog	Transitional peat and mud swamp. Plano-concave surface profile, highest precipitation ~1,800 mm. Mostly present in northwest delta. Rather well developed tidal channel system. Complex hydrology results in combined forest, shrub, and herbaceous cover.	Marisma, litoral marino	Interaction of rainfall, tides, and to a lesser degree, rivers, in these areas results in complex hydrologic regime. Tidal oscillations, however, are a constant process.	Substrates are primarily peat but represent a mixture of peat and mud. Because these areas are controlled by a rather complex and variable hydrologic regime, sediment dynamics vary. Tidal oscillations move the most water and sediment but may not be the most important in controlling sediment and erosion. Tidal channel development, abandonment, and infilling are common.	Sul-faquents, Tropo-hemists, Tropo-fibrists.	Interdistribu-tary flood basins; low to high (topographical ly) forested swamp; distributary channel systems—levees and crevasse splays—forested.

Table 8, cont.

Principal hydro-logic agents[1,2]	Setting/ surface com-position[1]	Drainage class[1]	Identifi-cation code[1]	Associated landforms	General description[1]	Associated geomorphic terms used in Venezuela [3]	Hydrology	Landforming processes	Soils[3,4]	Geo-environ-mental class[5]
River	Mud plain	Inundated	Pd2-23	Inter-distributary tide and flood basin	Plano-concave, somewhat irregular profile. Rather poorly developed surface drainage system. Located adjacent to major distributaries. Import of clay is by both overbank flooding and tidal transport. Interior portions contain small tidal basins filled with peat deposits. Vegetation is mostly deciduous and palm forest.	Planicie cenagosa, planicie de desborde	Inundated and/or saturated for most or all of year. Rivers are the principal hydrologic agent; influence of rain and tides is about equal.	Overbank flooding is important for importing terrigenous material. Tides import some material and are important in redistributing both plant and mineral sediments. Because pulsed discharge associated with floods is a major hydrologic agent, sediment regimes vary in space and time.	Hydra-quents, Sulihemists, Tropo-hemists	Interdistribu-tary flood basins; intermediate to high (topograph-ically) forested swamp.
River	Mud plain	Deficient drainage	Pd2-22	Very poorly drained interdis-tributary basins	Plano-concave, somewhat irregular surface profile. Rimmed by levees, which tend to hydraulically isolate these areas from major caños, greatly reducing the influence of tides. Levees typically <2 m above low water in dry season. Internally surface drainage anastomosing, poorly developed. Naturally covered with deciduous forest but are better drained areas commonly cleared for grazing and agriculture (fig. 27p).	Planicie cenagosa, planicie de desborde	Inundation and/or saturation prolonged but generally not perennial. Tide and rain less prevalent than in basins toward the coast. Stage levels vary widely during the year.	Overbank flooding is the primary sedimentation/ erosion agent. Sediment is generally coarser grained near the levee and finer away from it. Sedimentation rates low. However, subsidence rates are relatively low, and large portions therefore remain relatively well drained. Sediment/erosion processes include levee and back-levee and flood-basin deposition, and lateral channel migration. In the long term, lateral sedimentation/erosion processes predominate.	Tropa-quents, Tropa-quepts, Fluva-quents	Interdistribu-tary flood basin; high (topograph-ically) forested and herbaceous swamps.

Table 8, cont.

Principal hydro-logic agents[1,2]	Setting/ surface com-position[1]	Drainage class[1]	Identifi-cation code[1]	Associated landforms	General description[1]	Associated geomorphic terms used in Venezuela [3]	Hydrology	Landforming processes	Soils[3,4]	Geo-environ-mental class[5]
River	Alluvial	Inundated	Pd2-13	Levee, distal levee, flood basin lakes, crevasse splays	Plano-convex to slightly plano-concave toward center, commonly irregular surface profile. Levees typically <2 m above low water in dry season. Anastomosing, poorly developed drainage system. Flood basin lakes common (fig. 27m, n).	Napa de desborde, cubeta de desborde	Primarily controlled by river discharge. Rain and tides are also significant. Inundated and/or saturated during the wet season. Stage levels vary widely during the year.	Overbank flooding is the primary sedimentation/ erosion agent. Sediment is generally coarser grained near the levee. Tides transport vegetal material and control shape of channels. In areas with prolonged standing water, peats may accumulate and become intercalated with the mineral deposits in basin centers. Low sedimentation rates. However subsidence rates are relatively low; therefore, large portions remain relatively well drained. Sediment/erosion processes include levee and back-levee and flood-basin deposition, and lateral channel migration. In the long term, lateral sedimentation/erosion processes predominate.	Fluva-quents, Tropa-quepts	Interdistribu-tary flood basins; low (topographi-cally) herbaceous swamp; mixed herbaceous and forested swamp.

Table 8, cont.

Principal hydro-logic agents[1,2]	Setting/ surface com-position[1]	Drainage class[1]	Identifi-cation code[1]	Associated landforms	General description[1]	Associated geomorphic terms used in Venezuela [3]	Hydrology	Landforming processes	Soils[3,4]	Geo-environ-mental class[5]
River	Alluvial	Deficient drainage	Pd2-12	Very poorly drained distal levee, flood basin lakes	Concave surface profile. Bordered mostly by distal levee but, in places, mud flats. Naturally forested, but commonly cleared for agriculture and grazing (fig. 27p).	Napa de decantación, cubeta de decantación	Primarily controlled by river discharge. Rain and tides are also significant. Inundation and/or saturation prolonged but generally not perennial. Stage levels vary widely during the year, reaching 3 to 4 m deep during the wet season.	Overbank flooding is the primary sedimentation/ erosion agent. Sediment is generally coarser grained near the levee. Tides transport vegetal material and control shape of channels. In areas with prolonged standing water, peats may accumulate and become intercalated with the mineral deposits in basin centers. Low sedimentation rates. However subsidence rates are relatively low; therefore, large portions remain relatively well drained. Sediment/ erosion processes include levee and back-levee and flood-basin deposition, and lateral channel migration. In the long term, lateral sedimentation/erosion processes predominate.	Sulfa-quents, Tropa-quepts	Interdistribu-tary flood basin; low to high (topographi-cally) herbaceous swamp; grades seaward to mixed forested and herbaceous swamp.

Table 8, cont.

Principal hydro-logic agents[1,2]	Setting/ surface com-position[1]	Drainage class[1]	Identifi-cation code[1]	Associated landforms	General description[1]	Associated geomorphic terms used in Venezuela [3]	Hydrology	Landforming processes	Soils[3,4]	Geo-environ-mental class[5]
River	Alluvial	Inundated	Pd1-13	Distal levee, flood basin lakes, crevasse splays	Plano-concave to plano-concave, commonly irregular surface profile (fig. 27n).	Napa de decantación, cubeta de decantación	Hydrology controlled by river discharge, although rain is also significant. Inundated and/or saturated during the wet season. Inundated and/or saturated for prolonged periods. Length of saturation increases landward.	Overbank flooding is the primary sedimentation/ erosion agent. Sediment is generally coarser grained near the levee. Tides transport vegetal material and control shape of channels. In areas with prolonged standing water, peats may accumulate and become intercalated with the mineral deposits in basin centers. Low sedimentation rates; however, subsidence rates are relatively low, and large portions therefore remain relatively well drained. Sediment/erosion processes include levee and back-levee and flood-basin deposition, and lateral channel migration. In the long term, lateral sedimentation/erosion processes predominate. In portions, areas are composed of Pleistocene Mesa Fm., indicating nondeposition and erosion.	Fluva-quents, Tropa-quepts	Interdistribu-tary flood basin; primarily herbaceous but with mixed forested and herbaceous swamps.

Table 8, cont.

Principal hydro-logic agents[1,2]	Setting/ surface com-position[1]	Drainage class[1]	Identifi-cation code[1]	Associated landforms	General description[1]	Associated geomorphic terms used in Venezuela[3]	Hydrology	Landforming processes	Soils[3,4]	Geo-environ-mental class[5]
River	Alluvial	Deficient drainage	Pd1-12	Levee and crevasse splay	Highest relief and highest elevation in the delta. Levees are mostly silt and typically 2 to 3 m (but as much as 8 m) above low water in the dry season. Because of soil texture, short period of inundation, good drainage, and proximity to transportation route (via the caños) commonly used for agriculture and native village sites (fig. 27a, c, o, q).	Dique y napa de desborde	Inundated by overbank flooding only during the high water of the wet season. Lower areas may remain saturated for entire wet season and early dry season.	One of the more dynamic delta environments. Overbank flooding is the primary sedimentation/ erosion agent. Sediment is generally coarser grained near the levee and finer away from it. Low sedimentation rates. However, subsidence rates are relatively low, and large portions remain therefore relatively well drained. Sediment/erosion processes include levee and back-levee and flood-basin deposition, and lateral channel migration. In the long term, lateral sedimentation/erosion processes predominate.	Dystropepts	Distributary channel system; levees and crevasse splays, primarily forested.

[1]CVG-TECMIN, C.A. (1991a-f)

[2]Direct rainfall is an important hydrologic agent throughout the delta

[3]Geohidra Consultores, C.A. (1997a, b); ENSR Venezuela (1998); FUNINDES USB (1998)

[4]Perennially saturated; therefore, soil development is poor

[5]See maps and explanation for more detailed discussion of geoenvironmental mapping in the Orinoco Delta (pls. 2 and 3)

Table 9. Summary of characteristics of Orinoco Delta distributary channels ("caños").[1]

Traverse identifier	General location	Observation point/sample position identifier	Channel width (m)	Observation point/sample position in caño	Observation point/channel depth (m)	Channel bottom composition
BLP19981117JCG	North end of Boca de Guanipa	BLP199811171636JCG	~2,100	East	10	
	"	BLP199811171650JCG	~2,100	East-east center	10	
	"	BLP199811171705JCG	~2,100	East center	8.6	
	"	BLP199811171719JCG	~2,100	Center	6.3	
	"	BLP199811171725JCG	~2,100	West center	9	
	"	BLP199811171737JCG	~2,100	West-west center	9.3	
	"	BLP199811171742JCG	~2,100	West	1.5	
1999/2/8/2/RCS	South end of Boca de Guanipa	1999/2/8/2a/RCS	1,200	Near east bank	2.5	Fine sand
	"	1999/2/8/2b/RCS	1,200	East center	4.3	
	"	1999/2/8/2c/RCS	1,200	Center	6.6	Very fine & fine sand
	"	1999/2/8/2d/RCS	1,200	West center	12	
	"	1999/2/8/2e/RCS	1,200	Near west bank	14.5	Fine sand & mud
1999/2/7/1/AA	Caño Manamo at Boca Tigre	1999/2/7/1/1030/AA	800	East	6	Very fine sand
	"	1999/2/7/1/1030/AA	800	Center	8.6	Fine sand
	"	1999/2/7/1/1030/AA	800	West	10	Sandy mud
1999/2/8/4/AA	Caño Manamo at Tucupita	1999/2/8/4/1600/AA	~1,000	East	7.1	Mud
	"	1999/2/8/4/1600/AA	~1,000	Center	7.6	Sandy mud
	"	1999/2/8/4/1600/AA	~1,000	West	2.5	Mud
1999/2/7/7/RCS	Lower Caño Pedernales	1999/2/7/7a/RCS	140	East	16.5	Muddy sand
	"	1999/2/7/7b/RCS	140	Center	12	Very fine & fine sand
	"	1999/2/7/7c/RCS	140	West	11.5	Sandy mud
1999/2/9/4/RCS	Middle Caño Pedernales	1999/2/9/4a/RCS	40	North	3.1	Organic-rich muddy sand
	"	1999/2/9/4b/RCS	40	Center	3.7	Medium-brown fine sand
	"	1999/2/9/4c/RCS	40	South	3.7	Dark-brown muddy sand
1999/2/9/5/RCS	Upper Caño Pedernales	1999/2/9/5a/RCS	20	East	1.8	
	"	1999/2/9/5b/RCS	20	Center	1.8	Organic mud with coarse vegetal debris
	"	1999/2/9/5c/RCS	20	West	0.6	
Geohidra Consultores, C.A. (1997a) Macareo	Lower Caño Macareo	Geohidra (1997a) MacareoA	697	Near northeast bank	7.5	Sandy mud

Table 9 (cont.)

Traverse identifier	General location	Observation point/sample position identifier	Channel width (m)	Observation point/sample position in caño	Observation point/channel depth (m)	Channel bottom composition
	"	Geohidra (1997a) MacareoB	697	Northeast center	10.5	Sandy
	"	Geohidra (1997a) MacareoC	697	Southwest center	8.5	Sand
	"	Geohidra (1997a) MacareoD	697	Near southwest bank	6.3	Sandy mud
1998/11/22/3/JCG	Middle Caño Macareo	1998/11/22/3/JCG	~300	Center	12	Fine sand
1999/2/9/4/1240/A	Upper Caño Macareo	1999/2/9/4A/1240/AA	~500	South	10	Very fine sand
	"	1999/2/9/4B/1240/AA	~500	Center	16	Fine sand
	"	1999/2/9/4C/1240/AA	~500	North center	11.5	
	"	1999/2/9/4D/1240/AA	~500	North	24	Coarse sand
1999/2/7/2/RCS	Caño Morocoto Tributary	1999/2/7/2a/RCS	22	East	4.7	
	"	1999/2/7/2b/RCS	22	Center	5.8	
	"	1999/2/7/2c/RCS	22	West	6.2	Mud and vegetal debris

[1]A more detailed description of Orinoco Delta caño characteristics is available in data base on accompanying CD.

Table 10. Suspended material concentrations, Orinoco Delta region.[1]

Month	Year	Zone	Material in suspension at depth (mg/L)	Material in suspension at the surface (mg/L)
April	1988	Caribbean Sea	3.9	3.6
	1988	Gulf of Paria	4.2	3.8
	1982/83	Orinoco River at Ciudad Bolívar	30–250	30–250
May–June	1987	Caribbean Sea	-	2.0
	1987	Gulf of Paria	-	2.1
	1987	Orinoco Delta	-	4.9
	1882/83	Orinoco River at Ciudad Bolívar	150–225	150–225
September	1988	Caribbean Sea	3.9	3.6
	1988	Gulf of Paria	4.5	2.4
	1982/83	Orinoco River at Ciudad Bolívar	60	60
November	1978	Gulf of Paria	9.0	7.8
	1978	Orinoco Delta	11.2	10.7
	1982/83	Orinoco River at Ciudad Bolívar	120–160	120–160

Zone	Surface area (km^2)	Approximate volume (L)	Suspended-sediment concentration (mg/L)	Suspended sediment (metric tons/mo)
Caribbean Sea	13,000	2.4×10^{14}	3.3	7.6×10^5
Gulf of Paria	7,500	1.2×10^{14}	5.3	6.4×10^5
Orinoco Delta	24,500	7.5×10^{14}	8.3	6.25×10^6
Total	45,000	1.1×10^{14}		7.7×10^6

[1]Source: Monente (1989/1990b); Meade and others (1990)

Table 11. Geo-environmental map units based on visual interpretation of Landsat imagery.

Marine-Influenced Coastal Environments

1. Mangroves on coastal facies, mud and locally sandy mud substrates, prominent depositional features apparent locally, permanently flooded
2. Forested swamp, mud and peat substrates, permanently flooded
3. High (topographically) herbaceous swamp, organic/peat substrates, permanently flooded
4. Low (topographically) herbaceous swamp, ponded water, organic/peat substrates, permanently flooded
5. Mixed herbaceous and forested swamp, organic/peat substrates, permanently flooded

Marine-Influenced Distributary-Channel and Island System

6. Mangroves, mud and sandy mud substrates, depositional patterns apparent locally, semipermanently flooded
7. Forested swamp, mud and sandy mud substrates, semipermanently to seasonally flooded
8. Herbaceous swamp, mud, sandy mud, and organic substrates, semipermanently flooded
9. Transitional areas between mangrove and forested or herbaceous swamps, channel-flank environments, low forested swamp with local mangroves and herbaceous vegetation, muddy peat and peat substrates, semipermanently to permanently flooded

Fluvial/Marine Transitional Environments

10. Low (topographically) herbaceous swamp, organic/peat substrates, permanently flooded
11. High (topographically) herbaceous swamp, organic/peat substrates, permanently flooded
12. Mixed herbaceous and forested swamp, organic/peat substrates, permanently flooded

Distributary-Channel Systems

13. Levee and crevasse splay, forested, locally tidally modified, sand and mud substrates, moriche palms dominant in some areas, seasonally flooded
14. Levee and crevasse splay, herbaceous vegetation, sand and mud substrates, seasonally flooded
15. Tidal creek/crevasse splay, moriche palms dominant, mud and sand substrates, seasonally flooded

Interdistributary Flood Basins

16. Low (topographically) forested swamp, mud and organic substrates, permanently flooded
17. Intermediate (topographically) forested swamp, mud and organic substrates, semipermanently to permanently flooded
18. High (topographically) forested swamp, mud and organic substrates, semipermanently to seasonally flooded, locally includes transitional forested areas between levee/crevasse splay and flood basins
19. Low herbaceous swamp and open water, mud and organic substrates, semipermanently to permanently flooded, locally mapped along channel margins
20. High herbaceous swamp, mud and organic substrates, seasonally flooded
21. Primarily herbaceous but with mixtures of forested swamp, mud and organic substrates, semipermanently to seasonally flooded

Table 12. Areal extent of mapped environments in the northwestern Orinoco Delta (see plate 2).

	km^2	Percent
Marine-Influenced Coastal Environments		
1. Mangroves on coastal facies	165.51	2.48
2. Forested swamp, mud and peat substrates, permanently flooded	127.23	1.90
3. High (topographically) herbaceous swamp	178.19	2.67
4. Low (topographically) herbaceous swamp	12.37	0.19
5. Mixed herbaceous and forested swamp	124.54	1.86
Subtotal	**607.84**	**9.10**
Marine-Influenced Distributary Channel and Island System		
6. Mangroves, mud and sandy mud substrates	546.98	8.19
7. Forested swamp	27.67	0.41
8. Herbaceous swamp	32.85	0.49
9. Transitional forested areas between mangrove And forested or herbaceous swamps	50.43	0.75
Subtotal	**657.92**	**9.85**
Fluvial/Marine Transitional Environments		
10. Low (topographically) herbaceous swamp	53.19	0.80
11. High (topographically) herbaceous swamp	294.04	4.40
12. Mixed herbaceous and forested swamp	180.26	2.70
Subtotal	**527.49**	**7.89**
Distributary-Channel Systems		
13. Levee and crevasse splay, forested, locally tidally modified	908.93	13.60
14. Levee and crevasse splay, herbaceous vegetation	1.76	0.03
15. Tidal creek/crevasse splay, moriche palms dominant	68.63	1.03
Subtotal	**979.32**	**14.66**
Interdistributary Flood Basins		
16. Low (topographically) forested swamp	370.87	5.55
17. Intermediate (topographically) forested swamp	881.39	13.19
18. High (topographically) forested swamp	997.36	14.93
19. Low herbaceous swamp and open water	76.99	1.15
20. High herbaceous swamp	97.38	1.46
21. Primarily herbaceous but with mixtures of forested swamp	527.62	7.90
Subtotal	**2,951.62**	**44.18**
Water	956.57	14.32
Villages (Pedernales and Capure)	0.55	0.01
Mud volcanoes visited in 1998	0.16	0.00
Subtotal	**957.28**	**14.33**
Total	**6,681.47**	**100.00**

Table 13. Map units classified through computer-assisted methods.

1. Mangrove Forest
2. Forested Levee/Crevasse Splay and Other Forested Areas
3. Low (topographically) Forested Flood Basin
4. Intermediate Forested Flood Basin
5. High Forested Flood Basin
6. Coastal Woodlands
7. Herbaceous Swamp
8. Low Herbaceous Swamp
9. Herbaceous Swamp/Shrubs
10. Moriche Palm
11. Coconut Palm Groves
12. Water

Table 14. Probability of correct classification of training data.

Class No.	1	2	3	4	5	6	7	8	9	10	11	12
Accuracy (%)	89.8	88.6	51.8	62.3	77.7	53.0	91.9	36.3	80.0	11.0	81.5	99.2

Table 15. Map units classified through computer-assisted methods, southwestern part of delta.

- Distributary-Channel System, Primarily
  - Levee and crevasse/tidal splay, forested
  - Tidal creek/crevasse splay, forested, moriche palm dominant
- Interdistributary Flood Basin, Primarily
  - Low (topographically) forested swamp
  - Intermediate (topographically) forested swamp
  - High (topographically) forested swamp
  - Primarily herbaceous but with mixtures of forested swamp
  - Low herbaceous swamp
  - High herbaceous swamp
- Coastal Plain Grading into Quaternary Uplands
  - High herbaceous swamp grading into herbaceous upland vegetation
  - Herbaceous upland vegetation
  - Pine forest
- Urban Areas
- Water
- Clouds/Shadows

Table 16. Summary of Orinoco Delta subsurface data used to generate estimates of sediment accumulation and subsidence rate.

Core ID no.	General location	Source of subsurface information	Depth to dated horizon (mm)	Method to date horizon	Date of horizon	Estimated sediment accumulation rate (mm/yr)	Estimated subsidence rate (mm/yr)
1998/10/ 12/2/AA	Upper delta–C. Manamito levee[1]	Bureau field work	5,300	C14	6,430±60 yr B.P.	0.8	0.8
1998/10/ 17/2/AA	Upper delta flood basin[1]	Bureau field work	5,650	C14	6,280±70 yr B.P.	0.9	0.9
1998/11/ 20/3/AA	C. Manamito levee swale[1]	Bureau field work	6,550	C14	6,510±50 yr B.P.	1.0	1.0
1999/2/8/ 1/RCS	NW delta along west bank of Boca Guanipa[1]	Bureau field work	7,500	C14	2,840±50 yr B.P.	2.6	2.6
1999/2/9/ 1/RCS	Middle delta–C. Pedernales trib. [1]	Bureau field work	7,100	C14	3,500±40 yr B.P.	2.0	2.0
A_2	Gulf of Paria[2]	INTEVEP (1981)	67,000 (+ 22,900) water depth) = 89,900	Estimated	7,500 yr B.P.	8.9	4.6
A_4	Gulf of Paria[2]	Fugro (1979)	45,400 (+ 26,100 water depth) = 71,500	Estimated	7,500 yr B.P.	6.0	2.2
A_5	NW delta (Pedernales)[2]	Kidwell and Hunt (1958)	60,000	Estimated	7,500 yr B.P.	8.0	3.3
B_4	Lower delta–Punta Pescadores[2]	Geohidra Consultores, C.A.(1997b)	76,000	Estimated	7,500 yr B.P.	10.1	2.8
B_5	Lower delta–Punta Pescadores[2]	Geohidra Consultores, C.A.(1997b)	100,000+	Estimated	7,500 yr B.P.	13.3	6.0+

[1]See figure 6b for locations and data base of shallow-core data on accompanying CD for locations and sources of data
[2]See figure 44

Appendices

APPENDIX 1

PHOTOGRAPHS OF SELECTED PLANTS OF THE ORINOCO DELTA

The following plant photographs were taken primarily in the western portion of the delta between Tucupita and Pedernales by William A. White and Jay A. Raney during field surveys in October and November 1998. Identification of plants is based principally on consultations during the November survey with Dr. Valois González, Universidad Central de Venezuela. Dr. González also kindly examined the photographs, identified plants to species level, cited authors, noted family names, and provided a brief description of where the species typically occur in the delta. We gratefully acknowledge the major contribution made by Dr. Valois González to this manual of selected plants of the Orinoco Delta.

The 58 photographs include 54 species and encompass 33 families of plants. Many of the more common plants are illustrated, but the photographs represent only a small fraction of the total number of plant species in the western part of the delta. Although work on this project has been suspended, it is hoped that this collection of digital images will be useful to others working in the delta and that it will serve as a foundation for additional studies.

Paspalum repens Berg.
Family: Poaceae
Common name: Gamelote volador

This grass species, together with *Echinocloa polystachya,* form the so-called floating meadow. It is very common along the upper reaches of the main Orinoco Delta distributaries.

Eichhornia crassipes (Mart.) Solms
Family: Pontederiaceae
Common name: Bora

Common aquatic herb in the lagoons and along streams of the upper delta.

Andropogon bicornis L.
Family: Poaeceae
Common name: Cola de vaca

Not a very common grass, but it will grow, forming small clumps, in the herbaceous swamp dominated by *Lagenocarpus guianensis.*

Flowering plant at left:
Ipomoea sp.
Family: Convolvulaceae

Orinoco Delta Plants

Paspalum repens (center)
Eichhornia crassipes (bottom)

Scientific name

Gamelote volador (center)
Bora (bottom)

Common name

Andropogon bicornis (right)
Ipomoea (left)

Scientific name

Cola de vaca (right)

Common name

QAc4817(a)c

Sacciolepis striata (L.) Nash
Family: Poaeceae

One of the few grasses that can grow as companion species in the herbaceous swamp (as shown below) dominated by Cyperaceae.

Lagenocarpus guianensis Nees
Family: Cyperaceae
Common Name: Cortadera

The dominant Cyperaceae of the herbaceous swamp communities in the lower and middle delta.

Sacciolepis striata

Scientific name

Common name

Lagenocarpus guianensis

Scientific name

Cortadera

Common name

Desmoncus orthacanthos Mart.
Family: Arecaceae
Common name: Camuare

Vigorous climbers forming dense thickets in clearings along riverine forests.

Bactris pilosa M. Karst.
Family: Arecaceae
Common name Caña negra

Prickly palms along lower courses of the Orinoco Delta distributaries.

Bactris campestris Mart.
Family: Arecaceae
Common name: Corozo

Undergrowth palm clustered with few to several trunks. Very common in palm and swamp forests of the lower delta.

Desmoncus orthacanthos

Scientific name

Camuare

Common name

Bactris pilosa

Scientific name

Caña negra

Common name

Bactris campestris

Scientific name

Corozo

Common name

Calathea lutea (Aubl.) Schult
Family: Marantaceae
Common name: Casupo

Caulescent herb in marshy areas and in forest clearings, always associated with strong light.

Renealmia thyrsoidea (Ruiz & Pav.) Poepp. & Endl.
Family: Zingiberaceae
Common name: Cunopio

Caulescent herb in the undergrowth of marsh forests, upper and middle delta.

Calathea lutea

Scientific name

Casupo

Common name

Renealmia thyrsoidea

Scientific name

Cunopio

Common name

Xanthosoma sagittifolia (L.) Schott.
Family: Araceae
Common name: Ocumo

Neotropical but cultivated as a root tuber.

Solanum stramoniifolium Jacq.
Family: Solanaceae
Common name: Manzana del diablo

Weedy shrub in seasonally flooded grasslands of the upper delta.

Artocarpus altilis Fasb.
Family: Moraceae
Common name: Arbol de pan

Tree introduced from Polynesia and grown in home gardens for its edible seeds and use in cooking.

Xanthosoma sagittifolia
Scientific name

Ocumo
Common name

Solanum stramoniifolium
Scientific name

Manzana del diablo
Common name

Artocarpus altilis
Scientific name

Arbol de pan
Common name

Phyllanthus elsiae Urb.
Family: Euphorbiaceae
Common name: Cerecillo

Phyllanthus elsiae Urb.
Family: Euphorbiaceae
Common name: Cerecillo

Relatively common tree along riverine forests in the upper delta.

Phyllanthus elsiae

Scientific name

Cerecillo

Common name

Phyllanthus elsiae

Scientific name

Cerecillo

Common name

Rhizophora sp.
Family: Rhizophoraceae
Common name: Mangle rojo

Avicennia germinans (L.)
Family: Avicenniaceae
Common name: Mangle negro

Laguncularia racemosa (L.) Gaertn
Family: Combretaceae
Common name: Mangle blanco or Mereicillo

Mangroves form dense communities along marine-influenced distributaries and in marine coastal environments; they play a key role in trapping riverine and marine sediments and forming accretionary shorelines and islands.

Avicennia germinans (L.)
Family: Avicenniaceae
Common name: Mangle negro

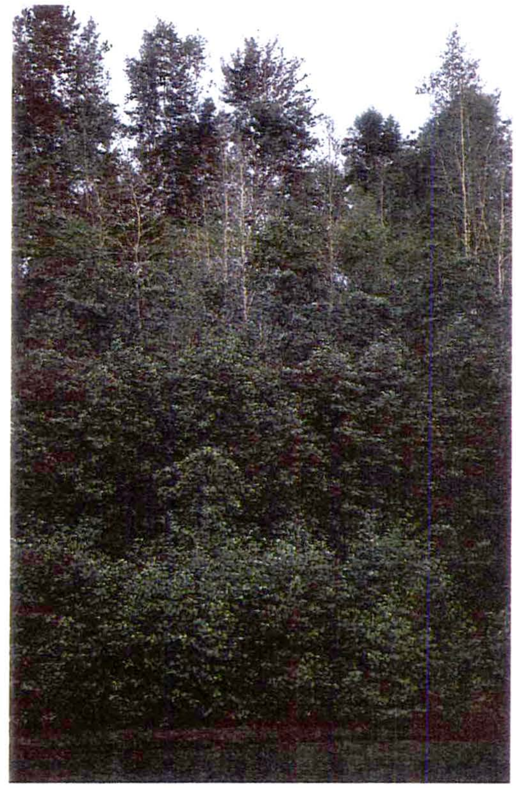
Rhizophora sp.
Family: Rhizophoraceae
Common name: Mangle rojo

Rhizophora sp.

Scientific name

Mangle rojo

Common name



Avicennia germinans (top)
Laguncularia racemosa (bottom)

Scientific name

Mangle negro (top)
Mangle blanco or Mereicillo (bottom)

Common name

Avicennia germinans (left)
Rhizophora sp. (right)

Scientific name

Mangle negro (left)
Mangle rojo (right)

Common name

Spondias mombin L.
Family: Anacardiaceae
Common name: Jobo

A common and dominant tree in different kinds of forests of the upper delta.

Ficus dendrocida H.B.K.
Family: Moraceae
Common name: Matapalo

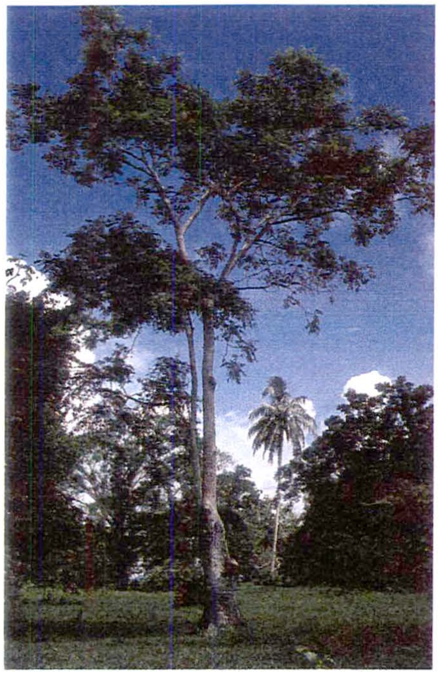
Common strangler tree in the levee forests of the upper delta.

Symphonia globulifera L.f.
Family: Clusiaceae
Common name: Paramancillo

Dominant tree in swamp forests of the middle and lower delta.

Ceiba pentandra (L.) Gaertn
Family: Bombacaceae
Common name: Ceiba

Tree present mainly in the forest of the upper delta.

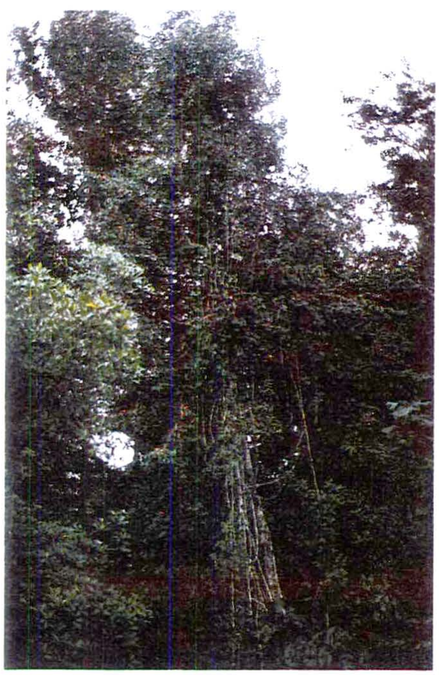


Spondias mombin
Scientific name

Jobo
Common name

Ficus dendrocida
Scientific name

Matapalo
Common name



Symphonia globulifera
Scientific name

Paramancillo
Common name

Ceiba pentandra
Scientific name

Ceiba
Common name

Canna indica L.
Family: Cannaceae
Common name: Capacho

Giant herb sometimes cultivated as an ornamental in home gardens. Upper delta.

Dioclea guianensis Benth.
Family: Fabaceae
Common name: Ojo de Zamuro

Subligneous or herbaceous twiner along river banks in the upper delta.

Canna indica

Scientific name

Capacho

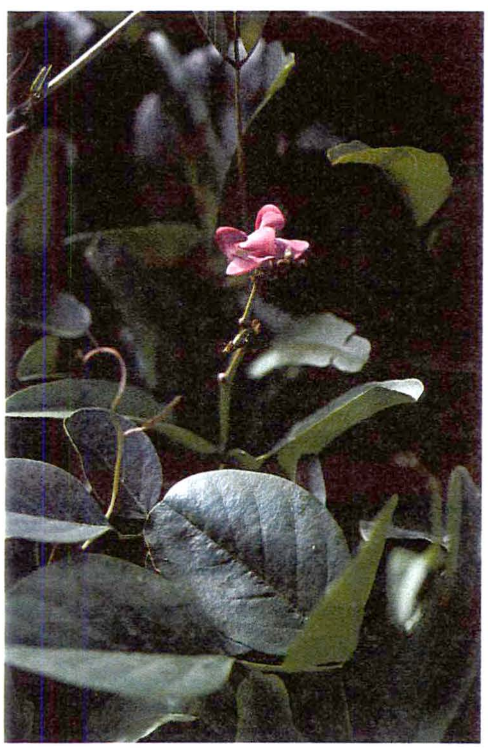
Common name

Canna indica

Scientific name

Capacho

Common name



Dioclea guianensis

Scientific name

Ojo de Zamuro

Common name

Heliconia marginata (Griggs) Pittier
Family: Heliconiaceae
Common name: Platanillo

Very common giant herb in the undergrowth of levee forests in gaps and clearings; also in marsh forests.

Lantana camara L.
Family: Verbenaceae
Common name: Cariaguito colorado

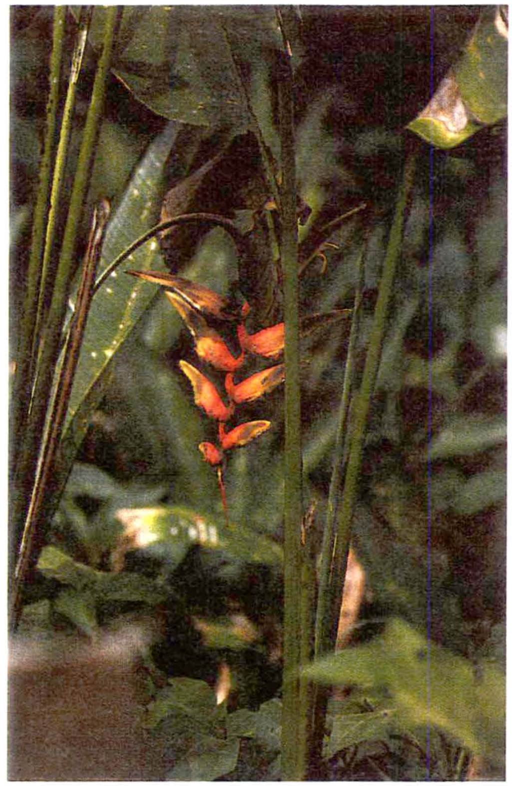
Shrub associated with abandoned and shifting agricultural fields in the upper delta.

Heliconia marginata

Scientific name

Platanillo

Common name



Heliconia marginata

Scientific name

Platanillo

Common name

Lantana camara

Scientific name

Cariaguito colorado

Common name

Mimosa arenosa (Willd) Poir
Family: Mimosaceae
Common name: Cujicillo

Weedy shrub.

Mimosa pudica L.
Family: Mimosaecea
Common name: Dormidera

Common thorny, weedy subshrub associated with overgrazed, seasonally flooded grasslands.

Mimosa arenosa

Scientific name

Cujicillo

Common name

Mimosa pudica

Scientific name

Dormidera

Common name

Tamarindus indica L.
Family: Caesalpiniaceae
Common name: Tamarindo

Paleotropical tree introduced in Venezuela in the delta area; planted in home gardens to make refreshing beverage with fruit.

Theobroma cacao L.
Family: Sterculiaceae
Common name: Cacao

Cash-crop tree planted in the undergrowth of tall evergreen forests associated with levees and banks of crevasse splays in the upper delta.

Tamarindus indica
Scientific name

Tamarindo
Common name

Theobroma cacao
Scientific name

Cacao
Common name

Inga edulis Mart.
Family: Mimosaceae
Common name: Guamo rojo

Very common tree along levees of riverine forests.

Tabebuia insignis var. *monophylla* (Mig.) Sandw.
Family: Begoniaceae
Common name: Apamate

One of the dominant tree species in peat-swamp forests and also a shrub or tree in the herbaceous swamps of *Lagenocarpus guianensis*.

Gustavia augusta L.
Family: Lecythidaceae
Common name: Codo de mono

Common tree in seasonally flooded forests in the upper delta.

Erythrina fusca Lour.
Family: Fabaceae
Common name: Bucare de agua

Tree that can form monospecific swamp forests associated with mineral soils in the upper delta.

Inga edulis

Scientific name

Guamo rojo

Common name

Tabebuia insignis var. *monophylla*

Scientific name

Apamate

Common name

Gustavia augusta

Scientific name

Codo de mono

Common name

Erythrina fusca

Scientific name

Bucare de agua

Common name

Ficus sp. (*guianensis*?)
Family: Moraceae

Lower delta.

Sapium glandulosum L. (Morong)
Family: Euphorbiaceae
Common name: Lechero mapolo

Photograph of a young sapling. Very common tree present in different kinds of forests in the upper delta.

Pachira aquatica Aubl.
Family: Bombacaceae
Common name: Cacao de agua

Very common tree in riverine swamp forests in the middle delta.

Ficus sp.

Scientific name

Common name

Sapium glandulosum

Scientific name

Lechero mapolo

Common name

Pachira aquatica

Scientific name

Cacao de agua

Common name

Ichnosiphon arouma (Aubl.) Koern.
Family: Marantaceae
Common name: Tirite

Giant herb; common in the ground of peat-swamp forests, lower and middle delta.

Rapatea paludosa Aubl.
Family: Rapateaceae

Predominant herb in the ground layer of the palm swamp community dominated by *Mauritia flexuosa*.

Ichnosiphon arouma

Scientific name

Tirite

Common name

Rapatea paludosa

Scientific name

Common name

Costus arabicus L.
Family: Costaceae
Common name: Caña de la india

Giant herb common in the undergrowth of marsh and swamp forests.

Aniseia martinicensis (Jacq.) Choisy
Family: Convolvulaceae

Herbaceous vine in marshy areas along shore in the lower delta.

Costus arabicus
Scientific name

Caña de la india
Common name

Aniseia martinicensis
Scientific name

Common name

Chrysobalanus icaco L.
Family: Chrysobalanaceae
Common name: Icaco

Common shrub or tree forming monospecific shrub communities in the middle and lower delta.

Tapirira guianensis Autl.
Family: Anacardiaceae
Common name: Patillo

Tree not very common along riverine forests; also occurs in the upper discontinuous tree layer of herbaceous swamps.

Chrysobalanus icaco

Scientific name

Icaco

Common name

Tapirira guianensis

Scientific name

Patillo

Common name

Clusia sp. (possibly *nemorosa* G. Mey.
Family: Clusiaceae
Common name: Copey

Some species of this genus occur more in swamp forests; others, such as *Clusia memorosa,* grow in clumps of shrubs or trees that interrupt the herbaceous layer of the herbaceous swamp of *Lagenocarpus guianensis.*

Vismia cayennensis (Tacq.) Pers.
Family: Clusiaceae
Common name: Cacre

Shrub in secondary riverine forests.

Clusia sp.

Scientific name

Copey

Common name

Vismia cayennensis

Scientific name

Cacre

Common name

Annona glabra L.
Family: Annonaceae
Common name: Gaunabana

Small tree; common in swamp and marsh forest.

Pentaclethra macroloba (Willd.) Kuntze
Family: Mimosaceae
Common name: Cabelliño

A tree typically growing along riverine swamp forests in the middle delta.

Annona glabra

Scientific name

Gaunabana

Common name

Pentaclethra macroloba

Scientific name

Cabelliño

Common name

Ricinus communis L.
Family: Euphorbiaceae
Common name: Tartago

Shrub introduced from Africa, but naturalized and typically growing in open areas. A medicinal shrub from which seed oil is used as a laxative.

Costus sp.
Family: Costaceae

Herb collected along Caño Cocuina, middle delta.

Miconia prasina (Swartz) DC.
Family: Melastomataceae
Common name: Nigua

Common shrub undergrowth in "Morichales."

Ricinus communis

Scientific name

Tartago

Common name

Costus sp.

Scientific name

Common name

Miconia prasina

Scientific name

Nigua

Common name

Cecropia peltata L.
Family: Cecropiaceae
Common name: Yagrumo

A fast-growing tree in large clearings of riverine forests.

Blechnum serrulatum L. C. Rich.
Family: Blechnacea
Common name: Helecho serrucho

Fern species that forms pure communities in the lower delta and is very tolerant of fire.

Mimosa sp.
Family: Mimosaceae

Heavily armed shrub that forms impenetrable barriers when growing in dense, monospecific communities on levees and other high ground.

Cecropia peltata
Scientific name

Yagrumo
Common name

Blechnum serrulatum
Scientific name

Helecho serrucho
Common name

Mimosa sp.
Scientific name

Common name

Calathea lutea (Aubl.) Schult.
Family: Marantaceae
Common name: Casupo

Heliconia marginata (Griggs) Pittier
Family: Heliconiaceae
Common name: Platanillo

Echinochloa polystachya (Kunth) Hitchc.
Family: Poaceae
Common name: Pasto aleman

Common herbs growing in marshy areas, levee forests, and forest clearings.

Montricardia aborescens L.
Family: Araceae
Common name: Rábano de agua

A very widespread giant herb forming pure communities in the upper delta; also occurring in the undergrowth of mangroves, palms, and swamp forest.

Calathea lutea (left center)
Heliconia marginata (right center)
Echinochloa polystachya (bottom)

Scientific name

Casupo (left center)
Platanillo (right center)
Pasto aleman (bottom)

Common name

Montricardia aborescens

Scientific name

Rábano de agua

Common name

Coccoloba latifolia Lam.
Family: Polygonaceae
Common name: Uvero

Tree in open-marsh forests in the upper delta.

Heliconia psittacorum L.f.
Family: Heliconiaceae

Giant herb very common in the undergrowth of open palm swamp communities.

Coccoloba latifolia
Scientific name

Uvero
Common name

Heliconia psittacorum
Scientific name

Common name

Index of Plants in Appendix 1

APPENDIX 2

MUD VOLCANOES OF THE ORINOCO DELTA, EASTERN VENEZUELA

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ABSTRACT

Mud volcanoes along the Orinoco Delta northwest margin are part of a regional belt of mud volcanism and diapirism that formed in response to rapid foredeep sedimentation and subsequent tectonic compression along the Caribbean–South American plate boundary. Mud volcanoes highlight the importance of tectonic influences on the development of this major delta and its proximity to an active plate margin. Evaluation of the Orinoco Delta mud volcanoes and those elsewhere indicate that mud volcanoes are important indicators of tectonic conditions along deformation fronts of plate margins.

INTRODUCTION

The Orinoco Delta of eastern Venezuela contains 20,000 km^2 of pristine forests and marshes subdivided by networks of fluvial and tidal channels. The delta occupies a structural trough located adjacent to the deformation front of the Southeast Caribbean plate boundary zone (SCPBZ; *sensu* Robertson and Burke, 1989) (Fig. 1). The trough is filled by >10,000 m of primarily Miocene to Recent deep-marine, shelf, and deltaic sediments (Barnola, 1960; Pees et al., 1968; DiCroce et al., 1999). Basin subsidence and sediment infilling occurred principally in response to transpression related to eastward migration of the Caribbean Plate relative to South America (Robertson and Burke, 1989; Algar and Pindell, 1993).

Subaerial mud volcanoes are known in fewer than 30 regions worldwide and comprehensive assessments of their origins and tectonic significance are limited (cf. Higgins and Saunders, 1974; Hedberg, 1980). Although they are known from offshore environments, mud volcanoes are rare in subaerial deltaic settings (Morgan et al., 1968). Mud volcanoes of the northwestern Orinoco Delta provide dramatic relief to the surrounding delta plain. These features are part of a regional belt (Fig. 1) of mud volcanism and diapirism that extends from eastern Venezuela, across southern Trinidad and parts of the Barbados Ridge Complex (Kugler, 1933; Higgins and Saunders, 1967; Pees et al., 1968; Biju-Duval et al., 1982; Westbrook and Brown, 1983). Our main objectives are to interpret the origin of Orinoco mud volcanoes and to explain their importance to Orinoco Delta evolution.

ORINOCO DELTA MUD VOLCANOES

Orinoco Delta mud volcanoes cluster along the crest of the northeast-southwest-trending Pedernales anticline. This structure is contiguous with the Southern Range anticline of Trinidad and overlies the Eastern Venezuelan Basin axis (Pees et al., 1968) (Kidwell and Hunt, 1958; Barnola, 1960; Pees et al., 1968; Algar and Pindell, 1993) (Fig. 2). The Pedernales anticline, active since the late Pleistocene, is cored by a mud diapir that originates from depths as great as 6,000 m (Pees et al., 1968; Bennett et al., 1994).

Field observations (1998 and 1999), GPS surveys, and LANDSAT Thematic Mapper imagery were used to determine the location, geomorphology, and sedimentology of five of seven mud volcanoes and the La Brea tar seep (Fig. 2). Orinoco mud volcanoes are mound shaped, 10 to 15 m high, and as much as 400 m in diameter. Scarce or anomalous vegetation surrounds active vents (i.e., *tassik* areas of Higgins and Saunders, 1974) (Fig. 3 A, B). Historic accounts indicate that mud-volcano eruptions involve fluidized mud, gas, and water, and they can be violent (Arnold and Macready, 1956; Wilson and Birchwood, 1965). Recent mud flows and craters filled with waters that bubble intermittently as a result of gas exsolution demonstrate that four out of the five mud volcanoes are currently active.

La Plata mud volcano, the largest active feature in the delta (Fig. 3B), is located on the northeast edge of a rapidly accreting island near the mouth of a major Orinoco Delta distributary (Fig. 2). The mud volcano's crest, ~15 m above sea level, has a diameter of ~250 m and is covered by erosional rills and lithic clasts (Fig. 3C). Clasts range from granules to boulders as much as 40 cm in diameter and include quartz, chert, quartzite, gneiss, sandstone, siltstone, pyrite-rich black shale, limestone, and ironstone. Granule and pebble-size clasts of chert, quartz, and quartzite are well rounded, whereas sandstone, shale, and limestone clasts tend to be angular to subround (Fig. 3D). Some limestone clasts show evidence of etching and pitting. Wave erosion along the northeast flank exposes gray mud that encases numerous black-shale and siltstone clasts. Only one small vent is active, but vegetated mudflows and inactive vents along the flanks provide evidence of multiple episodes of eruptive activity. Major violent eruptions occurred at La Plata in 1948 (Mariño and Zanín, 1983) and 1995.

The Pedernales mud volcano, the largest in the region, is currently dormant. Rising ~15 m above sea level, it has a diameter of ~350 m, has no active vents or craters, and is densely vegetated. Irregular depressions represent possibly collapsed vents. Abandoned concrete buildings and walkways built by local inhabitants along the crest of the mud volcano have subsided into several of the depressions. Along the north flank of the mud volcano, wave erosion has exposed steeply dipping (>20°) carbonaceous siltstones of the Plio-Pleistocene Las Piedras Formation. Preserved bedding and absence of similar outcrops in the immediate area suggest that these deposits were uplifted along faults.

Hydrocarbon seeps associated with mud volcanoes have been a major impetus for oil and gas exploration in the delta. Vents having oil films and minor tar flows are common at the Palm Grove mud volcano (Fig. 2). La Brea is a tar seep that consists of a flat, tar-capped, and wave-eroded mudflow (Fig. 3E). It rises ~1 m above adjacent mangrove swamps, parallels the shoreline for ~1 km, and extends inland for ~100 m. Tar that veneers the land surface emanates from numerous small vents. Underlying muds have been thoroughly impregnated by hydrocarbons.

MUD-VOLCANO ORIGINS

Essentially all reported mud volcanoes are associated with thick sequences of overpressured, organic-rich, clayey sediments (Hedberg, 1974; 1980; Kopp, 1985). Mud-volcano occurrence near the basin axis indicates that rapid accumulation of Miocene and Pliocene marine muds has played a major role in the development of Orinoco mud volcanoes. Paleontologic data show that Miocene black shales are the source material of Trinidad mud volcanoes (Higgins and Saunders, 1974), and abundant black-shale clasts at La Plata indicate that the same may be true of Orinoco mud volcanoes. Well-rounded clasts of resistant rock types at Pedernales and La Plata, as well as at several Trinidad mud volcanoes, suggest that the source beds of the mud volcanoes were intercalated with fluvial gravels or marine slumps that contained reworked fluvial gravels (cf. Higgins and Saunders, 1974).

The location of the Orinoco mud volcanoes along the Pedernales anticline suggests that tectonic compression is also a major factor influencing mud-volcano development. Mud volcanoes in southern Trinidad occupy similar positions along the crest of the Southern Anticline (Salvador and Stainforth, 1965; Wilson and Birchwood, 1965). We infer that southeast-directed tectonic stresses along the south SCPBZ margin, coupled with thick mud accumulations in the

Pedernales region, led to the development of overpressured conditions and diapiric anticlines. Faults along the crests of these structures provided pathways for fluidized muds, which migrated upward through overlying strata and erupted at the land surface (cf. Wilson and Birchwood, 1965; Higgins and Saunders, 1974; Barber et al., 1986; Algar, 1993). Orinoco mud volcanoes are interpreted to be fault-controlled, surface manifestations of the buried mud diapir—an interpretation similar to those inferred at other localities (e.g., Morgan et al., 1968; Barber et al., 1986). The absence of mud volcanoes in the northern SCPBZ (Fig. 1) may reflect northward thinning of Miocene and Pliocene strata (cf. Brown and Westbrook, 1987).

Methane generation and clay-mineral diagenesis probably contribute to the development of overpressured conditions. We concur with Higgins and Saunders (1974), however, in that these factors are probably secondary to tectonic and depositional controls because they do not explain the distribution of the mud volcanoes and diapirs parallel to the SCPBZ.

TECTONIC SIGNIFICANCE OF ORINOCO DELTA MUD VOLCANOES

Orinoco mud volcanoes follow the general pattern of mud volcanism observed around the world (Fig. 4). A global survey shows that 23 out of the 27 areas of active mud volcanism are located near convergent plate boundaries or suture zones associated with regional fold and thrust belts (Higgins and Saunders, 1974; Kopp, 1985). These observations suggest that tectonic compression plays a primary role in the development of most mud volcanoes.

Orinoco volcanoes demonstrate that tectonically driven mud diapirism is influencing the delta's subaerial development. Near Pedernales the shoreline approximately parallels and is generally coincident with the axis of the anticline (Figs. 1 and 2). Shoreline position and the shallow depth of deformed Las Piedras strata suggest that the anticline at least partly controls the position of the delta margin and extent of delta progradation northward into the Gulf of Paria.

Most deltas are located in tectonically quiescent areas (Coleman, 1981) where mud volcanism and diapirism is caused principally by sediment loading in offshore environments (Morgan et al., 1968; Chen and Stanley, 1993), and has little affect on subaerial delta development.

CONCLUSIONS

1. Orinoco Delta mud volcanoes are part of a belt of mud volcanism and diapirism that parallels the SCPBZ. Mud volcanoes formed in response to rapid foredeep sedimentation and transpression along the plate boundary and highlight the proximity of the Orinoco Delta to an active plate margin.
2. Orinoco mud volcanoes are dramatic surface manifestations of tectonically driven diapirism and differ from those formed principally by sediment loading in offshore environments. Most major deltas develop in tectonically quiescent settings and therefore have no subaerial mud volcanoes.
3. The location of Orinoco mud volcanoes is controlled by anticlinal structures that developed along the deformation front of the SCPBZ. These structures also influence the position of the delta margin.

ACKNOWLEDGMENTS

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Table 1. Summary information on mud volcanoes worldwide.

No.	Location	Tectonic setting	Structural setting	Sedimentary basin thickness	Age of mud volcano sediments	Mud volcano clast composition	No. of volcanoes	Mud volcano dimensions Diameter (m)	Height (m)	Hydrocarbon and fluid composition	References
1	**Azerbaijan**	Iranian–Afghan and Eurasian convergent plate boundary					226				Goubkin and Federov (1937); Khalilov and Kerimov (1981)
2	**Barbados Ridge**	Caribbean–Atlantic plate subduction zone	Broad area of folded and thrust-faulted sediments within accretionary prism							Methane	Stride et al. (1982); Brown and Westbrook (1987)
3	**Burma**	Regional strike-slip fault	Related to early Cenozoic foldbelt and regional strike-slip fault		Cretaceous–Eocene	Coarse sandstone subordinate shale and limestone		45	25		Chibber (1934)
4	**Colombia**	South American–Nazca convergent plate boundary	Tertiary foldbelt of the western Cordillera		Tertiary			50	15		Higgins and Saunders (1974)
	Indonesia	Eurasian–Indian convergent plate boundary									
5	Timor				Borbonaro scaly clay	Large boulders of sandstone	21	2,000			Barber et al. (1986)
6	Java		Associated with anticlines			Turbidite sandstone to 2 m diameter		303			Humphrey (1963)
7	Sumatra										Higgins and Saunders (1974)
8	North Borneo				Upper Cretaceous–lower Tertiary						Higgins and Saunders (1974)
9	**Mediterranean Ridge**	African–Eurasian transpressional plate boundary			Miocene		2				Robertson et al. (1996)
10	**Italy and Sicily**	African–Eurasian transpressional plate boundary	Strike-slip fault		Tertiary		50–60		<2	Bituminous sands, methane	Abbate et al. (1970)
11	**Mexico**	Center of Papaloapeen Basin	Crest of an anticline	$\geq$ 5,750 m	Oligocene–Miocene		1	25	6		Humphrey (1963)
12	**New Zealand**	Pacific–Australian convergent	Northeast-trending fault	6,100 m	Miocene–Pliocene	Marine and terrigenous clastic rock	3				Ridd (1970)
	Mangaehu Stream	Plate boundary	East-west-striking high-angle fault	2,700 m			1				
	Hangaroa River		High-angle fault				1			Flame gases	
	Arakihi Road		North-northwest- trending fault								
13	**North Panama**	Nazca–Caribbean convergent plate boundary									Breen et al. (1988)
14	**Pakistan** Makran	Indian and Iranian–Afghan convergent plate boundary; oceanic thrust beneath continental plate	Ornach fault and foldbelt		Oligocene–Miocene	Clay and carbonate Mixture, minor quartz	47			Methane and unsaturated hydrocarbon	Ahmed (1969) Stiffe (1873); Snead (1964); Wilson and Birchwood (1965)
15	**Romania**	Caucasus suture zone	Along the axis of the Berca anticline		Miocene–Pliocene		Dozens				Higgins and Saunders (1974)
16	**Black Sea**	Caucasus suture zone	Diapiric anticlines of the Apsheron Peninsula		Oligocene–Miocene and Pliocene	Minor sandstone, limestone, and dolomite			400–500		Basov and Ivanov (1996)

No.	Location	Tectonic setting	Structural setting	Sedimentary basin thickness	Age of mud volcano sediments	Mud volcano clast composition	No. of volcanoes	Mud volcano dimensions: Diameter (m)	Mud volcano dimensions: Height (m)	Hydrocarbon and fluid composition	References
17	**Taiwan**	Philippine–Eurasian convergent plate boundary			Upper Tertiary to Holocene		64				Shih (1967)
18	**Trinidad**	South American–Caribbean transpressional plate boundary	Southern Trinidad fold and thrust belt, crests of anticlines	1,515 m	Tertiary	Shale and sandstone		182	15–18	Oil sands, petroleum gas	Arnold and Macready (1956)
	Mud Island					Heterogeneous sandstone and gravel	Many				Wilson and Birchwood (1965)
	Chatam, Mud Island				Miocene	Carbonaceous conglomerate and gravelly sandstone				Mostly methane	Higgins et al.(1967)
	Marac mud volcano			3,000–4,000 m			26	10–500		Heavy, tarry oil	Higgins and Saunders (1974); Kugler (1933); Kerr at al. (1970)
19	**Venezuela, Orinoco Delta**	South American–Caribbean transpressional plate boundary	Diapir-cored anticline	>10,000 m	Cretaceous–Holocene	Rounded to angular pebble to boulder-size clasts of shale, sandstone, chert, limestone, metamorphics	>10	50–500	10–20	Oil, tar, water	Kidwell and Hunt (1958); Barnola et al. (1960)
20	**Ecuador**	South American–Nazca convergent plate boundary			Eocene						Marchant and Black (1960)
21	**Southern Caspian**	Eurasian and Iranian–Afghan compressional plate boundary									Gansser (1960)
22	**New Guinea**	Indian–Eurasian convergent plate boundary									Williams et al. (1984)
23	**Sakhalin**	Suture zone near the Eurasian–Pacific convergent plate boundary			Upper Cretaceous						Gorkun and Siryk (1968)
24	**Mississippi Delta, US**	Passive margin	Delta front	3,000 m	Plio-Pleistocene						Morgan et al. (1968)
25	**Tanganyika**	Intraplate setting									Richard (1945)
26	**Gulf of Mexico**	Passive margin	Continental shelf margin	>1,000 m	Quaternary						Sieck (1973), Neurauter and Roberts (1994)
27	**Yangtze Delta, China**	Passive margin	Continental shelf margin	>60 m	Upper Pleistocene						(Chen and Stanley, 1993)

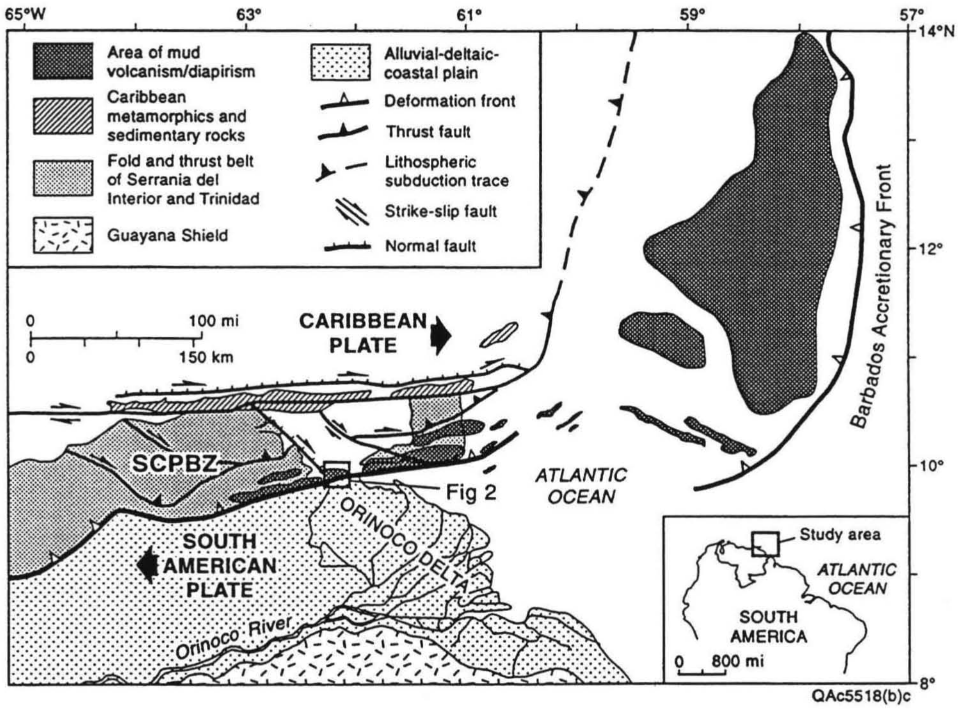

Figure 1. Northern South America (see inset) showing the geology, major structural elements, and areas of mud volcanism and diapirism. (Modified from Westbrook and Smith, 1983; Algar and Pindell, 1993; and DiCroce et al., 1999).

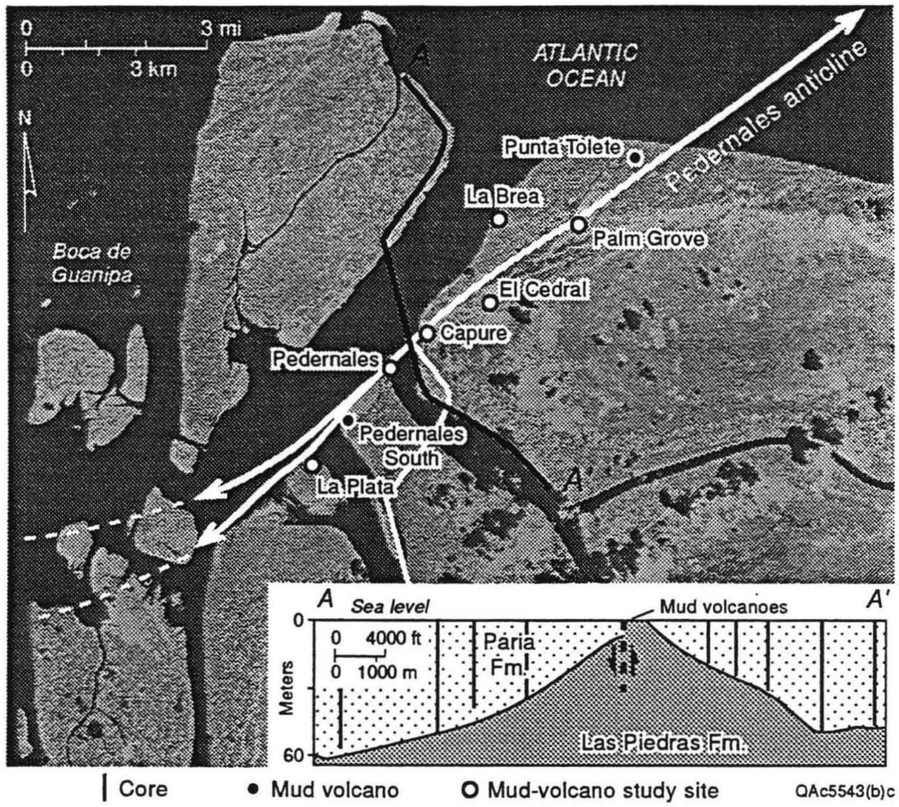

Figure 2. LANDSAT Thematic Mapper gray-scale image showing the distribution of Orinoco mud volcanoes along the axis of the Pedernales anticline. Cross section shows deformed Plio-Pleistocene strata of the Las Piedras Formation overlain by the Holocene Paria Formation. (Modified from Kidwell and Hunt, 1958).

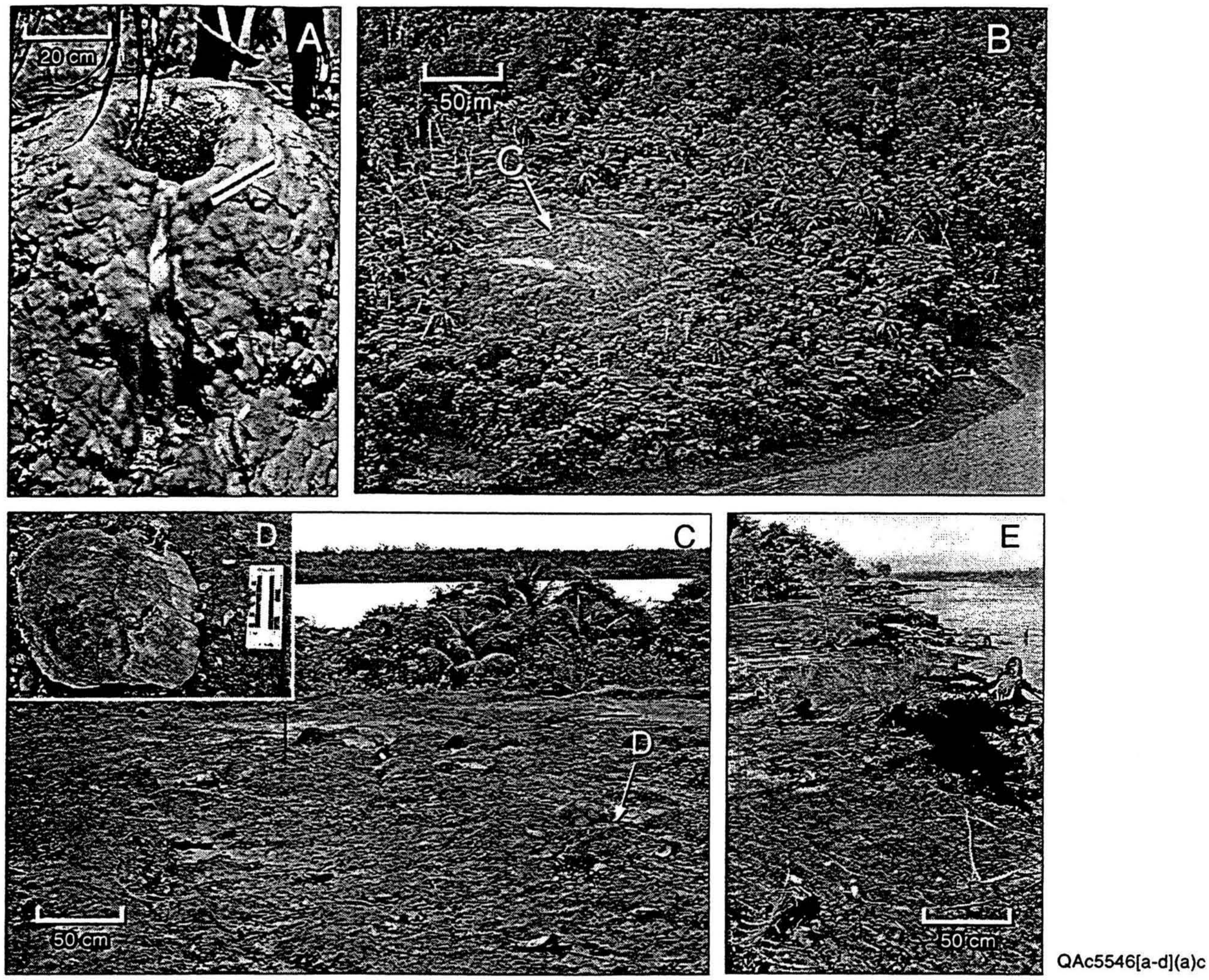

Figure 3. A. Active vent of the El Cedral mud volcano. B. Oblique aerial photograph of the La Plata mud volcano showing crest with little vegetation. View is to the southwest. C. Surface of the La Plata mud volcano showing the abundance of large clasts in the mudflow deposits. View is to the northeast. D. Rounded limestone clast with striations and pitting probably caused by acid etching during an eruption. E. La Brea tar seep showing the tar-covered, wave-eroded mudflow and partly exhumed mangrove stumps. View is to the southwest.

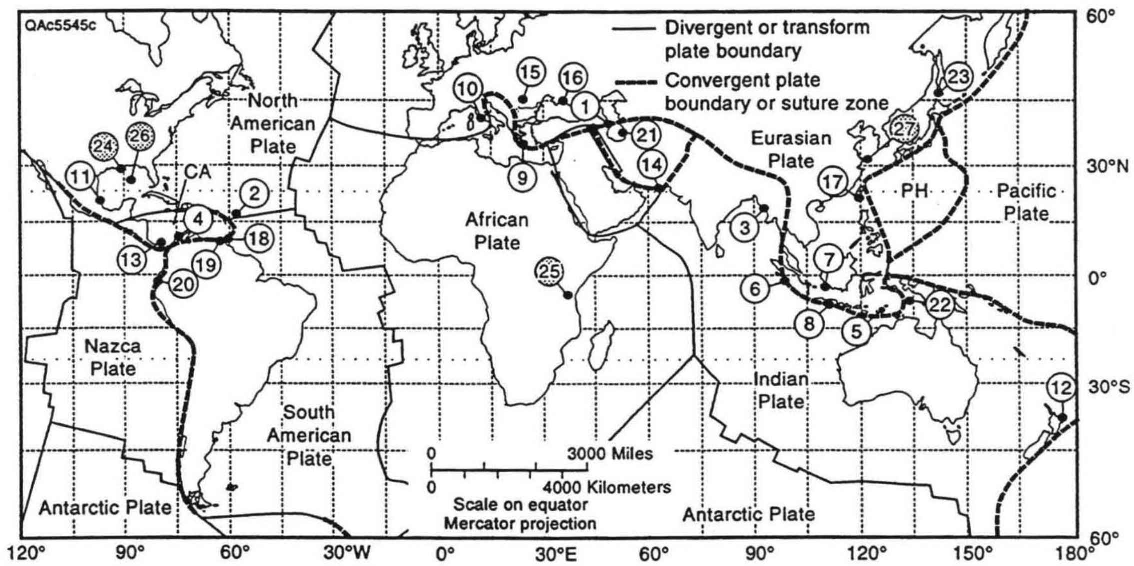

Figure 4. Global distribution of major areas of mud volcanism. CA = Caribbean; PH = Philippines. Shaded circles containing numbers denote mud volcanoes within intraplate settings. Open circles containing numbers refer to mud volcanoes located near active plate margins. 1=Azerbaijan, 2=Barbados Ridge, 3=Burma, 4=Colombia, 5=Timor, 6=Java, 7-Sumatra, 8=North Borneo, 9=Mediterranean Ridge, 10=Italy and Sicily, 11=Mexico, 12=New Zealand, 13=North Panama, 14=Pakistan, 15=Romania, 16=Black Sea, 17=Taiwan, 18=Trinidad, 19= Orinoco Delta, 20=Ecuador, 21=Southeast Caspian Sea, 22=New Guinea, 23=Sakhalin, 24=Mississippi Delta, 25=Tanganyika, 26=Gulf of Mexico, 27=Yangtze Delta. A more comprehensive summary of the reported mud volcanoes is available through the GSA Data Repository. (Modified from Higgins and Saunders, 1974).

APPENDIX 3

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ABBREVIATIONS

AVGMP	Asociación Venezolana de Geología, Minería y Petróleo [Venezuelan Association of Geology, Mining, and Petroleum]
ASOVAC	Asociación Venezolana para el Avance de la Ciencia [Venezuelan Association for Advancement of Science]
COPLANARH	Comisión Nacional de Aprovehamiento de los Recursos Hidráulicos [Planning Commission for the Development of Hydraulic Resources]
CORDIPLAN	Oficina Nacional de Coordinación de Planificación [National Office of Planning Coordination]
CVG	Corporación Venezolana de Guayana [Venezuelan Corporation of Guayana]
FUNINDES	Fundación de Investigación y Desarrollo [Foundation of Research and Development]
ICT	Instituto de Ciencias de la Tierra [Institute of Earth Sciences].
INAVI	Instituto Nacional de la Vivienda [National Institute of Housing], Venezuela
INC	Instituto Nacional de Canalizaciones [National Institute for Channelization]
IND	Instituto Mecánica de Fluidos [Fluids Mechanics Institute]
IVEPLAN	Instituto Venezolano de Planificación [Venezuelan Planning Institute]
MAC	Ministerio de Agricultura y Cría [Ministry of Agriculture and Animal Husbandry]
MARNR	Ministerio del Ambiente y de los Recursos Naturales Renovables [Ministry of the Environment and of the Natural Renewable Resources]
MINDUR	Ministerio de Desarrollo Urbano [Ministry of Urban Development]
OCEI	Oficina Central de Estadística e Informática [Central Office of Statistics and Information], Venezuela
PROA	Proyecto Orinoco–Apure [Orinoco–Apure project]
SUNY	State University of New York
SVG	Sociedad Venezolana de Geólogos [Venezuelan Society of Geologists]
SVIH	Socidad Venezolana de Ingeniería Hidráulica [Venezuelan Society of Hydraulic Engineering]
UCLA	University of California at Los Angeles
UCV	Universidad Central de Venezuela [Central University of Venezuela]
UDO	Universidad de Oriente [University of the East]
ULA	Universidad de los Andes [University of the Andes]
USGS	United States Geological Survey
UT	The University of Texas at Austin
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