HOLOCENE EVOLUTION OF THE CHIANGUINOLA PEAT DEPOSIT, PANAMA:
SEDIMENTOLOGY OF A MARINE-INFLUENCED TROPICAL PEAT DEPOSIT ON A
TECTONICALLY ACTIVE COAST

by

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We accept this thesis as conforming to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

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ABSTRACT

The evolution and structure of a large peat deposit on the Caribbean coast of western Panama, Central America is evaluated as a possible analogue for the deposition of low-ash, low sulphur coals. Effects of earthquake-driven subsidence events on the peat and the peat-forming vegetation are investigated, and implications of tectonic subsidence on the evolution of this deposit and on the currently developing model of coastal tropical coal deposition are described.

The deposit is approximately 80 km² in extent, averages 6.5 m in thickness, and occupies the width of the narrow coastal plain between the Talamanca Cordillera and barrier beach on a seismically active part of the Caribbean coast. Based on vegetation zonation, topography and hydrology, the modern Changuinola mire complex can be divided into a raised, concentrically zoned, ombrotrophic western section, and a dissected and partially rheotrophic eastern section. Differing hydrological regimes of these two sections are reflected in the physical and chemical stratigraphy of the peat. In the western section, a vertical succession of peat types, highly humified at the base and margins, and more fibric in the upper central part, is the result of internal hydrological boundaries, created by density and permeability variations in the peat. The mire is insulated from marine and fluvial influences by topography and hydrology, and displays no evidence of fluctuating sea level. Coal formed in such an environment would be low in sulphur and ash, dull and massive at the base and margins, and finely banded in the upper central part. The eastern section of the mire is in part rheotrophic, with a complex mosaic of vegetation types, and is segmented into distinct drainage areas by tidal blackwater creek channels. Effects of this marine influence are localized to the bay and channel margins. Coals formed
in this environment would have large variations in sulphur over distances of a few metres laterally, and a few centimetres vertically.

Earthquake-driven coastal subsidence is greatest in the southeast, and has lead to drowning of the deposit. Subsidence events raise the level in the blackwater creeks, moving the front of marine influence to the northwest (inland), and leading to the replacement of freshwater vegetation with mangroves. The degree of penetration of marine waters remains restricted, however, to marginal peats. An increase in the scale of subsidence events may overcome the response capability of the mangroves and lead to disruption of internal hydrological boundaries and ultimate deflation and drowning of the mire.
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DEDICATION

to

Marlene Rice
without whom this would not have begun,

Sammy Sanchez
without whom it would undoubtedly have ended abruptly,

and

Doris Phillips
without whom it would never have been completed.

Gracias a todos.
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FOREWORD

Science is a collaborative discipline, and this study has attempted to take a multi-disciplinary approach to a large subject. As a result, the expertise of many individuals has contributed to the end result. In addition, in accordance with University guidelines, and with the agreement of the Committee, the thesis has taken the form of a series of four research papers, each with a distinct focus, and each forming a chapter of the thesis. All four of these papers have been submitted for publication in professional journals, each naming as co-authors the individuals who have contributed.

The papers on which Chapters Two, Three, Four and Five are based are co-authored by Dr. R.M. Bustin, thesis supervisor, who has provided advice, support and editorial guidance throughout the research. The paper which forms the basis of Chapter Three, on vegetation and palynology of the deposit, is co-authored by Dr. G.E. Rouse of the Departments of Botany and Geological Sciences, The University of British Columbia. Dr. Rouse provided guidance in preparation techniques, photography and palynological terminology. He also provided full access to his laboratory and darkroom, and shared his best microscope, as well as his editorial expertise. The paper which forms the basis of Chapter Five is co-authored by Dr. L.E. Lowe of the Department of Soil Science, The University of British Columbia. Dr. Lowe’s laboratory performed analysis of sulphur forms on 12 peat samples, and he patiently and critically guided the manuscript through its many revisions. I am grateful to each of my co-authors for their invaluable assistance.
All of the research, analysis and interpretation not specifically mentioned above was performed by Stephen Phillips, in accordance with the guidelines of the University. The papers which relate to the aforementioned Chapters are as follows:

Publications:


Publications submitted:


CHAPTER 1: INTRODUCTION

The last half of the twentieth century has seen an increasing awareness world-wide of the fragility of ecosystems and the implications of environmental change. Along with this interest in present environmental change has grown a realization of the importance of the geological record as an indicator of past changes in local as well as global environments. Coal deposits have long been utilized as sources of palaeoenvironmental information, comprising as they do a detailed and sometimes continuous record of vegetation and climate in palaeo-wetlands, over large areas of the earth's surface, for tens to hundreds of thousands of years. In turn, in recent years, extensive modern wetlands, particularly in tropical latitudes, are being increasingly studied as analogues for ancient coal depositional systems. By detailed, multi-disciplinary examinations of modern peat-forming systems, scientists are coming to an understanding of the processes by which thick deposits of peat can accumulate, in what manner they record changing environmental conditions, and by what mechanisms they might be preserved.

In the normal measure of things, it is expected that when an organism dies, it will decompose and its components return to the ecosystem as raw material for the continuation of the system. Were all dead organic matter preserved, the earth's surface would be obscured by it. Thus a peat deposit is an indication of an imbalance, of the inability of normal decompositional processes to keep up with the rate of accumulating organic debris. This can be due to rapid accumulation, or to suppression of the mechanisms of decomposition. In peat deposition the latter predominates. Peat is a sediment, an accumulation of predominantly organic material derived from the preserved remains of plants along with associated inorganic detrital material, and other inorganics generated biochemically and geochemically during the process of accumulation. In order for this process, which may be termed 'peatification', to proceed, certain
physical and chemical conditions must be present. Thus peat sedimentation is associated with particular environments which meet these conditions. In turn, variations within these environments are associated with variations within the resulting peat deposits, and given the right conditions, within coal measures that may eventually form from the peat. Most of the material that makes up a peat deposit is added at the top, within a few centimeters of the growing surface. Changes occurring at the surface, such as in the type of vegetation or the proportions of organic to inorganic deposition, will be reflected in a horizontal stratification of the deposit which is evident both macroscopically in cores or hand specimens, and microscopically in the assemblage of preserved palynomorphs and in microtomed thin sections. Thus peat deposits can appropriately be studied in stratigraphic columns as are other sediments, variations in the stratigraphy and sedimentology allowing for inferences as to the environment of deposition.

The peat deposit which is the focus of this study is located near the town of Changuinola on the Caribbean coast of Panama, in the humid tropics of Central America (Fig. 1.1). The site is a wetland lying within a few centimetres of sea level in a region which is tectonically active and subject to periodic earthquakes. It is one of many coastal mires to be found in this region of Central America - several are marked in Figure 1.2, a Landsat satellite image of western Panama and eastern Costa Rica - and is of particular interest because its lateral extent (about 80 km²) and thickness are comparable to palaeo-mires which have given rise to economic coal deposits. The deposit is thus felt to provide an appropriate analogue for the deposition of tropical, coastal coals in tectonically active settings. It is hoped that the present work may contribute to the continuing development and refinement of a process model for the accumulation of coal deposits, particularly in tropical coastal environments.

1.1 OBJECTIVES AND METHODS

This investigation into the evolution and structure of the Changuinola peat deposit has two main objectives. The first is to evaluate the deposit as a possible analogue for the deposition of low-ash, low-
Figure 1.1. Southern Central America. Major tectonic features on both the Caribbean and Pacific sides of the Central America Arc are shown, including the aseismic Cocos Ridge, which has effectively choked-off subduction at the eastern end of the Middle America Trench, and the north Panama thrust belt, which converges with the coast near Puerto Limon. Dashed line outlines extent of the Limon - Bocas del Toro back-arc basin. Cone-shaped symbols are volcanos. The rectangle outlines the area of the Landsat image shown in Figure 1.2.
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sulphur coals. The second objective is to document the effects of earthquake-driven subsidence events on the peat and the peat-forming vegetation, and to assess the implications of such events on the evolution of this deposit and on the currently developing model of coastal tropical coal deposition.

In order to address the first of these objectives it is necessary to utilize techniques which lend themselves to interpretation in terms of coal geology. Environmental studies of coal use a variety of approaches, including palynology and palaeobotany of the peat-forming vegetation, geochemistry and isotopic composition of the coal, distribution of coal macerals and mineral matter, and studies of associated clastic depositional environments (the rocks which surround the coal). At the onset of the study, it was evident that certain large-scale aspects of the Changuinola deposit needed to be addressed in order to establish a context in which detailed analysis would have any meaning. The geometry, internal stratigraphy, and evolutionary history of the deposit had to be established, and the absence of any information on the nature of the peat-forming vegetation addressed, in order to determine the applicability of the deposit to coal studies. An initial study by Dr. A.D. Cohen and others (Cohen et al., 1989, 1990) laid the groundwork, and a fundamental series of papers on the coastal peat deposits of tropical Malesia (Anderson, 1964, 1983; Anderson and Mueller, 1975; Bruenig, 1976, 1990; Esterle, 1990; Cobb and Cecil, 1993) provided a model of mire evolution through increasing oligotrophy. These bodies of work formed the starting point for this study. It was decided that phytoral analysis and detailed petrography of the peat would be more appropriate tools for a second phase of analysis. This study utilizes a survey of the modern vegetation, palynological profiles, the results of particle-size analysis (a quantitative measure of the degree of humification of the peat), sulphur chemistry, ash (mineral matter) content, and pH and salinity measurements to characterize the peat. In addition, it looks at the nature of the barrier sand body which underlies much of the deposit, and forms the seaward margin of the modern mire.
The second objective is to assess the effects of coseismic coastal subsidence and sudden sea level change on the mire, and the implications for the evolution of the deposit of a tectonic setting which included punctuated coastal subsidence. The study commenced 10 weeks after a major (M_s =7.5) earthquake shook the region. Many lives were lost, roads, bridges and airstrips were destroyed, and the entire infrastructure of the region was damaged. Measurements of sea level change were made along the affected coastline, and leveling surveys used to establish the amount of local subsidence. Over the course of three years, detailed salinity and pH measurements were made in transects across the marine margin of the deposit, and an analysis of sulphur forms used to detect changes in geochemistry and microbial activity brought on by sudden subsidence and marine inundation. Evidence of former subsidence events was sought in the stratigraphy of long submerged peat beneath and on the shores of Almirante Bay. This line of inquiry suggests a subject for further, much more detailed research, as a datable record of earlier earthquakes would help to establish the cyclicity of such events, and possibly mitigate potential disasters in the future.

1.2 PRESENTATION

The four central chapters of this thesis each represent an individual manuscript, prepared for publication in refereed journals, which together comprise a unified body of work, in accordance with university guidelines. It is for this reason that each main chapter has its own Abstract, Conclusions and References, and thus forms a self-contained unit for readers interested in only certain aspects of this multifaceted study. A certain amount of repetition is unavoidable in such circumstances, particularly when discussing methods and providing background, but the goal of making the results of this research available to the interested public in as accessible and comprehensive a form as possible, I hope, outweighs the risk of boring readers of the entire thesis. Some internal references to appropriate chapters of the thesis have been inserted, in parentheses, along with external references. This is intended to benefit the reader of the thesis, without compromising the integrity of individual manuscripts.
The second chapter presents an overview of the geological and geomorphological setting of the Changuinola mire system, and discusses the geometry, internal structure and hydrology of the peat deposit. It presents an interpretation of the response of organic and clastic sedimentary processes to the regional tectonic setting, and proposes a model for the structural evolution of the deposit within the context of punctuated coastal subsidence.

Chapter Three presents the results of a botanical survey of the modern mire system, and discusses the floral composition of the peat-forming vegetation throughout the history of peat deposition, based on palynological analysis of the peat and of surface litter. By this means, a history of floral succession, which in turn reflects the fundamental hydrological evolution of the mire, is described. The chapter compares the results of this study with the Anderson (1964) model of mire evolution developed from observations of peat deposits in the Old World tropics.

The fourth chapter discusses some geochemical characteristics of the peat. It deals specifically with the relationships between sulphur content, pH and salinity of the peat, and defines the manner in which the climate, biology and tectonic setting are expressed in the peat geochemistry. It then suggests some implications of the data for the environmental interpretation of coal deposits.

Chapter Five addresses the effects of the 1991 earthquake on the geochemistry of peat along the newly submerged marine margin. It compares pH and salinity values onshore and offshore, and describes changes in the distribution of forms of sulphur which have taken place as a result of the sudden rise in sea level. In this way it lays a groundwork for analysis of forms of sulphur in coals which bear a transgressive signature as a result of rapid, tectonically-driven rather than gradual, eustatically-driven subsidence.
The work concludes in Chapter Six by addressing the broader goals of the investigation, and suggests some directions for future research which have come out of this study. There is then a series of Appendices which contain the raw data from which the conclusions are drawn, and a brief explanation of terminology and procedures used.

1.3 REFERENCES CITED


CHAPTER 2

SEDIMENTOLOGY OF THE CHANGUINOLA PEAT DEPOSIT: ORGANIC AND CLASTIC SEDIMENTARY RESPONSE TO PUNCTUATED COASTAL SUBSIDENCE
CHAPTER 2: SEDIMENTOLOGY OF THE CHANGUINOLA PEAT DEPOSIT: ORGANIC AND CLASTIC SEDIMENTARY RESPONSE TO PUNCTUATED COASTAL SUBSIDENCE

2.1 ABSTRACT

An extensive peat deposit on the Caribbean coast near Changuinola, Panama has developed in an area subject to periodic earthquake-driven coseismic subsidence. Thick, low-ash, low-sulphur peat is accumulating immediately behind an aggrading and prograding barrier system, and adjacent to a flood-prone, sediment laden river. Measurements of changes in local sea level as a result of a recent (April, 1991) earthquake reveal 30 to 50 cm of subsidence, greatest at the southeastern extent of the study area, where the peat surface is submerged to a depth of 3 metres beneath the shallow waters of Almirante Bay. In the eastern part of the deposit, the effects of sea-level rise are evident in the degree of humification, ash and sulphur content of mangrove and back-mangrove peats offshore or immediately adjacent to the marine margin, and in peats associated with brackish tidal channels which drain the deposit. However, most of the deposit shows no indications of marine influence, even though approximately 40% of the deposit is below present sea level. The western section of the deposit has evolved from low-lying, Raphita palm swamps originating in swales on the barrier bar, into an oligotrophic bog-plain with a water table elevated 6.75 m above sea level. As the mire evolved, transitions in vegetation resulted in transitions in peat types. Highly humified forest-swamp and palm-swamp peats underlie and surround well-preserved, fibric sedge peats, and create a partial hydrological bounding surface which restricts subsurface drainage from the central bog. The high water table and elevated topography of the mire, and the low permeability and erosion-resistance of the dense, woody peat effectively insulate the deposit from both clastic influx and the extensive
intrusion of marine waters. It is evident that thick peat, and hence coal, deposits can accumulate due
to tectonically driven, punctuated subsidence, rather than gradual eustatic sea level rise, without
leaving a record of high clastic input within the peat, even immediately adjacent to environments of
active clastic deposition.
2.2 INTRODUCTION

The usefulness of depositional models in coal exploration is well established. Detailed descriptions of depositional environments and tectonic settings can be generalised into predictive models that are of economic value in both exploration and mine planning (Horne et al., 1978). However, correlation of compositional variations in coals with paleoenvironments of peat deposition requires detailed descriptions of like environments (McCabe, 1987). Thick coal beds require very thick accumulations of peat, and provide science with one of the most certain, yet most puzzling, records of environmental conditions at particular locations over geological time spans. Certain because we know, or think we know, what kind of conditions of climate and hydrology must prevail in order to allow peat to accumulate, and somewhat less certainly, for how long. Puzzling because, given the dictum of uniformitarianism, we see few if any modern day examples of analogous peat accumulation. Early analogues were sought in the boreal and temperate peatlands of Eurasia and Canada, and the subtropical swamps of southeastern United States, but recent attention has focused on thick coastal peats accumulating in the Old World tropics. Tropical coastal depositional environments are believed to have been the settings for many known coal deposits (Wanless et al., 1969; Anderson and Muller, 1975; Cobb and Cecil, 1994). Tropical coastal peats, however, are still relatively poorly understood, and differ in a number of ways from the temperate and sub-tropical studies on which early depositional models are based. Tropical climate affects air and water temperatures, water table and hydroperiod, seasonality, growth and decomposition rates, and the composition of the peat-forming floral community. The focus of this study is the relationship between organic and clastic sedimentation in a large peat deposit near the town of Changuinola in northwest Panama. The object is to determine the effects of periodic coseismic coastal subsidence on the character and geometry of peat accumulation and preservation, and by extension, on analogous coals.
Extensive coastal peats are currently being deposited in a variety of sedimentary environments along part of the seismically active Caribbean coast of Panama. Like the vast peat swamps of Indonesia and Malaysia (Anderson, 1963, 1984; Cobb and Cecil, 1993) peat has been accumulating in coastal Panama at least since the stabilization of sea level some 4500 years ago (Pirazzoli 1991), and possibly for much longer: lignites of probable Miocene age have been collected from coastal outcrops but never studied (Bohnenberger and Dengo, 1978). The Changuinola deposit occupies the strand plain behind an actively prograding barrier beach on a microtidal (range of 30 cm, diurnal) shoreline at 9°20' N latitude, 82° 20' W longitude on the Caribbean coast (Fig. 2-1). This complex mire system has developed within a few hundred metres of the wave-dominated coast, in a tectonically active area that has experienced local coseismic subsidence. The peat deposit covers about 60 km² onshore, and another 20 km² offshore beneath the shallow marine sediments of Almirante Bay. Cohen et al. (1989, 1990) first described the deposit, studied jointly by the U.S. Los Alamos National Laboratories and the Instituto de Recursos Hidraulicos y Electrificacion of the Republic of Panama (IRHE), with the objective of assessing its resource potential as fuel for a peat- and coal-fired thermoelectric facility. They found the peat to be up to 9 metres thick, and the dense forest vegetation surrounding a plain of sedges, grasses and stunted vegetation suggested that the deposit may be domed in a manner similar to the Malaysian peat deposits described in detail by Anderson (1964). Accumulation of organic sediments (peat) in this setting reflects an imbalance between organic productivity and decomposition. Plant growth and peat accumulation have exceeded net subsidence in part of the mire complex, such that 40% of the volume of the deposit is now below sea level, unlike the alluvial Malaysian mires, which are almost all above mean sea level. The present study commenced 10 weeks after a M₇.5 (surface magnitude) earthquake on April 22, 1991, epicentred 90 km to the west in the valley of the Rio Estrella, Costa Rica, which resulted in variable
coastal subsidence in the area, and the flooding of parts of the marine margin of the deposit along the shore of Almirante Bay (Fig. 2-2).

Peat deposition has occurred in many geological settings, including montane and alluvial settings in which burial and preservation, and hence the development of significant coal deposits, is unlikely. As with other sediments, peat accumulation and preservation requires accommodation space, subsiding sedimentary basins. There are both similarities and significant differences between the setting of the now well-known coastal Malaysian peats and this Neo-tropical deposit in Panama. As in Malaysia, the Panamanian climate is humid-tropical, and temperature averages 26°C, with a ± 3° range. However, there is no dry season on the Caribbean coast of Panama; the annual precipitation of 3000 mm is uniformly distributed throughout the year (IRHE, 1988). Tidal effects are minimal, and strong tradewind-driven longshore currents transport sediments to the southeast. Tropical storms and hurricanes pass to the north, but associated flood events are frequent. This extensive peat deposit owes its existence to the ever-wet climate, and its morphology to the interaction between tectonically driven coastal subsidence, river sedimentation, and coastal processes related to waves, tide and current.

2.3 METHODS

a) Measures of Earthquake-induced Subsidence

The most recent coseismic subsidence in the study area occurred during the April 22, 1991 event. The very small (30 cm) normal tide range, and the presence of a tidal station at Almirante permitted measurement of post-earthquake sea levels along about 30 km of shoreline bordering two sides of the peat deposit. Liquefaction of soils (fine-grained sands) was widespread on the alluvial plain as a result of the 1991 earthquake. The problem of distinguishing between liquefaction effects and extensive preserved peat (coal) deposits are frequently associated with coastal margins of actively
Figure 2-1. Insert shows the location of the study area on the Caribbean side of the Talamanca Cordillera, opposite the northeast moving Cocos Ridge. Large map shows general geology of part of the Limon-Bocas del Toro Basin, and bathymetry of the continental shelf off the study area in northwestern Panama.

Legend:
QR-Ala Quaternary Alajuela Fm. - alluvium, peat (vegetation pattern), corals
TM-Miocene Venado? Fm. - calcarenites, lutites, sst
TM-CAvi Miocene Canazas Group: Virigua Fm. - ands, basalts, breccias, dike swarms
TO-SEus Oligocene Senos-R-Usca Group and Fm. - mdst, cgl, sst, tuffs
K-CHA Cretaceous Changuinola Group and Fm. - lst, mdst, sst, lavas, tuffs, andesites.
Figure 2-2. Areas of observed and modelled uplift and subsidence along the Caribbean coast of Panama and Costa Rica as a result of the April 22nd, 1991 Ms=7.5 earthquake. The model is adapted from Plafker and Ward (1992), with additional subsidence data from this study. The profile of elevation change is generalized from published and unpublished data by Astorga (1991), Denyer and Arias (1992), OVSICORI (1991), Plafker and Ward (1992), Phillips (1992) and Soulas (unpub. data).
and true structural subsidence was addressed by measuring subsidence at sites where bedrock is exposed in the intertidal zone at the northeast and northwest corners of Pta. Serrabata, two locations on Isla Carenero, and at Hospital Point on Isla Bastimentos in the Bocas del Toro archipelago. The extent to which the (non-bedrock) margins of the peat deposit were affected by subsidence was established through conversation with knowledgeable local inhabitants, and by the degree to which shoreline vegetation showed the effects of drowning and saline intrusion into the groundwater (Phillips et al., 1994). Low-level colour infrared air photographs of the margin 2 years after the earthquake show a die-back zone varying from 5 to 50 m along the shores of Almirante Bay (Fig 2-3).

b) Levelling Surveys

Vertical control and topography across the deposit and the barrier beach was established by the surveying of levelling lines (Fig. 2-4). Elevations on the landward side of the deposit are based on bench marks established by IRHE along the Almirante railway line. These bench marks, and datum at the Almirante tide station were corrected by IRHE in 1992. Elevation at the barrier coast is tied to estimates of coastal subsidence based on changes in the swash zone, trenching across the beach, and on the drowning of shoreline vegetation. Elevation change for the affected outer coastline is shown in Figure 2-2.

c) Remote Sensing

Drainage patterns and hydrology of the deposit, and present vegetation zonation were established on the basis of SPOT multispectral satellite imagery, high altitude black and white, and low altitude colour infrared photography. Non-surveyed sampling sites were located using a Magellan® GPS (Global Positioning System) receiver.
Figure 2.3. Low level, oblique, colour infrared air photograph of part of the subsided margin of the peat deposit along the shore of Almirante Bay. The mangrove fringe forest, salt-tolerant sawgrass, and hardwood swamp are all healthy shades of pink and red. In the centre foreground, marine water has permeated 100 m into the swamp, as shown by the dying vegetation (green tint). The peat deposit is 6 m thick at this site, and it extends 1 km offshore beneath the bay. The white spot in the centre foreground is a boat at drill site BDD 22D on Figure 2.4.
d) Hydrology

Cross-sections of the major drainage channels (blackwater creeks) were constructed, and flow rates during high and low-precipitation periods in 4 major creeks were used to estimate fluctuations in discharge. (Fig. 2-5). Discharge rates are difficult to measure confidently, however, due to the tidal nature of the drainage in the eastern section, and the dispersed western drainage pattern. Water table fluctuations are estimated from field observations, but no quantitative data on hydroperiod are available.

e) Clastic Sediments

Sediment samples were taken at a point bar 2 km upstream from the mouth of the Changuinola River, at the mouth, and at 4 sites along the length of the barrier beach (Fig. 2-4). Beach samples are from the upper 5 cm of the beach, at the top of the normal swash zone. Grains were examined in thin section for size, shape, sorting, and mineralogy, and sieved into the following grain sizes: -1Φ, 0Φ, +1Φ, +2Φ, +3Φ and +4Φ. Similar procedures were followed for 4 samples taken from the base of the peat deposit using a Macauley-type hand operated corer, and samples recovered from rotary drill holes at 2 additional sites, from depths of 10 and 20 m. Characteristics of the samples were compared in order to establish the nature of the basal sediments. Sediment from 78 cores was recovered and described in the field as to colour, grain size and estimated organic matter content. Sedimentary structures in the barrier beach were examined in three shallow trenches dug at right angles to the coast, 2 across the beach berm and one in the back beach, 13 months after the 1991 subsidence event (Fig. 2-6).

f) Vegetation Survey

Vegetation distribution was determined using multispectral SPOT satellite imagery (Fig. 2-7), high and low level air photographs, and by ground surveys. Major peat-forming plant species were collected with the assistance of Sr. A. Hernandez and staff of the herbaria of the Smithsonian
Figure 2-4. Map of the Changuinola peat deposit, showing sample sites referred to in Chapter 2. The heavy SW-NE line is the surveyed transect cross-section (Fig. 2-9), and the lighter NW-SE line is that of the longitudinal cross-section (Fig. 2-12). Heavy dashed line separates Eastern and Western sections. The Eastern Section of the deposit is that part influenced by the 4 major blackwater creeks shown (see also the satellite image Fig. 7). Arrows show sites at which subsidence was measured or estimated. Large capitals are sites at which detailed physical or chemical analyses were performed. Other sample sites are shown for easy reference to cross-sections.
Tropical Research Institute in Balboa and the University of Panama, Panama City. Pollen slides were prepared from surface samples from sites representative of the 7 vegetation zones (phasic communities) identified in the vegetation survey, and from 2 cores, one in the central part of the deposit and the second near the eastern margin. Pollen was concentrated, using standard palynological techniques, from the fine fraction of the peat (< 0.25 mm).

**g) Peat Sampling**

Peat cores from the surface to the base of the deposit were taken at 78 sites, using hand operated Hiller- and Macauley-type coring devices, and a 3.5 cm diameter vibracore. Samples were recovered in 25 or 30 cm increments whenever possible, described in the field, double-bagged and stored at room temperature until they could be refrigerated or frozen. Salinity and pH for most samples were measured at the time of collection, and verified in the laboratory using a Cardy® Model PH1 digital pH meter, and a Cardy® Model C121 digital salt meter. Surface litter samples were collected (to 5 cm depth) and 25 cm cubes cut with a machete.

**h) Peat Characterization**

A variety of methods was used to characterize the peat recovered in cores. In addition to pH and salinity, total sulphur content (dry weight percent) of 203 samples (dried at 50°C, crushed to 100 mesh) was determined using a Leco® SC-132 Sulphur Analyzer (see Tabatabai, 1992, p.313 for a description of this instrument) and verified using wet chemical methods (Appendix G). Mineral matter content (wt % ash) of 137 samples was determined by weight loss on ignition in a muffle furnace at 550°C (ASTM-D 2974: Jarret, 1982). Peat is defined according to ash content using the Organic Sediments Research Centre, University of South Carolina, standard (Andrejko et al., 1983). By this standard, peat is defined as Low (<5 wt%), Medium (5-15 wt%) and High Ash (15-25 wt%). Above 25 wt% is carbonaceous sediment. Moisture content of wet peat, drained of superficial water, was
Figure 2-5. Cross sections, and high- and low-discharge rates measured in the three largest blackwater creeks. Salinity and pH of bottom and surface water is shown. The banks of the channels are peat, and the channel floors are clean medium grained sands. Measurements were taken 1 km upstream from Almirante Bay (see Fig. 2-4).
Figure 2-6. Cartoon showing the northwest part of the barrier beach, and a cross-section of the barrier at site BEACH 1. Sediment from the Changuinola River is consistently carried to the southeast by longshore drift. The sediment plume is visible in Figure 2-8. Inserts show sedimentary structures revealed in trenches dug across the beach berm at the sites indicated. The surveyed elevation of the barrier is shown, as is the site of peat accumulation in the swales. The canal, dredged in 1908, is visible as a straight line in the satellite imagery (Figs. 2-7 and 2-8). Vertical exaggeration is about 500x.
Figure 2.7. False colour spot satellite image of the area of the detail map (Fig. 2.4). Concentric zoning of vegetation is most obvious in the western part of the deposit, but is also visible around 3 lesser domes in the eastern section. A larger scale SPOT image is reproduced on page 93. Black is sediment laden water, and white is clear water (see Fig. 2.8).

Figure 2.8. False colour SPOT satellite image of the narrow coastal plain and barrier shoreline. The sediment plume of the Changuinola River is clearly visible trailing off to the east. A plume of sediment is entering Almirante Bay on the flood tide (right centre), but most of the bay margin of the peat deposit is free of clastic input, and is an area of carbonate deposition (dark blue). Bananas are in pink on the floodplain.
measured by air drying at 50°C (wt % moisture lost), and is used in plots as an approximation of the
density of the peat. Degree of humification of the peat was established by particle-size distribution of
each sample. Degree of humification of the peats is based on the relative proportions of coarse,
medium and fine constituents as determined using a wet-sieving procedure modified from Staneck and
Silc (1977), according to the following scheme (Esterle et al., 1987):

<table>
<thead>
<tr>
<th>Category</th>
<th>Coarse (C)</th>
<th>Medium (M)</th>
<th>Fine (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>wt %</td>
<td>&gt;25% &gt;2.0 mm</td>
<td>&lt;25% &gt;2.0 mm</td>
<td>&lt;25% &gt;2.0 mm</td>
</tr>
<tr>
<td>sieve</td>
<td>&lt;30% &lt;0.25 mm (von Post fibric to coarse hemic)</td>
<td>&lt;30% &lt;0.25 mm (hemic)</td>
<td>&gt;30% &lt;0.25 mm (hemic to fine hemic)</td>
</tr>
</tbody>
</table>

These three categories are used for the plotting of core data. In this study we chose to use
wet sieving as a means of measuring tissue preservation because the technique lends itself well to the
large incremental samples recovered by Macauley and Hillyer corers, usually 25 or 30 cm of core at a
time. We report the results of sieving as percentages of total by dry weight, as the methods of
measuring volume are less accurate, and do not lend themselves well to woody or fibric peats. The
degree of stratigraphic correlation possible using the bulk technique is necessarily limited, but the
spacing of sample sites (500 to 1500 m at best), and the absence of continuous marker beds such as a
volcanic ash fall, make precise correlation impossible by any of the means at our disposal. The
method thoroughly homogenizes the increment, and thus generalizes the interpretation to a 25 or 30
cm scale. However, there is little literature on the discriminating ability of wet sieving of peat,
particularly woody tropical peat (Staneck and Silc, 1977), thus only by comparison to other methods
could we judge the effectiveness of the technique. Particle size by wet sieving is compared with
palynological analysis for a site in the central deposit (ED 3) and one from the eastern section (BDD
23).

Mineral matter was separated-out by gravity, and the results of sieving with 2.0 mm and
0.25 mm sieves were dried in a 50°C oven, weighed, and plotted as the proportion of C, M and F
components for 13 core sites (Fig. 2-4). Tissue preservation (degree of humification) is described in field observations, and in the written descriptions in this report using a modified von Post Humification Scale adapted to tropical peats by Esterle (1990). There are 5 field categories: sapric, fine hemic, hemic, coarse hemic and fibric. The traditional use of field-determined peat types has been used only sparingly in the study of these tropical peats, as recent work (Esterle, 1990) suggests low correspondence between field classifications and the actual particle-size distributions as determined by point counting or sieving methods. Reference is made to the field categories, alongside particle-size distributions, because peat workers are familiar with this index of tissue preservation (von Post, 1922). No sapric peat was encountered in any core. Peat Classification is based on the identification of macroscopic plant parts and palynomorphs in the peat, compared to plant and pollen associations identified in the surface samples, and uses botanical (e.g. Rhizophora peat, sedge peat) nomenclature.

2.4 GEOLOGICAL SETTING

The Changuinola deposit is situated at the easternmost onshore extent of the Limón-Bocas del Toro sedimentary basin (Fig. 1-1). The Bocas del Toro Basin in Panama, and its westward extension in Costa Rica, the Limón Basin, together make up the Tertiary and Quaternary back-arc basin behind the volcanic ranges of the Guanacaste and Central Cordilleras in Costa Rica, and the uplifted Tertiary marine sediments and intercalated Upper Miocene volcanics and plutonic rocks of the Talamanca Cordillera of western Panama. The onshore part of the basin extends about 400 km from the Costa Rica-Nicaragua border southeastward into Panama, narrowing eastward and becoming an offshore feature east of Laguna Chiriqui (Escalante, 1990).

The Costa Rica - Panama island arc was created by subduction of the Cocos plate beneath the western edge of the Caribbean plate. Andesitic arc building proceeded from latest Cretaceous through Eocene, and uplift and expansion of the emergent island arc continued through the Miocene.
The oldest sedimentary rocks are of the Cretaceous Changuinola Formation, interbedded foraminiferal limestones, tuffs and lava flows, known from a single exposure in the valley of the Rio Changuinola (Fisher and Pessagno, 1965). Overlying Tertiary and Quaternary sequences, approximately 7000 metres of predominantly marine clastic deposits, are known from exploratory drilling carried out by several oil companies since the 1920's. The major island arc sedimentary sequences were deposited from the Oligocene to the middle Miocene as basaltic talus deposits, pro-delta and shallow offshore sandstones, limestones and shales. During Middle Miocene uplift of the Talamanca Cordillera, subsidence in the Limón Basin resulted in deposition of the Gatun Formation. This is a succession of volcaniclastics and carbonates that also includes isolated lignite lenses. Lignites and lignitic siltstones are interbedded with argillaceous and sandy sedimentary rocks (Bohnenberger and Dengo, 1978).

From Miocene to late Pliocene, the basin was the site of gradually shoaling marine deposition. The top of the sequence is the La Gruta Limestone Member, approximately 450 metres thick. From early Pleistocene to the present, the region has experienced a significant rate of emergence (72 m/Ma.; Coates and Obando, in press), likely in response to shallow subduction of the Cocos Ridge (Collins et al., in press).

The aseismic Cocos Ridge has effectively blocked subduction at the eastern end of the Middle America Trench, leading to deformation in an overall SW-NE compressional regime across the Isthmus of Panama. The structural geology of the Caribbean coastal area adjacent to the Ridge is dominated by a series of southwest dipping thrust faults, striking NW-SE sub-parallel to the coast (Camacho and Viquez, 1992; Denyer et al., 1992). The general emergent trend, related by Collins and others (in press), and Coates and Obando (in press) to crustal doming is punctuated by occasional coseismic vertical movements; uplift and coseismic folding near Limón (Denyer et al., 1991), and subsidence and localised marine transgression in the area of Almirante Bay. The $M_s=7.5$ earthquake in the Valle de la Estrella, Costa Rica, on April 22, 1991, and subsequent aftershocks affected 150 km
of the Caribbean coastline of Costa Rica and Panama (Fig. 2-2). Part of the affected coastline, from
the mouth of the Rio Changuinola southeast 12 km to the Boca del Drago channel, consists of a
barrier beach behind which the large Changuinola peat swamp has developed (Fig. 2-4). Studies
conducted since the earthquake of April 1991 suggest that the break in the trend of the coastline
marked by Almirante Bay may be related to as-yet unmapped faults which segment the coast into a
series of tilted blocks (E. Camacho, personal communication).

Offshore in the Panama Basin, the North Panama Deformed Belt (Fig. 2-1) is an extensive,
thick (to 7000 m) accretionary wedge which displays recent compression-related thrust faulting and
soft-sediment deformation. The Belt approaches the coast in the near-offshore between Puerto Limón
and Laguna Chiriqui, where continuous seismic reflection profiles show faulting, upthrusting and
deformation in the most recent sediments (Clowes, 1987). These profiles also reveal erosion, in the
form of canyons and coast-parallel channels (near-shore profile CSP3-4; Clowes Fig. 5.2a).

2.5 GEOMORPHOLOGY

The northwest coast of Panama is a site of active clastic and organic sediment deposition.
Much of the coastal plain is under a variable cover of Quaternary and Recent alluvium, and the coast
is characterised by a series of barrier beaches behind which lagoons and extensive paralic swamps are
developed. The uplifted and folded sedimentary rocks of the Talamanca Range are deeply incised by a
number of large rivers, which transport sediment northward off the Cordillera to the Caribbean coast.
The Changuinola peat deposit has developed behind a barrier beach extending 12 km southeast from
the mouth of the Changuinola River, which drains an area of approximately 3200 km². Wind driven
currents move sediment consistently alongshore to the southeast, as shown in Figure 2-8, a satellite
view of the sediment plume of the Changuinola River. Sedimentation rates are high along this
microtidal (± 30 cm) coast, creating the ridge-and-swale morphology typical of prograding barrier systems (Reinson, 1984). Cores behind the shoreline show well-sorted barrier sands (Table 2-2) underlying *Raphia* palm peat 4 km landward of the present coastline and 673 cm below sea level. Thus the barrier coastline is both aggrading in response to subsidence and prograding seaward across the continental shelf. Nearshore bathymetry reveals a shelf widest to the northwest off the coast of Nicaragua (Fig. 2-1), which becomes narrower and more frequently incised by submarine canyons to the southeast near Limón. Canyons are present off the narrow shelf northwest of Limón, where subsidence was recorded as a result of the 1991 earthquake (Plafker and Ward, 1992). Southeast of the point at Limón, the shelf widens somewhat, and is free of canyons until past the Panama border at the Sixaola River, beyond which it again narrows rapidly, and a canyon is present at the 100 fathom contour 12 km off the Changuinola River mouth. Another, larger canyon is present seaward of Boca del Toro (Fig. 2-1). The shelf seaward of the barrier is narrow (12.5 km) and has a gradient of 4.2 m/km out to the 20 fathom line about 9 km offshore. A surface current of 1 to 2 knots moves sediment consistently to the southeast of the river mouth (personal observations). The size and shape of the sediment plume, which sweeps to the east and away from the remnant canyon, is revealed in false-colour SPOT multispectral satellite imagery (Fig. 2-8). The barrier coastline terminates at Punta Serrabata, where a tombolo connects the barrier beach to a rocky outcrop which was formerly an island.

Shelf bathymetry reflects erosion of the exposed coastal plain during the last glacial lowstand. In particular, the distribution of submarine canyons gives some indication of the underlying structural control on coastal morphology, and of the lateral migration of the major rivers during the Holocene. Major drainage across the coastal plain is directed towards those segments of the coast which are experiencing coseismic subsidence, such as the region around the mouth of the Rio Matina northwest of the point at Puerto Limón, and the section of coast to the southeast of the Rio Sixaola in
Panama, which is the focus of this study. Subsiding coastal regions are distinguished by extensive paralic swamps, and in some cases embayments, whereas those parts of the coast which recorded uplift in the most recent earthquake are typically emergent sandy or rocky shores with disrupted and irregular drainage of the coastal plain. To the southeast of the Changuinola mire, Almirante Bay is a recessive coastal feature which is likely related to the tectonic regime described above.

2.6 VEGETATION

Floral diversity in the present peat deposit is low and distinctly zoned (Cohen et al, 1989; Phillips et al., in review) into a sequence of 'phasic communities' similar to those described for the oligotrophic peat swamps of Western Malesia (Anderson, 1964; 1984) and Borneo (Bruenig, 1990). Factors which account for floral zonation on peat are not fully understood, but are related to microtopography, nutrient levels, water table and pH of the groundwater, and to variations in the porosity and permeability of the peat itself. Concentric zonation in surface vegetation is echoed in a vertical floral succession from the base to the top of the deposit resulting from peat accumulation, elevated water table, and increasing oligotrophy of the mire. The 'Anderson model' of domed peat development has been summarized by numerous authors (Bruenig, 1990; Phillips et al., 1994) and related to coal depositional environments by others (Esterle, 1990; Cobb and Cecil, 1993). The Changuinola deposit includes 7 phasic communities, 6 of which contribute a distinctive peat type to the accumulating deposit. These phasic communities are: i) *Rhizophora* mangrove fringe swamp; ii) mixed back-mangrove swamp; iii) *Raphia taedigera* palm swamp; iv) *Campnosperma panamensis* forest swamp; v) mixed forest-swamp; vi) sawgrass ± stunted forest swamp; vii) *Myrica-Cyrilla* bog-plain. Distinctive communities of peat-forming plants, along with their associated groundwater environments, determine much about the character of the peat which develops, and result in a stratigraphic succession which reflects the trophic evolution of the mire through time. Consequently,
schemes which identify and classify peat (and coal) according to the principal floral components inherently imply much about the environment of deposition.

False-colour satellite imagery shows the deposit to have two regions with differing vegetation patterns and surface drainage (Fig. 2-7). The western part displays a radial drainage pattern and concentrically zoned vegetation which reflects a domed topography attributed in the Anderson model to an evolution toward increasing oligotrophy with increasing peat accumulation. No large streams flow west or north out of the mire; surface drainage off the central dome is principally as a sluggish sheet-flow in the low-gradient areas from the central bog plain towards the Talamancas. Channelized flow, in blackwater creeks which extend to the base of the peat, drains the higher-gradient margins towards the barrier and Almirante Bay. Creeks draining into the bay are stratified and brackish up to 3 km upstream, despite the low tidal range (Fig. 2-5). These creeks dissect the eastern part of the deposit into hydrologically distinct units visible in the satellite imagery. In this study we relate peat characteristics in the western and eastern parts of the deposit to their respective states of ombrotrophy and rheotrophy, which in turn are related to the factors controlling height of the water table, and of sea level.

2.7 AGE AND GEOMETRY OF THE DEPOSIT

The main body of the peat deposit is roughly rectangular in shape with long axis parallel to the coast and occupies the entire 8 km width of the coastal plain between the Talamanca hills and the outer barrier. Peat extends from the lower alluvial plain of the Changuinola river 12.5 km southeast to the marine margin of Almirante Bay, and at least another 1 km beneath the bay. Greatest thickness of peat sampled was 950 cm (Cohen at al., 1989) and 833 cm (this study), and overall average peat thickness is estimated at 650 cm. Maximum elevation of peat measured is +667 cm above datum, and
the greatest depth -673 cm. Approximately 40% of the volume of the deposit is below present sea level. Datum (mean sea level) is considered accurate to within 10 cm.

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Note: * denotes AMS dating, CAMS-13316, L. Livermore Nat'l Laboratory

Estimates of the age of the peat deposit are based on the 4 radiocarbon dates listed in Table 2-1. These dates give the following accumulation rates for different peat types:

- mangrove/back mangrove peat (No.1) = 2.25 mm/a (from -4.75 m below present SL to present SL),
- mangrove/back mangrove/forest peat (No.4) = 2.52 mm/a (from -4.75 m to present SL),
- palm/forest peat (No.2) = 1.48 mm/a (from 8 m to 4.75 m below peat surface), and
- sedge peat (No.3) = 5.58 mm/a (from 4.75 m below peat surface to peat surface).

The oldest peat tested, from 54 cm above the base of core MILE 5 in the central western section, gave a corrected age of 3040 ± 80 BP in woody, hemic *Raphia*/mixed-forest peat over grey sand. The base of the deepest peat core sampled (LAKE 9 - not dated) is topographically some 2 m below the dated sample, and thus may represent an additional 1000 to 1500 years of peat accumulation, giving an approximate age of 4000 to 4500 years for the deposit. This age is similar to that of many Malesian coastal peat deposits (Anderson, 1983). It is possible that older peat may exist at lower elevations, most likely close to the Talamanca foothills, but none were dated in this study.

The surface of the peat in the western section is an asymmetrical 'dome', only slightly raised on the shore side, and sloping more steeply close to the barrier (Fig. 2-9). The maximum measured gradient, in palm forest along the northern margin, is 1 m in 330 m, comparable to gradients in most
Figure 2-9. Top: SW-NE cross-section of the peat deposit, showing location of cores and distribution of Coarse, Medium and Fine peat in relation to the generalized peat stratigraphy. At ED 3, near the centre, a schematic core shows results of pollen analysis (see Fig. 2-14). Bottom: Results of the particle size analysis (wet sieving) of 8 cores along the transect, showing uniformly moderate- to highly humified peat at the margins and base. The greatest contrast in humification is between the upper and lower parts of LAKE 10, ED3 and to a lesser extent MILE 5. Black shading, and dotted spikes indicate mineral matter > 4%. No correlation between mineral layers was possible.
Malesian mires, which commonly grade at 1 m in 300 to 500 m (Anderson, 1983), but in contrast to the river-margin gradients of 1 in 25 (McCabe, 1987) to 1 in 65 (Esterle, 1990) in some Sarawak mires, probably influenced by erosion of the banks. The margin bordering the Talamanca hills grades at about 1 m in 1 km. No topographic survey data are available for the flood-plain margin, but analysis of SPOT imagery using the width of concentric vegetation zones to approximate topographic contours suggests a gradient no steeper than 1 in 500.

Topographic control of the underlying basal sands is provided by two transects normal to the coast, and by isolated sample sites parallel to the barrier. The barrier has a ridge-and-swale architecture characteristic of prograding barrier coastlines (Reinson, 1984), that can be traced at the base of the peat (Figs. 2-6 and 2-9). Cores are spaced at around 500 m intervals, but probes were made at closer spacing, as the modern, subaerial barrier has a ridge 'wavelength' of between 50 and 100 m. Traces of the barrier structure are also visible up to 2.5 km shoreward of the barrier in false-colour satellite imagery (Fig. 2-7). Peat originates in the swale immediately behind the beach berm where, despite the high porosity of the barrier sand, a linear marsh or swamp is established, due to high growth rates, dense vegetative cover, and precipitation which normally exceeds evapotranspiration rates (Fig. 2-6). Along a surveyed transect, the distance from the top of the swash zone to the nearest measured thickness of 'swale' peat (40 cm of peat, under 50 cm standing water in Raphia swamp) is 94 metres.

2.8 SEA LEVEL CHANGE AND PUNCTUATED SUBSIDENCE

"No lives were lost, here (Punta Mono) or at the other Indian settlements, in the neighbourhood, but the ground appeared rent in various places, the sand on the beach was either raised in ridges, or depressed in furrows; a place which, in the evening had been a small lagoon, or pond, in which several canoes were floating, was now become quite dry; most of the huts were violently cracked and twisted; and the effects, of the earthquake, were everywhere visible."

from Voyages and Excursions in Central America, by Orlando Roberts, 1827.
There exists a popular and historical record of seismic activity on the coast of Panama and Costa Rica dating back to at least 1798, and reports of such events back to the late 1500's (Camacho and Viquez, 1993). Earthquakes are known to have occurred in 1798, 1822, 1912 (2) and 1991, all estimated (by Guendel, 1991) or recorded as greater than magnitude 7 on the Richter scale (Roberts, 1827; Gonzalez-Viquez, 1910; Guendel, 1991). Roberts' observations at Punta Mono in 1822 could have been repeated almost verbatim in 1991 when the Point was again uplifted, a nearby river mouth closed, and parts of the back-barrier lagoon were left high and dry.

a) Subsidence in 1991

Coseismic subsidence occurred along 30 km of the coast between the mouth of the Rio Changuinola and Hospital Point on the northwest tip of Isla Bastimentos during the April 22, 1991 earthquake. Liquefaction effects were widespread and spectacular throughout the alluvial plain (Astorga, 1991; Denyer et al., 1991; Guendel, 1991). Describing the scene a few days after the event, Guendel (1991) wrote that Changuinola "perhaps represents one of the most dramatic cases of local to regional soil liquefaction ever documented in Central America". Mobilized sediment was consistently very fine-grained grey sand, which erupted as sand volcanoes and sheet flows from crevasses up to 500 m in length throughout the lower flood plain. Liquefaction-related subsidence was widespread, but uplift may also have occurred, leading to shoaling of dredged channels. Areas of coarser-grained sediment, however, such as the beach and river-mouth bars, were free of any signs of liquefaction, and we estimate a maximum 35 cm subsidence at the river mouth, based on measurements of the degree of burial or submergence of trees rooted in beach sand (Fig. 2-10), and on sedimentary structures described in a later section.
Figure 2.10. Photograph of drowned tree on the shore side of the beach berm at site Beach 2. The tree was growing at a spot that is now 33 cm below present mean sea level.
The problem of distinguishing between liquefaction effects and true structural subsidence occupied several investigators after the 1991 event (Astorga, 1991; Camacho et al., 1991; Denyer et al., 1991; Guendell, 1991; Sherstobitoff, 1991). Greatest reported subsidence, and greatest earthquake damage, was in the communities of Changuinola, Almirante and Bocas del Toro. The former is on the Changuinola flood plain, and experienced extensive liquefaction and surface fissuring, as well as local subsidence which left irrigation pumps standing suspended on their pipes 50 cm above ground level. The latter two towns are built in part on dredged fill in former mangrove swamps, and variable subsidence in the filled areas can be attributed to liquefaction and settling. Bocas del Toro, however, experienced a uniform subsidence which unhappily left the entire sewer system below sea level (personal observations, and personal communications with Ing. E. Reyes and others, IRHE). Extensive shoreline observations were needed to establish the degree and extent of subsidence directly affecting the peat deposit and barrier beach. Destruction of the tide gauge at Almirante necessitated re-surveying of bench marks used for topographic control in this study, and we consider the elevations published here to be internally consistent, but with the possibility of an absolute error of a few centimetres.

Plafker et al. (1992) studied elevation change from the 1991 event along the affected coast from the Matina River in Costa Rica southeast to Punta Mona, and one site in Panama. They found the effects more or less consistent with movement on a 25° to 40° SW dipping thrust fault at a depth of 40 km beneath the valley of the Rio Estrella in Costa Rica (Fig. 2-2). Southeast of the Changuinola River, the amount of subsidence increases. At the easternmost extent of the barrier beacha tombolo connects the beach to Punta Serrabata (Fig. 2-1), the exposed coast of which consists of limestones and shelly sandstones of the Late Miocene Water Cay Formation and the Pliocene La Gruta Member. We estimate subsidence of 50 cm at Boca del Drago, and about 70 cm at Isla Carenero, the most profoundly affected location on the coast, based on measurements on dock pilings and rocky
shorelines. Across the Boca del Toro channel, 500 m southeast of Carenero at Hospital Point and at Bastimentos, no subsidence was detected along the rocky shore.

\[ b) \text{Long-term Sea Level Change} \]

Regional Holocene estimates of sea level change are much more poorly constrained than local historical data. Three published studies of Holocene sea level change in the western Caribbean, based on radiocarbon dating of mangrove peats (Bartlett and Barghoorn, 1973; Woodroffe, 1988; Berger, 1983), and a predicted sea level curve for eastern Panama (Peltier, 1988) give a poorly constrained estimate for regional sea level change in the study area (Pirazzoli, 1991). Since the Pleistocene sea level low stand of about 18,000 years ago, Caribbean Central America experienced a generally transgressive regime until about 4500 years ago, when sea level more or less stabilized and the modern Changuinola peat deposit began to accumulate. The Bartlett and Barghoorn curve, located closest to the area now under consideration, is based on a single radiocarbon date of 35,500 yr.BP which Bush et al. (1992) consider to be of questionable value, since it implies considerable uplift of the Gatun Lowlands (Canal Zone of central Panama). Ample evidence exists for Holocene sea level change in the area of the Changuinola peat deposit, but no data on local long-term sea level change has been published. Regional sea level estimates for 4000 yr.BP are between -7.5 m and -1 m, and for 2000 yr.BP, less than 1 m below present sea level (Pirazzoli, 1991). In this study a maximum 1 m eustatic rise in regional sea level over the past 2000 years is assumed, due to the high degree of uncertainty associated with the higher estimates (Bush et al., 1992). This estimate is compared to 2 sub-sea level dates (a $^{14}$C standard date and an AMS date) of mangrove and forest peat from sites now lying offshore in Almirante Bay (Fig. 2-1; Table 2-1). This shallow body of salt-water forms the eastern termination of the barrier coastline, and terrigenous sediments extend a considerable distance beneath the bay. Submerged peat was sampled at water depths of more than three metres. The peat is underlain by medium grained grey sand, and in places overlain by a thin layer of silty sands, lime mud,
and coral. Beneath the grey sands, uncremented calcareous mud with abundant coral fragments occurs from around 10 m depth down to at least 50 metres.

Radiocarbon dates show that local relative sea-level rise has been proceeding for more than 2000 years (Table 2-1; Figure 2-4; dating by Beta Analytic Inc). Two samples of peat from 475-478 cm below present mean sea level were dated by radiocarbon and AMS methods with a corrected age of 2010 ± 60 (BDD 19A) and 1880 ± 60 yr. BP (BDD 34). BDD19A is a combination vibracore-Macauley series taken in 195 cm water depth at a site 600 m offshore in Almirante Bay. The core consisted of mangrove (*Rhizophora*) and back-mangrove (*Rhizophora - Laguncularia - Acrostichum*) peat from the base to the top of the core (-510 cm to -195 cm; sample salinity 17%o, pH 7.07), showing that the site was within the mangrove fringe - back mangrove zone throughout the period for which peat is preserved, and thus that the shoreline during that period was some 600 m farther east than at present. Taking into account the 30 cm tidal range, local sea level in Almirante Bay has risen by between 350 and 450 cm in 2000 yrs, a maximum rate of about 2.2 mm/a. at the drowned site, where accumulation did not keep pace with subsidence. BDD 34 is a series of 50 cm long half-cores taken with a Macauley corer in 60 cm water depth at the outer limit of the pre-earthquake mangrove zone, on a sheltered shore essentially free of clastic sediment input. The base of the core at 673 cm is in fine hemic mangrove peat over rooted medium grained grey sand containing large wood fragments. Above the base, the peat alternates between *Raphia* and forest-swamp peat, and sulphurous mangrove and back-mangrove peat, representing periods when the site was alternately at and above sea level. The dated *Raphia* palm peat, now at -475 cm (sample salinity 7%o, pH 5.76), suggests average (net) subsidence of 2.1 to 2.6 mm/a. at a site at which peat accumulation evidently kept pace with subsidence until fairly recently. Autocompaction of the peat has not been factored-in to these estimates, due to the absence of any apparent density increases with depth in the extremely compact fine hemic woody peats.
Evidence from the Changuinola peat deposit suggests 4000 or more years of subsidence, at a net rate of 2.2 to 2.6 mm/a. for the past 2000 years. Historically, this subsidence has occurred as a series of coseismic events, and the stratigraphy of the marine-marginal peats suggests that this style of punctuated subsidence has been the norm during that period. The upper rate is evidently slightly higher than that at which mangrove peat can accumulate in the eastern part of the deposit, and the greater lateral extent of the deposit in the past suggests a slower rate of subsidence during the early history of the mire.

2.9 ORGANIC AND CLASTIC SEDIMENTOLOGY

2.9.1 CLASTIC SEDIMENTS

a) Changuinola River Floodplain

Sediments of the floodplain occupy 60 km², between the SanSan mire on the northwest and the Changuinola mire to the southeast (Fig. 2-1), and interfinger with the northwestern margin of the peat deposit. Sediments consist of boulder and cobble- to silt-size sediments originating in the folded sedimentary rocks of the northern Talamanca range. River bar clastics are dominated by feldspar and volcanic rock fragments. To the southeast of the floodplain, the lateral transition from alluvium to peat occurs over about 1000 m, the intervening sediments being interfingered floodplain silts and sands, cm-thick leaf beds, and thin peats (Fig. 2-11). Cohen et al. (1990) reported the ash content of two cores (BDT 5 and 4) located about 500 m and 1000 m from the nearest active channel on the floodplain (Fig. 2-12). The cores are not peat, but rather are carbonaceous sediment with ash (mineral matter) content varying from 30.3 to 61.6 wt% at the site closest to the river, and 27.2 to 43.8 wt% closer to the mire. In the same study, a core 2.4 km from the river (BDT 13) consisted of low- to medium-ash peat (range 0.9 to 12.9 wt% ash) throughout the entire 945 cm depth.
Figure 2.11. Laminated silts, sands, peat and cm-thick leaf beds of the alluvial plain. Deposits are moderately bio-turbated; entrances of two rodent burrows can be seen, centre and right of centre.
Figure 2-12. NW-SE cross-section from the Changuinola River to Almirante Bay. The generalized peat stratigraphy in the NW is based on zoning of present vegetation mapped from satellite imagery, tied to data from a limited number of cores. In the SE a small dome, visible in Fig. 7, is profiled. Asterisk (*) indicates data from Cohen et al., 1990. The stratigraphy in the SE is shown in more detail in Figure 2-15.
**b) Barrier System**

Most studies of barrier beach and strandplain evolution have recognized the importance of tidal range on the morphology of barrier beaches (Glaeser, 1978). However, data for much of the development of facies models in the '60's and '70's came from the temperate eastern seaboard of North America, where seasonal storms are the norm and much of the event-driven Holocene stratigraphic record is written by hurricanes. The Changuinola barrier beach is microtidal and wave-dominated, unbroken by tidal channels and seldom overtopped by storm waves.

Morphology of the barrier is shown in Figure 2-6. The exposed barrier consists of 3 parallel sand ridges, the highest of which is the most seaward (1.68 m, 1.44 m, 0.6 m at Beach 1). The landward decrease in elevation is a consequence of ongoing subsidence of the shoreline. The 'wavelength' of 40-50 m between ridges reflects the relation between rates of subsidence and progradation.

i) *Sedimentary structures* - The effects of rapid subsidence and subsequent aggradation and progradation are evident in the sedimentary structures revealed by trenching on the barrier. Trenches were made at two sites: Beach 1, at a central point on the barrier 7.5 km from the Changuinola River, and Beach 2, close to the river mouth (Fig. 2-6). At Beach 1, landward dipping (6°) planar washover beds of the back-berm overlie 9° seaward-dipping beds of the former berm-face to a depth of about 30 cm. At site Beach 2 the present shoreface is medium grained sand, steeply dipping (20°) seaward, with a wave cut notch above the top of the swash zone. A few weeks after the earthquake-induced subsidence, the barrier had resumed its original height and was not experiencing washover during normal wave conditions. Trenching across the berm revealed steep (20°) medium grained seaward-dipping beds, corresponding to a remnant beach face, overlying and truncating shallow landward-dipping fine sands of the pre-earthquake back-beach. The medium sands are in turn truncated and overlain by finer grained landward-dipping beds of the post-earthquake (present) back-beach, to a
Figure 2.13-a. Planar laminated back beach sands at site Beach 2.

Figure 2.13-b. Photograph of bedding structures in a trench across the beach berm at Beach 2, shown schematically in Figure 2.6. In the photo, the sea is to the left, and flat-lying washover beds rest on steeply seaward-dipping beach face sands. The barrier aggraded about 30 cm, and prograded several metres in the 13 months that elapsed between the subsidence of the beach and the trenching.
thickness of 30 to 50 cm (Figs. 2-13-a and 2.13-b). This sequence is interpreted as a record of the landward-stepping of the beach face, caused by coseismic subsidence, followed by rapid aggradation and progradation of the beach face and back beach.

**ii) Grain-size and Mineralogy** - Table 2-2 shows the distribution of grain size of sediments from 12 sites shown in Figure 2-4, including a point bar in the Changuinola River, proximal and distal sands along the length of the barrier, and basal samples from below the peat deposit. Mineralogy, sorting, grain size and rounding from 12 sites are listed in Table 2-3. Grain size of the proximal barrier sands changes little along 9 km of barrier shoreline: well-sorted medium to fine grained, angular to sub-angular sands, with an immature mineralogy including pyroxenes, feldspar and volcanic glass and less than 10% quartz grains. Heavy minerals are rapidly winnowed out down-coast (Tables 2-2 and 2-3). Basal sand landward of Beach 1 (half way along the modern bar, site Lake 3) plots in the same grain size range as the barrier sands. At the distal end of the barrier (Beach 4, 11 km), siliciclastics are predominantly very fine sand (> 4 Φ) dominated by felspathic grains, to which a coarse to very fine carbonate component originating in the offshore barrier reef is added. The distal barrier experienced a greater degree of subsidence (an estimated 50 cm); the beach berm has not regained its former elevation, and the beach face is submerged and impassable due to fallen trees.

c) Peat Basal Sediments

Sediments underlying the peat deposit can be divided into clean medium to fine grained barrier sands, fine to very fine sands with palm and sedge roots associated with drainage channels and thin palm-swamp peat, and silts and clays associated with drainage from the Talamancan slopes along the southwest margin of the deposit. Those from greater depth (-10 m, well below the peat-sand contact) are similar in grain size to the barrier sands, and display the same trend of decreasing heavy mineral content and increasing feldspars and volcanic rock fragments with increasing distance from
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<tr>
<td>Beach 4</td>
<td>11 km</td>
<td>vpoor</td>
<td>tr</td>
<td>sa</td>
<td>.07</td>
<td>5</td>
<td>a</td>
<td>.13</td>
<td>20</td>
<td>a</td>
<td>.13</td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>a</td>
<td>.07</td>
<td></td>
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</tr>
<tr>
<td>BDD 23</td>
<td>13.5 km</td>
<td>poor</td>
<td>tr</td>
<td>r</td>
<td>.07</td>
<td>5</td>
<td>r</td>
<td>.07</td>
<td>50</td>
<td>a</td>
<td>.26</td>
<td>45</td>
<td>a</td>
<td>.33</td>
<td>tr</td>
<td>a</td>
<td>.07</td>
<td></td>
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</tr>
<tr>
<td>CS 3</td>
<td>13.5 km</td>
<td>mod</td>
<td>5</td>
<td>sr</td>
<td>.07</td>
<td>5</td>
<td>a</td>
<td>.13</td>
<td>80</td>
<td>a-sr</td>
<td>.78</td>
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<td>.13</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BDD 22D</td>
<td>14 km</td>
<td>well</td>
<td>tr</td>
<td>sr</td>
<td>.13</td>
<td>5</td>
<td>a</td>
<td>.26</td>
<td>70</td>
<td>sr-a</td>
<td>.26</td>
<td>5</td>
<td>r</td>
<td>.26</td>
<td>15</td>
<td>a</td>
<td>.26</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>D=10 m</td>
<td>BDD 22D</td>
<td>well</td>
<td>tr</td>
<td>a</td>
<td>.26</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100</td>
<td>a</td>
<td>.39</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>D=20 m</td>
<td>BDD 33</td>
<td>mod</td>
<td>5</td>
<td>a</td>
<td>.07</td>
<td>45</td>
<td>a</td>
<td>.33</td>
<td>50</td>
<td>sr</td>
<td>.39</td>
<td>tr</td>
<td>a</td>
<td>.07</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Notes: Sz = estimated mean grain size in mm, Ab = abundance, Ro = roundness
- r = rounded, s = sub-, a = angular; volcrf = volcanic rock fragments.
- feldspar is both plagioclase and kspar; pyroxene is almost all clino-, possibly with a trace of olivine and amphibole.
- carbonates are shells, coral fragments, and lime mud.
- D = Depth of sample in metres
<table>
<thead>
<tr>
<th>Sample</th>
<th>Sieve Sizes (Phi scale)</th>
<th>Distance from River</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&gt;-1φ</td>
<td>&gt; 0φ</td>
</tr>
<tr>
<td>Point bar</td>
<td>%</td>
<td>0.00</td>
</tr>
<tr>
<td>Beach 0</td>
<td>%</td>
<td>0.00</td>
</tr>
<tr>
<td>Beach 2</td>
<td>%</td>
<td>3.61</td>
</tr>
<tr>
<td>Beach 1</td>
<td>%</td>
<td>0.00</td>
</tr>
<tr>
<td>Outer beach</td>
<td>%</td>
<td>0.00</td>
</tr>
<tr>
<td>Beach 4</td>
<td>%</td>
<td>1.97</td>
</tr>
<tr>
<td>BDD 22D D=10m</td>
<td>%</td>
<td>0.08</td>
</tr>
<tr>
<td>BDD 22D D=20m</td>
<td>%</td>
<td>5.05</td>
</tr>
<tr>
<td>BDD 33 D=10m</td>
<td>%</td>
<td>0.11</td>
</tr>
<tr>
<td>BDD 23-b D=5m</td>
<td>%</td>
<td>0.21</td>
</tr>
<tr>
<td>BDD 23-b D=6m</td>
<td>%</td>
<td>1.23</td>
</tr>
<tr>
<td>Lake 3 D=3.3m</td>
<td>%</td>
<td>0.05</td>
</tr>
</tbody>
</table>
the main river channel. Basal sands from sites associated with long-lived channels (eg. BDD 23) are less well-sorted than the beach samples, although lithologically similar. To the southeast beneath the basal sands at 20 m depth is poorly sorted carbonate with a slightly bimodal distribution (Tables 2-2 and 2-3).

d) Almirante Bay

Fine-grained clastic sediments enter the Boca del Drago channel on the flood tide as the distal sediment plume of the Changuinola River (Fig. 2-8) and are deposited along the eastern margin of the deposit and in the deeper north-central part of the bay. Fine clastics sourced on the flanks of the Talamancas also enter the bay via the Rio Banano, from the southwest corner of the bay and are transported toward Pta. Pondsock. Most of the bay margin bordering the swamp is essentially free of clastic sediments, however, and active carbonate sedimentation is occurring. Sediments are an algal carbonate mud, and numerous coralline forms. Two offshore patch reefs were drilled, with limited success, to determine the nature of underlying sediments. Carbonate sediments with a bimodal grain size distribution (lime mud, and coral debris) were found to at least 6 m depth at both sites, and to at least 20 m beneath the basal sands of core BDD31 (Table 2-3).

2.9.2 ORGANIC SEDIMENTATION

a) Peat characterization

The physical and chemical characteristics of the peat are summarized in Table 2-4. The table shows high, low and mean values and standard deviation for pH, total sulphur, wt % moisture, salinity and ash for the eastern and western sections, and for selected mangrove peat samples, which represent a special case in the east. Significant differences in all parameters are evident in the averaged values from the domed, ombrotrophic west and the dissected, and in part rheotrophic eastern section.
<table>
<thead>
<tr>
<th></th>
<th>Western Section</th>
<th></th>
<th>Eastern section</th>
<th>Rhizophora mangrove peats</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean  s  n=</td>
<td>mean  s  n=</td>
<td>mean  s  n=</td>
<td>s  n=</td>
</tr>
<tr>
<td>pH</td>
<td>4.38 0.59 321</td>
<td>5.74 1.09 389</td>
<td>6.5 0.58 70</td>
<td></td>
</tr>
<tr>
<td>high - low</td>
<td>6.29-2.82</td>
<td>7.89-2.67</td>
<td>7.6-5.4</td>
<td></td>
</tr>
<tr>
<td>wt% Sulphur</td>
<td>0.23 0.18 227</td>
<td>2.24 2.55 143</td>
<td>3.52 1.09 36</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.51-0.08</td>
<td>13.7-0.08</td>
<td>5.9-0.4</td>
<td></td>
</tr>
<tr>
<td>wt% Salinity</td>
<td>&lt;0.01 n.d.</td>
<td>0.69 0.87 413</td>
<td>1.42 0.96 104</td>
<td></td>
</tr>
<tr>
<td>high - low</td>
<td>2.7 - 0</td>
<td>2.7 - 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>wt% Moisture</td>
<td>92.74 5.1 76</td>
<td>84.28 7.66 134</td>
<td>84.49 5.45 45</td>
<td></td>
</tr>
<tr>
<td></td>
<td>99.2-67.1</td>
<td>95.7 - 60</td>
<td>94.1-67.5</td>
<td></td>
</tr>
<tr>
<td>% Ash</td>
<td>3.29 6.39 85</td>
<td>10.49 9.19 43</td>
<td>18.57 19.72 21</td>
<td></td>
</tr>
<tr>
<td>high - low</td>
<td>38% - 0%</td>
<td>54% - 1%</td>
<td>92% - 4%</td>
<td></td>
</tr>
</tbody>
</table>

Notes: s.d. = one standard deviation; n = number of samples in data set
b) Geochemical Parameters

In previous reports (Phillips et al., 1994; Phillips and Bustin, in press) the relationship between pH, salinity and total sulphur content of the peats has been explored in detail. High sulphur content is spatially related to marine or brackish influence. Coastal mangrove and back-mangrove peats with moderately high S content (1 to 5 wt% S) and high salinity (> 0.5 wt%) dominate the eastern margin and extend beneath the salt water and shallow marine sediments of the adjoining bay. Marine influence extends only a short distance onshore, except in the vicinity of brackish blackwater creeks which drain the swamp into Almirante Bay. Peats associated with these channels are low in salinity (< 0.5 wt%) but very high in S (5 to ~14 wt% S), around 90% of which is carbon-bonded sulphides, apparently the result of an ongoing biogeochemical chain of S reactions leading to the concentration of C-S forms. The western part of the deposit is domed and oligotrophic, and the vegetation and the peat are concentrically zoned. Stunted, sawgrass-dominated vegetation produces fibric, very low S (< 0.25 wt% S) peat found in the upper few metres of the central bog plain. Around and below the bog plain peats, dense hemic and fine hemic peat, the product of mixed-forest and palm-forest swamp vegetation, has consistently higher S content, averaging between 0.25 and 0.5 wt% S.

The highest sulphur content (>5 wt%) is found in peats near the brackish influence of blackwater drainage channels up to several km from the coast. Very high sulphur was also found in the basal peats in the deepest parts of the deposit (Cohen et al., 1989), which are interpreted to have been associated with channels. Very high sulphur content is found even where salinity is undetectable in peat, porewater or basal sediments, and despite the low pH of these peats that normally inhibits bacterial sulphate reduction.
c) Degree of Humification, Ash, and Moisture Content

Tissue preservation is a standard parameter in environmental studies of both peat and coal (Stach et al., 1982). Diessel (1986) devised a Tissue Preservation Index (TPI), based on the relative volumes of structured (i.e. well-preserved cell walls) and unstructured (finely comminuted, or gelified) tissue which he then used in interpreting the degree of wetness of the mires in which some Australian coals originated. Numerous authors (Lamberson et al., 1991; Obaje et al., 1994) have since applied this principle to other coals, with various qualifications, but with the common assumption that highly degraded humic coals originate in a relatively oxygenated environment, and coals with a high proportion of structured tissue in a waterlogged, acidic and poorly oxygenated mire. In coal studies, the TPI is determined by the point counting of macerals, a volumetric measure. It is possible to apply volumetric estimates to peat samples, by measuring the volume of sieving results (Stanec and Silc, 1971), or point counting of thin sections (Cohen, 1968) or polished epoxy-impregnated blocks (Esterle et al., 1990). However, direct volumetric comparisons of peat to coal cannot be made, due to the variable compactability of different peat types, and also the selective loss of matrix material during coalification (Shearer, 1994), thus proportions by weight are used in this study. The method, although not directly comparable to coal methodology, is accurate and allows for the analysis of large samples.

Ash content is also used as an environmental indicator in coal studies, and has been related to particle size or degree of humification in low ash peats (Davis et al., 1984). It is generally assumed that: a) oxygenated environments which produce highly degraded peat will also selectively concentrate whatever mineral matter happens to be present; and b) that peat deposited in mires close to sites of active clastic sedimentation will contain higher proportions of mineral matter than more distant sites.
### TABLE 2-5A: CORE DESCRIPTIONS OF PEATS FROM THE WESTERN SECTION OF THE DEPOSIT

<table>
<thead>
<tr>
<th>CORE</th>
<th>MILE 1</th>
<th>MILE 1.5</th>
<th>MILE 3</th>
<th>MILE 5</th>
<th>ED 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peat Elevation: Top and Base</td>
<td>+ 617 cm</td>
<td>+ 637 cm</td>
<td>+ 655 cm</td>
<td>+ 655 cm</td>
<td>+ 624 cm</td>
</tr>
<tr>
<td>(+ = above SL; - = below SL)</td>
<td>+148 cm</td>
<td>+ 7 cm</td>
<td>- 165 cm</td>
<td>- 209 cm</td>
<td>- 186 cm</td>
</tr>
<tr>
<td>Modern Vegetation</td>
<td>Raphia palm-swamp</td>
<td>Mixed forest-swamp</td>
<td>Sawgrass / stunted forest</td>
<td>Myrica m. - Cyrilla r., sedges, grasses: bog-plain</td>
<td>Myrica m. - Cyrilla r., sedges, grasses: bog-plain</td>
</tr>
<tr>
<td>Humification</td>
<td>49.9% to 21.4%</td>
<td>n.d.</td>
<td>58.8% to 19.6%</td>
<td>66.2% to 4.0%</td>
<td>60.6% to 5.40%</td>
</tr>
<tr>
<td>(percent coarse fibres)</td>
<td>avg. 32.5%</td>
<td>n.d.</td>
<td>avg. 39.6%</td>
<td>avg. 36.1%</td>
<td>avg. 39.9%</td>
</tr>
<tr>
<td>Salinity Range (wt%)</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Total Sulphur Range (wt%)</td>
<td>0.16 to 0.51</td>
<td>n.d.</td>
<td>0.14 to 0.3</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>pH Range</td>
<td>3.6 (top) to 4.9 (base)</td>
<td>3.3 (top) to 4.8 (base)</td>
<td>3.8 (top) to 5.1 (base)</td>
<td>3.6 (top) to 5.5 (base)</td>
<td>3.6 (top) to 5.6 (base)</td>
</tr>
<tr>
<td>Moisture Range</td>
<td>91.3% to 94.9%</td>
<td>n.d.</td>
<td>90.3% to 97.1%</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>Ash Range</td>
<td>n.d.</td>
<td>14% to &lt; 1%; spikes at 120 cm (4%) and 510 cm (14%)</td>
<td>1.0% or less except for a single spike at 300 cm (14%)</td>
<td>10% to &lt; 1%; spikes at 90 (10%), 390 (4%), 480 (6%) and 570 cm (4%)</td>
<td>6% to &lt; 1%; spikes at 60 cm (6%), 240 cm (4%) and the basal metre (8%)</td>
</tr>
<tr>
<td>Basal Sediments</td>
<td>Rooted grey clay</td>
<td>Peaty grey clay</td>
<td>Peaty silt and VF grey sand</td>
<td>Yellowish-grey peaty sand, over F grey sandy Channel sands</td>
<td>Rooted F grey sands</td>
</tr>
<tr>
<td>Peat Classification (depths in cm)</td>
<td>0-124 F Hemic</td>
<td>0-270 C Hemic-Fibric</td>
<td>0-270 Fibric-C Hemic</td>
<td>0-330 Fibric-C Hemic</td>
<td>0-630 Fibric-C Hemic</td>
</tr>
<tr>
<td>Notes: C = coarse, F = fine, n.d. = not determined</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 2-5A: Continued

<table>
<thead>
<tr>
<th>CORE</th>
<th>LAKE 10</th>
<th>LAKE 8</th>
<th>LAKE 6.5</th>
<th>LAKE 2</th>
<th>NL 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peat Elevation: Top and Base</td>
<td>+ 500 cm</td>
<td>+ 397 cm</td>
<td>+ 342 cm</td>
<td>+ 254 cm</td>
<td>+ 150 cm</td>
</tr>
<tr>
<td>(+ = above SL; - = below SL)</td>
<td>- 320 cm</td>
<td>- 295 cm</td>
<td>- 193 cm</td>
<td>- 76 cm</td>
<td>- 130 cm</td>
</tr>
<tr>
<td>Modern Vegetation</td>
<td>Myrica m. - Cyrilla r., sedges, grasses: bog-plain</td>
<td>Myrica m. - Cyrilla r., sedges, grasses: tree hammock</td>
<td>Sawgrass / stunted forest</td>
<td>Mixed forest-swamp</td>
<td>Raphia palm-swamp</td>
</tr>
<tr>
<td>Humification</td>
<td>73.7% to 3.50%</td>
<td>39.8% to 18.1%</td>
<td>40.2% to 15.0%</td>
<td>22.4% to 2.8%</td>
<td>26.4% to 5.10%</td>
</tr>
<tr>
<td>(percent coarse fibres)</td>
<td>avg. 32.0%</td>
<td>avg. 29.7%</td>
<td>avg. 29.2%</td>
<td>avg. 10.8%</td>
<td>avg. 16.9%</td>
</tr>
<tr>
<td>Salinity Range (wt%)</td>
<td>&lt; 0.01 throughout</td>
<td>&lt; 0.01 throughout</td>
<td>&lt; 0.01 throughout</td>
<td>0.02 (top) to &lt; 0.01</td>
<td>0.01 (top) to &lt; 0.01</td>
</tr>
<tr>
<td>Total Sulphur Range (wt%)</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>pH Range</td>
<td>3.6 (top) to 5.8 (base)</td>
<td>3.7 (top) to 5.4 (base)</td>
<td>3.2 (top) to 5.2 (base)</td>
<td>2.8 (top) to 4.9 (base)</td>
<td>3.9 (top) to 4.9 (base)</td>
</tr>
<tr>
<td>Ash Range</td>
<td>&lt; 1% throughout</td>
<td>&lt; 1% throughout</td>
<td>10% to &lt; 1%; spikes at 275cm (10%), 425 (4%) and 525 (10%)</td>
<td>8% to &lt; 1%; spike at 150cm (8%)</td>
<td>&lt; 1% throughout</td>
</tr>
<tr>
<td>Basal Sediments</td>
<td>Peaty F and VF yellowish grey sand over clean F grey sand</td>
<td>Clean F and VF grey sand</td>
<td>Peaty F and VF yellowish grey sand over clean F grey sand</td>
<td>Clean F and VF grey sand (Barrier)</td>
<td>Peaty, rooted grey sand (Barrier-swale)</td>
</tr>
<tr>
<td>Peat Classification (depths in cm)</td>
<td>0-300 Fibric-C Hemic</td>
<td>0-225 C Hemic</td>
<td>0-475 Hemic</td>
<td>475-500 C Hemic</td>
<td>F Hemic throughout</td>
</tr>
<tr>
<td>Notes: C = coarse, F = fine, n.d. = not determined</td>
<td>300-550 Hemic</td>
<td>225-550 Hemic</td>
<td>475-500 C Hemic</td>
<td>500-550 F Hemic</td>
<td>F Hemic throughout</td>
</tr>
<tr>
<td>TABLE 2-5B: CORE DESCRIPTIONS FOR THE EASTERN SECTION</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------------------------------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CORE</strong></td>
<td><strong>BDD 23</strong></td>
<td><strong>BDD 22</strong></td>
<td><strong>BDD 31</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peat Elevation: Top and Base (+ = above SL; - = below SL)</td>
<td>+ 10 cm</td>
<td>+ 5 cm</td>
<td>sea level (high tide line)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- 450 cm</td>
<td>- 590 cm</td>
<td>- 400 cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modern Vegetation</td>
<td><em>Camposperma panamensis</em> forest-swamp</td>
<td><em>Rhizophora mangle</em> fringe forest</td>
<td><em>Rhizophora mangle</em> fringe forest</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Humification (percent coarse fibres)</td>
<td>30% to 16%</td>
<td>27% to 3.7%</td>
<td>22% to 2.5%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>avg. 19%</td>
<td>avg. 12%</td>
<td>avg. 1%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Salinity Range (wt%)</td>
<td>&lt;0.01 throughout</td>
<td>0.59 to 2.20</td>
<td>0.11 to 0.41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Sulphur Range (wt%)</td>
<td>0.27 to 13.7</td>
<td>n.d.</td>
<td>1.07 to 8.43</td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH Range</td>
<td>3.6 (top) to 5.9 (base)</td>
<td>6.7 (top) to 7.9 (base)</td>
<td>4.3 to 7.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture Range</td>
<td>76% to 95%</td>
<td>n.d.</td>
<td>75.4% to 85.3%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>avg. 90%</td>
<td>avg. 81.7%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ash Range</td>
<td>16% to &lt;1% spike at 100cm (16%; no carbonate)</td>
<td>65% (shells, diatoms, ostracodes, forams, sponge spicules) to 5% (mineral grains, mixed lithology)</td>
<td>5% to &lt;1% spikes at 100cm (57%; no carbonate) and 150cm (38%; shelly)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basal Sediments</td>
<td>Rooted F to VF sand, over clean F to VF sand. (Channel sands)</td>
<td>Carbonate: rounded coral and shell fragments, plus dispersed mineral grains</td>
<td>Clean F to VF sand (Barrier)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peat Classification (depth in cm)</td>
<td>0 - 285 Coarse Hemic</td>
<td>0 - 150 Hemic</td>
<td>0 - 165 Hemic and Fine</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>285 - 450 Hemic and Fine Hemic</td>
<td>150 - 590 Fine Hemic</td>
<td>Hemic, Woody</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>165 - 400 Fine Hemic</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Notes:** C = coarse, F = fine, n.d. = not determined
The proportions of coarse, medium and fine organic particles in bulk peat samples representing 25 or 30 cm core increments are used to generate plots depicting the degree of humification of the peat at 3 sites in the eastern section of the deposit and 8 sites along a surveyed transect in the west. All proportions are given as per cent of the total dry weight of the sample on a mineral-matter free basis. Moisture content, also recorded for some samples, is related to the degree of humification and the density of the peat. The deposit is divided into eastern and western sections on the basis of vegetation zonation, and hydrological characteristics, and the results are presented separately in Table 2-5A and 2-5B.

i) Western Section: --- Given the permanently high water table associated with everwet climate, the preservation of structured plant parts is good in oligotrophic mires, where low pH of the groundwater and low nutrient availability discourages both bacterial activity and luxuriant subaerial biomass production. Plants thriving in such conditions tend to have stunted above-ground components, but extensive root systems, that contribute to the fibrous component of the resultant peat. Figure 2-9 (upper panel) shows a cross section through the western part of the deposit illustrating the distribution of well-preserved fibric peat and more humified hemic and fine hemic peat along the SW-NE cross-section shown in Figure 2-4. Stratigraphy is based on the degree of tissue preservation (particle size distribution) in 8 cores (Fig. 2-9 lower panel) along a surveyed transect from the foothill margin to the barrier. Characteristics of the peat are summarized in Table 2-5A, and peat type is correlated with pollen stratigraphy in core ED 3, near the centre of the transect (Fig. 2-14). As can be seen in the lower panel (Fig. 2-9) particle size and humification in the marginal peats (Mile 1 near the southwest margin, NL1 and Lake 6.5 toward the barrier bar) tend to be uniform for the full depth of the peat. In the central deposit (Lake 10, Ed 3, Mile 5 and Mile 3 in the central bog plain, and Lake 8 in a Myrica-Cyrilla tree 'hammock') there is a contrast between the upper fibric and coarse hemic peats,
Figure 2-14. Comparison of the results of wet sieving (particle size distribution) with palynological analysis of core ED 3 from the central part of the bog-plain. *Myrica + Cyrilla,* and *Palmae* (Raphia pollen + palm phytoliths) represent the trend clearly. The wet sieving results distinguish basal hemic and fine hemic forest-swamp peats from upper fibric and coarse hemic sedge peats, reflecting vegetation changes and increasing oligotrophy in the mire. The sawgrass/stunted forest-swamp pollen zone is transitional, and variable both in palynomorph assemblages and in degree of humification of the peat. Pollen data is discussed in detail in Chapter 3.

Particle sizes are as follows:
Coarse > 2.0 mm  Medium > 0.25 mm  Fine < 0.25 mm

VonPost classes are defined on page 21, and described in the Appendices.
and underlying hemic and fine hemic peats. Degree of humification is greatest in areas of greatest surface gradient.

ii) Eastern Section: --- The complex vegetation zonation of the eastern part of the deposit, visible in Figure 2-7, reflects an equally complex topography, hydrology, and peat stratigraphy in that part of the deposit which is drained by the brackish blackwater creeks emptying into Almirante Bay. Sedimentation within the mangrove fringe varies with location, from sandy peat to limey peat. *Rhizophora mangle* (the red mangrove) is the only mangrove colonizing the marine margin - the white mangrove species *Languncularia racemosa* is common to dominant in the immediate back-mangrove swamp and bordering brackish blackwater creeks. *Rhizophora* does not favour either silty or carbonate substrates, and isolated individuals are found rooted in coral as much as a kilometre offshore. A species of thin-shelled oyster (*Crassostrea* sp.?), easily recognizable in core, is normally found attached to *Rhizophora* roots from the upper limit to about 30 cm below the lower limit of the tidal zone, and when found stratified within otherwise shell-free peat suggest possible past subsidence events. In addition to the mangrove fringe and back-mangrove forest swamps along the bay and creek margins, there are three areas of domed, oligotrophic sawgrass marsh and stunted forest-swamp, each surrounded by a complex of *Raphia* and hardwood forest-swamps. Figure 2-15 shows particle size variation in three cores in a cross section from Almirante Bay through one of these lesser domes to a the blackwater channel, Canal Viejo. Particle size in the forest-swamp and mangrove swamp peats is uniformly fine; at the coastal sites the <2.0 mm component averages 87% to 93%, and in only 2 samples was there a fibric (>2.0 mm) component greater than 25%. All samples were classified as hemic or fine hemic; there was no sapric peat encountered, despite the high degree of humification. Peat characteristics are summarized in Table 2-5B.
Figure 2-15. A generalized view of wet sieving results of cores from across the marine margin of Almirante Bay and up Canal Viejo, a brackish blackwater creek. The section approximates the SE end of the cross section in Figure 2-12, although BDD 31 is displaced. BDD 31 is a typical mangrove peat core, highly humified throughout, and having both carbonate-rich and clastic ash layers. BDD 22 represents a saline estuarine site, also in the mangrove fringes-forest. The sediments are not strictly speaking peat, as they contain >25% non-humic materials. The ash includes scattered grains of feldspar, mica and quartz, but is dominated by the remains of marine organisms. The peat is very highly humified, fine hemic throughout. BDD 23 is also highly humified throughout, and is associated at the base with brackish drainage. Near the base the sulphur content is almost 14 wt%. The basal peat was deposited in a back-mangrove zone. Figure 2-16 relates the results of particle size analysis to the palynology of core BDD 23.
Figure 2-16. A comparison of the wet sieving results for core BDD 23 with palynological analysis (Chapter 3). Raphia palm peat tends to be less humified than woody angiosperm forest-swamp peats. The source of the mineral ash spike at 100 cm is unknown, but may be related in some way to an attempt at dredging Canal Viejo in 1899. The site is about 50 m north of the present channel.
BDD 31 is an example of an intertidal mangrove site (Fig. 2-15). Between 100 and 150 cm depth there is a shelly layer and a silty layer suggesting a possible subsidence event, followed by a resumption of mineral-free peat accumulation. The BDD 22 core (upper part) represents a modern estuarine site, taken at the outlet of a tidal blackwater creek. Due to the high content of bivalve shell fragments, diatom frustules, ostracode valves, foram tests, fish scales and teeth and sponge spicules (24% to 72% by weight), the sediment is not true peat. Estuarine microfauna are not present in the basal 160 cm of the peat. Silt-sized quartz, mica and other grains were present throughout the core. Below the silty base of the peat is carbonate sand consisting of well-rounded shell and coral fragments. These deposits are considered to represent shallow offshore (back-reef) sediments over which the barrier and peat deposit have prograded. The base of site BDD 23 represents an earlier channel margin site influenced by the brackish waters of a blackwater creek. Transitions in peat type from top to base of the core echo lateral transitions in surface vegetation (Phillips et al., in review), from *Camposperma* forest-swamp peat, to mixed-forest, *Raphia* palm, and back-mangrove peat. The history of floral succession, interpreted from the palynology of the core, is plotted alongside particle size distribution and ash content of the peat in Figure 2-16.

2.10 DISCUSSION

### 2.10.1 CLASTIC SEDIMENTARY RESPONSE TO RECENT TECTONISM

#### a) Changuinola River Floodplain

Rivers draining the Caribbean side of the Cordillera are prone to flooding, (2 such events occurred in the Changuinola flood plain during the 3 years of this study), and the sedimentological record is written by the interrelationship between flood events and tectonic events. The lower Changuinola flood plain has been affected by agricultural activity, but certain inferences can be made regarding the Holocene evolution of the floodplain based on sedimentary response to recent subsidence. In the early Holocene it appears that the Changuinola river may have flowed southeast
from the defile at which it exits the foothills, along or parallel to the course of the present Rio Banano (see Fig. 2-4), and crossed the continental shelf via the deep canyon of Boca del Toro (Fig. 2-1). A 180 m deep incised channel extends from near the mouth of the Rio Banano across Almirante Bay (much of which is less than 5 m deep) and through the Boca del Toro passage, indicating erosion to a very low base level. Local records and locally produced maps of the lower Changuinola floodplain (unpublished data of the Chiriqui Land Company; C. Stephens, pers. comm.) since the turn of the century document numerous changes in the main channel of the Changuinola River. Before 1920 the Changuinola drained to the northeast during floods, through the mouth of the neighbouring SanSan River. A channel switch, which occurred at the defile, and dam building by the banana companies, brought an end to this, and the Changuinola now absorbs all the floodwaters.

In July 1991, 10 weeks after the earthquake, a major storm struck the stretch of coast affected by the earthquake, with very different effects in regions of uplift and of subsidence. On the coast 60 km to the northwest, 10,000 hectares of the coastal plain shoreward of the mouth of the Rio Estrella, the major river in the area, were devastated by flooding, the result of uplift at the coast which partially dammed the river mouth and caused floodwaters to back-up onto the alluvial plain. The areas of coastal uplift are not prone to the development of extensive mires, despite their susceptibility to flooding, as the rivers deposit much of their sediment load on the coastal plain. The flooding Changuinola River did not, however, inundate the coastal plain nor the immediately adjacent peat swamp to the southeast, the surface of which is somewhat elevated above normal flood levels and heavily forested with Raphia palm and hardwoods. Earthquake-induced subsidence lowered the elevation of the alluvial plain; the flooding river broached a levée, but remained channelized, entering an abandoned oxbow and breaching the lowered barrier beachovernight. During the flood, the introduction of overbank sediments into the peat swamp was minimal, and has been restricted to areas within 500 - 1000 m of the river during the entire period of peat accumulation, as evident from the low
ash content of peats 2 km away. Subsidence events evidently resulted in channelized stream flow, still allowing the accumulation of low ash strand plain peats. The areas of peat deposition are better insulated from flood influence than areas of alluvium, by virtue of their elevation and the low erodability of the peat.

b) Barrier Beach

The tectonic setting dictates the scale of evolution of the barrier, in both time and space. Punctuated subsidence provides accommodation space for the aggradation of the sand body, apparently in 30 to 50 cm increments. The amount of subsidence, which determines whether the barrier will step seaward or landward, increases to the southeast, although it has not yet been established whether the thickness of the barrier sand body is greater in that direction. The cumulative rate of subsidence also determines whether organic sedimentation is terrigenous peat, or shallow marine carbonates, such as are present at the south-eastern extreme of the barrier system. Regional tectonics also determine the effective width of the continental shelf, which eventually may limit the seaward migration of the barrier. Shelf gradient may not be a limiting factor; Glaeser (1978) calculated that 24% of the world's barrier coastlines are associated with seas marginal to arcs (i.e. fore-arc or back-arc settings), and that there is no correlation between shelf gradient and the presence of barrier islands or barrier beaches. A supply of sand-size sediment, and tidal flux are the controlling factors in generating barrier coastlines, and tides and storms dictate barrier morphology and back-barrier sedimentation.

Four factors define the depositional environment of the barrier beach, working in consort to determine its morphology and composition: tectonic setting, sediment source, climate and tidal range. Each has geological significance, and would leave a signature on the confining rocks of a strand-plain coal. Barrier sands display structures and mineralogy which reflect tectonic influence. Bedding
structures and beach morphology reflect the style of subsidence, which occurs as discrete earthquake-driven events, and which is greatest to the southeast. Three sediment sources contribute to the barrier beach. Immature sands of the Changuinola River are the principal source, originating at the northwest end of the barrier. The second source is an offshore coral reef, present at the extreme southeast end of the barrier, which both donates carbonate sands and debris to the barrier and creates a low-energy beach and a sediment trap in the shallow back-reef environment seaward of the barrier. The third sediment source is the lush tropical vegetation, which responds to subsidence through changes in phasic community along the marine margins, stabilizes beach ridges and deposits peat in swales.

2.10.2 HYDROLOGICAL CONTROLS ON PEAT ACCUMULATION

Hydrological controls on peat accumulation and peat character include source of recharge, rate of recharge, hydroperiod, rate of discharge from the mire, nature and morphology of the confining layer, and permeability and heterogeneity of the peat (Clymo, 1983). In the case of ombrotrophic mires, recharge is limited to atmospheric sources, and water enters the mire from above and flows out. In rheotrophic mires, some water flows in, entering from the bottom or edges of the mire. Rate of recharge is the amount of water entering, and hydroperiod, which is the period of fluctuation of the water table, is a measure of the regularity of recharge (Myers, 1990). The confining layer is the seal which prevents the mire from draining. Peat accumulates when the water table is above the mire surface, and deteriorates when it dries out.

Peat permeability is highly variable and very poorly constrained, but generally varies directly with peat density, and thus with particle size and compaction. We do not have a great deal of quantitative data on peat permeability in the Changuinola deposit, and substitute moisture content and particle size distributions as proxy data for degree of humification and thus peat density. Two studies of peat permeability based on the rate of intrusion of saline waters into freshwater peat at sites in
Almirante Bay, although not complete, indicate very low permeability for mangrove peat, which tends to be dense and compact (85% moisture), and slightly higher permeabilities for *Raphia* and forest-swamp peats (85-90% moisture). The bog-plain sedge peats and stunted forest peats sampled in this study average 95% moisture content, and have much higher permeability.

*a) Western Section:* — Hydrology dictates the fundamental physical and chemical characteristics of the organic sediments in the western section of the deposit. At the present stage of evolution of the deposit, hydrological controls in the ombrotrophic western region are internally driven, rather than being a reflection of tectonic forces. As there is no evidence that recharge occurs from below the modern mire is assumed to be effectively ombrotrophic. At the Talamancan margin and the Changuinola River margin, discharge water flows out of the deposit as surface sheet flow, and in shallow (<50 cm) streams. Along the back-barrier margin, which has the steepest gradient, drainage has been disrupted by the dredging of a canal into which five small streams discharge. One of these cuts to the base of the peat, and connects four small sandy bottomed lakes which are remnants of back-barrier lagoons.

There is some variation in the height of the water table across the western part of the deposit, and a corresponding variation in the degree of humification of the peat. The surface is slightly domed, and the vegetation and the peat are concentrically zoned. The Anderson model of floral succession and increasing oligotrophy in the evolution of raised forested mires in SE Asia has been shown to be applicable to the Changuinola mire system as well (see Chapter 3; Phillips et al., in review). Tissue preservation as estimated by particle size reveals the same overall stratigraphic pattern seen in sulphur and pH profiles and moisture content, and generally correlates with more detailed palyno-stratigraphic analyses (Fig. 2-14). The margins of the deposit are generally well
decomposed hemic and fine hemic peat from top to base, whereas in most of the central bog plain 3 to 5 m of fibric to coarse hemic peat overlie more decomposed hemic and fine hemic peat (Fig. 2-9).

Stunted, sawgrass (sedge)-dominated vegetation produces fibric, low pH and very low S (< 0.25 wt% S) peat found in the upper few metres of the central bog plain. Around and below the bog plain peats, mixed-forest and palm-forest swamps produce hemic and fine hemic peat, still low in pH, but with higher S content, between 0.25 and 0.5 wt% S. The sulphur in these peats is principally assimilatory, and the high level of humification concentrates resistant compounds, including those that incorporate sulphur. It is expected that the same process of concentration by digestion would serve to increase ash content as well. However in this study no significant correlation ($r^2 = 0.04$) is found between wt% total sulphur and wt% ash (HTA) for all low ash (<10%) and low S (<0.5%) peats for which data are available. Thus either the ash content is not directly related to degree of humification, or another factor such as the sulphur content of the original phyterals must be sought in explaining sulphur concentrations. Again, however, beyond the broadest distinction between herbaceous and woody peats, we find no significant difference in the total sulphur content of the different types of woody peat (*Raphia, Campnosperma*, mixed forest-swamp), and the variable sulphur content of the original plant material, although not thoroughly studied, still are less significant than the degree of humification in low-sulphur peats (Phillips and Bustin, in press). We conclude that some aspect of the biotic processes involved in the degradation of woody debris leads to approximately double the concentration of organic sulphur compounds in woody peat than those processes which produce coarse hemic and fibric peat from bog-plain vegetation.

It is apparent that degree of humification is much more dependent on hydroperiod and height of the water table than on the measured pH of the peat in cores. High levels of humification occur in very low pH sites if they are subject to fluctuating water table, or if the plant community has a large
subaerial biomass. Water table fluctuations are greatest where surface gradients are steepest (between NL 1 and Lake 6.5 in Figure 2-9), corresponding to the zone of dense forest-swamp. These are the sites of most uniform hemic peat accumulation, and also presumably sites of high evapo-transpiration from the luxuriant foliage. Highest consistent water table is in *Raphia* swamp on shallow peat around the margins of the deposit, and in the central bog-plain and the lesser domes to the east (Fig. 2-7), which are vegetated with algal mats and a sparse and stunted flora, and where evapo-transpiration rates are accordingly low. *Raphia* peats tend to be coarse hemic to hemic, and sedge peats fibric to coarse hemic.

The most distinctive features of the bog-plain peats are their fibric nature, reddish colour and extremely high moisture content. Drained of superficial water, western peat samples averaged 93% moisture content (average includes the deeper forest-swamp peats: range is 67% to 99%), compared to an average of 84% for the eastern peats (Tables 2-5A and B). Equally distinctive is the calculated rate of accumulation of 5.58 mm/a., based on a radiocarbon age of 850 ± 80 years for coarse hemic peat (45% fibrous) 475 cm below the surface. This high rate contrasts sharply with rates published by Anderson (1983) for peats in the upper part of Malaysian domed deposits (2.22 mm/a for the upper 5 m of peat in his phasic community 6). Anderson found that accumulation rates were lower in the later-stage (his phasic community 6 and 7), oligotrophic swamps, possibly due to reduced biomass production. However, the central domes of the Malaysian deposits are stunted bog-forests, not sawgrass swamps, and the peat surface of the bog-forests frequently dries out. The Changuinola deposit is apparently quite different in this respect; the bog plain surface is not only normally submerged, but along much of the surveyed transect, the upper root-mat is effectively floating on a very watery 'soup' of fine and medium-sized granular debris, and up to 60% well preserved roots and other fibres. In the light of the wetness of the bog-plain peats, the *in situ*
accumulation rate uncorrected for moisture content means little; if the water table were to drop in the central plain, the peat surface would follow it down, possibly to the extent of creating a depression.

The effective elevation of the central bog plain along the surveyed transect is 1 m in 7 km, with margin gradients a maximum 1 in 330. Winston (1994) has successfully fitted theoretical curves to existing peat dome profiles from Malaysian mires, assuming constant hydraulic conductivity (permeability) of all peat in the profile. However, his models do not account for the significant vertical variations in conductivity that are inherent in deposits fitting the Anderson model (as described in detail by Esterle, 1990), despite his recognition that vegetation type has an effect on hydraulic conductivity. In citing the case of a German bog in which later peat accumulation rates increased over early rates, he ascribes it to the effects of ongoing anaerobic decay at depth which creates an apparent increase in accumulation rate with time, without accommodating the implied increase in density and thus decrease in permeability. In situ accumulation rates mean little without factoring-in density variations. It may be that stacked hydraulic models can accommodate density changes, whether they be due to autocompaction, ongoing anaerobic decay, or floral succession. In the case of the Changuinola deposit, the profile is felt to be the result of ponding within a basin of low-permeability hemic and fine hemic peat.

The densest peats sampled, mangrove and forest peats, accumulate at rates comparable to Anderson's late-stage peat (mangrove peat at ca. 2.25 mm/a and back mangrove peat at ca. 2.52 mm/a (this study), vs. 2.22 mm/a of Anderson, 1983). The very high in situ rate of accumulation of sedge peats reflects lack of compaction. The domed central bog plain is essentially a mass of well-preserved root material floating in an acidic, nutrient-poor bath, contained within a basin of dense, woody peat of extremely low permeability. Discharge from the central mire is by surficial drainage, subsurface flow being effectively dammed by the surrounding forest-swamp peat, and
evapotranspiration is limited by the stunted vegetation. Only toward the steeper NE margin does the surface dry out and water table drop to 10-20 cm below the peat surface. The disposition of hemic and fine hemic peat at the base and margins of the deposits, which form a type of internal bounding surface, suggests that these dense, low permeability peats form a bowl within which the floating bog-plain has developed. The rate of accumulation of these peats is in inverse proportion to peat density, and suggests a process in which the variable hydrological characteristics of the peat dictate the height of the water table, and hence the surface topography. The differential in accumulation rates that allows for the evolution of a 'lip' of dense, low-permeability peat is a function of the difference in biomass production of forest peat vs sedge peat - i.e. it is created by increasing oligotrophy, as Anderson concluded. Increased degradation due to occasional drying-out of the surface serves to increase density, and decrease permeability, but does not appear to be enough to counterbalance the high rate of biomass production. This is undoubtedly due to the high rainfall and relatively small fluctuations in water table.

b) Eastern Section: In the western part of the deposit, the major transitions in peat characteristics are the stratigraphic boundaries created by the upward evolution of the mire. Sea level, which almost bisects the western cross section of the deposit, does not appear to form an hydraulic bounding surface, as there is no indication of saline influence at the base of the peat. In contrast, the complex hydrology of the eastern section has created a complex stratigraphy, over which in places a transgressive marine signature is superimposed. The overriding hydrological control throughout is the amount, and trend, of punctuated subsidence. The complexity is evident in palynological analyses, but very much generalized in analysis based on degree of humification at the resolution attempted in this study (Fig. 2-16). Plots of changes in humification, and of variations in the geochemical characteristics, allow the construction of a generalized stratigraphy in which controlling trends are evident (Figs. 2-9 and 2-15).
There are 4 major tidal blackwater creeks draining the eastern section of the mire into Almirante Bay (two have been modified by dredging, and one of those now forms part of a canal). The mire is discharging down-dip, the streams flowing parallel to the barrier in the direction of maximum subsidence. All are long-lived, extend right to the base of the peat, have sandy or silty sediments at the channel floors, and have a stratified salinity profile, with fresh water at the surface and salinities of 19 to 23 ppt in the bottom waters. Discharge rates fluctuate considerably between drier and wetter periods (Fig. 2-5). A few smaller creeks are eroded into the peat, but the major channels effectively divide the eastern section of the deposit into hydrologically distinct sectors bounded by channel-margin peats with a distinctive geochemical signature which has low salinity and very high (5 to 14 wt%) sulphur. Each of these sectors has its own discharge pattern. SPOT satellite imagery reveals small domes in 3 of the eastern sectors, based on vegetation zoning and surface water drainage patterns (Fig. 2-7). There are two possible explanations for these domes: firstly, they may be incipient bog plains experiencing elevation and increasing oligotrophy; secondly, they may be remnants of a more widespread bog plain which is 'deflating' due to incision by blackwater creeks (Fig. 2-17). Present surface vegetation zoning, which is roughly concentric about the domes, suggests the former. However, coring has revealed fibric peat at sites in the east which are now heavily forested, but may at one time have borne a stunted vegetation. Spacing of coring sites is inadequate to make a final judgement. The implications are profound; either the mire is evolving toward a more extensive bog plain, or it is drowning.

The high rate of basement subsidence along the eastern margin of the mire has resulted in a second form of hydrological boundary within the eastern section of the deposit, the sea level boundary. This boundary is diachronous, trending approximately at right angles to the above-mentioned drainage
Freshwater palm-swamp and forest swamp peat on alluvial plain, and in swale on barrier. Drainage of the deposit is represented by the symbols:
- Surface drainage (thick arrow = high flow or channelized flow)
- = Flow out of deposit (toward viewer)
+ = Flow into deposit (away from viewer)

Mangrove and back-mangrove peat around tidal channels;
Mixed forest-swamp peat expands over alluvial and swale peats;
Barrier aggrades and progrades.

River channel shifts due to subsidence;
Peat accumulates faster than subsidence rate;
Forest swamp expands laterally and vertically with rising water table;
Barrier aggrades and progrades.

Sawgrass - stunted forest-swamp peat accumulates with increasing oligotrophy in central area;
Barrier aggrades and progrades, followed seaward by forest-swamp.

Continued small subsidence events
Bog-plain develops on partial hydrological bounding surfaces of dense peat;
Aggradation and progradation of barrier and peat dome continue.

Larger subsidence event
Sea water intrudes into deposit via blackwater creeks - back mangrove and mangrove peat accumulates;
More direct drainage into the sea leads to higher discharge via creeks, and partial collapse of perched water table in dome;
Part of deposit drowns.

Sea water intrudes into deposit via blackwater creeks - back mangrove and mangrove peat accumulates;
More direct drainage into the sea leads to higher discharge via creeks, and partial collapse of perched water table in dome;
Part of deposit drowns.

Figure 2-17. Proposed model of peat development on the barrier coast as a result of periodic punctuated subsidence. Black shading indicates mangrove and back-mangrove peats. Solid greys are forest-swamp and palm swamp peats. Patterned areas are fibric sawgrass/stunted forest-swamp and bog plain peats.
channels and normal to the trend of the outer coastline, defined by the northwest-migrating margin of Almirante Bay. This boundary steps eastward with each subsidence event, driving biological and geochemical responses within the mire system in time with the tectonic clock, and thus can be expected to overprint those areas susceptible to flooding with its transgressive signature, and drive the stratified, brackish headwaters of the blackwater creeks deeper into the deposit.

The highest sulphur content (>5 wt%) is found in peats proximal to the brackish influence of blackwater drainage channels up to several km from the coast. Very high (~14 wt%) sulphur was also found in the basal peats in the deepest parts of the deposit (Cohen et al., 1990), which are thus interpreted to have been associated with earlier channels. Very high sulphur content is found even where salinity is undetectable in peat, porewater or basal sediments, and despite the low pH of these peats which inhibits bacterial sulphate reduction (Fig. 4-6). Peats associated with these channels are low in salinity (<0.5 wt%) and very high in S (5 to ~14 wt% S), around 90% of which is stable carbon-bonded sulphides, apparently the result of a biogeochemical chain of S reactions leading to the concentration of carbon-bonded sulphur forms (Chapter 4). The peats are formed in a back-mangrove swamp, from a complex vegetative community that includes salt-tolerant (Raphia, Laguncularia, Acrostichum) and non-salt tolerant tree species (including Symphonia globulifera, Campnosperma panamensis and Ilex guianensis) and shrubs (Miconia curvipes, Cespedezia macrophylla and Ouratea sp.). Sedges, grasses and ferns are common. The resultant peats are medium- to fine-granular (hemic to fine hemic), consisting almost entirely of degraded wood, with occasional wood fragments and roots. They are lighter in colour, and slightly less dense and higher in moisture content than Rhizophora peat.
2.10.3: IMPLICATIONS FOR COAL GEOLOGY

a) Transgressive and regressive signatures, and the relation of peat deposition to active clastic sedimentation

Coal geologists often assume that low-lying coastal peat deposits must be highly susceptible to storm generated clastic 'contamination', as is common today in North America. The inter-tropical convergence zone, which is free of cyclonic storms, is relatively narrow, but hurricane-free coastlines may well have been more extensive in the past, with a different distribution of continental masses and oceanic-atmospheric circulation. Hence the development of extensive wave- rather than storm-dominated coasts should not be discounted. Such coastlines are ideal for the formation of low ash, low sulphur strand-plain coals immediately adjacent to environments of active clastic deposition.

In the Changuinola deposit thick, low-ash peat is accumulating on a rapidly subsiding coastline within less than a kilometre of both a flood-prone, sediment-laden river, and an actively prograding and aggrading barrier beach. Both climate and tectonics find eloquent and subtle expression in this seemingly unlikely combination. Estimates vary, but most agree that compaction ratios of 7:1 to 10:1 are not unreasonable for peat to bituminous coal (Ryer and Langer, 1980); the factor may be less for dense woody peat (< 85% moisture), and considerably more for very wet (> 90% moisture) peat. The Changuinola deposit, preserved in its present configuration, potentially represents a single coal bed some 8 km in width and 12 km in length, oriented NW-SE with the long axis parallel to the coastline. On the northwest and southwest margins, the hypothetical bed interfingers with alluvium and clays, and thickens quickly from carbonaceous sediments to 60 to 100 cm of low ash coal (700 cm of peat), over a distance of 500 m (Figs. 2-9 and 2-12). To the northeast, behind the shoreline, the bed tapers-out more gradually, over 2500 m, cut by occasional channels. To the southeast, with more complex geometry, the bed tapers out beneath shallow marine carbonates,
again over about 2500 m, and in places ends abruptly in vertically walled channels, 3 to 10 m wide and up to 3 km in length, oriented roughly parallel to the barrier sand body.

The cessation of peat accumulation, and the burial and preservation of the deposit, could result from both tectonic and climatic causes. The observed trend of drowning and burial beneath shallow marine sediments in the southeast, as a result of an increase in the net rate of subsidence, may escalate until mangrove growth is impossible. This has occurred already in the southeast, as shown by the presence of drowned peat surfaces several kilometres away in Almirante Bay, and the focus of peat deposition has migrated northwest with ongoing subsidence. Thus a transgressive termination of peat deposition is considered the most likely end. A second possible cause is a change toward a drier and more seasonal climate, which could lead to increased degradation and partial 'deflation' of the deposit, and also to an increase in siliciclastic sediment influx (Cecil et al., 1993). This may eventually result in aggradation of the coastal plain and burial of the deposit beneath fluvial sediments.

At present, the Caribbean coastline southeast of Puerto Limón is in an overall regressive regime, despite the fact that it is subsiding rather than being uplifted, from about the Sixaola River to Punta Serrabara (Collins et al., 1994; Miyamura, 1975). The northwest section of the peat deposit bears what, in terms of coal geology, would be considered a regressive signature. Well-sorted barrier beachesands are aggrading in response to subsidence and prograding seaward over shallow marine carbonates and silts of the continental shelf. The peat behind the barrier sands is prograding along with the barrier, is aggrading as the water table is elevated by internal hydrological processes, and is successionaly zoned both vertically and horizontally. Cores from near the centre of the deposit carry no indications of transgression throughout perhaps 4000 years of peat deposition. A few km to the southeast, and in places at the base of the deposit, back-mangrove peat is overlain by a succession of freshwater forest-swamp peats. Coal resulting from this part of the deposit would be low in sulphur
and ash, and would be judged regressive from in-seam evidence. Evidence of the influence of rapidly rising sea-level lies in the aggradation and the somewhat ambiguous bedding structures of the barrier sand body, and in the presence of large numbers of buried logs and stumps, some in growth position, in beach deposits behind the berm crest, rather than within the peat.

To the southeast, marine transgression, marked by the superposition of seaward on landward deposits, has resulted in the burial of a large area of drowned peat under carbonates and silts. About 40% of the peat deposit is below present sea level, despite having been more extensive during much of its history. If preserved as coal, the environment would be interpreted as transgressive; i.e. the deposit formed during tectonically-driven local transgression. The net rate of subsidence has determined whether the peat accumulation rate has kept ahead of or fallen behind relative sea level rise, which is greatest to the southeast. Hence the transgression is proceeding from southeast to northwest, parallel to the trend of the coast and the long axes of both the peat deposit and the major sand bodies. Internal expressions of the transgressive signature include the presence of shelly layers within cores of otherwise carbonate-free and relatively low-ash mangrove and back-mangrove peats, and indications of a redistribution of sulphur forms that occurs as sea water periodically inundates previously fresh and brackish marginal peats (Chapter 5). At the flooding surface, and along the margins of the brackish drainage channels, the peat is coherent and resists erosion. Were it preserved, the coal roof would be in the form of an irregular xylic (peat) hardground with abundant teredo-bored logs (the teredolites ichnofacies; Savrda, 1991) beneath fine grained carbonates and corals.

There remains some question as to how profoundly transgressing marine waters can overprint freshwater peats with a marine signature. In Chapter 5 the short-term effects of earthquake-induced flooding (Phillips et al., 1994), and in Chapter 4, the distribution of total sulphur and forms of sulphur in the marine- and brackish-influenced peats (Phillips and Bustin, in press) are examined. The
difficulty of distinguishing primary sulphur from secondary, 'transgressive' sulphur in mangrove and back-mangrove peats has been approached but not yet fully resolved. In most samples described in those studies marine penetration was limited to 1 to 2 m, and sulphur content did not increase with flooding. However, it is difficult to extend short term observations of transgressed peats to transgressive coals. It is likely that the rate of subsidence and subsequent sedimentation may affect the degree to which marine waters ultimately affect the coal. The short term observations, however, point to the importance of the progenitor vegetation, which determines peat density and permeability, in admitting or limiting marine influence.

Lithotype variations in a hypothetical coal bed would preserve a record of syndepositional variations in degree of humification, and thus reflect variations in vegetation, peat density and hence the hydrology and trophic state of the progenitor mire. Highly humified woody peats from the margins and base of the central deposit would yield massive, dull, fine-grained coal, high in huminite. Fibric and coarse hemic sedge peats from the central bog plain and lesser domes in the southeast would form finely banded bright coal with abundant structured macerals. Because of the variations in peat density between forest peats and sedge peats it is likely that upon burial and dehydration the relative proportions of woody coal over herbaceous coal would shift in the direction of a relatively greater volume of woody coal. The large volume of herbaceous bog plain peat would become a relatively small volume of bright banded coal, fulfilling observations of Phillips and DiMichele (1981) that most economic coals have formed from large woody vegetation.

2.11 CONCLUSIONS

The Anderson model of floral succession and increasing oligotrophy with increasing peat accumulation appears to account for the evolution of the Changuinola peat deposit, with two important differences related to the depositional environment which manifest themselves in the
hydrological controls on peat accumulation. The environmental factors that distinguish this deposit from the Malaysian and Indonesian prototypes are: i) tectonically-driven punctuated subsidence, that results in periodic rapid rise in relative sea level rather than gradual eustatic rise; and ii) absence of a dry season and hence of the regular drying-out of the peat surface which strongly influences the southeast Asian bog forest peats. Thus climate and tectonic setting result in a variant of the model that may be applied to the interpretation of environments of coal deposition.

On the Panama coast thick, low-ash peats have accumulated in an environment in which subsidence is earthquake-driven, and occurs instantaneously and incrementally. The net rate of punctuated subsidence has been very close to peat accumulation rates during the last 2000 years of peat deposition. The amount of subsidence in the most recent event was greatest to the southeast, an area where the peat deposit has drowned beneath marine waters. However, although approximately 40% of the deposit is below sea level, marine influence is not apparent in most of the deposit. Rather, it is restricted to that part of the deposit in the southeast where the subsidence rate is greatest and the swamp has drowned due to the inability of the mangrove vegetation to keep-up with the subsidence, or where the swamp is influenced by tidal blackwater creeks.

The western part of the deposit is a domed ombrogenous bog with an elevated water table which displays no internal evidence of the influence of punctuated coastal subsidence. In the ever-wet climate the bog plain surface never dries out, but is commonly submerged beneath 10-20 cm of water. Discharge from the central bog is restricted to surface flow, probably as a result of low hydraulic conductivity in the dense marginal forest peats. Underlying the bog plain are stratified palm-swamp and forest-swamp peats which act as low-permeability hydrological bounding surfaces. Rainwater drains slowly in a radial pattern, and the resulting oligotrophic bog produces a body of peat which is effectively a suspension of well-preserved root material in a dilute granular matrix. Only in the elasic
sediments of the base and the barrier, and in the eastern, transgressed peats, is a record of coseismic subsidence preserved. Thus it is evident that thick peat, and hence coal, deposits can accumulate due to tectonically driven punctuated subsidence, rather than gradual eustatic sea level rise, without leaving a record of increased elastic input within the peat, even immediately adjacent to environments of active elastic deposition.

The development of partial hydrological bounding surfaces is an effect of changes in vegetation and peat type through time, and an indication of changes in the trophic state of the mire driven by internal hydrological controls. Rapid punctuated subsidence imposes an external hydrological control, that of rising sea level. At low net subsidence rates, vegetation responds; dense, low-permeability mangrove and back-mangrove peats accumulate, and marine influence is excluded from all but a narrow marine margin, and areas in close proximity to brackish drainage channels. In these laterally restricted parts of the Changuinola deposit the degree of humification of peat is uniformly high, and the marine hydrological influence is in the form of a front which migrates to the northwest with each subsidence event. At higher net subsidence rates, it is likely that increased discharge into blackwater creeks would lead to a lowering of the peat surface and eventual drowning of the deposit and burial beneath shallow marine carbonates. A small reduction in the net rate of subsidence of the bottom of Chiriqui Lagoon and Almirante Bay could result in the infilling of these large areas by extensive peat swamps, starting with mangrove islands.

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2.12 REFERENCES CITED


CHAPTER 3

VEGETATION ZONES AND DIAGNOSTIC POLLEN PROFILES OF A COASTAL PEAT SWAMP, BOCAS DEL TORO, PANAMA
3.1 ABSTRACT

A survey of the dominant vegetative cover of a large domed coastal swamp near Changuinola in the Province of Bocas del Toro, Panama, has been undertaken as an initial step in reconstructing the Holocene history of peat accumulation on this coast. Seven phasic communities of peat-forming vegetation are defined and mapped: 1) *Rhizophora mangle* mangrove swamp; 2) mixed back-mangrove swamp; 3) *Raphia taedigera* palm swamp; 4) mixed forest-swamp; 5) *Campnosperma panamensis* forest-swamp; 6) Sawgrass ± stunted forest-swamp; 7) *Myrica-Cyrilla* bog-plain. Pollen extracted from surface peat samples and collected from dominant vegetation at representative sites is used to prepare a pollen profile of each phasic community. These profiles are then compared to pollen distribution in 2 peat cores, one from the deep central part of the deposit and the second from a site near the marine margin, in order to construct a history, by floral succession, of the 4000 year evolution of the deposit.

The Changuinola mire originated as freshwater palm swamps that developed in close proximity to both the Changuinola River mouth, probably behind a barrier bar and freshwater lagoon system, and a low energy, mangrove-dominated bay. The early swamp was likely drained to the southeast by brackish blackwater creeks much as it is today, and formerly extended considerably farther in the direction of Almirante Bay. The *Raphia* swamp was succeeded by hardwood forest-swamp dominated by a very limited number of specialised species, only one of which (*Campnosperma panamensis*), is prone to forming monospecific stands. Increasing accumulation of woody peat promoted by the everwet climate impeded drainage of the mire, leading to doming, increased oligotrophy, and establishment of bog-plain
conditions in the oldest, central regions of the mire. Mire development did not require the initial mangrove
phase which is common to the peat swamps of southeast Asia, as the palm *Raphia taedigera* is able to
colonize and institute peat accumulation in a variety of freshwater and brackish environments.
3.2 INTRODUCTION

Peat-forming mires are dynamic organo-chemical systems which evolve through time in concert with changing conditions of growth and preservation. Stratification within Holocene peat deposits has been used to construct histories of environmental change over periods of several thousand years (e.g. Barber 1981), and the stratigraphy of coal measures is used to reconstruct environmental changes on a scale of hundreds of thousands to millions of years (volumes edited by Scott, 1987; Lyons and Alpern 1989; others). Thick extensive peat deposits may develop wherever precipitation exceeds evapotranspiration throughout most of the year, allowing vegetated wetlands with high water tables to persist year-round. Today the most extensive, and most studied, peatlands are found in the middle and high latitudes of the northern hemisphere. These formed as an effect of continental glaciation, and may, in fact, be moribund and in retreat. In the geological past, however, the large coal deposits of the Carboniferous, as well as some Cretaceous and Tertiary coals, bear witness to the existence in earlier times of vast, long-lived forested peatlands in tropical and subtropical climes.

Recently, attention has turned to the study of Holocene tropical peat swamps, in part due to increasing awareness of the importance of, and growing threat to, tropical forest ecosystems, and partly as a result of the emergence of a process model for deposition of coals derived from primarily arborescent vegetation, in tropical or sub-tropical conditions (Anderson and Muller, 1975; Esterle et al., 1989; Cobb and Cecil, 1994). Pioneering work on the evolution of forest-swamps in southeast Asia by J.A.R. Anderson has lead to the development of what is now termed the Anderson model of domed peat development in the Old World tropics, described in detail in Anderson's own publications (Anderson 1961,1964, 1983; Anderson and Muller 1975), and summarized and to some extent formalized by Bruenig (1990) and Esterle and Ferm (1994).
Anderson's work concentrates on the vegetation, soil chemistry, topography and stratigraphy of domed, alluvial forest-swamps of vast size, and peat thicknesses up to 17 m, which have developed in the last 3000-4000 years along the lower reaches of the Baram and Rejang Rivers of northern Borneo. Anderson also describes the coastal swamps of peninsular Malaysia, and Sumatra, which are planar rather than domed. Anderson constructs a depositional model based on vegetational succession, in which a colonizing halophyte (mangrove) community stabilizes a silty prograding shoreline, trapping sediments and creating a protected environment amongst the mass of mangrove roots. The new environment becomes available to a succession of increasingly less salt-tolerant plant species as the shoreline continues to prograde, and a perched, non-saline, acidic water table develops within organic detritus accumulating over mangrove clays. Critical to this process is an ever-wet climate, in which abundant (~3000 mm/a) rainfall throughout the year maintains the water table and allows the accumulation of thick peat, the surface of which becomes increasingly elevated. As it builds above the reach of nutrient-rich tidal and river flood waters, the peat swamp takes the form of a flattened dome or inverted pie-plate, the centre of which becomes increasingly oligotrophic. Shortage of nutrients and greater acidity result in a sequence of increasingly more specialized plant associations occupying the raised central portions of these domed mires. The vegetation develops in a series of stages, in which recognizable associations of plants, termed 'phasic communities', succeed each other according to the degree of oligotrophy and doming. The planar forest-swamps of peninsular Malaysia are less-developed examples, which are elevated to a lesser degree, and in which the final stage in the succession has not been reached.

Anderson (1964) defines a lateral sequence of six identifiable forest types, or 'phasic communities', from the perimeter to the centre of the fully developed Marudi domed deposit on the Baram River delta in Sarawak. The surface expression of this succession can be clearly seen in aerial photographs of fully developed domes (reproduced in Anderson, 1983) as a series of roughly concentric forested zones radiating out from a central bog-plain occupied by a stunted, low diversity community.
representing the final phase in the model of dome development, his phasic community (PC) 6. Anderson's phasic communities PC5 through PC1 represent distinctive associations of arboreal species, generally of increasing size, towards the margins of the deposit. The zones approximate topographic contours, with rapid transitions occurring on the relatively steep edges of the dome, where drainage is better and nutrient concentrations are higher (Bruenig 1990, referencing unpublished work by Salfeld, 1974 and Waughman, 1974), and where in some cases the peat is thinner.

Palyno-stratigraphic analysis of peat cores by Muller (1963, 1964) and Anderson and Muller (1975) show that a vertical sequence of pollen facies is present from the base to the surface of the peat. Correlation of pollen in the peat cores to pollen of surface vegetation reveals that vertical transitions generally echo the lateral sequence of phasic communities. From these observations a model of vegetational succession, reflecting increasing oligotrophy through time, was constructed. The authors point out that palynological analysis of the Marudi peats has some limitations, principal among them being lack of information about the local floral biology, pollen production and dispersal mechanisms of many of the plants. In addition, pollen cannot generally be differentiated at the species level, and specific forest-types could not be distinguished due to the presence of several species of the genus Shorea, the pollen of which are indistinguishable. On the other hand, the principal tree species are believed to be mainly insect pollinated, and this in conjunction with the density of the foliage, and the generally weak winds prevalent in that area result in restricted pollen transport. This factor reduces overlap between phasic communities, and makes correlation between stratification in the peat and zonation in the surface vegetation more certain.

Until very recently, overviews of world peat distribution have made little mention of extensive peatlands in the Neo-tropics, and their existence was rarely mentioned in the literature (exceptions include Christen, 1973; Cohen et al., 1985, 1989, 1990; bibliography in Lottes and Ziegler, 1994). Cohen et al.
(1989) describe the large coastal peat deposit near Changuinola in western Panama, studied jointly by the U.S. Los Alamos National Laboratories and the Instituto de Recursos Hidraulicos y Electrificacíon of the Republic of Panama with the objective of assessing its resource potential as fuel for a peat-fired thermoelectric facility. They found the peat to be up to 9 metres thick, and the dense forest vegetation surrounding a plain of sedges, grasses and stunted vegetation suggested that the deposit might be domed. The present study presents an overview of the dominant peat-forming vegetation of the Changuinola mire, defining 7 phasic communities according to their principal species. Pollen 'fingerprints' (sensu Cohen, 1975) for each phase are then constructed using counts of the dominant identifiable pollen types concentrated from surface litter, and surface (upper 25 cm) peat samples. Finally, the pollen stratigraphy of two peat cores is recorded, one from the thick central region and a second from near the eastern margin of the deposit. By correlating transitions in the cores with the modern vegetation, the Anderson model is tested and a history of the evolution of the mire proposed.

3.3 GEOGRAPHY AND CLIMATE

The Changuinola peat deposit has developed in a back-barrier setting on the Caribbean coast of Panama, at 9° 20' N latitude, 82° 20' W longitude, on a microtidal (~ 30 cm), wave dominated shoreline (Fig. 3.1). Although tidal effects in the western Caribbean are minimal, strong wind-driven longshore currents transport sediments to the southeast. Tropical storms and hurricanes pass well to the north, but associated floods are frequent. The climate is humid-tropical and temperature averages 26° C, with a ± 3° range. There is no dry season; the annual precipitation of 3000 mm is uniformly distributed throughout the year (IRHE, 1988). Surface winds are predominantly from the north to north-east throughout the year, but strong south- westerlies blow down the slopes of the Talamanca Ranges one or two days in each month. Normal windblown transport of pollen is from NE to SW, from the Caribbean barrier bar toward the centre of the mire. The NE margin is occupied by dense Raphia-swamp and mixed forest-swamp. There is no mangrove fringe forest present along the windward margin of the mire.
Figure 3.1: Location map of the Changuinola peat deposit on the Caribbean coast of Panama. Sample sites which are mentioned in the text are shown, as are lines representing the NW-SE cross-section, and the NE-SW levelling traverse and cross-section. The shaded area includes that part of the deposit that has been sampled offshore of the mangrove fringe zone in Almirante Bay.
The NW coast of Panama is a region of active clastic and organic sediment deposition. Much of the coastal plain is covered by Quaternary and Recent alluvium, and the coast is characterized by a series of prograding barrier bars behind which occasional lagoons and extensive paralic swamps are developed. Sedimentation rates are high, and the peat deposit has developed adjacent to the Changuinola River, on the back of a prograding barrier bar, the characteristic ridge-and-swale architecture of which can be traced at the base of the peat. (Fig. 3.2) The present-day mire occupies the narrow coastal plain between the folded Miocene sediments of the Talamanca Range foothills and the exposed Caribbean coast. At the eastern terminus of this coastline, where the terrigenous sediments extend beneath Almirante Bay, peat occurs submerged to depths of three metres or more, underlain by medium grained grey sand, and in places overlain by a thin layer of silty sands, lime mud, and coral. Approximately 40% of the deposit is below present sea level and the base of the peat is 670 cm below sea level at the lowest measured point. Most basal sediments are well-sorted medium grained grey sands similar to those currently being deposited on the coast by the Changuinola River.

3.4 METHODS

a) Problems:

The coastal mires of Caribbean Central America are not well known. Access to most of the 1000 km of coast between Cabo de Honduras in northeast Honduras, and Colon in eastern Panama is almost exclusively by boat and light aircraft. Botanical studies in the region are mostly limited to those concerning the welfare of plantation crops such as bananas and cacao, and thus have focused on the vegetation of the alluvial plains rather than that of the extensive and virtually impenetrable forest-swamps that occupy much of the coastal plain. The Changuinola mire is used, but little known by the local inhabitants, who clear wet pastures and hunt for food around the margins, cut timber along the banks of the blackwater creeks which drain into Almirante Bay, and attempt the occasional rice crop between the stumps left by small scale logging. A systematic description of the vegetation of the area, indeed of the
Figure 3-2. NE-SW cross section of the deposit along levelling transect, showing surface vegetation zoned into concentric phasic communities (PCs). Vegetation zones correspond to those visible in satellite images (Fig. 3-3), verified by sampling. Vertical exaggeration is x 500.
province of Bocas del Toro, has yet to be attempted, although some reference material is available (notably by Holdridge and Budowski, 1956, summarised in Porter, 1973). At the onset of the project, only local names were available for the majority of plants in the mire.

b) Satellite Imagery

The mapping of vegetation zones in most of the 80 km² Changuinola mire was accomplished using a combination of normal and oblique air photos (using black and white, normal colour and infrared films), and SPOT multispectral satellite imagery (Fig. 3.3; also Figs. 2.7 and 2.8). Detailed mapping of drainage channels and identification of many of the vegetation types required low-level aerial photography, particularly in the complex eastern section of the deposit (see Fig. 2.3). The concentric zonation of the phasic communities in the raised western section did not emerge, however, until false-colour satellite images were generated. Using 'groundtruth' developed during the cutting of trails, and a Magellan® GPS (Global Positioning System) receiver for positioning, we have assigned 7 phasic community descriptions to the categories in the digital images and photo-based maps.

c) Levelling Surveys

Three levelling surveys were conducted from the margins to the centre of the swamp in order to determine if the surface is domed. A complication arose in that at the start of the study, in April 1991, a Ms (surface magnitude) 7.5 earthquake, epicentred 90 km to the west in the Rio Estrella valley, resulted in approximately 50 cm of coseismic subsidence across the study area. Thus it was necessary to re-establish datum before levelling lines could be run.

d) Coring of Peat and Collection of Surface Samples

Cores were taken from the surface to the base of the peat at 78 sites. Samples were recovered in 25 or 30 cm increments, wherever possible, using Hiller- or Macauley-type hand operated coring devices.
Figure 3.3. False colour SPOT satellite image of the Changuinola peat deposit. The black area (top and right) is silt-laden surface water in the Caribbean and Almirante Bay. The large white patch is clear shallow water in the Bay. Areas of peat doming are in shades of blue and green (central western bog plain, and 4 smaller areas in the eastern section; PC 7). These bog-plains are surrounded by gold (sedge and stunted forest-swamp; PC 6). The yellow areas are Raphia palm swamp (PC 3). Red and flecked white are mixed forest-swamp and Campnosperma p. forest swamp (PC 4 and 5).
Figure 3.4. Vegetation-zone map of the area shown in the SPOT image. Interpretation of the distinguishable Phasic Communities are shaded according to the legend.
Salinity and pH for each sample were measured at the time of collection, and verified in the laboratory (distilled water), using a Cardy® Model PH1 digital pH metre, and a Cardy® Model Cl21 digital salt metre. In addition, surface litter samples were collected (to 5 cm depth) and 25 cm cubes cut with a machete, at one site in each of the 7 phasic communities. All samples were double-bagged and stored in as cool a location as possible until they could be refrigerated or frozen.

\textit{e) Collection and Identification of Plants}

Leaves and, where possible, flowers, of major species from each of the 7 phasic communities were collected with the assistance of Sr. Andres Hernandez, botanist with the Forest Dynamics Project of the Smithsonian Tropical Research Institute (STRI), Barro Colorado Island, Panama. Arboreal pollen was collected by Sr. Sammy Sanchez with a .22 calibre rifle. Identification was made by Sr. Hernandez and staff of the herbaria of the Smithsonian Tropical Research Institute in Balboa and the University of Panama, Panama City. A list of the major species identified is included as Appendix F.

\textit{f) Peat Classification, Pollen Preparation and Identification}

Pollen slides were prepared from surface samples from sites representative of 6 of the 7 phasic communities, and from 2 cores, one in the central part of the deposit and the second near the eastern margin. Pollen was prepared and concentrated using standard palynological techniques from the fine fraction of the peat (< 0.25 mm). Samples were first separated into coarse, medium and fine fractions using a wet-sieving procedure modified from Staneck and Silc (1977). By this method, the sample is thoroughly mixed before the pollen is extracted. This system was used in order to make a quantitative assessment of the degree of humification of the peat. Degree of humification is traditionally described using a modified von Post Humification Scale, adapted to tropical peats by Esterle (1990). The categories are sapric, fine hemic, hemic, coarse hemic and fibric. The use of field-determined peat types has been used only sparingly in the study of these tropical peats, as recent work (Esterle, 1990) suggests
low correspondence between field categories and the actual particle-size distributions as determined by point counting or sieving methods. Peat classification is based on the identification of macroscopic plant parts and palynomorphs in the peat, compared to plant and pollen associations identified in the surface samples, and uses botanical (e.g. *Rhizophora* peat, sedge peat) nomenclature (Cohen, 1968).

Following identification of the dominant species present in the modern vegetation, descriptions and photomicrographs of the pollen were prepared. Published descriptions for some Panamanian pollen species are available, notably in Bartlett and Barghoorn (1973), Graham (1979, 1988a and b) and in the superb publication of Roubik and Moreno (1991). Reference slides from the collections in the paleoecology department of STRI, Balboa, were made available. Finally, as many gaps as possible were filled using the herbarium collections at The University of Panama, and the Smithsonian Tropical Research Institute, and by collection of fresh samples on-site in the mire. Descriptions of some species of interest, or for which no prior publication was found, are included here as Appendix E.

**g) Pollen Counts and Pollen Diagrams**

As indicated by the title of this paper, the palynological analysis presented here is intended to establish a stratigraphy of the deposit sufficient to reveal its broad evolutionary history. To accomplish this it is necessary to relate the pollen preserved in the peat with modern plants, plant associations and communities. A complication encountered in attempting ecological interpretation from pollen stratigraphy is selective preservation. For example, the pollen of cerillo (*Symphonia globulifera*), a dominant tree, was absent from surface samples and most of the cores. One can only count what is preserved, and it is quite possible that what is preserved significantly misrepresents what actually was. To minimize this selective bias, pollen profiles were prepared that would be representative of the preserved pollen record for each community. To establish the pollen 'fingerprint' for each phasic community, a count of 1000 grains, where possible, was made from surface litter and surface peat.
samples (3 sites produced less than 750 grains each from multiple slides). The results were combined, and the percentage of the total count plotted for the most numerous palynomorphs. Although it would be preferable to compare counts from numerous similar sites to better represent each phasic community, it was felt that including the upper 25 cm of the peat gave considerable range to the sample, and given the sampling interval in the cores (25 or 30 cm) finer discrimination was not necessary. No attempt is made to relate the pollen found in the peat to the species which numerically dominate each community - the problems associated with proportional representation of dominant plants in pollen profiles are well known. Rather it was hoped that recognizable 'fingerprints' would emerge which could then be related to pollen recovered from cores.

Counts of 200 grains for each 25-30 cm increment of two cores were used to construct the pollen stratigraphy of the central and eastern sections of the deposit (Appendix D). Pollen diagrams of the two cores were constructed using selected palynomorphs or combinations of palynomorphs that are considered to be valid markers, as determined from the surface samples (fingerprints), and which best define transitions in vegetation. In both surface and core samples, the following grains were omitted from the counts: all single-celled fungal spores, all fungal hyphae, all fragments less than 2/3 complete, and any ambiguous palynomorph. In identifying palynomorphs, botanical names are used wherever possible.

3.5 RESULTS AND INTERPRETATION

a) Vegetation Distribution

All of the vegetation described in this study is rooted in peat varying in depth from less than 1 m, in a narrow strip behind the barrier bar, to about 9 m in the central mire. Vegetation on mineral soil adjacent to the Changuinola mire complex is diverse and luxuriant. In a trial 20 m x 20 m quadrant (the basic unit of a forest monitoring system developed by the Forest Dynamics Program at STRI), 164 species of trees and shrubs > 2 cm dbh (diameter, breast height) were identified. This diversity is typical.
of humid forested lowlands (A. Hernandez, pers. comm.). Floral diversity on peat soils is low (Myers 1990): 54 major species were identified, along multiple transects through all phasic communities in the mire complex (Appendix F). No detailed accounting of species present in forest sample plots (400 m²) along the transects was possible for this preliminary survey. Vegetation communities were identified by comparing field notes taken during the cutting of trails for levelling surveys with low-level (300 m) aerial photographs. Identification of the major phasic communities was then verified by the rather laborious process of cutting trails into areas of interest visible on high altitude air photos in order to identify the trees.

The domed western section of the mire is mapped as a set of phasic communities in a somewhat similar manner to that described for the oligotrophic peat swamps of Western Malesia and Borneo (Anderson 1964, 1984), and that terminology has been adopted in this study. The eastern section is a complex mosaic of forest types, and includes three areas in which incipient doming is evident. Large areas of the mire are occupied by dense *Raphia* palm-swamp (locally called 'Matomba' (the plant) and 'matombal' (the swamp) in Panama, 'Yoliло' and yolillal in Costa Rica) and a variety of sawgrasses ('cortadera' and cortaderal), on both shallow and deep peat.

*i) Mappable Vegetation Zones:* — Multispectral SPOT satellite imagery with a resolution of about 15 m was used to distinguish the distribution of phasic communities by isolating and enhancing the spectral characteristics of the various vegetation types present in the Changuinola mire. Factors like openness of canopy, reflectivity of foliage, and the extent to which standing water is present serve to distinguish vegetation zones, which can be mapped in false colour. A false colour vegetation map is reproduced as Figure 3.3 and interpreted in Figure 3.4. The concentric zonation of vegetation around the large central bog plain can be clearly seen. In addition, incipient doming is evident in three areas to the east, two of
which may be coalescing. The narrow mangrove fringe forest and back-mangrove (PC1 and PC2), and variations in the mixed forest-swamp (PC4) types, cannot be reliably distinguished at this scale. Phasic communities 3, 6 and 7 are distinct and 4 is mapped as hardwood-dominated forest. Elevation of the sites varies from 0 m (intertidal) at BDD 25, to 6.24 m in the bog-plain (ED 3).

\[ \text{ii) Description of the Phasic Communities:} \] The vegetation of the Changuinola mire has been divided into 7 phasic communities representing the sequence of zones from the margin to the centre of the deposit:

1) \textit{Rhizophora mangle} mangrove swamp; 2) mixed back-mangrove swamp; 3) \textit{Raphia taedigera} palm swamp; 4) mixed forest-swamp; 5) \textit{Campnosperma panamensis} forest-swamp; 6) Sawgrass ± stunted forest-swamp; 7) \textit{Myrica-Cyrilla} bog-plain. The pH and salinity of peat cores from each community are shown in the lower part of Figure 3.5.

\[ \text{Phasic Community 1: } \textit{Rhizophora mangle} \text{ mangrove swamp} \]

Site Description: BDD 25

The mangrove fringe forest is a narrow zone restricted to the sheltered shoreline of Almirante Bay and extending eastward into shallow areas of Laguna Chiriqui. This community is nowhere present on the outer coast, but dominates large areas of the shallow offshore in the lee of the Bocas del Toro Archipelago. In the shallow offshore, \textit{Rhizophora mangle} and an epiphytic \textit{Clusia} sp., are dominant, but in the fringe forest, the community is slightly more varied. Even in sheltered waters, where the community thrives, its extent is limited to about 30 metres breadth by the small tidal range (normally 30 cm).

The dominant species are: \textit{Rhizophora mangle}, \textit{Acrostichum aureum}, \textit{Raphia taedigera}, and a few salt-tolerant grasses and sedges, of which only \textit{Rhynchospora macrostachya} (Cyperaceae) has been identified. \textit{Rhizophora mangle} is the red mangrove, the dominant arborescent species and commonly the
Zonation in the Changuinola peat swamp

Figure 3-5. Cartoon showing typical lateral sequence of Phasic Communities, from mangrove fringe to bog plain. Representative core data shows pH and salinity (wt%) profiles from the surface to the base of the peat.
Figure 3.6-a. Photograph of PC2 (Back-mangrove swamp): centre - a fallen *Laguncularia racemosa*, showing root mass and pneumatophores; left and background - *Rhizophora* prop roots.

Figure 3.6-b. Photograph of *Campnosperma* forest swamp, showing the distinctive, uniform canopy. Centre foreground, a small *Euterpe precatoria* palm; left and right of centre, the fine foliage of 'gavilan' (*Pithecellobium* sp.).
only mangrove present in the fringe forest. *Acrostichum aureum*, known locally as helecho de manglar or mangrove fern, is a large (to 3 metres) and vigorously opportunistic colonizer of sheltered shorelines. It is particularly in evidence along the recently subsided shoreline, where it is thriving amongst the debris of salt-killed mixed forest, and is even present as new growth in the intertidal zone. *Raphia taedigera*, the Raphia palm, is common immediately shoreward of the mangrove fringe, and occasionally present at the high tide line. *Raphia* standing offshore as a result of earthquake-induced subsidence appeared to be slowly succumbing to the high salinity (30 to 34 %) 30 months after the seismic event.

**Phasic Community 2: Back-mangrove forest-swamp**

**Site Description: BDD 26A** (Fig. 3.6-a)

The back-mangrove swamp is one of the more complex communities evaluated in the Changuinola swamp complex. The observations here incorporate a number of sites, both coastal back-mangrove forest, and mixed forest marginal to the blackwater creeks which drain the eastern section of the peat swamp into Almirante Bay. Thus the sites have close associations with both true marine and brackish environments. The forest community is dominated by *Laguncularia racemosa* and *Raphia taedigera*, but open sawgrass swamps ('cortaderal') are also common behind the mangrove fringe. Along the banks of blackwater creeks, secondary species vary with distance upstream from the coast; the community grades from an essentially *Rhizophora* fringe-forest near the coast, to a mixed freshwater forest-swamp and floating sedge-grass swamp at about 2 km upstream. Figure 2.5 shows salinity profiles of three major creeks measured 1 km upstream, after one week of dry weather.

In the lower stream reaches, *Laguncularia racemosa*, *Rhizophora*, and *Acrostichum aureum* dominate. Secondary species include a *Clusia* sp. epiphyte on the roots of the red mangrove. More than 1 km inland, the following additional species may occur: *Raphia; Euterpe precatoria*, a stilt palm; *Pithecellobium* sp. tree; *Cassipourea elliptica*, a small to medium sized tree; *Chrysobalanus icaco*, a
shrub or small tree; *Cyclopeltis semicordata*, a fern common around the roots and bases of white and red mangroves, sedges, grasses and sawgrass. The fleshy-rooted, spiny arrowhead plant *Dieffenbachia longispata* is common. The above all show salt tolerance to some degree.

Non-salt tolerant species include *Symphonia globulifera*, an important prop-rooted upper story tree (ca. 30 m); *Campnosperma panamensis*, an important buttressed tree; an *Alchornea* sp., a rare, buttressed tree; the shrubs *Miconia curvipes*, *Cespedezia macrophylla*, *Ouratea* sp. and *Neea* sp.1. Bromeliad epiphytes are common. *Ilex guianensis*, a medium to large tree (locally called 'plomo'), is present, although more common in the mixed-forest zones. The occurrence of *Ilex guianensis* has previously been associated with higher elevations, and with markedly seasonal rainfall (Johnston, 1949) although its presence in Bocas del Toro is noted by Bartlett and Barghoorn (1973).

**Phasic Community 3: Raphia taedigera** Palm Swamp

**Site Description:** BDD 8  (Fig. 3.6-c)

*Raphia taedigera* Martius (Calamaea) is a large palm having multiple trunks 50-80 cm in diameter, and enormous leaves 15 m or more in length, spreading widely from just above ground level. The plant is a significant contributor to peat deposition, as it has an extensive root system with pneumatophores (“pneumatozones” - Kahn and de Granville, 1992). In-situ trunk bases have been encountered at depths of three metres in peat cores, incidentally settling the question of whether *Raphia* may be an introduced species in Central America (Otedoh, 1977). *Raphia* is one of only three species which forms monospecific stands in the Changuinola swamp complex (the others are *Campnosperma panamensis*, and *Rhizophora mangle*). It forms large stands in all the marginal areas of the deposit, as well as being a significant component in the back-mangrove and mixed forest-swamp communities. The monospecific *Raphia* forest is dark and almost free of understory vegetation. Water table can be up to a
Figure 3.6-c. Photograph of PC3 Raphia palm swamp, with scdgc marsh in foreground: centre - dense Raphia taedigera forest; Symphonia globulifera emergents.
metre above the peat surface. The two herbs Sagittaria and Dieffenbachia are common. In thin freshwater peat, Sagittaria can reach a height of 3 metres, although both are normally a metre or less.

The large prop-rooted Symphonia globulifera ('cerillo') is the commonest emergent hardwood, found as isolated individuals or small groups. Isolated buttressed Campnosperma p. emergents are also present, as are Ilex. Other shrubs, herbs and ferns are present but not identified in this community.

**Phasic Community 4: Mixed forest-swamp**

Site Description: LAKE 2

The mixed forest-swamp is not a single community, but a general description of the tree-dominated swamplands which are not monospecific stands. The various phases are defined by the two or three dominant tree species. Mixed forests mappable from low level air photos are: i) Raphia-Campnosperma; ii) Raphia-Symphonia-Euterpe; iii) Symphonia-Raphia ± other hardwoods iv) Symphonia-Campnosperma-sawgrass v) Raphia + hardwoods on thin peat. Symphonia is the most common and distinctive dominant, observed in all the hardwood-dominated forests, but it does not form monospecific stands. Allen (1956) reports that it does form such stands in Costa Rican fresh water swamps on the Pacific coast. The loop-roots of this species are pervasive over large areas of the mixed forest-swamp surface. Scattered Ilex ('plomo') is also common to all the forest-swamp types encountered. The site LAKE 2 is typical of Type iii) Symphonia-Raphia-hardwood forest.

**Phasic Community 5: Campnosperma panamensis forest-swamp**

Site Description: BDD 23 (Fig. 3.6-b)

*Campnosperma panamensis* forms large monospecific stands on moderately deep peat. These stands are easily recognizable by the irregular, unbroken canopy, and by the slender mottled white trunks, branchless for 10 to 15 metres. Air photos from 1954, 1981 and 1992 reveal striking differences in the distribution of the distinctive *Campnosperma* canopy within the complex region of mixed forest-swamp in the eastern part of the mire. It thus appears that these dense stands develop rapidly and are quite short-lived. Secondary trees in the middle storey are: *Euterpe precatoria*, a stilt palm, *Cassipourea eliptica*
Figure 3.6-d. Photograph of PC6 Sawgrass / stunted forest-swamp: The medium-sized, lobate-leafed tree in the foreground is *Campnosperma panamensis*, *Cyrilla racemiflora* are visible beyond the workers, and a *Symphonia globulifera* in the upper left corner.
and Pithecellobium sp., both of which attain greater size outside this community, and Ternstroemta
tepazapote, which is rare in the swamp. The understory vegetation is quite sparse and open. Principal
shrubs are Miconia curvipesulata, Tococa guutanensis and an Ardisia species, Sagittaria is the common
arrowhead plant, and Smilax is a common vine. The fern Trichomanes crinitum is found around the
bases of Campnosperma.

Phasic Community 6: Sawgrass / stunted forest-swamp  (Fig. 3.6-d)

No single site represents this phasic community. Extensive open-canopied forest, grading into
sparsely-treed sawgrass swamps ('cortaderal' in Spanish) can be seen from the air, and in satellite
imagery, as a transition zone between the closed mixed forest-swamps and the bog plain. However, on
the ground the floral composition is highly variable. Thus the PC 6 sawgrass / stunted forest-swamp is
distinct as a mapping unit, but is a transitional vegetation zone. Identification of the various grasses and
sawgrasses (Gramineae, Cyperaceae) was not possible, with the exception of Rhynchospora
macrostachya, for which flowers were available. Some sawgrasses (Cyperus ligularis, Cyperus
odoratus) were identified from open areas around the margins of the swamp, on shallow peat in runnels
on the barrier bar, and in pastures, and may also be represented in the stunted forest and bog plain. PC 6
is found both marginal to the bog plain community, where it forms a transition zone from forest-swamps,
and as islands within the eastern forest-swamps. In the east, this community may be associated with both
old drainage channels, and 'topographic' highs (representing incipient peat doming, not basement highs).
In all situations, high water table is common, as are 'floating' surfaces. Peat recovered from this
environment is very wet (difficult to sample) orange-red, fibrous to coarse hemic, and of low bulk density.
Stunted Campnosperma and shrubby Symphonia occur, but the dominant trees are Myrica mexicana and
Cyrilla racemiflora. Bartlett and Barghoorn (1973) report that Myrica is found only along the margins
of residual patches of forest in high, dry windswept grasslands above 600-800 m elevation. Cyrilla has
been reported from only one isolated site in Panama, at relatively high elevation at Cerro Jefe, near the
Canal Zone (A. Hernandez, pers. com.). In the Okefenokee Swamp of Georgia, however, *Cyrilla racemiflora* is the dominant species forming tree "hammocks", isolated clumps of low-growing trees within open swamp areas (Cohen, 1975). Both of these trees are known locally as 'mangle cimarron' or 'bush mangrove' because of the wet conditions in which they grow. A rare arborescent *Clusia* sp., a large tree with enormous prop roots originating 4 metres or more above the peat surface, has not been reported elsewhere in Panama (A. Hernandez, pers. comm). *Ilex guianensis* occurs as a common shrub in this phasic community. *Chrysobalanus icaco* is a dominant shrub, and *Miconia curvipes* and *Myrsine pelucido-puntata* are present. Ferns, including *Salpinclaena* sp. are found intergrown in the sawgrass. Mosses are also present.

**Phasic Community 7: Myrica-Cyrilla bog-plain**

**Site Description: LAKE 10** (Fig. 3.6-e)

The term bog-plain here uses bog in the sense of an ombrotrophic mire, a system depending entirely on rainfall for its water and nutrients (Moore, 1989) rather than as a community dominated by mosses. Mosses and stunted sedges and grasses are present, as are algal mats in the open water between the bases of the sawgrass and shrubs. Woody vegetation is stunted and shrubby. *Myrica mexicana* and *Cyrilla racemiflora* are dominant, both as shrubs in the open areas, and as low-growing trees (diameter to 20 cm or more, b.h.) forming the 'hammocks' which are scattered across the plain. *Chrysobalanus icaco* and very stunted *Camposperma* and *Clusia* sp., small *Sagittaria*, and ferns are present. Cohen et al. (1989) identified *Sphagnum*, and the insect-eating *Drosera* (sundew) and *Utricularia* (bladderworts). Walking across this terrain one must step on the bases of the sedge plants, as the moss- or algae-covered surface will not support weight. Water depth is a metre or more. The more 'solid' ground in the shrub hammocks is also at least partially floating, and if allowed to, the corer will drop several metres under it's own weight.
Figure 3.6-e. Photograph of PC7 *Myrica-Cyrilla* bog plain: Algal mats are visible in the right foreground, along with stunted sedges and grasses and a small *Camphosperma p*.; *Myrica mexicana* along the horizon, (small leaves).
3.6 POLLEN DISTRIBUTION

The aim of the palynological investigation was, in combination with particle size and geochemical data, to identify major trends in changing ecological conditions within the coastal swamp during its approximately 4000 year history. Pollen 'fingerprints' representing 6 of the phasic communities were constructed, (Fig. 3.7-a to 3.7-f), from counts of surface samples in the hope that those communities could be recognized in the peat stratigraphy. Thus any sequential succession in the vegetation would be revealed, which could then be related to conditions of trophic state, pH, and pore water salinity associated with present vegetation. Selected palynomorphs referred-to in the following section are described and illustrated in Appendix E and in the Plates. PC 6, the sawgrass / stunted forest-swamp, is a variable community that represents a transition; no single site was thought to be representative of this community, hence no pollen fingerprint was constructed.

a) Surface Pollen Diagrams

PC 1: Rhizophora fringe forest (Fig. 3.7-a)

The most common palynomorphs from this site are an unidentified tricolporate pollen Type 1, Rhizophora mangle, monolete fern spores, Ilex gutanensis, and fungal spores. Rhizophora pollen has been shown to be a good sea-level indicator (Muller, 1959; Van der Hammen, 1963), although in this study it represents only about 9% of the total count in both PC 1 and PC 2. Thus the pollen record significantly underrepresents the species. This is undoubtedly due to the narrowness of the mangrove fringe, as observed by Van der Hammen (1963), and the fact that the prevailing wind blows offshore across the mangrove fringe. Type 1, along with a second unidentified tricolporate, Type 2, were encountered only in mangrove fringe and back-mangrove samples. Ilex pollen, which is clearly allochthonous, is present in almost all samples from the Changuinola mire. In addition, this is the only site at which Myrica mexicana pollen is absent. Acrostichum aureum is also absent from this sample, although that fern is common in this phasic community and was observed in other mangrove peat from.
Figure 3.7-a

Phasic community 1

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<th>Species</th>
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<th>% of total</th>
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<tr>
<td>Rhizophora mangle</td>
<td>43</td>
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<td>Tricolpate type 1</td>
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</tr>
<tr>
<td>Tricolpate type 2</td>
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<td>Camposperma panamensis</td>
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<tr>
<td>Myrica mexicana</td>
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<td>0.0</td>
</tr>
<tr>
<td>Ilex guianensis</td>
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<td>3.8</td>
</tr>
<tr>
<td>Cyperaceae</td>
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<td>0.0</td>
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<tr>
<td>Gramineae</td>
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Figure 3.7-b

Phasic community 2

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Figure 3.7. Pollen 'fingerprints' from surface peat samples, PC 1 and PC 2.
cores. The pollen diagram reflects the low diversity of this community. The medium size fraction (<2.0 mm and >0.25 mm) of this surface sample contained abundant calcareous foraminifera and ostracodes.

PC 2: Back-mangrove forest-swamp (Fig. 3.7-b)

Sampling at this site was by 3.5 cm diameter vibracore, the top 30 cm of which was processed for pollen analysis, thus surface litter was not well represented. Palynomorphs were few and poorly preserved, and fewer than 300 grains were counted from multiple slides. *Rhizophora, Laguncularia* and *Acrostichum* are present, as they are in the present vegetation, and both Cyperaceae and Gramineae are well- and perhaps over-represented. Monolete fern spores represent about 10% of the total count. Tricolporates Type 1 and Type 2 are present but much reduced from PC 1. Microforaminifera tests are present, and dinoflagellate cysts are abundant, but were not counted. Many fragments, damaged and pitted grains were found. The absence of *Ilex* pollen may be a function of the small number of total grains encountered.

PC 3: *Raphia* palm swamp (Fig. 3.7-c)

The pollen of *Raphia taedigera*, fungal spores, monolete fern spores and a diverse arboreal pollen component characterize this site. An unidentified *Chenopodipollis* (?) -type of periporate pollen, Type 39, is the second most abundant grain (9%), and *Ilex* is plentiful (6.5%). Also common is a spikey spherical phytolith, superficially identical to those found in the epidermis of certain Old World palm leaves (Rosen, 1992) and here assumed to be associated with *Raphia*, rather than the much rarer palm *Euterpe precatoria*. An important palynomorph is the large fungal spore *Fusiformisporites sp.*, which is present in *Raphia* swamp peats, but is much more common in the mixed forest and *Campnosperma* forest-swamp peats.
Figure 3.7-c

Phasic community 3

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</tbody>
</table>

Species

1. *Campnosperma panamensis* 44 4.4
2. *Myrica mexicana* 28 2.8
3. *Myrica type A* 8 0.8
4. *Ilex guianensis* 66 6.5
5. *pericolporate C (39)* 91 9.0
6. *Raphia taedigera* 101 10.0
7. *Cyperaceae* 42 4.2
8. *Gramineae* 4 0.4
9. *Triete ferns* 0 0.0
10. *Monolette ferns* 75 7.4
11. *Fungal spore type 14* 58 5.7
12. *Fusiformisporites* 5 0.5
13. *Other f-form spores* 52 5.1
14. *Cyperaceae* 574 56.8
15. *Other* 436 43.2

Figure 3.7-d

Phasic community 4

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Species

1. *Campnosperma panamensis* 20 1.9
2. *Myrica mexicana* 4 0.4
3. *Ilex guianensis* 38 3.7
4. *tricolporate D (40)(Tiliaceae?)* 29 2.8
5. *tricolporate E (48)* 63 6.1
6. *Raphia taedigera* 12 1.2
7. *Cyperaceae* 1 0.1
8. *Gramineae* 0 0.0
9. *Triete fern of Metaxy sp.* 42 4.0
10. *Monolette fern 1* 45 4.3
11. *Monolette fern 2* 34 3.3
12. *Cyclopettis s.* 104 10.0
13. *other monolette ferns* 163 15.7
14. *Fusiformisporites* 13 1.3
15. *other f-form spores* 32 3.1
16. *Other* 600 57.7
17. *Other* 439 42.3

Figure 3-7 cont'd. Pollen fingerprints from PC 3 and PC 4.
Ilex and Myrica pollen are common in both Raphia and mixed forest-swamp. These species were previously only reported together at higher elevations, associated with a marked dry season. This combination is noted by Bartlett and Barghoorn (1973, p.245) and used as a basis for interpreting a period of cooler, drier climate in the Isthmus of Panama during the period 7300-4200 B.P. Clearly the combination is also present within a few metres of sea level in an equable, everwet regime. Pollen of Ilex sp is found in association with Rhizophora at 35,500 BP (Bartlett and Barghoorn, 1973).

PC 4: Mixed forest-swamp (Fig. 3.7-d)

High dicot pollen diversity, and a large proportion of both trilete and monolet fern spores (37% of the total count) characterize this community. Noteworthy is the absence of pollen of Symphonia globulifera, which is the dominant tree presently growing at this site, and throughout much of the mixed forest-swamp. Only 6 grains of Symphonia pollen were counted in the entire study, the paucity possibly indicating entomophily. Despite the prolific flowering of this species, it is clearly not a viable palynostratigraphic indicator. Sedge and grass pollen are virtually absent. Fusiformisporites is common.

PC 5: Campnosperma forest-swamp (Fig 3.7-c)

Pollen of both Campnosperma panamensis and another Anacardiaceae-type pollen are abundant in this environment. The second species differs from Campnosperma in being more prolate (P/E of 1.6 vs 1.2 to 1.4), but bears very similar exine structure. Raphia and Euterpe are both present in the pollen profile, as they are in the modern vegetation. Fusiformisporites sp A and sp. C are about equally represented, and fungal spores as a group are more common in this than any other phasic community. Fusiformisporites is of particular interest, as it has been described in the Eocene (Fusiformisporites crabbii, Rouse, 1962; F. pseudocrabbii, Elsik, 1968, Texas; F. rugosus Sheffey and Dilcher, 1971, Tennessee and Kentucky); and Paleocene and Plio-Pleistocene (Elsik, 1980) of North America as well as from the Lower Eocene, and Holocene (possibly as re-worked grains) of Jamaica, (Germeraad, 1979) but
### Figure 3.7-c

#### Phasic community 5

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#### PC 5: Campnosperma forest-swamp

![PC 5: Campnosperma forest-swamp](image)

### Figure 3.7-f

#### Phasic community 7

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#### PC 7: Bog plain

![PC 7: Bog plain](image)

### Figure 3-7 cont'd. Pollen fingerprints from PC 5 and PC 7.
not, to our knowledge, from modern peat. Trilete and monolete fern spores each represent about 3% of the total count.

PC 6: Sawgrass / stunted forest-swamp

No pollen fingerprint was constructed for this phasic community, despite its utility as a mapping unit, as it is transitional between forest-swamp and bog plain communities, and is highly variable in floral composition.

PC 7: Bog plain (Fig. 3.7f)

The presence of *Cyrilla racemiflora*, both in the modern vegetation and in the observed pollen record, is restricted to phasic community 7. Two unidentified tricolporate species (Types 26 and 54) are also common and exclusive to the bog-plain sites. Triletes dominate the spore count only in this environment. Several species of trilete spores together account for 5% of the total. Monolete fern spores are scarce.

**b) Pollen From Cores**

Pollen analysis was performed on two cores, one from the domed centre (ED-3, Fig. 3.8) and a second (BDD-23, Fig. 3.9) from the planar eastern part of the Changuinola mire. ED-3 is an 802 cm peat core collected from a bog plain site of stunted shrubs, sawgrass and algal mats. The peat was sampled in 30 cm increments from the surface, at an elevation of 6.24 m, to the base in rooted, fine grained grey sand 178 cm below present sea level. BDD-23 is a 450 cm peat core over 40 cm of peaty, rooted sand, on a base of clean, grey, carbonate-free sand at 490 cm. The site is 1.5 km from the present marine margin, and all but the upper 15 cm of this core is below sea level. The BDD-23 site is presently at the edge of a monospecific stand of *Camposperma*, adjoining an area of *Raphia* / mixed hardwood
swamp. Sampling was attempted in 25 cm increments, but recovery was erratic due to the large amounts of wood encountered.

ED-3 (PC 7) Pollen Diagram (Fig. 3.8)

The pollen diagram for ED-3 was constructed using those palynomorphs or combinations that best illustrate stratigraphic variations in the core. The palynomorph assemblage from the earliest stage of mire development (810-720 cm) at this site is consistent with a PC 3 Raphia palm-swamp, including dominant monolete ferns and Palmae pollen. Raphia and Euterpe palms and the distinctive periporate Type 39 are present. Palm phytoliths, included in Palmae, are abundant in the deepest sample (23% of the total grains counted). Ilex and many monolete ferns are also well represented in this earliest stage. Fusiformisporites A and C are also present. Halophytes are absent, and there is no evidence of marine influence. Basal sediments are angular medium-grained grey sands containing abundant roots, and closely resemble the sediments of the present barrier bar.

The second stage, from 720 to 630 cm, is dominated by Campnosperma, and fungal spores. This assemblage is interpreted as PC 5 (Campnosperma forest-swamp) succeeding the palm swamp. Fusiformisporites spp. disappear at 660 cm, but other dicellular spores persist. Both palms are present, and ferns become reduced in both numbers and diversity in the upper half of this stage. Sedges and grasses occur at their lowest levels.

In stage three, between 630 and 390 cm, there is first a decrease in hardwoods (except Ilex) and an increase in palms, followed by a decrease in palm pollen as well. Grasses and sedges increase substantially, and ferns are plentiful. Cyrilla makes its first appearance at 510 cm. and Raphia disappears. The gradational change that is apparent throughout this section represents the PC 6 transitional, open, somewhat stunted forest/sawgrass zone which occupies a large proportion of the
Figure 3.8. Pollen diagram of core ED 3. Data is in Appendix D.
western mire and indicates incipient doming. Types 26 and 54 make their appearance at the bottom of this zone, and become increasingly common.

Stage four consists of the upper 390 cm of the core, dominated by a steady increase in the pollen of *Cyrilla*, *Myrica*, and Types 26 and 54. Grasses, sedges and fungal spores are common. *Ilex* and *Camnonsperma* gradually disappear. The assemblage represents PC 7, and records the increasing oligotrophy of the maturing domed bog-plain.

BDD-23 (PC 4) Pollen Diagram (Fig. 3.9)

From 600 to 490 cm depth at this site, clean grey sand with occasional roots was recovered. From 490 - 450 cm, rooted, sulphurous peaty sand with abundant wood fragments occurs. Pollen in the basal peats from 450 up to 285 cm is dominated by a PC 2 back-mangrove assemblage of *Rhizophora*, *Laguncularia* and *Acrostichum*, here plotted together, and the Types 1 and 2 tricolporates. *Ilex* is also present between 450 and 350 cm, but is absent from the 300-350 cm sample. As this absence was also observed in the PC 2 pollen fingerprint, it may still be a function of sample size, as the 300-350 cm sample had by far the least grains, and the most poorly preserved, of all those studied. The 450 cm peat sample is very high in sulphur (13.7 wt%). This has been interpreted as an indication of the influence of brackish waters, probably due to proximity to brackish blackwater creeks, rather than true marine conditions (Phillips et al., 1994; Phillips and Bustin, in review). The presence of *Laguncularia* and *Camnonsperma* pollen supports this interpretation.

From 285 to 150 cm the pollen assemblage indicates the succession of *Raphia* palm-swamp vegetation. *Raphia* pollen and phytoliths, and Type 39 pollen are abundant. *Ilex* and *Myrica* increase and the halophytes disappear. *Fusiformisporites* is abundant, as are fern spores, and there is a high diversity of minor arboreal species. From 150 to 100 cm, a mixed forest-swamp assemblage dominates.
Figure 3.9. Pollen diagram of core BDD 23. Data is in Appendix D.
Palms decrease as dicots increase, and there is a peak in *Fusiformisporites* abundance. *Symphonia globulifera* pollen occurs at the top of this section (2 grains).

The upper 100 cm is dominated by *Campnosperma* and *Campnosperma*-type pollen, and by a diverse assemblage of minor dicots. Palm pollen and phytoliths are also plentiful. Type 39 tapers-out, and *Fusiformisporites* is present but much reduced. The assemblage is consistent with the present PC 5 *Campnosperma* forest-swamp vegetation at this site.

3.7 DISCUSSION

Description of the floral succession from single or widely separated cores is necessarily restricted to broadly general interpretations, and no serious attempt can be made to correlate between the two cores analysed here, which are separated by 6.5 km of trackless swamp. Nonetheless, the two pollen records from the Changuinola deposit reveal successional changes in vegetation both in the domed central part of the deposit and in the eastern, planar section approaching the marine margin of Bahia Almirante (Fig. 3.10). The central mire had its origins as a freshwater *Raphia* palm swamp upon sandy sediments very similar to those of the modern barrier bar. The comparable *Raphia* community presently exists on the thin peats in the runnels and directly behind the modern barrier. Further east at BDD 23, back-mangrove forest-swamp, likely close to brackish blackwater creeks draining into Almirante Bay, were succeeded by *Raphia* palm swamp. A similar circumstance is seen in the dense *Raphia* forest which crowds the back-mangrove zone along present blackwater creeks, and even behind mangrove fringe-forest, where *Raphia* proves to be remarkably salt-tolerant. Swamp-forest succession based on early colonization by *Raphia taedigera* has been postulated in Costa Rican coastal swamps (Anderson and Mori, 1967; Myers, 1990) and in African palm swamps (Richards, 1952). Anderson and Mori (1967) describe a succession in which the early, closed *Raphia* forest canopy eventually matures and opens-up, allowing the succession of
Figure 3-10. NW-SE cross section of the Changuinola peat deposit, as interpreted from pollen in cores and surface vegetation zones. Location of the cross section is shown on Fig. 3-1. Sites marked with an asterisk (*) core data from Cohen et al., 1990. Vertical exaggeration is x 500.
hardwood forest-swamp. A similar sequence is seen in both cores, one to a mixed forest (Fig. 3.10) and the other to monospecific *Camponsperma* forest-swamp (Fig 3.9).

The succession from forest-swamp, through a progressively less diverse, less arboreal and more ecologically specialized plant community, to oligotrophic bog-plain, is admittedly a broadly generalized one. The limited number of samples and the resolution of the sampling program does not permit a detailed stratigraphy, and it is certain that many variations can occur within and between cores, but the general vertical trend is clear. The phasic communities, at least in some sites in the Changuinola deposit, succeed each other in the order in which they are numbered. This is not to say that they must always occur sequentially, nor that they have equal roles in the development of the deposit. In the modern mire, *Raphia*-swamp occupies a far greater area, and is ecologically far more variable than is monospecific *Camponsperma* forest-swamp. It may not be reasonable to suggest that *Camponsperma* forest represents a true phase in a succession, given its present limited distribution, and it is with some surprise that we found the PC 5 pollen fingerprint occurring in both cores. The Asian species *Camponsperma cortacea*, and *Camponsperma squamata* are reportedly prolific pollen producers (Anderson and Muller, 1975), and it is possible that the counterpart *Camponsperma panamensis* is significantly overrepresented in some areas of the Changuinola mire. Nonetheless, the pollen of that species is decidedly not ubiquitous, nor do its numbers overshadow other species, so its presence is considered significant.

Lateral relations between the phasic communities, moving from the margins toward the centre of the mire, are somewhat variable, but generally follow a similar sequence to that described in the vertical sequence. The mire complex is roughly rectangular in plan view. Each side is physiographically distinct: the SE is a low energy, mangrove-fringed marine shore, the NE a high energy, wave dominated barrier coastline, the NW a large, flood-prone alluvial plain, and the SW an abrupt transition to deeply eroded hill country. On all sides but one the same general sequence is seen: From mineral soil supporting a
diverse vegetation, peat depth increases through a belt of *Raphia* palm swamp. The *Raphia* gives way to mixed forest-swamp, to *Camposperma* swamp, in some cases to sawgrass swamp (Fig. 3.10), and eventually the bog plain is reached. The exception to this sequence is in the SE along the shore of Almirante Bay. Here vegetation forms a complex mosaic which reflects the influence of marine and brackish conditions, coastal subsidence and periodically rising sea level. In this area drainage is more complex, and doming and increasing oligotrophy have not proceeded to the same degree, even though the peat depth is not significantly less. Incipient doming is occurring, however. If peat accumulation rates exceed the rate of coseismic subsidence, the small domes may eventually coalesce. Moving from the mangrove fringe forest toward the centre of one of these small domes, the sequence is variable, and any of the phasic communities may be absent, including the *Raphia* palm swamp.

We have adopted the term 'phasic community' from Anderson, believing that it is not meant to imply an inevitable successional sequence, but rather is intended to describe the observed continuity between lateral and vertical relations within the Malaysian peat swamps, in just the same sense that the geological concept of facies relations is intended to describe observable relations, rather than imply cause and effect in these relations. The concept of 'facies association' (defined in the geological sense by Walther's Law) states that in an evolving depositional system, units which are laterally contiguous in space will be vertically contiguous in time. This clearly applies to the Changuinola deposit (Fig. 3.10).

Anderson (1964) also uses the concept of a "catenary sequence" of phasic communities to relate the distribution of vegetation zones directly to the domed topography of the Malaysian peat deposits. Our observations of zoning in the Changuinola mire are not sufficiently well-controlled to justify the use of that term, and we are not able to state that the gradient of the peat surface controls the distribution of the vegetation. Anderson relates both gradient and doming to peat accumulation rates based on radiocarbon dating of peat in cores. Describing a 12 m core, Anderson (1983) reports the following radiocarbon
dates: 5 m = 2255 ± 60; 10 m = 3850 ± 55; 12 m = 4270 ± 70. These give accumulation rates of 4.76 mm per annum for the early (12-10 m) basal (mangrove) peat, 3.14 mm/a for the intermediate (forest-swamp) stage, and 2.22 mm/a for the upper (PC 6?) 5 m of peat. This slowing of accumulation accounts for a deposit which, while generally domed, is quite steep on the edges and flat in the raised centre.

Accumulation rates for the Changuinola deposit portray a somewhat different history, summarized for different peat types as follows. Dates are the radiocarbon age in years before present (BP) from three cores:

- 4.75 m = 2110 ± 60 BP in fine hemic mangrove peat throughout,
- 4.75 m = 1880 ± 60 BP in woody, fine hemic mangrove/back mangrove peat,
- 4.75 m = 850 ± 80 BP in fibric, bog-plain sedge peat,

and

- 8.0 m = 3040 ± 80 BP in woody, hemic palm / mixed forest peat.

These dates give the following accumulation rates for different peat types:

- mangrove/back mangrove peat 2.25 mm/a (from 4.75 m below present SL to present SL),
- back mangrove/ forest peat 2.52 mm/a (from 4.75 m to the present surface),
- palm/forest peat 1.48 mm/a (from 8 m to 4.75 m),

and

- sedge peat 5.58 mm/a (from 4.75 m to surface)

It can be seen from these results, particularly in the sedge peats, that there is a great deal of variation in rates of accumulation of in situ peat. The above values are as much an indication of variations in bulk density and compaction as they are of accumulation rate. The rate of accumulation is in inverse proportion to peat density (Chapter 2.), and a true comparison of preservation and accumulation in different environments would require factoring-in compaction and density variations. The above in situ values, however, suggest that the hydrological characteristics of the peat dictate the height of the water table, and hence the surface topography. The densest peats sampled, mangrove and forest peats, accumulate at rates comparable to Anderson's late-stage peat. The very high rate of accumulation of
sedge peats reflects lack of compaction. (The fibric nature of these peats makes it difficult to remove younger root material, and great care must be taken to avoid contamination.) The domed central bog plain is essentially a mass of well-preserved root material floating in an acidic, nutrient-poor humic soup, contained within a basin of dense, woody peat of extremely low-permeability. Drainage of the central mire is superficial, subsurface flow being effectively dammed by the surrounding forest-swamp peat.

3.8 SUMMARY AND CONCLUSIONS

The general trend of vegetational development and peat accumulation in the Changuinola deposit can be seen in Figure 3.10. The deposit originated as freshwater palm swamps that developed in close proximity to both the Changuinola River mouth, probably behind a barrier bar and freshwater lagoon system, and a low energy, mangrove dominated bay. The early swamp was likely drained to the southeast by brackish blackwater creeks much as it is today, and formerly extended considerably farther in the direction of Almirante Bay. The *Raphia* swamp was succeeded by hardwood forest-swamp dominated by a limited number of specialised species, only one of which, *Campnosperma panamensis*, is prone to forming monospecific stands. Increasing accumulation of woody peat promoted by the everwet climate impeded drainage of the mire, leading to increased oligotrophy, and establishment of bog-plain conditions in the oldest, central regions of the mire. It is significant that peat development did not require the mangrove phase common to the Sarawak peat swamps, as *Raphia taedigera* is able to colonize and institute peat accumulation in a variety of environments. *Raphia* is found thriving on both mineral soil and deep peat, with pH varying from 8 to 3, and salinity up to about 30 ppt.

The Changuinola mire complex has several features in common with the extensive coastal mires of southeast Asia, as well as some fundamental differences. In surface morphology, and in the zoned distribution of vegetation, this neo-tropical mire closely resembles the swamps of Malesia described by J.A.R. Anderson (1961,1964), although the degree of doming is so slight that the term is more useful as a
category of mire than as a description of the topography: the maximum gradient recorded is 1m in 330m, in mixed forest swamp near the NE margin of the mire. Pollen analysis shows a succession of vegetation from the base to the surface of the peat deposit which echoes the lateral sequence of phasic communities from the margins to the centre of the mire. Thus the model of peat accumulation in an environment of increasing oligotrophy described by Anderson applies to the Changuinola mire complex, despite significant differences in geography, vegetation, and depositional environment compared to the southeast Asian deposits.

Thick, extensive peat deposits can develop on a high energy shoreline in close association with active clastic sedimentation if the sediment supply is sufficient to cause aggradation-progradation, and an everwet climate maintains high water tables.

In this region, mangroves are not essential to the development of extensive coastal peats. *Raphia* is a primary colonizer in the Changuinola mire, and represents the first stage in the succession in non-mangrove environments.

Dominating, sufficient to exclude floodwaters, can be related to factors other than differential peat accumulation rates, and is dependent on peat density and permeability. Peat density is associated with the peat-forming vegetation and thus with ecological conditions. The late-stage bog-plain accumulation rate is very rapid, because the density is very low - the sedge peats are not dense and compacted like the forest peats, and they are mostly floating.

The concept of 'facies association' (in the geological sense, which states that in an evolving depositional system, units which are laterally contiguous in space will be vertically contiguous in time - Walther's Law) applies to the organic sediments of the Changuinola mire, and in the broadest sense could
be expected to apply to petrographic variations in coals originating in domed peat swamps. This would apply whether dealing with palynofacies, or with lithofacies if it can be shown that there is a relation between coal-forming vegetation and microlithotypes.

In the course of this study, certain practical considerations became apparent. The first is that, with sufficient work 'on the ground', satellite imagery can be used not only to determine the existence and extent of tropical peatlands, but also the vegetation types, some aspects of the drainage patterns, 'degree of wetness', etc., all valuable elements in the monitoring and managing of wetland resources. This is particularly important in remote areas, and in developing countries.

Ecological and climatic interpretation based on pollen profiles is fraught with danger, as exemplified by the association of cooling, and increased seasonality with the Myrica-Ilex pollen connection in the Bartlett and Barghoorn (1973) core from 7200-4300 B.P. Much more work is needed in the tropics before we can apply palynological principals with the same degree of confidence as in high latitudes. In the present case, a more in-depth palynological study, with better representation of pollen fingerprints to their vegetation, would include multiple core and surface samples from each phasic community in order to reduce the under- and over-representation inevitable from single-site sampling.

ACKNOWLEDGEMENTS

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CHAPTER 4

SULPHUR IN THE CHANGUINOLA PEAT DEPOSIT, PANAMA, AS AN INDICATOR OF THE ENVIRONMENTS OF DEPOSITION OF PEAT AND COAL
CHAPTER 4: SULPHUR IN THE CHANGUINOLA PEAT DEPOSIT, PANAMA, AS AN INDICATOR OF THE ENVIRONMENTS OF DEPOSITION OF PEAT AND COAL

4.1 ABSTRACT

The sulphur (S) content of coal is frequently used to infer aspects of paleo-climate, trophic state, and proximity to marine influence, of the mire in which it was deposited. In this study, the S content of peat in a large back-barrier mire on the Caribbean coast of Panama is related to climatic, biological and tectonic factors of the depositional environment. Earthquake-generated subsidence is greatest to the southeast, leading to drowning of the deposit beneath Almirante Bay, and 40% of the peat is now below sea level. Coastal mangrove peats with moderately high S content (1 to 5 wt% S) and high salinity (> 0.5 wt%) dominate the eastern margin and extend beneath the salt water and shallow marine sediments of the adjoining bay. Marine influence extends only a short distance onshore, except in the vicinity of brackish blackwater creeks which drain the swamp. Peats associated with these tidal channels are low in salinity (< 0.5 wt%) and very high in S (5 to ~14 wt% S), apparently the result of a biogeochemical chain of S reactions leading to the concentration of C-S sulphides. The western part of the deposit is domed, and the vegetation and the peat are concentrically zoned. Stunted, sawgrass-dominated vegetation which produces fibric, very low S (< 0.25 wt% S) peat, occupies the central bog plain. Around the bog plain, mixed-forest and palm-forest swamps produce dense hemic and fine hemic peat with higher S content, between 0.25 and 0.5 wt% S. The S content is in proportion to the degree of humification of the peat, and both are independent of the pH of the groundwater. The distribution of organic and inorganic sulphur forms in the tropical peats are found to be comparable to published values for temperate and subtropical peats, despite differences in vegetation and climate. The distribution of high sulphur peats in the eastern and low sulphur in the western part of the deposit, and the SE - NW transgression parallel to the trend of the coastline reflects the regional structural trend of coseismic subsidence greatest to the southeast.
4.2 INTRODUCTION

Sulphur content and distribution are important factors in the evaluation of peat and coal deposits, and are frequently used in the reconstruction of paleoenvironments of coal measures. A large coastal peat swamp near Changuinola in western Panama has been studied as a model for low-sulphur back-barrier coal deposition. The peat deposit, which averages 6 to 8 m in thickness, has an area of 80 km², about 20 km² of which is offshore beneath the shallow marine sediments of Almirante Bay (Fig. 4.1). The association of a thick, laterally extensive peat deposit with alluvial, barrier-bar, and shallow-marine sediments makes it an excellent analogue for marine influenced tropical coal deposits. In addition, the deposit is in a tectonically active setting, in which earthquake-generated coastal subsidence is leading to deposition of carbonate sediments over peat.

Primary sulphur content of peat is dependent on the availability of aqueous sulphate to living plants and bacteria. Aqueous sulphate (SO₄²⁻) in rain, groundwater and the oceans is the principal source of sulphur found in peat (concentration of sulphur is from <1 to 8 ppm in fresh water, 885 ppm in seawater; Gross 1982). Sulphate is reduced by respiring plants and sulphur-reducing bacteria. Plants use the oxygen, as CO₂, for respiration, and fix some of the sulphur, as carbon-bonded (C-S) sulphur, in a variety of amino acids and related compounds, and as so-called ester sulphates (C-OSO₃) in polysaccharides, choline sulphate, phenols, and other compounds (Casagrande et al., 1976). Reduced sulphur, as sulphide, may be taken up by rootlets, and subsequently re-oxidized to a variety of oxidation states, in the form of polysulphides, elemental, or pyritic sulphur. In strictly ombrotrophic bogs and swamps, the atmosphere is the sole source of primary sulphur, whereas in minerotrophic mires, and those with brackish and marine influence (ie. rheotrophic), groundwater and seawater are important sources. In brackish and marine-influenced peat, sulphur concentration can be very high (>10% dry weight), much higher than can be accounted for by pore-water sulphate concentration (Luther and Church 1992; Giblin and Wieder 1992).
Figure 4.1. Site map showing the known extent of the Changuinola peat deposit. Inset map of Central America shows the location of the site on the northwest coast of Panama. Sample sites for sulphur testing are marked. Site name is followed by the mean total sulphur content of the core in brackets, and one standard deviation, in italics.
freshwater, particularly ombrotrophic, settings, sulphur content tends to be low (< 1% dry weight). Thus the sulphur content of a coal is frequently used to infer the trophic nature of the progenitor mire, and its proximity to marine influences (Williams and Keith 1963; Raymond and Davies 1979; Chandra et al. 1983; Shimoyama 1984; Hunt and Hobday 1984; Querol et al. 1991; others).

In coals in which no marine influence is evident, sulphur content has been related to other aspects of the geochemistry of the precursor peat (Cecil et al. 1979; Renton et al. 1979; Renton and Bird 1991). These authors observe that acid peats (pH < 4) are characterized by well-preserved plant materials, low degrees of humification, and low sulphur content. In more neutral peats (pH 4 to 8), the environment is more favourable for bacterial activity, hence humification rates are likely to be high, preservation poor, and sulphur tends to become concentrated. Acidity in turn may reflect the trophic state of the mire, the presence of buffers in the groundwater and associated sediments, the degree of marine influence, and the composition of the peat-forming flora.

Since the early 1960's, work in modern peat-forming environments has contributed much to the understanding of sources of sulphur in peat and coal. Numerous problems remain however, particularly with regard to rapid lateral and vertical changes in sulphur form and concentration, the relation between peat sulphur and overlying marine clastics and carbonates, and the signatures left by rapid subsidence and marine inundation. The unique setting of the Changuinola deposit provides an opportunity to address some of these longstanding problems, as well as take a first detailed look at Neo-tropical forest-swamp peats from the perspective of coal science.

4.3 REGIONAL SETTING

a) Geography, Climate and Biology

Tropical coastal depositional environments are believed to have been the settings for many known coal deposits. (Wanless et al. 1969; Anderson and Muller 1975) Tropical coastal peats, however, are still relatively poorly understood, and differ in a number of ways from the temperate and
sub-tropical deposits on which many current depositional models have been based. Tropical climate affects air and water temperatures, seasonality, growth and decomposition rates, and the composition of the peat-forming floral community.

The Changuinola peat deposit has developed in a back-barrier setting on the Caribbean coast of Panama, at 9° 20' N latitude, 82° 20' W longitude (Fig. 4.1), on a microtidal (30 cm), wave dominated shoreline. Although tidal effects in the western Caribbean are minimal, strong wind-driven longshore currents transport sediments to the southeast. Tropical storms and hurricanes pass to the north, but associated flood events are frequent. The climate is humid-tropical and temperature averages 26°C, with a ±3° range. There is no dry season; annual precipitation is about 3000 mm, uniformly distributed throughout the year.

Vegetation on mineral soil is diverse and luxuriant. In a 20m x 20m quadrant, 164 species of trees and shrubs were identified (See Chapter 3, Appendices). This diversity is typical of humid forested lowlands (A. Hernandez, personal comm.). Floral diversity in the peat deposit, however, is low (54 major species representing the entire peat swamp) and distinctly zoned into a sequence of 'phasic communities' (terminology of Anderson 1964, and Bruenig 1976) similar to those described for the oligotrophic peat swamps of Western Malesia (Anderson 1964; 1983) and Borneo (Bruenig 1990). The factors which account for floral zonation on peat are not fully understood, but are generally considered to be related to nutrient levels, water table and pH of the groundwater. Thus distinctive phasic communities of peat-forming flora, along with their associated groundwater environments determine the character of the peat which will develop. Consequently, schemes which identify and classify peat according to its principal floral components inherently imply much about the environment of deposition. The Changuinola deposit includes 7 phasic communities, some of which can be further subdivided according to the presence of secondary species. These are: i) *Rhizophora mangle* mangrove-swamp; ii) mixed back-mangrove swamp; iii) *Raphia taedigera* palm-swamp; iv)
Campnosperma panamensis forest-swamp: v) mixed forest-swamp; vi) Cyperaceae (sawgrass) ± stunted forest-swamp; vii) Cyperaceae bog-plain.

b) Geomorphology

The NW coast of Panama is a site of active clastic and organic sediment deposition. Much of the coastal plain is under a variable cover of Quaternary and Recent alluvium, and the coast is characterised by a series of prograding barrier bars behind which a chain of lagoons and paralic swamps is developed. Several large rivers transport sediments northward off the Talamanca Cordillera, and wind driven currents move sediments consistently alongshore to the southeast. Sedimentation rates are high, and the peat deposit has developed on the back of a prograding barrier bar, the characteristic ridge-and-swale architecture of which is described in Chapter 2. Basal sediments are well-sorted medium grained grey sands similar to those currently being deposited on the coast by the Changuinola River. At the eastern termination of this coastline, where the terrigenous sediments extend beneath Almirante Bay, peat occurs submerged to depths of 3 m or more, underlain by medium grained grey sand, and in places overlain by a thin layer of silty sand, lime mud, and coral.

Levelling lines surveyed across the peat deposit show a slightly domed surface that has a maximum elevation of 6.75 m in the centre of the swamp, a maximum gradient of 1:330 (the NE margin) and a base that is from 4 to 7 m below sea level. An estimated 40% of the volume of the peat is below present sea level. An offshore sample from 475 cm below sea level was radiocarbon dated at 2110 ± 60 a. This mangrove peat is overlain by 265 cm of brackish-water peat, 15 cm of carbonate sediment, and 195 cm of salt water. Assuming deposition close to mean sea level, and only minor changes in regional sea level over this period (Pirazzoli 1991; Chapter 2), about 4.5 m of net subsidence is estimated to have occurred in the past 2000 years, including that generated by a Ms (surface magnitude) 7.5 earthquake in April 1991, 10 weeks before the start of this study.
c) Geological Setting

The study area is at the easternmost onshore extent of the Limon-Bocas del Toro sedimentary basin. The Bocas del Toro Basin in Panama, and its westward extension in Costa Rica, the Limon Basin, together make up the Tertiary and Quaternary back-arc basin behind the volcanic ranges of the Talamanca Cordillera of southeastern Central America. Chapter 2 gives an overview of the regional geology, and the tectonic setting of the area.

Regional vertical movement along the coast has been established on the basis of sea level changes as observed in the degree of exposure of near-shore coral reefs, limits of intertidal organisms on dock pilings, and changes in the swash zone on beaches at eighteen points between the mouth of the Rio Matina in the northwest and Punta Mona (Gandoca) to the southeast (Astorga 1991; Plafker and Ward 1992). These observations have been augmented (Camacho, unpublished data; See Chapter 2) to include the coastline of Panama from the Rio Sixaola at the Costa Rica border to the Boca del Toro channel and Cayo Solarte to the southeast. In addition to regional vertical movements are local liquefaction effects, on a scale of tens to hundreds of metres, both of subsidence and uplift (Camacho et al. 1992). It is concluded that 50 cm to 70 cm of regional structural subsidence occurred. These conclusions are based on aerial photographs, observations of the swash zone of beaches and of plant mortality along vegetated shorelines in the area, and on interviews with individuals familiar with the area and with a working knowledge of sea and river levels before the event.

4.4 SAMPLING AND EXPERIMENTAL

Figure 4.1 shows in plan view the extent of the peat deposits between the Changuinola River and Isla Colon. Marked sample sites represent cores taken to the base of the peat, by Cohen and others (1989) and by Phillips and Bustin (1991 to 1993). Most samples were collected using Hiller- or Macauley-type hand-operated coring devices. Samples were described in the field, and bagged in 25 cm or 30 cm increments. Continuous cores were collected in 3.5 cm diameter plastic sleeves using a small vibracore, refrigerated and subsequently frozen for long term storage. Salinity and pH
were measured in the field and verified in the laboratory. A digital pH-meter (Cardy® Model PH1) was used both in the field and the laboratory to measure the pH of the wet peat and porewater. At the same time, salinity was measured using a digital salt-meter (Cardy® Model C121), which measures sodium ion concentration, and then applies a correction factor to calculate total salinity for values > 0.01 wt%. Total sulphur content (dry weight percent) of 203 samples (dried at 50°C, crushed to 100 mesh) was determined using a Leco® SC-132 Sulphur Analyzer (see Tabatabai 1992, p.313 for a description of this instrument) and verified using wet chemical methods. For a coastal sample site, and for site BDD23 adjacent to a major drainage channel, total sulphur was sub-divided into organic sulphur, in both carbon-bonded sulphide (C-S) and ester sulphate (oxidized compounds reducible by HI) form, and inorganic forms expressed as mineral sulphate, elemental sulphur and pyritic (+ marcasite) sulphur. The procedures for determining the proportions of the various forms of sulphur are described in detail by Lowe (1986) and Tabatabai (1992) (Appendix G), who also discuss some of the shortcomings of the methods. In addition, previously published total sulphur values of another 206 samples (Cohen et al. 1990) are incorporated in this study.

Degree of humification of the peats is based on the relative proportions of coarse, medium and fine constituents as determined using a wet-sieving procedure modified from Staneck and Silc (1977), according to the following scheme (Esterle et al 1987):

- **Coarse**: >25% >2.0 mm <30% <0.25 mm
- **Medium**: <25% >2.0 mm <30% <0.25 mm
- **Fine**: <25% >2.0 mm >30% <0.25 mm

The procedure is described in detail in Chapter 2. Degree of humification is described using a modified von Post Humification Scale adapted to tropical peats by Esterle (1990) (Appendix G). The categories are sapric, fine hemic, hemic, coarse hemic and fibric. Peat classification is based on the identification of macroscopic plant parts and palynomorphs in the peat, compared to plant and pollen associations present in the modern swamp. For some samples, the percent moisture content of
drained wet peat was measured by re-weighing after drying at 50°C until no further weight loss occurred.

4.5 RESULTS

a) Geochemical Parameters

i) Sulphur and Salinity.---Sulphur content of the Changuinola peat varies from less than 0.01 wt% to in excess of 13 wt%. Although a full spectrum of sulphur values is present, the samples fall into low-sulphur (0.01 to 1.0 wt%) and high-sulphur (> 1.0 wt%) populations when plotted against other parameters such as pH (Fig. 4.2). Average sulphur content of each core, shown on Figure 4.1, shows a geographical distribution, in which the western part of the deposit is made up of low sulphur peats (mean of 0.23 wt%, standard deviation = 0.18; Fig. 4.3). The eastern part, comprising peat within 3 km of Almirante Bay, has much higher sulphur content and much greater variability (mean of 2.24 wt%, s = 2.55; Fig. 4.4). Figure 4.4 further reveals two populations of sulphur values in the eastern section, a lower- and a higher-sulphur group. Both plots suggest that there is little correspondence between sulphur content and depth of burial (and hence age) of the sample, but that lateral distance from the south-east marine margin is significant.

To clarify the apparent relationship between average sulphur content and proximity to the marine influence of Almirante Bay, the salinity of all samples was plotted against sulphur. Salinity is readily measurable in the field, and in the present study proved a useful indicator of the presence of marine influence in porewaters. Salinity cannot be related directly to aqueous sulphate content without qualification: aqueous sulphate may not diffuse through peat pore water in the same manner as other mineral salts. Sulphate diffusion is biologically mediated (Brown 1985) and thus driven by a differential that is heavily modified by an ongoing "sulphate reduction front", whereas diffusion of mineral salts is determined primarily by the ability of groundwater to circulate. This may create complications in using salinity to approximate the movement of sulphate-rich waters in rheotrophic mires, but is unlikely to be a problem in ombrotrophic situations, in which the supply of atmospheric
Figure 4.2: wt% Sulphur (logarithmic scale) vs pH, n=216.
Figure 4.3. Scatter plot of wt% sulphur vs depth, western part of the deposit. $n = 244$.

Figure 4.4. Scatter plot of wt% sulphur vs depth for samples in the eastern part of the deposit. Note the distinct bimodal distribution in sulphur content. $n = 144$. 

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sulphur to the mire can be assumed to be relatively constant, and uniformly distributed. With the exception of three basal samples, the highest salinity found in the ombrotrophic western peats is 0.02 wt%, the vast majority of the samples being below the sensitivity of the meter (0.01 wt%). This is also true of the porewater in the basal sediments at all sites measured. In the eastern peats, some of which are rheotrophic, salinity is highly variable (<0.01 to 2.7 wt%). For interpretive purposes three sample populations are differentiated based on a plot of S vs salinity (Fig. 4.5). These are:

- Group I: sulphur < 1.0 wt%; salinity < 1.0 wt%
- Group II: sulphur > 1.0 wt%; salinity < 1.0 wt%
- Group III: sulphur > 1.0 wt%; salinity > 1.0 wt%

The three groups can be used to map porewater environments. Figure 4.6 (plan view and cross-section) approximates the three-dimensional distribution of the three groups. In the western section, all peat is Group I, except at the bases of the three deepest cores, which are placed in Group II (based on low basal porewater salinity of nearby sites). In the eastern section, the distribution is more complex (reflecting the complex history of the marine margin). Some inland sites are entirely Group I, whereas all the marine-margin and offshore sites are Group III. Group II samples (medium to high sulphur, low salinity) are found only near major drainage features (blackwater creeks). Salinity of surface waters (upper 3 m) along the marine margins is between 2.9 and 3.2 wt%. Salinity profiles of the three major blackwater creek channels which drain the eastern half of the deposit are shown in Figure 2-5. Salinity and pH were measured at points 1 km into the swamp. Stream banks are lined with dense stands of mixed *Rhizophora mangle* (red mangrove) and *Laguncularia racemosa* (white mangrove), and tidal effects and mixing are prominent despite there being only a 30 cm tidal range. Salinity of creek bottom water is 70% of the salinity of the bay, and at 1 m below the surface creek water is 25%, of bay water salinity.

**ii) Sulphur and pH.---** The pH of all samples collected was measured in the field, and pH of local waters was also tested at regular intervals: pH of rainwater is 6.9 to 7.0, and the sea water in the Caribbean and Almirante Bay between 6.9 and 7.4 in
Figure 4.5. Scatter plot of total sulphur (logarithmic scale) vs salinity. The fields Group I, Group II and Group III represent sulphur-salinity groups as defined in the text. n = 213.
Figure 4.6. Areal and depth distribution of sulphur Groups I, II and III in the Changuinola peat deposit. Across the top of the diagram, variations in total sulphur and pH with depth along a W-E cross section. Below, plan view and cross section from Changuinola River to Almirante Bay. Asterisk (*) signifies data from Cohen et al., 1989.
the upper 3 m. The pH of water in the blackwater creeks, measured after about one week of dry weather, is near-neutral (Fig. 2.5). The near-neutrality of the drainage water in the blackwater creeks contrasts with the commonly low pH of water draining from temperate peat bogs. For example, very acidic bog water results in fish kills in Norwegian streams at the end of dry periods, when low water tables resulted in the oxidation of sulphides in the acrotelm. The resulting sulphate is then flushed out of the peat, with the onset of wet weather (Brown 1985). The ever-wet conditions in the Changuinola swamp, combined with the buffering effect of admixed seawater, presumably maintain a high pH, and thus very favourable conditions for bacterial sulphate reduction, at least in the immediate vicinity of the creeks.

Figures 4.7-1 and 4.7-2 plot pH against depth for samples in the western section (n = 321) and the eastern section (n = 387) of the deposit respectively. In the west, pH is low (mean of 4.4) and fairly uniform (standard deviation of 0.6), and displays a moderate positive correlation with increasing depth (r = 0.4). Eastern samples are on average less acidic (mean of 5.7) and more variable (s = 1.1). Correlation with increasing depth is very weak (r = 0.16). The higher degree of variability reflects the complex history of the eastern section and the presence of marine and brackish influences at varying levels in cores.

The contrast in geochemical values between eastern and western data sets, as well as differences in vegetation, and the physical character of the peat, reflects differing hydrological conditions in the ombrotrophic western part of the deposit and the locally rheotrophic, marine influenced eastern section (See Chapter 2). In order to clarify the distinctions, the results will be described under separate headings for east and west.

b) Total Sulphur Distribution

i) Sulphur and pH in the Western Section of the Deposit.---The western section of the deposit is a slightly domed, roughly concentrically-zoned mire, the centre of which is an extensive bog-plain.
Figure 4.7. Scatter plots of pH vs Depth (cm) for samples in the eastern and western sections of the deposit. Low correlation in the east reflects the complex hydrology and stratigraphy in the areas bordering Almirante Bay.

*n = 387, mean pH = 4.4 (s.d. = 0.6), range 2.82 to 6.29, 
r (correlation) = +0.16

*n = 324, mean pH = 5.7 (s.d. = 0.6), range 2.67 to 7.89, 
r (correlation) = +0.4
The surface of this region is permanently submerged, and drainage is by surface run-off in a radial pattern. The bog plain vegetation is an impoverished community dominated by sawgrass (sedges), together with *Sagittaria lancifolia*, *Dieffenbachia longispata*, ferns, grasses, mosses and algae. Stunted *Myrica mexicana*-*Cyrilla racemiflora* tree hammocks are scattered sparsely across the plain. Sawgrass-stunted forest-swamp, *Campnosperma panamensis* and mixed forest-swamp, and *Raphia* palm-swamp surround the central bog plain.

Despite the variations in vegetation, the absolute sulphur content of all peat types is low. Sulphur is lowest in the bog plain peats, and slightly higher in the marginal zones. Towards the barrier bar, windborne sulphate may add to nutrient availability, and in shallow peat towards the southwest margin groundwater-borne nutrients may be more available. In all cores, pH (dashed lines in Fig. 4.6) shows an erratic but overall increase with depth, coinciding with increases in the degree of humification of the peat. This increase overshadows the effect of concentrated humic and fulvic acids in the more degraded peats, which would tend to lower the pH at depth, but the same trend of increasing pH with depth is found in almost every core. The trend in pH does, however, echo transitions in peat type, and in floral association as determined by pollen analysis, from principally *Campnosperma panamensis* and mixed forest- and palm-swamp peat in the lower parts to bog-plain sawgrass peats in the upper parts of the cores. Utilizing particle size distribution by wet-seiving to quantify the degree of humification of the peat, a very close correspondence between increases in humification and increased sulphur concentration is found (Figure 4.8).

In the bog-plain cores, the pH of the underlying forest-swamp peats is higher than that of the overlying sawgrass peats. Thus higher pH is associated with forest-swamp peat, increasing depth (age), and slightly higher total sulphur content. To further explore these three relationships, data from the bog plain (MILE 5 - Fig. 4.8) is compared to that from site LAKE 2, located in mixed forest-swamp 1200 m from the barrier beach. This core, Figure 4.9, is composed of fine hemic woody peat throughout its entire depth, and the particle size distribution is consistent throughout. The sulphur
Figure 4.8. Variation in particle size (humification) pH and sulphur in an 870 cm core from the central part of the deposit (MILE 5) showing the close correspondence between increases in humification and increases in sulphur content. The particle size categories are coarse (c > 2.0 mm), medium (m > 0.25 mm), and fine (f < 0.25 mm).

Figure 4-9. Variation in particle size (humification) pH and sulphur concentration in a forest-swamp core from near the margin of the western section (LAKE 2), showing an inverse relationship between pH and sulphur content. Particle sizes are as for Fig. 4.8.
concentration is higher than in sawgrass peat, and decreases slightly with depth independent of humification. The pH of the LAKE 2 forest-swamp peat is lower (avg. 3.7) than that of the MILE 5 core (avg. 4.2), and pH increases with depth. This low pH peat is both highly humified, and relatively high in sulphur content. Low sulphur peats originating from forest-swamp vegetation have higher sulphur content than do sawgrass peats from the bog plain, regardless of pH. The range in sulphur variation is considerable (0.16 wt%); thus fine hemic peats have about twice the sulphur content of coarse hemic peat. All samples had salinity below 0.02 wt% (Group I).

ii) Sulphur, Salinity and pH in the Eastern Section of the Deposit.—-The upper panel in Figure 4.6 shows sulphur and pH values for a series of cores along the NW-SE cross-section from the Changuinola River floodplain to the submerged peat beneath Almirante Bay. The eastern part of the deposit is that part within the influence of tidal creeks which drain into Almirante Bay, represented by cores BDD 8, 23, 20 and 19A in Figure 4.6. Present vegetation is a complex mosaic of mixed forest-swamp, monospecific stands of Campnosperma panamensis, Raphia palm and sawgrass (Cyperaceae), with mixed mangrove and back-mangrove communities bordering the creeks up to 2 km from the coast. The bay margin is bordered by Rhizophora mangrove fringe forest. The complexity of the vegetation reflects the complex hydrology of this section, which is divided by the three major channels (Figs. 4.1 and 2.5) into areas of low salinity and sulphur (Group I) forest and sedge peats, bordered by Group II back-mangrove peats, and Group III Rhizophora peats.

Site BDD 8 is in mixed forest-swamp near the head of a blackwater creek 3 km inland, and BDD 23 is 1.5 km closer to the bay, in similar vegetation. The sites are about 50 m from the present channel of Canal Viejo, and salinity is < 0.1%. In the upper 2.5 m at both sites the peat is forest-swamp and Raphia peat, pH is below 4.5, and sulphur content is less than 0.5 wt% (i.e. Group I). Lower in the cores, pH increases rapidly to near-neutrality. Sulphur remains low at the inland site, but increases to 13.7 wt% at BDD 23 in back-mangrove (Laguncularia-Acrostichum-Rhizophora) peat (Group II). At the coast (BDD 20) pH varies between 5.4 and 6.3. Sulphur averages 3.2 wt%,
Figure 4.10. Total sulphur and pH vs Depth for core CS 3.
and increases with depth (Fig. 4.6). About 600 m offshore at BDD 19A, sulphur is slightly higher (mean 3.8) and pH is neutral to alkaline (7 to 7.6). Both are Group III, predominantly *Rhizophora*, peat.

In the coastal mangrove fringe (Group III) peats, pH averages around 5.8 (s = 1.35; n = 237). The peat is consistently low in moisture content and highly humified (Fine Hemic to Hemic). Group II forest-swamp peats associated with drainage channels also are highly humified woody peats, but are lower in pH. Figure 4.10 shows pH and total sulphur for core CS 3, a site located 25 m from the banks of Caño Sucio (Black Creek) and 2 km upstream from the mouth. pH for peat in the core averages 3.4. Sulphur content varies from 0.52 to 8.09 wt% with no relation to pH. The basal sand 25 cm below the contact has a pH of 7.46 and a sulphur content of 3.19 wt%. From such cores it is evident that highly humified, high sulphur peat can form in a low pH environment.

c) Forms of Sulphur

In order to compare the sulphur distribution of Groups I, II, and III peats in the complex coastal zone, the total sulphur content of a coastal mangrove peat (site BI 3) and forest-swamp-back mangrove peat (the upper and lower parts of core BDD 23 respectively) is sub-divided into organic (C-S or carbon-bonded S, and ester sulphate), and inorganic forms (mineral sulphate, pyritic S and elemental S). The results of the analysis are summarized in Tables 4.1 and 4.2.

*i) BI 3: An Example of a Group III Peat.*—The pH, total S, salinity and the distribution of forms of sulphur in a 2.5 m mangrove peat core taken at site BI 3, across Almirante Bay on the shore of Isla Colon are shown in Figure 4.11. The top of the core is above sea level, but the peat pore water becomes strongly saline with depth. There is a very close correspondence between increase in salinity of the peat and the sulphur content, most particularly in aqueous sulphate content, and also in ester sulphate. It is not clear why the pH decreases at the level where salinity increases; dissimilatory
Table 4.1. Forms of sulphur at four levels in core BI 3.

<table>
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<th>No</th>
<th>SAMPLE</th>
<th>SITE</th>
<th>DEPTH</th>
<th>TOTALSULPH</th>
<th>%INORGANIC</th>
<th>HI-S</th>
<th>SO4</th>
<th>PYRITIC</th>
<th>ELEMENTAL</th>
<th>%ORGANIC</th>
<th>C-S</th>
<th>ORGSO4</th>
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<td>means as % of Total</td>
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<td>0.93%</td>
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<td>4.20%</td>
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</tr>
<tr>
<td>4</td>
<td>BI3-150-175</td>
<td>175</td>
<td>3.78</td>
<td>1.31</td>
<td>0.713</td>
<td>0.016</td>
<td>nd</td>
<td>nd</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>pH=6.22</td>
<td></td>
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<td></td>
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<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>mean</td>
<td></td>
<td></td>
<td>0.93</td>
<td>0.81</td>
<td>0.015</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>means as % of Total</td>
<td>100%</td>
<td>20%</td>
<td>20.10%</td>
<td>0.40%</td>
<td>nd</td>
<td>80%</td>
<td>70%</td>
<td>9.80%</td>
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</tr>
</tbody>
</table>

Note: HI-S is sulphur reducible by HI; C-S is carbon-bonded sulphur.

Table 4.2. Forms of sulphur at 4 levels in core BDD 23

<table>
<thead>
<tr>
<th>No</th>
<th>SAMPLE</th>
<th>SITE</th>
<th>DEPTH</th>
<th>TOTALSULPH</th>
<th>%INORGANIC</th>
<th>HI-S</th>
<th>SO4</th>
<th>PYRITIC</th>
<th>ELEMENTAL</th>
<th>%ORGANIC</th>
<th>C-S</th>
<th>ORGSO4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BDD23-5</td>
<td>175</td>
<td>0.38</td>
<td>0.0718</td>
<td>0.001</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td></td>
<td></td>
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<td>pH=4.07</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Camptosperma mean</td>
<td></td>
<td></td>
<td>0.0572</td>
<td>0.0006</td>
<td>0.316</td>
<td>0.064</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>means as % of total S</td>
<td>100%</td>
<td>0.20%</td>
<td>0.20%</td>
<td>nd</td>
<td>99.80%</td>
<td>83%</td>
<td>16.80%</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>2</td>
<td>BDD23-8</td>
<td>250</td>
<td>0.78</td>
<td>0.1301</td>
<td>0.008</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td></td>
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<td>pH=4.38</td>
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<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>forest-swamp mean</td>
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<td></td>
<td>0.1415</td>
<td>0.007</td>
<td>0.644</td>
<td>0.128</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>means as % of total S</td>
<td>100%</td>
<td>0.60%</td>
<td>0.60%</td>
<td>nd</td>
<td>99.40%</td>
<td>83%</td>
<td>16.40%</td>
<td></td>
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<td></td>
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<tr>
<td>3</td>
<td>BDD23-11</td>
<td>400</td>
<td>13.70</td>
<td>2.9685</td>
<td>0.93</td>
<td>0.255</td>
<td>0.11</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>pH=4.66</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>back-mangrove mean</td>
<td></td>
<td></td>
<td>3.1548</td>
<td>0.744</td>
<td>0.254</td>
<td>0.069</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>means as % of total S</td>
<td>100%</td>
<td>8.30%</td>
<td>6.10%</td>
<td>1.66%</td>
<td>0.70%</td>
<td>91.70%</td>
<td>78%</td>
<td>13.70%</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>4</td>
<td>BDD23-13</td>
<td>450</td>
<td>1.43</td>
<td>0.8647</td>
<td>0.367</td>
<td>0.026</td>
<td>0.015</td>
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</tr>
<tr>
<td></td>
<td>pH=5.94</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>back-mangrove mean</td>
<td></td>
<td></td>
<td>0.9173</td>
<td>0.317</td>
<td>0.033</td>
<td>0.01</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>means as % of total S</td>
<td>100%</td>
<td>27%</td>
<td>23.90%</td>
<td>2.08%</td>
<td>1.00%</td>
<td>73%</td>
<td>38%</td>
<td>35%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: HI-S is sulphur reducible by HI; C-S is carbon-bonded sulphur.

n.d. = not determined
Figure 4.11. Summary of the geochemical characteristics of a coastal mangrove–back mangrove peat core, taken just above the high tide line at site BI 3. Variations in salinity, total sulphur, forms of sulphur and pH with depth are shown. The increase in the proportion of inorganic sulphate corresponds with an increase in salinity. Sulphur data from Table 4.1.
sulphate reduction, the process carried on by sulphate-reducing bacteria, increases alkalinity, which buffers pore water pH (Giblin and Wieder 1992), but any buffering effect from this activity or from the intrusion of marine waters is not apparent here. The opposite occurs, as the pore water pH drops from 6.4 to 5.4 in the upper 1 m.

There is an added complication in analysing shoreline cores from the Changuinola deposit as a result of recent seismic activity. When sampled, the peat surface at core BI3 was 10 cm above high tide level, but 13 months earlier, this site was 50 cm higher in elevation and somewhat farther onshore. Thus there has been substantial modification of the porewater geochemistry as a result of earthquake-driven subsidence (See Chapter 5; Phillips et al., 1994). Samples from farther onshore show that prior to subsidence, salinity in this core would have been lower. Consequently, the aqueous sulphate content in particular is higher than normal for mangrove peat. Additionally, the total sulphur is lower than in other mangrove peats tested. An analysis of means test (paired 2-sample t-test; n = 34) comparing the BI3 peats with intertidal mangrove peats shows a significant difference in means ($\alpha = .05$) of total sulphur content: 2.19 at BI 3, vs 3.45 for 34 other mangrove peats. Figure 4.12 plots salinity profiles of five mangrove-peat cores, 3 onshore and 2 from > 500 m offshore, and shows that the general trend is to a decrease in salinity with depth in the onshore cores, as hydraulic head in the fresh groundwater system, combined with low permeability of the dense woody peat, resists marine intrusion. Offshore cores are more saline, particularly near the top. Again, the BI 3 core is not exactly typical, resembling neither the onshore nor the offshore curves. The relationship between salinity and aqueous sulphate is reasonable, however, and other aspects of the distribution, particularly from the uppermost sample, are considered to be applicable to mangrove-fringe peats.

Casagrande and others (1977; 1986) found that ester sulphate normally comprises around 24% of the sulphur in high sulphur peats. This agrees fairly well with the findings of Phillips et al. (1994) (ester sulphate averaged 19.9% of total S in Panamanian peat), and with Lowe and Bustin (1985) (ester sulphate averaged 18.9% of total S in Fraser delta peats). Those studies documented
Figure 4.12: Wt% salinity vs Depth in 5 mangrove cores. 2 of the cores are now offshore and permanently submerged and 3 are in the intertidal mangrove fringe forest.
marine-margin peats which have not been overprinted with a transgressive signature (see Chapter 5), and suggests that in this core both 34.4% (at 75 cm) and 9.8% (at 175 cm) are unusual values. This spatial variability in ester sulphate content likely reflects variable responses to the recent transgression due to the heterogeneity of redox environments and bacterial populations within the peat. The specific causes and direction of changes in this fraction are unclear and difficult to interpret. High ester sulphate, along with high (>4%) elemental sulphur content in the middle of core BI 3, suggest that sulphate-reducing bacteria may be actively producing H₂S stimulated by the influx of marine water. Low ester sulphate content can also be an effect of bacterial reduction of organic sulphates, but with the very high aqueous sulphate concentration in this sample (20.1%), bacteria are not expected to favour ester sulphates for reduction. Pyrite content is very low.

**ii) BDD 23: An Example of Group I and Group II Peats.**—The sulphur profile of core BDD 23 records a change in the environment of deposition at this site, from a back-mangrove forest near the base, to *Raphia* - sedge, and then to *Campnosperma* - mixed forest in the upper 250 cm. The transition is reflected in the change from Group II at the base to Group I above. Group I is defined as low salinity, low sulphur, and Group II as low salinity, high sulphur peat. Table 4.2 and Figure 4.13 summarize the results of the analysis of forms of sulphur at four levels of core BDD 23. The samples are from depths of 175, 250, 400 and 450 cm. In all samples organic sulphur is dominant, comprising from 99.8% to 91.7% in the peat samples, and 73% of total sulphur in the sandy peat at 450 cm. The total sulphur curve shows the remarkable contrast between the upper 250 cm and the lower 240 cm of peat in this core. The transition is evident in the % moisture curve; the forest-swamp and sedge peats are wetter, less dense, and more acid (pH around 4.15 vs 5) than the back-mangrove peat.

In the low-sulphur (Group I) samples from the upper part of the core the distribution of sulphur forms is consistent with peat from an ombrotrophic mire: there is a small amount of aqueous sulphate present, but the bulk is split between carbon bonded (C-S) sulphur (83% of total S) and organic (ester) sulphate (>16%). These values are similar to those recorded by Casagrande et al.
Figure 4.13. Summary of the geochemical characteristics of core BDD 23, located about 50 m from Canal Viejo, a tidal blackwater creek which drains the eastern part of the deposit into Almirante Bay. Shown are variations in forms of sulphur, total sulphur, moisture content and pH with depth. Moisture content is used as proxy data for peat density, as described in Chapter 2. Sulphur data from Table 4.2.
for low sulphur peats from the Okefenokee Swamp. The source of this assimilatory sulphur is predominantly the peat-forming vegetation itself, as discussed later. Variations in concentration may reflect specific vegetation, or the degree to which atmospheric sulphate is available for assimilation. Periodic high water table and high surface runoff may lead to little sulphate entering the soil, whereas drier conditions and more permeable peat may increase available sulphur in the system. Atmospheric-sourced sulphate is rapidly assimilated into the organic sulphur pool, in a matter of hours or days (Brown 1985) under anaerobic conditions through the medium of dissimilatory sulphate-reducing bacteria. However, the absence of detectable elemental sulphur and the uniform proportions of ester sulphate and C-S suggest very low levels of bacterial sulphate reduction. The pH of these peats (mean of 4.15) is below normal tolerance for sulphate-reducing bacteria (Postgate 1984). Sources of Fe$^{2+}$ in this elastic-sediment starved ombrotrophic environment are limited to plant materials and pyrite formation is likely Fe as well as pH-limited. Thus the sulphur content of peat at the upper levels has not been influenced by sulphate-rich water present in the nearby tidal creek or groundwater.

The lower levels in core BDD 23 have high total sulphur content, particularly at the 400 cm level (13.7 wt% S), which is 90 cm above the base of the peat. Aqueous sulphate has been in ample supply, although it is presently in much lower concentration (6.1% of total) than it is in the basal sandy peat (23.9%), or in the newly-flooded peats of BI 3 (24.7%). Aqueous sulphate is present in the same proportion as in BI 3 mangrove peat that is not affected by secondary enrichment (i.e. normal for a marine-margin peat). Proportionally, the sulphur distribution most resembles that of the uppermost sample at BI 3, and others which have not been overprinted, although here the ester sulphate fraction is somewhat lower than in those samples. This may reflect a difference between mangrove fringe vegetation (BI 3) and this mixed-mangrove vegetation. The higher aqueous sulphate content of the basal sandy peat may be due to lower levels of sulphate reduction, or to its greater permeability and proximity to the underlying rooted sand, and brackish waters of the creek, but salinity is below .01 wt%. Pyrite represents 2% of total S in the basal sediments, 1.9% at 400 cm., and was not detected in the top 2.5 m. This low pyrite content differs from the BDT 3 site analysed by Cohen et al. (1990)
in which pyrite was interpreted to be the dominant sulphur form, based on SEM and petrographic analysis. That sample is mangrove peat with 14.9 wt% total sulphur. *Rhizophora* root peat frequently has high pyrite content (Cohen et al. 1984; Altschuler et al. 1983). However, at pH 4.9, the mixed-mangrove peat in this sample is somewhat more acidic than previously studied mangrove peats.

4.6 DISCUSSION

a) Sulphur, pH and Marine Influence

There is a clear relationship between marine influence and sulphur content in the Changuinola peats. In the western section of the deposit the peat is consistently low in sulphur. Cohen et al (1990) observed that sulphur content increased to the northeast, in the direction of the barrier bar, and suggested a possible marine influence from the Caribbean Sea. This study found no evidence of marine influence (beyond windblown saline aerosols) in the peats developed behind the barrier. Cohen et al. (1990) also found the lowest sulphur values associated with sedge-grass-fern peats (0.1%-0.3%), and somewhat higher values for the forest-swamp peats, as is confirmed by this study. Increase in sulphur coincides with higher degree of humification towards the margins of the deposit, just as it does towards the base, where palm-forest and swamp-forest peats dominate. Sulphur in these peats is principally assimilatory and high degrees of humification concentrate resistant compounds, including those that incorporate sulphur.

The variability evident in the eastern part of the cross-section (Figs. 4.1, 4.4) reflects the profound effects, but limited extent, of marine influence. In the upper half of core BDD 23 (Fig. 4.13), 50 m from a tidal channel and almost completely below sea level, sulphur, pH and salinity trends resemble those of the ombrotrophic western samples (i.e. MILE 5, Fig. 4.8). Sites associated with channels are lower in pH, and higher in sulphur content, although more variable than the strictly marine samples, and resemble the lower part of BDD 23. Total sulphur and pH of coastal mangrove-fringe sites at the shoreline resemble those of BDD 20 (Fig. 4.6), and to some extent BI 3 (Fig. 4.11), particularly the uppermost part of that core. In the inter-tidal environment total sulphur content tends
to increase in the upper metre or so, to 3% to 4% sulphur, and remain at those levels until near the basal sediments, where it decreases. The relationship between assimilatory sulphur concentration and degree of humification that is found in the low sulphur peats of the central part of the deposit is not evident in the marine- and channel-margin peats: the scale of variation in total sulphur is so great in samples associated with drainage channels that any relationship to degree of humification is overshadowed.

The expected relationship between high sulphur content and near-neutral pH, based on the pH preferences of the sulphur-reducing bacteria, is not evident in the brackish peats. Channel margin peats have pH around 5 and yet high sulphur content (5 - 14 wt%, 92% of which is organically bound). This high reduced organic sulphur content is a most interesting aspect of these channel-margin peats. Carbon-bonded sulphur compounds in peat and soil are not well understood, but include thiols, organic sulphides and disulphides, and sulphur-containing humic and fulvic acids which could be diagenetic products of reactions under reducing conditions between lignin-type materials and inorganic reduced sulphur (SH-, Sx2-) (Luther and Church 1992). Given anoxic conditions, microenvironments of tolerable pH, an ongoing supply of mineral sulphate, and sufficient organic matter, these very high concentrations imply an enduring biogeochemical chain of sulphur reactions, with carbon-bonded forms as the end result.

b) Sulphur and Vegetation

High degrees of humification are associated with woody forest-swamp peats and lesser degrees with bog-plain peats. This is in part a reflection of environmental conditions, and secondarily a consequence of the floral response to these conditions. Preservation is best and humification lowest in the topographically high central region. Here, the floral community of sparse sawgrasses, stunted arborescent species, shrubs, mosses and algae reflects the oligotrophic state of the mire. Competition for available nutrients contributes to the high degree of preservation: for example, Sphagnum spp. adapted to highly stressed environments, have the capacity to lower the pH of the growing
environment, reducing its viability for less adaptable taxa, and thus reducing species diversity. Low pH, combined with a large proportion of the biomass of the stunted vegetation being in the form of roots and rootlets, means that biomass production is low but preservation is high. The fibric and coarse hemic peats which are formed in this environment are of relatively low bulk density, high moisture content, and do not concentrate sulphur to high levels. Observed S levels for coarse hemic sawgrass peats are around 0.10 to 0.25 wt% sulphur.

Woody forest peats form in environments dominated by a luxuriant arborescent vegetation, much of the biomass of which is above the peat surface. Intense degradation above and just below the surface results in a high proportion of fine- to clay-size particles in the upper level of the peat. To these may be added more resistant lignin-rich elements of wood, bark and cuticle, resins, spores and pollen, ingrown roots, and a significant chitinous component from insects. Table 4.3 lists the total sulphur content of a number of fresh plant parts from this and other studies. The fine hemic and hemic peat thus formed is dense and compact, with relatively low moisture content and high bulk density and sulphur content. The most highly degraded forest-swamp peats (LAKE 2, Figure 4.9, for example) contain 0.25 to 0.5 wt% sulphur.

Halophytes of the marine mangrove fringe forest and back-mangrove association colonize the margin of Almirante Bay and form a distinctive fine, dense hemic peat composed primarily of rootlets and root tissues. (Florida Rhizophora peat has been characterised by Cohen (1968) as root peat and sedimentary peat, the latter distinguished by containing more than 5% non-root material.) Dominant plants in this narrow fringe forest are Rhizophora mangle, Acrosticum aureum, Raphia taedigera, and salt-tolerant sedges and grasses. Sulphur content of 36 Rhizophora peat samples from shoreline and now-submerged offshore sites averaged 3.52 wt% (s = 1.1, range from 1.07 to 5.98).

Behind the mangrove fringe, any of several sub-classes of mixed forest-swamp, monospecific Camprosperma panamensis (hardwood) or Raphia taedigera (palm) forest occur. The woody peats
**TABLE 4.3 A: Total sulphur content of some plant parts from this study:**

<table>
<thead>
<tr>
<th>Forest-swamp</th>
<th>Plant Part</th>
<th>wt% sulphur</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Campnosperma panamensis</em></td>
<td>wood/bark</td>
<td>0.093</td>
</tr>
<tr>
<td><em>Heliconia latispatha</em></td>
<td>leaf</td>
<td>0.48</td>
</tr>
<tr>
<td><em>Symphonia globulifera</em></td>
<td>resin</td>
<td>0.39</td>
</tr>
<tr>
<td><em>Myrica mexicana</em></td>
<td>wood/bark</td>
<td>0.045</td>
</tr>
<tr>
<td>Mangrove association</td>
<td>root</td>
<td>2.1</td>
</tr>
<tr>
<td><em>Rhizophora mangle</em></td>
<td>base</td>
<td>0.15</td>
</tr>
<tr>
<td><em>Acrostichum aureum</em></td>
<td>base</td>
<td>1.33</td>
</tr>
</tbody>
</table>

**TABLE 4.3 B: Some published total S content of plants:**

<table>
<thead>
<tr>
<th>Source</th>
<th>wt% sulphur</th>
<th>source</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Rhizophora m.</em></td>
<td>leaf</td>
<td>0.18</td>
</tr>
<tr>
<td><em>Rhizophora m.</em></td>
<td>root</td>
<td>0.23</td>
</tr>
<tr>
<td><em>Laguncularia r.</em></td>
<td>leaf</td>
<td>0.25</td>
</tr>
<tr>
<td><em>Laguncularia r.</em></td>
<td>root</td>
<td>0.06</td>
</tr>
<tr>
<td>plants (Little Shark River)</td>
<td></td>
<td>1.83</td>
</tr>
<tr>
<td>plants (Minnie's Lake)</td>
<td></td>
<td>0.078</td>
</tr>
<tr>
<td>surface litter (&quot;</td>
<td></td>
<td>0.028</td>
</tr>
<tr>
<td>plants (Chesser Prairie)</td>
<td></td>
<td>0.24</td>
</tr>
<tr>
<td>surface litter (&quot;</td>
<td></td>
<td>0.093</td>
</tr>
<tr>
<td><em>Mariscus jamaicense</em></td>
<td>leaves</td>
<td>0.058</td>
</tr>
<tr>
<td></td>
<td>basal culm</td>
<td>0.049</td>
</tr>
<tr>
<td></td>
<td>rootstock</td>
<td>0.166</td>
</tr>
<tr>
<td></td>
<td>fine rootlets</td>
<td>0.072</td>
</tr>
</tbody>
</table>

*Source:*

a = Price and Casagrande, 1991
b = Casagrande et al., 1976
c = Altschuler et al., 1983
associated with these forest-swamps are consistently in the upper end of the low-sulphur (0.25 to 1.0 wt%) range, even though in many cases they extend to within 15 m of the shoreline. Detailed study of two different coastal fringe sites which experienced coseismic subsidence and marine inundation hint at the range of possibilities of marine influence in very similar environments. Thirteen months after the subsidence event, saline intrusion into the peat shoreward of the high tide line at one site (BI 3) was found to be only about 175 cm (Chapter 5), while at a second site (BDD 35) heightened salinity was measurable 80 m onshore, and is reflected in the dying-off of all non salt-tolerant species across this breadth of shoreline. A new community of halophytic peat-forming species (Rhizophora, Acrostichum, etc) is currently establishing itself across the subsided marine margin.

c) Sulphur and Climatic Influence

A comparison of peats in this study with temperate high sulphur peats suggests that although climate determines vegetation, and extensive woody forest-swamp peats do not seem to be forming in temperate climes at the present time, climate is not a strong influence on total sulphur concentrations or on the distribution of sulphur fractions in coastal peats. The proportions of sulphur fractions found in the onshore Changuinola peats unaffected by recent marine inundation (i.e. primary sulphur) are comparable to those found in temperate brackish peats of the Fraser Delta (Lowe and Bustin, 1985). Mean total sulphur for 12 tropical samples is 3.02 ± 0.9 wt%, compared to a mean of 3.03 ± 1.58 for 8 temperate brackish sedge peats. Mean organic sulphur content for the tropical peats tested is 94%, compared to 94.2% for the Fraser peats, and organic sulphate represents 19.9% in the tropical peats, and 18.9% in the temperate. The inorganic fractions vary slightly more: mineral sulphate 4.7% vs 3.6%; elemental sulphur 1.6% vs 1.1%; and pyritic sulphur 0.6% vs 1.2%, for tropical and temperate peats respectively. Thus pyrite is lower in the tropical peat, probably limited by Fe availability in this clastic sediment starved environment. Mineral sulphate and elemental sulphur are slightly more prominent in the tropical peat.
**d) Sulphur and Tectonic Influence**

Tectonically-driven regional sea-level fluctuations are the ultimate control on peat deposition in the Changuinola area, and the tectonic setting of the Changuinola deposit is in some ways reflected in the sulphur distribution in the peat. Since the late Holocene stabilization of global sea level, the Caribbean coast of southern Central America has been in an overall regressive mode, and uplift and high sedimentation rates have moved the shoreline seaward (Collins et al., 1994). At the same time regional structural movements have created both localized regressive and transgressive coastlines. To the northwest of this study area, in Costa Rica, coastal uplift has exposed nearshore reefs and caused erosion of carbonates and redeposition of offshore bar sediments. There are no major coastal swamps along this emergent coastline. However, 90 km to the east in Panama, seismic events, including the April 1991 event, have a long recorded history of causing subsidence. This has resulted in the development of extensive low-lying freshwater swamps, localised replacement of forest swamp vegetation by halophytic mangrove-fringe forest, and eventual drowning, as observed in the eastern part of the Changuinola peat deposit. In this regime, transgression is from SE to NW in the deposit, effectively parallel to the overall trend of the coastline. The distribution of medium and high sulphur peats reflects this geometry: medium-sulphur peats now underlie Almirante Bay at all sites sampled; very high sulphur peats are exclusively associated with present tidally influenced drainage channels, or topographic lows (old drainage) now below sea level; high-end low sulphur (0.5 to 1.0 wt% S) peats are found in forest swamp zones, including within metres of the mangrove fringe and centimetres of the high tide level. Farther west, very low S peats are found in developing bog-plains elevated a decimetre or more above sea level, and in the entire centre of the western part of the deposit. Organic sediments are thus recording regional vertical trends. Peat with both very high and very low primary sulphur content has accumulated due to rising sea level in a region which is experiencing overall uplift.
4.7 IMPLICATIONS FOR ENVIRONMENTAL STUDIES OF COAL

As has long been known to coal geologists, medium to high total sulphur content in peat is spatially related to marine or brackish influence (Williams and Keith 1963). This study confirms the relation. In addition, despite the short-term nature of these observations compared to coal studies, the distribution of sulphur in the Changuinola peat deposit provides some new insights into sulphur in coal and its usefulness as an environmental indicator.

As with the peat in this study, it may be possible to distinguish between primary syndepositional sulphur, secondary or overprinted sulphur due to transgression, and sulphur associated with channels and brackish environments in coal, based on proportions of forms of sulphur present. Diagenetic changes to organic and inorganic components during coalification inevitably smear depositional chemical signatures. However, clarification of the origins and proportions of labile and conservative S forms associated with particular conditions provides the starting point for environmental interpretation. For example, high stable C-S sulphur content in high sulphur coals is likely an indication of estuarine environments, or brackish drainage associated with channels, in which primary C-S tends to be high. Channels in peat tend to be long-lived and highly resistant to erosion, and restriction of brackish influence can be due to low permeability of the peat, doming of the peat surface, or hydraulic pressure from the high water table. Thus high C-S sulphur coals may be laterally restricted, and adjacent coals a few metres away may be low in primary sulphur, even though diagenetically enriched in pyrite.

Coals which originated as distinctly marine peats (i.e. from halophytes) are likely to have significant pyrite, both primary and diagenetic, but organic forms still dominate the primary component. The above characteristics can develop in both transgressive and regressive depositional regimes. The marine mangrove peat in this study has moderate total sulphur content (2 to 5 wt%).
principally in organic forms but with a significant inorganic component. Pyrite varies from 0.1 to 3.6 % of total sulphur.

Coals with a distinct transgressive signature are likely to have a large proportion of sulphur as diagenetic pyrite resulting from the influx of secondary inorganic sulphur, and possibly from ester sulphate. However, such coals are not necessarily high in total sulphur. Coastal peats that have experienced marine transgression and are now submerged display a transgressive signature which includes highly variable ester sulphate content and an increase in the proportion of inorganic sulphur forms (Phillips et al., 1994; Chapter 5). The influx of marine waters has resulted in a larger proportion of mobile sulphur forms relative to stable C-S sulphur, but has not resulted in large increases in total sulphur content. Tectonically driven coseismic subsidence can lead to long term flooding of coastal peats by sulphate-rich sea water. Over the short term the variability in the ester sulphate fraction, over cm-scale distances, is due to the heterogeneity of pore water environments and the highly variable permeability of peat. In the longer term, this overprinting would likely result in pockets of secondary pyrite formation in coal.

In oligotrophic settings with no groundwater sulphate sources, total sulphur content of peat is low. In coals in which no marine influence is evident, sulphur content has been related to the inferred pH of the precursor peat. In Changuinola peats with no marine influence, total sulphur content varies directly with the degree of humification of the peat, which in turn broadly reflects peat type, but bears little direct relation to pH. Peat-forming plant communities which have a high proportion of subaerial biomass (forest-swamp peats) produce a woody, highly humified hemic and fine hemic peat in which sulphur may be concentrated at levels double that of more fibrous, root-dominated peat (sedge peats) of raised bog-plain environments. Beyond the broad distinction between herbaceous peats and woody peats, there is no significant difference between the total sulphur content of the different types of woody peat (Raphia, Campanosperma, mixed). The variable sulphur content of the original plant material is less significant than the degree of humification in low-sulphur peats. In turn, degree of
humification is much more dependent on the height of the water table than on the pH of the peat or porewater. Thus it is risky to infer high paleo-pH of a coal swamp on the basis of highly humified peat precursors alone. High levels of humification occur in very low pH sites if the water level drops, or if the plant community has a large subaerial biomass. The sulphur found in these low-sulphur peats is overwhelmingly organic in form. Any pyrite in coal associated with peats from ombrotrophic bog environment is likely post-depositional.

4.8 CONCLUSIONS

The following observations can be made regarding the distribution of sulphur in the Changuinola peat deposit:

High sulphur content is spatially related to marine or brackish influence.

The highest sulphur content (>5 wt%) is found in peats proximal to the brackish influence of blackwater drainage channels up to several km from the coast. Very high sulphur was also found in the basal peats in the deepest parts of the deposit, which are interpreted to have been associated with channels. Very high sulphur content is found even where salinity is undetectable in peat, porewater or basal sediments, and despite the low pH of the peat, which inhibits bacterial sulphate reduction.

High sulphur peat is not necessarily high in pyrite, and large quantities of sulphur may be bound in unreactive organic compounds from which it is unlikely to be released biogenically.

Peat-forming plant communities which have a high proportion of subaerial biomass (ie. ombrotrophic forest-swamp peats) produce a woody, highly humified hemic and fine hemic peat in which sulphur may be concentrated at levels double that of more fibrous, root-dominated peat of raised bog-plain environments.

In the absence of marine influence, total sulphur content varies directly with the degree of humification of the peat, which in turn broadly reflects peat type. However, beyond the broadest distinction, between herbaceous and woody peats, there is no significant difference between the total sulphur content of the different types of woody peat (Raphia, Campnosperma, mixed forest-swamp).
Thus the variable sulphur content of the original plant material is less significant than the degree of humification in low-sulphur peats.

Degree of humification in peat is much more dependent on the height of the water table than on the pH of the peat or porewater. High levels of humification can occur in very low pH sites if the water level drops, or if the plant community has a large subaerial biomass. However, in an oligotrophic mire with no groundwater sulphate sources, total sulphur content remains low.

ACKNOWLEDGEMENTS

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4.9 REFERENCES CITED


CHAPTER 5

EARTHQUAKE-INDUCED FLOODING OF A TROPICAL COASTAL PEAT SWAMP: A MODERN ANALOGUE FOR HIGH SULPHUR COALS
5.1 ABSTRACT

High sulphur content of coal is generally attributed to marine inundation during or shortly following peat formation. When a large peat deposit on the Caribbean coast of Panama subsided during a 1991 earthquake, sulphate-rich seawater inundated the margin of the deposit, providing the opportunity to evaluate the role of short-term marine flooding on sulphur abundance and chemistry. Salinity and pH measurements across the new marine margin indicate that penetration of saline waters into the peat is restricted to < 2 m both vertically and horizontally. A comparison of forms of sulphur in the newly flooded peat vs adjacent, subaerial peat reveals that total sulphur content is not increased by flooding, but that the distribution of sulphur forms differs markedly after marine inundation: inorganic forms, particularly mineral sulphate, make up a higher proportion of the total; the organic sulphate fraction becomes highly variable; and the carbon-bonded sulphur content remains seemingly unaffected. Heightened bacterial activity is seen as a likely mediator in this redistribution of sulphur forms. Our results indicate that high sulphur content of coals and peats cannot form by short-term periodic flooding events such as storms but must reflect long term infiltration of marine or brackish waters measured on time scales of hundreds to thousands of years.
5.2 INTRODUCTION

It is a paradigm in coal geology that high sulphur (S) coals result from syn- or post-depositional inundation of peat by brackish or marine waters (e.g. Horne et al., 1978). The importance of short-term inundation by marine waters on S content of peat and, by analogy, coals has, however, never been tested. Aqueous sulphate (SO\(_4^{2-}\)) in rain, groundwater and the oceans is the principal source of S found in peat. Concentration of S is from <1 to 8 ppm in fresh water and 885 ppm in seawater. Sulphate is reduced by respiring plants and S-reducing bacteria. Plants use the oxygen for respiration, and fix some S, as carbon-bonded (C-S), in a variety of amino acids and related compounds, and as so-called ester sulphates (C-OSO\(_3\)) in polysaccharides, choline sulphate, phenols, and other compounds. Reduced S may be subsequently reoxidized to a variety of oxidation states, leading to the formation of polysulphides and of elemental or pyritic S. The primary S content of peat is dependent on the availability of aqueous sulphate to living plants and bacteria. In brackish and marine-influenced peat, S concentration can be high, and is not limited by pore-water sulphate concentration.

Part of the Caribbean coast of Panama is undergoing marine transgression as a result of earthquake-induced subsidence, and thick peat beds are overlain by shallow-water carbonate and clastic sediments (Fig. 5.1). On April 22, 1991 a magnitude 7.4 earthquake (Camacho et al., 1993) near Changuinola, Panama, led to 50 – 70 cm of coseismic subsidence and resulted in marine waters penetrating into the large back-barrier swamp. The effects of that rapid flooding on the concentration and distribution of a variety of S forms are assessed by comparing long-submerged peat, newly drowned peat, and immediately adjacent subaerial peat. By taking advantage of a
Figure 5.1. Site of the study on the Caribbean coast of Panama is shown, lower left, in relation to the epicentre of the 1991 earthquake in the Rio Estrella valley, Costa Rica. The block diagram illustrates the extent of marine transgression at site BI 3 as a result of earthquake-induced subsidence.
measurable subsidence event, this study attempts to provide insight into the processes that lead to the formation of very high sulphur coals (> 5% S), particularly the role of short-term marine flooding.

5.3 SAMPLING AND EXPERIMENTAL PROCEDURES

Samples were collected across a sea level transect and from three submerged offshore sites (Fig. 5.1). At the transect site, red mangrove (*Rhizophora mangle*) and sawgrass (*Rhyncospora* sp.) dominate the peat forming vegetation, both at the surface and throughout the peat cores. The following analyses were performed: pH, salinity and total S on all samples (Fig. 5.1, Table 5.1). On eight samples, forms of S were determined: organic S in both carbon-bonded sulphide (C–S) and ester sulphate (oxidized compounds reducible by HI) forms, and inorganic forms expressed as mineral sulphate, elemental S, and pyritic (+ marcasite) S (Table 5.2). The analytical methods used are described by Lowe (1986) and Tabatabai (1992).

5.4 RESULTS

a) Total Sulphur, Salinity and pH

Shallow onshore samples have low total S (0.29–0.65 wt%), and low salinity (0.02–0.05 wt%) except adjacent to the high tide line, where higher salinity (0.94 wt%) reflects the extent of wind blown salt and wave washover. Below sea-level, S values both onshore and offshore increase with depth, to the range of 3.0–4.5 wt%. Although total S increases steadily with depth, there is also substantial spatial variation (Fig. 5.2). Sulphur content of the basal carbonate sands is low (0.4 wt%). Salinity onshore is consistently low (<0.08 wt%) and spatially variable. Offshore, salinity is high near the peat-water interface (maximum 2.1 wt%), and decreases irregularly down to the base of the peat. Significantly, total S in the now inundated and much more saline part of the transect is not elevated compared to onshore values.
<table>
<thead>
<tr>
<th>Site</th>
<th>Depth (cm)</th>
<th>pH</th>
<th>Salinity (wt%)</th>
<th>Total S (wt%)</th>
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<tr>
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<td>0.05</td>
<td>0.52</td>
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<td>2.10</td>
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Table 5.1. Total sulphur data, BI 3 and offshore sites.
### TABLE 5.2. SULPHUR FRACTIONS IN EIGHT PEAT SAMPLES

<table>
<thead>
<tr>
<th>No.</th>
<th>Sample Site</th>
<th>Depth (cm)</th>
<th>Total Sulphur (wt%)</th>
<th>Inorganic Sulphur (%)</th>
<th>HI-S Sulphur (wt%)</th>
<th>ESS Sulphur (wt%)</th>
<th>Pyritic Sulphur (wt%)</th>
<th>Elemental Sulphur (wt%)</th>
<th>Organic Sulphur (%)</th>
<th>C-S Sulphur (wt%)</th>
<th>Organic Sulphate (wt%)</th>
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<td>1</td>
<td>BIT3-23</td>
<td>10</td>
<td>1.16</td>
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<td>0.24</td>
<td>0.014</td>
<td>0.005</td>
<td>n.d.</td>
<td>98</td>
<td>0.916</td>
<td>0.225</td>
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<tr>
<td></td>
<td></td>
<td>100%</td>
<td></td>
<td></td>
<td>1.19%</td>
<td>0.04%</td>
<td></td>
<td></td>
<td>79%</td>
<td>19.4%</td>
<td></td>
</tr>
<tr>
<td>2</td>
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<td>2.28</td>
<td>30</td>
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<td></td>
<td>35%</td>
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Note: HI-S is sulphur reducible by HI; ESS is easily soluble mineral sulphate; C-S is carbon bonded sulphur. n.d. = not determined
Total S was also determined for 12 peat samples collected from three sites that have been submerged for much longer periods. One sample (BDD19A) from 475 cm below present sea-level, radiocarbon dated at 2110 ± 60 yr., has a total S of 3.21 wt% (salinity of 2.0 wt%). It is overlain by 265 cm of peat, 15 cm of carbonate sediments, and 195 cm of salt water. Total S for all the long-submerged peats averages 3.2 ± 1.04 wt% (Table 5.1).

b) Forms of Sulphur

i) Organic Forms — Organic forms predominate in all samples (Table 5.2) ranging from 63 – 98% of total S. All onshore samples have > 90% organic S, whereas offshore samples have < 80% organic S. The two samples with the lowest proportion of organic S (samples 7 and 8) are submerged, and thus not surprisingly have the highest pore-water salinity and pH of all samples tested. Onshore, ester sulphate is uniform at 19 – 21% of total S. C-S ranges from 73 – 79%. In contrast, offshore ester sulphate varies widely, from 7% to 41% of total S, and generally decreases with depth. C-S varies from 27 – 70% of total S offshore, and increases with depth.

ii) Inorganic Forms - In all samples, mineral sulphate is the dominant inorganic form. Onshore, mineral sulphate comprises 1.2 – 6.6% of total S. Elemental S was only detectable in one sample, at 1.6%. Pyritic S represents 0.04 – 1% of total S. Offshore, mineral sulphate is found in much higher proportions, varying from 16.1 – 29.4% of total S. Elemental S constitutes 4.2 – 11.8% of total S, and pyritic S 0.1 – 3.6%. The presence of H₂S could be detected by a faint smell in all samples but was not measured.
Figure 5.2. Spatial variation in total sulphur and salinity of peat across the newly-submerged marine margin. Sample sites in boxes are also shown in Figure 5.1. Inset columns 1 - 8 depict variation in sulphur fractions for the eight numbered samples, based on data in Table 5.2. The columns are arranged from left to right in increasing distance from the peat/salt water interface, illustrating the effects of inundation on the relative proportions of C-S and ester sulphate, and the increase in aqueous sulphate. Iso-sulphur curves (dotted lines) of 1, 2 and 3% S reveal the spatial variability of these geochemical signatures: the depressed region is around the remains of a 1cm diameter mangrove root, which provides a conduit for rainwater. Vertical exaggeration is x10.
5.5 DISCUSSION

Sulphur concentration in marine-roofed coal is commonly highest at the top and decreases down-seam. Such a distribution has been used to suggest that marine or brackish water inundation results in S enrichment near the peat surface due to stimulation of anaerobic sulphate reduction. The decrease in S content with depth is considered to reflect the progressive bacterial depletion of $\text{SO}_4^{2-}$ as the water passes downward (Brown and Macqueen, 1984). Most high-S peats, however, do not show the trend observed in coals. Rather, total S in marine-influenced peats (Altschuler et al., 1983; Bustin et al., 1987) tends to increase with depth in the upper few cm, then remains relatively constant with increasing depth, as it does in this study.

The primary S content of the peat in this study is moderately high but typical of peats having formed in a marine-influenced environment by the progradation of a mangrove fringed shoreline (Given and Miller, 1985; Cohen et al., 1989). Higher S concentration toward the base of the peat is attributable to ongoing assimilatory bacterial reduction, and increased decomposition of organic matter with burial, leading to concentration of resistant compounds in the older, more degraded peat. Much higher S content, on the order of 10 wt%, was recorded in high-ash, brackish peats from the Florida Everglades (Casagrande et al., 1977), and levels as high as 13.7 wt% (92% organic) was found in samples collected near the site of this study (Cohen et al., 1989; Phillips et al., in press). It is still not clear, however, what environmental conditions lead to such high S content. If it is the result of secondary enrichment following marine inundation, it clearly requires more time than the 13 month exposure to marine waters of peats of this study. Brown and Macqueen (1985) determined that metabolic $\text{SO}_4^{2-}$ uptake from water inundating a peat surface may be delayed until the necessary reducing environment (Eh ~ 100 mv.) has been established near the peat surface. In their laboratory study this took only a few days. Once reducing conditions were established, molecular
diffusion driven by biologically mediated concentration gradients proceeded at a rate that, although dependent on sulphate concentration of the inundating waters, was generally comparable to the diffusion rate of H₂SO₄ in dilute aqueous solutions. In the present study it is not evident from total S content of the inundated vs. onshore samples that any measurable increase occurred as a result of the sudden flooding of the peat with seawater. In fact, iso-S contours (Fig. 5.2) are depressed to greater depths in the newly inundated peat. Salinity and S values from the long-submerged offshore cores (Table 5.1) suggest minimal percolation of seawater down through the peat during the period of submergence and no indications of total enrichment beyond that expected for mangrove peat.

Pore water salinity and pH distribution indicate that the lateral extent of marine infiltration is limited to ~ 2 m. Such restricted marine infiltration may be due to the ever-wet climate, which maintains a high water table and positive hydraulic head in the groundwater system year-round, together with variations in permeability of the peat. The higher salinity, and high mineral sulphate content of the offshore samples, (average 21% of total S), suggests that inundation has indeed allowed the introduction of aqueous sulphate into the peat. However, mineral sulphate content does not decrease consistently with depth, either proportionately or in absolute terms. The proportion of mineral sulphate in the onshore samples is low (1.19% to 6.6% of total S).

The presence of a significant amount of elemental S in offshore samples may indicate substantial sulphate-reducing bacterial activity. Elemental S may result directly from the reduction process or from the subsequent oxidation of dissimilatory hydrogen sulphide, for example around roots of mangroves. Pyrite, linked to bacterial activity in mangrove peats (Cohen et al., 1984) is also present to a greater extent in samples 7 and 8, where elemental S concentrations and pH (6.9 and

186
6.59) are highest. All of these factors indicate that a more favorable environment for heterotrophic sulphate reducing bacteria now exists in the offshore peat.

Onshore, the organic S fraction is dominated by C-S forms similar to those found in high-S coals, and as appears to be the norm for marine peats. Onshore ester sulphate is consistently around 20% of total S, comparable to values reported for other marine and brackish peats (Casagrande et al., 1977; Bustin et al., 1987). Both the organic S content, and the relative proportions of C-S to ester sulphate are much more variable in the offshore than onshore samples. The C-S pool in organic matter has been found to be more conservative than the ester sulphate fraction (Howarth and Stewart, 1992); thus changes in the environment are more likely to be reflected in the ester sulphate fraction. The two samples closest to the marine influence display very high ester sulphate content. In sample 7, ester sulphate is the dominant form (41%). However, a few cm lower in the core, that fraction represents only 7% of the total, and 75 cm below that, 9.8%. Assuming 20% to be a reasonable proportion of ester sulphate in high-S peats unaffected by secondary enrichment, it seems that samples a few centimetres apart can undergo variable secondary effects. Enrichment of the ester sulphate fraction may occur as the result of bacterially reduced inorganic S, in the form of elemental S, recombining with humic compounds in the peat (Casagrande et al., 1977). Depletion of the ester sulphate fraction may be caused by bacterial digestion of organic matter and increased peatification, as it is in low S peats. Thus, it is possible to speculate on a bacterially mediated flux in the ester sulphate fraction, and the results reported here may give some indication of the potential magnitude of that flux. Depletion of the ester sulphate fraction may also be affected directly by bacterial reduction, but in this case aqueous $SO_4^{2-}$ is in ample supply and is preferred over organic sulphate by bacteria (Altschuler et al, 1983). Thus, no decrease as a result of direct bacterial reduction is expected. Like anaerobic bacterial activity, increases in elemental S and pyrite are pH
and Eh dependent, and thus not inconsistent with variable ester sulphate content. In this study, the highest pyritic and elemental S contents are found in the sample with the highest ester sulphate, the lowest C-S fraction, and the highest pH. Microenvironments of varying oxidation-reduction potential associated with root penetration, or other permeability factors, may result in variable bacterial activity and may be a factor in the large variations in ester sulphate.

5.6 CONCLUSIONS

In the study area on the Caribbean coast of western Panama, tectonically driven subsidence is leading to inundation of a thick peat deposit and burial beneath marine sediments. No evidence of enhancement of total S concentration in peats inundated by normal marine water is evident. Spatial distribution of S fractions and of elevated pore-water salinity suggests ~175 cm of penetration of marine waters both horizontally and vertically in the 13 months that elapsed since inundation. Sulphur concentration increases with depth in the upper 175 cm, up to a level typical of, but no higher than, other mangrove peats sampled in this area.

The distribution of S forms differs markedly between onshore samples unaffected by inundation and those now under water. Inorganic S forms represent a much larger proportion of total S in offshore peat. A higher proportion of mineral sulphate is found in the offshore samples. Significant quantities of elemental S are present in all but the deepest of the offshore samples, whereas it is undetectable in the onshore samples. Pyritic S is present in all samples but is only >1% of total S in one of the offshore samples. Pyrite is not a dominant S form, and is not seen to be forming at the expense of ester sulphate.
The short-term effects of marine inundation are to increase the relative proportion of inorganic over organic S in peat and to introduce considerable variability in the ester sulphate content. Thus the proportion of ester sulphate may be the best indicator of the geochemical history of a peat deposit. The geological implications remain to be determined by detailed analyses of forms of S in marine-roofed coals.

By analogy with peats of this study, the high sulphur content of coals cannot reflect short-term or periodic storm flooding events but must reflect prolonged infiltration, probably measured on time scales of hundreds to thousands of years.

ACKNOWLEDGEMENTS

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5.7 REFERENCES CITED


6.1 CONCLUSIONS

"Let us suppose an earthquake, possessing the characteristic undulatory movement of the crust, in which I believe all earthquakes essentially to consist, suddenly to have disturbed the level of the wide peat-morasses, and adjoining flat tracts of forest on the one side, and the shallow sea on the other. The ocean, as usual in earthquakes, would drain off its waters for a moment, from the great Stigmaria marsh, and from all the swamps for which skirted it, and, by its recession, stir up the muddy soil, and drift away the fronds, twigs and smaller plants, and spread these, and the mud, broadly over the surface of the bog. Presently, however, the sea would roll in with impetuous force, and, reaching the fast land, prostrate every thing before it.”

Henry Darwin Rogers, 1842


When Henry Rogers, in the 1840’s, was seeking to understand the processes by which the Appalachian coal strata came about, he imagined the swampsy, tropical coast of ancient Pennsylvania wracked by periodic violent earthquakes, the sudden subsidence and subsequent tsunamis and flooding bringing a violent end to peat deposition and producing the widespread carbonaceous shale partings that he was finding in his explorations. It is a faculty of the human mind to imagine the processes which account for the world around us, and is a particularly valuable faculty for the geologist, who is often trying to reconstruct events, much of the evidence of which is long obliterated.

Detailed documentation of an event similar to that imagined by Henry Rogers may not support his conjectures, as in the present study of the Changuinola peat deposit, but both the speculation and the documentation have their roles in the evolution of a model which fits processes to products. Rogers imagined his Pennsylvanian Stigmaria marsh as a vast, perfectly planar marine savannah. The closest known modern analogues to coal-forming mires, the Changuinola mire system and the known thick peat deposits of southeast Asia, do not conform to this pattern, but develop an elevated topography and an
internal structure that encourages continuing peat accumulation, and insulates them from the surrounding clastic sedimentary environments. Several generations of geologists have since contributed to our understanding of the palaeogeography and topography of coal-forming mires. In any event, it would require a far more destructive earthquake than the Ms 7.5 shock which struck the Panama coast in 1991 to leave the kind of geological evidence envisaged by Rogers.

The goals of this investigation were to evaluate the Changuinola peat deposit as a possible analogue for the deposition of low ash, low sulphur coals, and to document the effects of earthquake-driven subsidence events on the peat and the peat-forming vegetation. The deposit differs in significant ways from previously studied tropical peats, and thus provides some new insight into the process of thick peat accumulation, and hence the nature of coal-forming depositional environments. In addition, and perhaps surprisingly, it is evident that the impact of rapid coseismic subsidence on the peat deposit is considerably more subtle than Henry Rogers would have expected.

This study shows that the development of elevated, oligotrophic bogs, as described in the Anderson model, and the accumulation of thick peat and hence coal deposits can occur in response to tectonically-driven punctuated subsidence, as well as gradual eustatic sea level rise. The process can proceed without leaving a record of increased clastic input within the peat, even immediately adjacent to environments of active clastic deposition. The approximately 10 m of relief on the basal sands, a product of the mode of subsidence and sedimentary response with which the barrier sands aggrade and prograde, is a significant difference between the Changuinola deposit and the modern southeast Asian peats, which have planar bases and are almost entirely above sea level.

Climatic influences have a profound effect on the nature of peat deposition. On this wave- rather than storm-dominated coastline, the back barrier environment is free of all but minor aeolian clastic input.
In the tropical climate peat accumulates on barrier sands in swales directly behind the beach, and progrades seaward with the barrier shoreline, without the colonizing mangrove fringe common to the Malesian deposits. In fact, the greater part of the deposit displays no internal evidence of marine influence, despite being approximately 40% below sea level. Although instantaneous subsidence of 30-50 cm left its mark in structures in the barrier sand body, it is not detectable in the peat behind the barrier. The part of the deposit which does display marine influence is at the southeastern extent of the barrier coast, adjacent to and beneath the shallow waters of Almirante Bay. There, the presence of marine influence, evident in the dominance of halophyte (mangrove) peats, and in the distribution of sulphur, reflects the regional structural trend of greatest subsidence to the southeast. Evidence of the punctuated nature of that subsidence is found in the presence of shelly layers within otherwise carbonate-free mangrove and back-mangrove peats. In addition, at least in the short-term, the distribution of forms of sulphur in newly-inundated peat is significantly different from the distribution in peat that has not been flooded. This suggests a future line of inquiry into longer-term geochemical signatures of rapid coseismic subsidence and marine inundation of coastal peatlands.

6.2 SUGGESTIONS FOR FURTHER RESEARCH

The Changuinola peat deposit is an excellent analogue for coal deposition, for the reasons stated above. One of the most valuable aspects of the deposit for coal studies is its almost untouched state. Like the European peats, many of the southeast Asian deposits are sites of intense human activity, have been drained or mined, and the forests have been logged. Differences in structure and hydrology between this deposit and those of southeast Asia leads to the question of whether there are peat deposits in tropical America which are developed on a base of less relief, and which more closely fit the Asian model.

There are numerous possibilities for more extensive and intensive study of the evolution and the detailed hydrology of the Changuinola deposit. Of interest are the long term effects of sudden inundation
on coastal peats, and burial of peat beneath lime-mud and coral. Also, there is the possibility of addressing one of the chief problems inherent in the use of modern peats as analogues for coal; the changes in the nature of coal-forming vegetation through time. Although the problem is greatest for Paleozoic coals, modern palm peat may well provide a very close analogue to Tertiary palm coals. The use of palm peat in artificial coalification studies thus has potential to reduce the problems inherent in assessing the effects of vegetation change. Finally, in addition to its potential for refining the evolving model of tropical coal development, the Changuinola deposit has interest because of the possibility of determining a history of coseismic subsidence for this part of the Caribbean coast based on radiocarbon dating of earthquake related stratification in submerged peat.
### APPENDIX A: SAMPLE SITE LOCATIONS AND ANALYTICAL KEY

Sal = salinity  
S t = total sulphur  
S f = forms of sulphur  
Pol = pollen analysis  
Hu = degree of humification (particle size)  
Ash = high temperature ash content  
Min = mineralogy of basal clastics  
14C = radiocarbon dating

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### LOCATION OF OTHER SAMPLE SITES from Cohen et al., 1989.

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3. BDT 3     | 350880   | 1039000  |
4. BDT 4     | 339700   | 1042400  |
5. BDT 5     | 339500   | 1042600  |
6. BDT 11    | 344200   | 1040000  |
7. BDT 12    | 344900   | 1080000  |
8. BDT 13    | 342000   | 1042550  |
9. BDT 14    | 346000   | 1038500  |
10. BDT 20   | 343000   | 1039200  |
11. BDT 21   | 342400   | 1038500  |
12. BDT 22   | 341000   | 1037700  |
13. BDT 23   | 344000   | 1036000  |
14. BDT 24   | 346000   | 1038500  |
15. PB 1     | 344050   | 1044300  |
16. PB 1A    | 343670   | 1043800  |
17. PB 2     | 345000   | 1043525  |
18. PB 2A    | 344800   | 1043125  |
19. PB 2B    | 344700   | 1042950  |
20. PB 3     | 346000   | 1042550  |
21. PB 3A    | 345550   | 1042200  |
22. PB 4     | 346900   | 1041800  |
23. PB 4A    | 346650   | 1041250  |
24. PB 4B    | 346450   | 1040850  |
25. PB 5     | 349650   | 1037700  |
26. PB 5A    | 349315   | 1037400  |
27. PB 5B    | 349200   | 1037300  |
28. PB 5C    | 348900   | 1037000  |
29. PB 6     | 348675   | 1038750  |
30. PB 6A    | 348375   | 1038450  |
31. PB 6B    | 348250   | 1038350  |
32. PB 6C    | 347950   | 1038050  |
33. PB 7     | 348175   | 1039275  |
34. PB 7A    | 347875   | 1038975  |
35. PB 7B    | 347800   | 1038875  |
36. PB 7C    | 347475   | 1038550  |
37. PB 9     | 340200   | 1036700  |
38. PB 9A    | 340700   | 1037300  |
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## APPENDIX B

### APPENDIX B: TEST RESULTS

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## APPENDIX B

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<td>MILE 5-21</td>
<td>600-630</td>
<td>630</td>
<td>4.28</td>
<td>0.17</td>
<td>&lt;0.01</td>
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</tr>
<tr>
<td>MILE 5-22</td>
<td>630-660</td>
<td>660</td>
<td>4.54</td>
<td>0.24</td>
<td>&lt;0.01</td>
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<td>660-690</td>
<td>690</td>
<td>4.53</td>
<td>0.23</td>
<td>&lt;0.01</td>
<td>90.3</td>
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<tr>
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<td>4.44</td>
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<td>720-750</td>
<td>750</td>
<td>4.63</td>
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<td>93.7</td>
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<td>750-780</td>
<td>780</td>
<td>4.83</td>
<td>0.24</td>
<td>&lt;0.01</td>
<td>95.7 3040+/-80</td>
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<tr>
<td>MILE 5-27</td>
<td>780-810</td>
<td>810</td>
<td>5.29</td>
<td>0.29</td>
<td>&lt;0.01</td>
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<tr>
<td>MILE 5-28</td>
<td>810-840</td>
<td>840</td>
<td>5.40</td>
<td>0.30</td>
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<tr>
<td>MILE 5-29</td>
<td>840-870</td>
<td>870</td>
<td>5.52</td>
<td>0.22</td>
<td>&lt;0.01</td>
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| NL 1         | 0              | 0            | 3.87 | 0.01               |               |                                 |                  |
| NL 1-1       | 0-25           | 25           | 3.87 | 0.01               |               |                                 |                  |
| NL 1-2       | 25-50          | 50           | 3.96 | <0.01              |               |                                 |                  |
## APPENDIX B

<table>
<thead>
<tr>
<th>SAMPLE NUMBER</th>
<th>DEPTH RANGE (cm)</th>
<th>PLOT DEPTH (cm)</th>
<th>pH</th>
<th>TOTAL SULPHUR (wt%)</th>
<th>SALINITY (wt%)</th>
<th>DRAINED MOISTURE (wt%)</th>
<th>14C AGE (a. B.P.)</th>
</tr>
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<tbody>
<tr>
<td>NL 1-3</td>
<td>50-75</td>
<td>75</td>
<td>4.29</td>
<td>&lt;0.01</td>
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<td>NL 1-4</td>
<td>75-100</td>
<td>100</td>
<td>3.92</td>
<td>&lt;0.01</td>
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<td>NL 1-5</td>
<td>100-125</td>
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<td>125-150</td>
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<td>NL 1-7</td>
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<td>NL 1-8</td>
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<td>&lt;0.01</td>
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<tr>
<td>NL 1-9</td>
<td>200-225</td>
<td>225</td>
<td>4.35</td>
<td>&lt;0.01</td>
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<td>NL 1-10</td>
<td>225-250</td>
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<td>4.47</td>
<td>&lt;0.01</td>
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</tr>
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<td>NL 1-11</td>
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<td>270</td>
<td>4.59</td>
<td>&lt;0.01</td>
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</tr>
<tr>
<td>NL 1-12</td>
<td>270-300</td>
<td>280</td>
<td>4.87</td>
<td>&lt;0.01</td>
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<tr>
<td>PTA POND-1</td>
<td>550-575</td>
<td>575</td>
<td>3.57</td>
<td>3.53</td>
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<td>PTA POND-2</td>
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<td>2.89</td>
<td>3.03</td>
<td>1.30</td>
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<td>65.5</td>
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APPENDIX C

APPENDIX C: RESULTS OF WET SIEVING

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>Depth</th>
<th>%M</th>
<th>%Z</th>
<th>%Ash</th>
<th>%C</th>
<th>%M</th>
<th>%F</th>
<th>Comments</th>
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<tr>
<td>BDD 22</td>
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</tr>
<tr>
<td>1 BDD 22-1</td>
<td>0</td>
<td>Hemic</td>
<td>0</td>
<td>24.4</td>
<td>10.7</td>
<td>30.7</td>
<td>34.2</td>
<td>diatoms, bugs, fragmental</td>
</tr>
<tr>
<td>2 BDD 22-2</td>
<td>100</td>
<td>C Hemic</td>
<td>100</td>
<td>32.8</td>
<td>20.6</td>
<td>20.4</td>
<td>26.2</td>
<td>spicules, tooth, diatoms, etc</td>
</tr>
<tr>
<td>3 BDD 22-3</td>
<td>150-200</td>
<td>Hemic</td>
<td>175</td>
<td>52.1</td>
<td>6.4</td>
<td>18.7</td>
<td>22.8</td>
<td>fish scales, forams, frags</td>
</tr>
<tr>
<td>4 BDD 22-4</td>
<td>200-250</td>
<td>F Hemic</td>
<td>225</td>
<td>50.8</td>
<td>1.8</td>
<td>7.1</td>
<td>40.3</td>
<td>ostracods, forams, diatoms, spicules</td>
</tr>
<tr>
<td>5 BDD 22-5</td>
<td>300-350</td>
<td>Hemic</td>
<td>325</td>
<td>59.0</td>
<td>4.6</td>
<td>18.1</td>
<td>18.3</td>
<td>ostracods, forams, diatoms, spicules</td>
</tr>
<tr>
<td>6 BDD 22-6</td>
<td>400-450</td>
<td>Hemic</td>
<td>425</td>
<td>65.4</td>
<td>2.7</td>
<td>19.2</td>
<td>12.7</td>
<td>Oshells: diat, spic, ost, for, shell</td>
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<tr>
<td>7 BDD 22D-1</td>
<td>560-590</td>
<td>F Hemic</td>
<td>560</td>
<td>5.0</td>
<td>9.6</td>
<td>32.4</td>
<td>53.0</td>
<td>no ostracods, mixed mins</td>
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<tr>
<td>8 BDD 22D-2</td>
<td>600+BASE</td>
<td>not peat</td>
<td>600</td>
<td>72.0</td>
<td>2.5</td>
<td>10.5</td>
<td>15.0</td>
<td>mins, pollen, no coral</td>
</tr>
<tr>
<td>9 BDD 22-7</td>
<td>600-650</td>
<td>not peat</td>
<td>625</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>rounded coral &amp; shells, ost, for, mins</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>10 NL 1-1</td>
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<td>F: Hemic</td>
<td>25</td>
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<td>clear water</td>
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<td>19.0</td>
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<td>40.2</td>
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<td>36.4</td>
<td>44.0</td>
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<td>50.5</td>
<td>Campsperma seed &quot;a&quot;</td>
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<td>12.5</td>
<td>44.7</td>
<td>42.8</td>
<td></td>
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<td>200-225</td>
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<td>11.4</td>
<td>32.9</td>
<td>55.7</td>
<td></td>
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<td>19 NL 1-10</td>
<td>225-250</td>
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<td>0.0</td>
<td>10.9</td>
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<td>48.0</td>
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<td>270</td>
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<td>5.1</td>
<td>43.3</td>
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<td></td>
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<td></td>
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<td>F Hemic</td>
<td>25</td>
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<td>27.8</td>
<td>29.2</td>
<td>43.0</td>
<td>gramy, wood frags: xtais</td>
</tr>
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<td>C Hemic</td>
<td>100</td>
<td>0.0</td>
<td>37.1</td>
<td>26.3</td>
<td>36.6</td>
<td>Camp seed a, roots: xtais</td>
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<td>0.0</td>
<td>28.9</td>
<td>33.2</td>
<td>33.9</td>
<td>grasy: xtais</td>
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<td>150</td>
<td>0.0</td>
<td>31.5</td>
<td>34.7</td>
<td>33.8</td>
<td>grasy: xtais</td>
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<td>175</td>
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<td>40.0</td>
<td>30.0</td>
<td>(Estimate due to loss), grasy: xtais</td>
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<td>200</td>
<td>0.0</td>
<td>40.2</td>
<td>36.4</td>
<td>23.4</td>
<td>corky Palm wood, woodfrags: xtais</td>
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<td>Hemic</td>
<td>225</td>
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<td>28.8</td>
<td>38.9</td>
<td>32.3</td>
<td>grasy, woodfrags</td>
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<td>C Hemic</td>
<td>250</td>
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<td>35.0</td>
<td>37.1</td>
<td>27.9</td>
<td>sm wood frag, grass</td>
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<td>275</td>
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<td>34.8</td>
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<td>300</td>
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<td>white mould</td>
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<td>43.8</td>
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<td>grasy</td>
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<td>SAMPLE</td>
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<td>%M</td>
<td>Z</td>
<td>%Ash</td>
<td>% C</td>
<td>% M</td>
<td>% F</td>
<td>Comments</td>
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<td>425</td>
<td>4.1</td>
<td>29.3</td>
<td>36.6</td>
<td>30.0</td>
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<td>425-450</td>
<td>C Hemic</td>
<td>450</td>
<td>0.1</td>
<td>35.5</td>
<td>40.0</td>
<td>24.4</td>
<td>grassy</td>
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<td>38 LAKE 6.5-17</td>
<td>450-475</td>
<td>Hemic</td>
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<td>25.9</td>
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<td>grassy</td>
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<td>39 LAKE 6.5-18</td>
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<td>C Hemic</td>
<td>500</td>
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<td>40 LAKE 6.5-19</td>
<td>500-525</td>
<td>F Hemic</td>
<td>525</td>
<td>10.0</td>
<td>15.0</td>
<td>35.0</td>
<td>40.0</td>
<td>wood, bark, frags: LTA on fines</td>
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<td>41 LAKE 6.5-20</td>
<td>525-550</td>
<td>notpeat</td>
<td>550</td>
<td>76.8</td>
<td>2.5</td>
<td>8.4</td>
<td>12.3</td>
<td>not peat: HTA; LTA on fines</td>
</tr>
<tr>
<td>LAKE 8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Base: frosted white, grey, and pale green silt, no carbonate, much wood with embedded mineral grains.</td>
</tr>
<tr>
<td>42 LAKE 8-1</td>
<td>0-50</td>
<td>F Hemic</td>
<td>50</td>
<td>0.0</td>
<td>18.1</td>
<td>46.6</td>
<td>35.3</td>
<td>grassy, roots: occ. frosted qtz, mica</td>
</tr>
<tr>
<td>43 LAKE 8-2</td>
<td>50-75</td>
<td>C Hemic</td>
<td>75</td>
<td>0.0</td>
<td>38.9</td>
<td>38.2</td>
<td>22.9</td>
<td>grassy, roots</td>
</tr>
<tr>
<td>44 LAKE 8-3</td>
<td>75-100</td>
<td>Hemic</td>
<td>100</td>
<td>0.0</td>
<td>21.5</td>
<td>41.1</td>
<td>37.4</td>
<td>H2O almost clear</td>
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<tr>
<td>45 LAKE 8-4</td>
<td>100-150</td>
<td>Fibric</td>
<td>150</td>
<td>0.0</td>
<td>55.3</td>
<td>29.4</td>
<td>15.3</td>
<td>Cyrilla leaf, wood, bark</td>
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<tr>
<td>46 LAKE 8-5</td>
<td>150-175</td>
<td>Fibric</td>
<td>175</td>
<td>0.0</td>
<td>39.8</td>
<td>32.2</td>
<td>28.0</td>
<td>peanut-shaped root tubes</td>
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<tr>
<td>47 LAKE 8-6</td>
<td>175-200</td>
<td>Hemic</td>
<td>200</td>
<td>0.0</td>
<td>30.6</td>
<td>43.5</td>
<td>25.9</td>
<td>peanuts, grassy, H2O clear</td>
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<tr>
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### APPENDIX C

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## APPENDIX C

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<th>% Ash</th>
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<th>% F</th>
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<table>
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<th>% M</th>
<th>% F</th>
<th>Comments</th>
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<tr>
<td>810</td>
<td>1.0</td>
<td>19.6</td>
<td>49.1</td>
<td>30.3</td>
<td>some mns</td>
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| ED 3-1  | 0-30   | Fibric | 30 | 0.0 | 45.8 | 22.9 | 31.3 | moss, grass, root mass                        |
| ED 3-2  | 30-60  | Fibric | 60 | 0.0 | 43.5 | 23.9 | 32.6 | corn, grassy                                  |
| ED 3-3  | 60-90  | Fibric | 90 | 0.0 | 50.9 | 20.8 | 28.3 | grassy, roots                                 |
| ED 3-4  | 90-120 | C Hemic| 120| 0.0 | 35.9 | 17.9 | 46.2 | twiggy, grassy                                |
| ED 3-5  | 120-150| Fibric | 150| 0.0 | 46.9 | 23.2 | 29.9 | twiggy, wood with bark                        |
| ED 3-6  | 150-180| Fibric | 180| 0.0 | 43.4 | 24.6 | 32.0 |                                             |
| ED 3-7  | 180-210| Fibric | 210| 0.0 | 53.1 | 23.3 | 23.6 | wood                                         |
| ED 3-8  | 210-240| Fibric | 240| 0.0 | 57.1 | 29.4 | 13.5 |                                             |
| ED 3-9  | 240-270| Fibric | 270| 0.0 | 57.1 | 29.1 | 19.2 |                                             |
| ED 3-10 | 270-300| Fibric | 300| 0.0 | 60.3 | 27.1 | 12.6 | Campnosperma seed                             |
| ED 3-11 | 300-330| Fibric | 330| 0.0 | 60.6 | 24.8 | 14.6 |                                             |
| ED 3-12 | 330-360| Fibric | 360| 0.0 | 60.5 | 29.3 | 10.2 |                                             |
| ED 3-13 | 360-390| Fibric | 390| 0.0 | 56.4 | 27.5 | 16.1 | wood frags                                    |
| ED 3-14 | 390-420| F Hemic| 420| 0.0 | 20.7 | 33.7 | 45.6 | Black H2O, woody granular peat                |
| ED 3-15 | 420-450| F Hemic| 450| 0.0 | 23.4 | 28.0 | 48.6 | Black H2O, woody granular peat                |
| ED 3-16 | 450-480| Fibric | 480| 0.0 | 44.9 | 29.3 | 25.8 | Fibrous, grassy, clear H2O                   |
| ED 3-17 | 480-510| Fibric | 510| 0.0 | 48.6 | 28.4 | 23.0 | Fibrous, grassy, clear H2O                   |
| ED 3-18 | 510-540| F Hemic| 540| 0.0 | 22.8 | 34.6 | 42.6 | Black H2O, woody granular peat                |
| ED 3-19 | 540-570| Hemic | 570| 0.0 | 34.8 | 37.6 | 27.6 | Fibrous, grassy, clear H2O                   |
| ED 3-20 | 570-600| Hemic | 600| 0.0 | 31.9 | 40.3 | 27.8 | Fibrous, grassy, clear H2O                   |
| ED 3-21 | 600-630| Hemic | 630| 0.0 | 34.5 | 38.1 | 27.4 | H2O grey                                     |
| ED 3-22 | 630-660| F Hemic| 660| 0.0 | 18.7 | 32.3 | 49.0 | Black (burnt?) pithy frags, black H2O        |
| ED 3-23 | 660-690| Hemic | 690| 0.0 | 34.0 | 40.0 | 26.0 | Black (burnt?) pithy frags, black H2O        |
| ED 3-24 | 690-720| Fibric | 720| 0.0 | 52.8 | 26.2 | 21.0 | wood frags                                   |
| ED 3-25 | 720-750| F Hemic| 750| 0.0 | 21.7 | 49.2 | 29.1 | wood frags                                   |
| ED 3-26 | 750-780| F Hemic| 780| 0.0 | 5.4  | 58.0 | 36.6 | H2O slightly murky                           |
| ED 3-27 | 780-810| F Hemic| 810| 0.0 | 10.8 | 36.5 | 52.7 | trace of mineral                              |

<table>
<thead>
<tr>
<th>BDD 23</th>
<th>POLLEN DONE: Base=frosted sand, mixed lithol., mica, mns embedded in woodfrags: Charcoal at top and base</th>
</tr>
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<tbody>
<tr>
<td>BDD 23-1</td>
<td>0-50</td>
</tr>
<tr>
<td>BDD 23-2</td>
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<td>BDD 23-3</td>
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<td>450-500</td>
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<td>BDD 23-14</td>
<td>500-600</td>
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</table>

<table>
<thead>
<tr>
<th>BDD 31</th>
<th>Sedimentary peat like BDD23 base; mns frosted grey &amp; white, mica, silty. Resin balls and fine granules.</th>
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</thead>
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<tr>
<td>BDD 31-1</td>
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</tr>
<tr>
<td>BDD 31-2</td>
<td>25-50</td>
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## APPENDIX C

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<th>SAMPLE</th>
<th>Depth</th>
<th>%M</th>
<th>Z</th>
<th>% Ash</th>
<th>% C</th>
<th>% M</th>
<th>% F</th>
<th>Comments</th>
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<td>27.9</td>
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<td>27.4</td>
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<td>47.1 fruit b</td>
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<td>29.9</td>
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<td>94.9</td>
<td>C: Wood</td>
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<td>66.2</td>
<td>16.2</td>
<td>17.6 sedge culm, large spore?</td>
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<td>24.4</td>
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<td>%Ash</td>
<td>% C</td>
<td>% M</td>
<td>% F</td>
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| 5             | 0            | 9.5              | 0                | 0.5              | 0           | 82.5        | 17.5          | 6             | 11.5        | 200         |
| 8.5           | 3            | 18.5             | 0                | 0                | 0           | 90.3        | 9.7           | 4             | 5.7         | 200         |
| 4             | 1.5          | 0                | 4                | 0.4              | 0           | 85.5        | 14.5          | 5.5           | 9           | 200         |
| 4             | 0            | 9.5              | 0                | 0                | 0           | 89          | 11            | 4.5           | 6.5         | 200         |
| 3.5           | 2            | 1                | 0                | 0                | 0           | 90          | 10            | 3             | 7           | 200         |
| 1.3           | 0.7          | 0                | 0.7              | 2.7              | 0           | 87          | 13            | 8             | 5           | 150         |
| 1             | 1.5          | 0                | 8                | 0                | 0           | 85.5        | 14.5          | 6             | 8.5         | 200         |
| 1             | 3            | 0                | 1                | 0                | 14          | 91          | 19            | 13            | 6           | 100         |
| 2             | 0            | 0                | 0                | 0                | 14          | 90          | 40            | 20            | 20          | 50          |
| 1.5           | 0            | 0                | 1                | 0                | 1           | 68          | 32            | 29.5          | 2.5         | 200         |
| 3             | 0            | 0                | 0.5              | 3.5              | 0           | 71          | 29            | 12.5          | 16.5        | 200         |
APPENDIX E: POLLEN DESCRIPTIONS
(Plates 1 to 3)

PLATE 1-1
*Trichomanes crinitum* (Hymenophyllaceae); Monolete fern spore, irregular ovoid, 41-51µm x 30-40 µm; sclerine plicate, echinate.
Ref. pc 5, fresh material.

PLATE 1-2
*Cyclopeltis semicordata* (Polypodiaceae - Tectariaceae): Monolete fern spore, kidney-shaped, 41µm X 25µm; laesura 22µm long, thickened margo, 1.5µm thick. Sclerine irregularly verrucate.
Ref. pc 4, fresh material, LAKE 2 type 4. GL 30.6,121.1; 31.3,126.4. Photos 19,20.

PLATE 1-3
*Salpichlaena* sp. (Blechnaceae): Monolete fern spore, kidney-shaped, 33-43µm x 29µm, laesura ca. 22µm long, exine thin, finely rugulate; sclerine frequently has one to several plicae paralleling or crossing the laesura.
Ref. fresh material. GL 29.2,121.4. Photos 23,30.

PLATE 1-4
*Cyathea (?) multiflora (?)* (Cyatheaceae): Trilete fern spore, amb triangular, 40-45µm x 32µm, laesurae ca. 10µm long. Exine stratified, sclerine thin, psilate.
Ref. fresh material (immature sample?), GL - Photos 21,22.

PLATE 1-5
*Lindsaeas* sp. (Dennstaetiaceae): Monolete fern spore, 36µm x 29µm. oblate, often pointed at ends, with laesura extending into points. Laesura irregular, extends length of spore; ends of laesura sometimes branching; margo entire, >1µm thick. Exine scabrate.
Ref. pc 7, fresh material. GL 30.1,121.2. Photos 31,32.

PLATE 1-6
Monolete fern type 1: Kidney-shaped spore, 57µm x 27µm, laesura 2/3 length of spore, distinct margo 2µm wide, 3 µm thick; sclerine psilate, perine psilate with 1 to several prominent folds (plicae), often merging or intersecting.
Ref. pc 4, LAKE 2 type 1. GL 34.3,110.7 Photo 24.

PLATE 1-7
Monolete fern type 2: Kidney-shaped spore, 63µm x 41µm, laesura 35µm long, sclerine psilate.
Ref. pc 4, LAKE 2 type 2.GL 31.9,113.3. Photo 27

PLATE 1-8
cf. *Verrucatosporites* sp., monolete fern type 3: Kidney-shaped spore, 41µm x 25µm, laesura 25µm long, sclerine weakly verrucate, perine psilate.
Ref. pc 4, LAKE 2 type 3. GL 32.8,113.5. Photo 26.

PLATE 1-9
Monolete fern type 8: Kidney-shaped spore, 35µm x 25µm, laesura 19µm long
Ref. pc 1, BDD 25 type A. GL 28.9,127.3. Photo 2.

PLATE 1-10
cf. *Metaxyza* sp. (Cyatheaceae) (Roubik & Moreno), trilette fern spore: amb rounded-triangular, eq. dia. 44-50µm, laesurae 18-22µm long, 2-3µm wide, sclerine thin, unstratified, scabrate to clavate.
Ref. pc 4, LAKE 2 type 29. GL 29.6,112.8. Photo 25.

PLATE 1-11
*Raphia taedigera* (Palmae): Monocolpate, shape irregular-reniform to sub-spherical, 23-27µm x 17-19µm, colpus straight, 15-19µm long x ca. 1.8µm wide. Exine reticulate
Ref. pc 3, fresh sample. Photos 33,34.

PLATE 1-12
Palm phytolith, probably *Raphia taedigera*. spikey sphere, 10-30 µm in diameter.

PLATE 1-13
*Euterpe precatoria* (Palmae): (*Euterpe precatoria* is the only palm, other than *Raphia* t., present in the swamp, but attempts to secure fresh pollen of this species failed): prolate, 25µm x 15µm, monolete; laesura straight, 22µm long x 1.5-2.3µm wide, with distinct margo; exine thin, scabrate.
Ref. pc 5, BDD 23 type 32. GL 24.8,119.1; 24.2,119.2. Photos 9,12.
PLATES 2-1; 3-1 and 3-2 (details)
Campnosperma panamensis (Anacardiaceae): tricolporate, prolate, 27-30 µm x 17-21 µm. Exine ca. 1.8 µm thick, nexine thicker than sexine; sexine striate, 0.7 µm thick, striae 0.5 µm wide, absent near pores. Colpi ca. 22 µm long, evenly spaced, costae colpi small.
Ref. pc 5, fresh material; BDD 23-23, 23-36. GL 43.5, 119.6; 43.5, 120.3 Photos 35-38

PLATE 2-3
Tricolporate type 1: Prolate, 28 µm x 15 µm, prominent transverse colpi
Ref. pc 1, BDD 25-1. GL 27.5, 112.8; 24.3, 117.8 Photos 1, 3.

PLATE 2-4
Tricolporate type 2: Prolate, 24 µm x 16 µm, well-developed transverse colpi.
Ref. pc 1, BDD 25-36. GL 30.2, 111.2; 36.4, 118.3 Photo 4.

PLATE 2-5
Tricolporate type 26: Oblate-spheroidal, 20 µm x 22 µm, exine 2 µm thick, stratified, sexine psilate, pores (ora?) open, with well developed vestibulum 4 µm wide x 4-6 µm deep.
Ref. pc 7, LAKE 10-type 26. GL 37.7, 124.5 Photo 13.

PLATE 2-6
Tricolporate type 54: Oblate, 23 µm x 16 µm, exine 1.5 µm thick, stratified, sexine rugulate, separated from nexine at pores, pores (ora?) open, 6 µm wide, with vestibulum, and membrane across oral floor; colpi about 3 µm deep, with margos about 1.5 µm wide.
Ref. pc 7, LAKE 10-type 54. GL 38.7, 119.5 Photo 39.

PLATE 2-7
Myrica mexicana: triporate, sub-obl ate, amb rounded-triangular, 26 µm, exine scabrate, ca. 1.2 µm thick; annulus arched, with fine teeth on lower surface.
Ref. pc 3, BDD 8-28 GL 39.4, 111.3. Photo 16.

PLATE 2-8
Myrica-type A: triporate, amb rounded-triangular with a distinct 3-armed fold around the pole; dia. 27 µm, exine finely scabrate, ca. 1.2 µm thick; pores open, 2.2 µm wide, vestibulum rounded, 6 µm x 3 µm deep; annulus arched, with prominent inward notch (lower left) and teeth-like projections on inner surface (arrow).
Ref. pc 3, BDD 8-41 GL 31.4, 118. Photo 19.

PLATE 2-9
Tricolporate type 33: 3-brevicolporate, amb circular, 23-27 µm dia, exine 1.75 µm thick, baculate, semi-tectate; endexinous thickenings beneath colporoids show as dark areas (arrows). (cf. Mortoniodendron?) (Graham, 1979).
Ref. pc 5, BDD 23 type 33 GL 23.8, 118.9, Photo 10.
PLATES 2-10, 3-3 (details)
Unknown type 39: cf. *Chenopodipollis* sp., amb circular-hexagonal, 21-24 μm, periporate; pores irregular ovoids without margo, ca. 4x2 μm; exine stratified, >2 μm thick, sexine bacculate-echinate.
Ref. pc 5, BDD 8-39, 8-40. GL 26.5, 112.4 Photos 17, 18.

PLATE 2-11
Tricolporate type 40 (Tiliaceae?): amb circular, 3-brevicolpate, dia. 32-36 μm, colpi equatorial; sexine clavate, semi-tectate; exine has 1 to several plicae ca. 4 μm wide and 22-25 μm long.
Ref. pc 4, LAKE 2-40 GL 35.6, 115.8. Photo 28.

PLATE 2-12
Tricolporate type 48 (Tiliaceae?): amb rounded, 3-brevicolpate, dia 27-31 μm; costa colpi present, weak margo, atrium present but reduced, with vestibulum; exine reticulate, ca. 2.5 μm thick, reticulum ca 1.5 μm thick.
Ref. LAKE 2-48 GL 35.8, 116.2; 27.1, 121.4. Photo 29.
PLATE 2: 1) Campnosperma panamensis; 2) Campnosperma-type; 3) Tricolporate type 1; 4) Tricolporate type 2; 5) Tricolporate type 26; 6) Tricolporate type 54; 7) Myrica mexicana; 8) Myrica type A; 9) Triporate type 33; 10) Periporate type 39; 11) Triporate type 40; 12) Triporate type 48.
PLATE 3-1
_Campnosperma panamensis_ low and high focus equatorial (left, top and bottom), and polar (right, top and bottom) views.

PLATE 3-2
_Campnosperma panamensis_ exine detail.

PLATE 3-3
Unknown type 39: _cf. Chenopodipollis_ sp. details of pore (top) and exine (bottom).

PLATE 3-4
_Fusiformisporites_ sp. A: Fusiform dicellate fungal spore, 73- 80μm x 40- 50μm, ovoid, striate; striations >3μm wide running length of hemisphere, branching in a few cases; central divider a thickened ring rather than a solid wall. Ref. pc 4, LAKE 2-41 GL 42.5,117.0 Photo 14.

PLATE 3-5
_Fusiformisporites_ sp. B: Fusiform dicellate fungal spore, 15μm x 10μm, blunt-ovoid, striate; striations ca. 1μm wide, ca. 10-12 per hemisphere, unbranched, running length of hemisphere. Ref. pc 4, LAKE 2-57 GL 30.1,125.6 Photo 15.

PLATE 3-5
_Fusiformisporites_ sp. C: Fusiform dicellate fungal spore, 36μm x 9μm, striate; striations ca. 1μm wide, 14-16 per hemisphere, running length of hemisphere, occ. branched. Poles with internal thickenings. Central divider is apparently a solid wall. Ref. pc 5, BDD 23 GL 20.4,118.5. Photos 7,8.
PLATE 3 (10 μm scale bar): 1) *Camposperma panamensis* low and high focus in both equatorial and polar views; 2) Detail of exine decoration of *Camposperma* (x 1780); 3) Periporate type 39, low and high focus. (20 μm scale bar): 4) *Fusiformisporites* sp. A; 5) *Fusiformisporites* sp. C.
## APPENDIX F: PLANTS IDENTIFIED IN THE CHANGUINOLA MIRE

APPENDIX F: List of species.  Dom = dominant;  C = common;  R = rare.

<table>
<thead>
<tr>
<th>FAMILY</th>
<th>SPECIES</th>
<th>TYPE/COMMON NAME/NOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alismataceae</td>
<td><em>Sagittaria lancifolia</em></td>
<td>C herb/ Otoye de lagarto</td>
</tr>
<tr>
<td>Anacardiaceae</td>
<td><em>Campnosperma panamensis</em></td>
<td>Dom tree/Orey, Ori</td>
</tr>
<tr>
<td>Annonaceae</td>
<td><em>Guatteria imuncta</em></td>
<td>C shrub/</td>
</tr>
<tr>
<td>Apocynaceae</td>
<td><em>Thevetia ahouai</em></td>
<td>C shrub/ Huevo de gato</td>
</tr>
<tr>
<td>Aquifoliaceae</td>
<td><em>Ilex guianensis</em></td>
<td>C tree/ Plomo</td>
</tr>
<tr>
<td>Araceae</td>
<td><em>Dieffenbachia longispata</em></td>
<td>C herb/ Otoye de lagarto (spiney)</td>
</tr>
<tr>
<td>Blechnaceae</td>
<td><em>Salpichlaena sp.</em></td>
<td>fern/ ostrich l</td>
</tr>
<tr>
<td>Bignoniaceae</td>
<td><em>Tabebuia rosea</em></td>
<td>R tree/ Roble de sabana</td>
</tr>
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<td>Burseraceae</td>
<td><em>Protium panamense</em></td>
<td>Dom tree/</td>
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<td>Chrysobalanaceae</td>
<td><em>Chrysobalanus icaco</em></td>
<td>C tree/ &quot;Round-leaf&quot;</td>
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<td>Combretaceae</td>
<td><em>Laguncularia racemosa</em></td>
<td>C tree/ White mangrove</td>
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<td><em>Cyathea? multiflora?</em></td>
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<td>Cyperaceae</td>
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<td>sawgrass/</td>
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<tr>
<td>Cyperaceae</td>
<td><em>Cyperus sp.</em></td>
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<td><em>Rhynchospora macrostachya</em></td>
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<td>Euphorbiaceae</td>
<td><em>Alchornea sp.</em></td>
<td>R tree/</td>
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<td>fern/ base of Ori (m-filamentous)</td>
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<td>R tree/</td>
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<td>Family</td>
<td>Genus</td>
<td>Species</td>
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<td><em>Myrsine</em></td>
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<td><em>Neea</em></td>
<td><em>sp.</em> 2</td>
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<td><em>Sterculia</em></td>
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<td><em>semicordata (s.w.)</em></td>
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<td>Theaceae</td>
<td><em>Ternstroemia</em></td>
<td><em>tepazapote</em></td>
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APPENDIX G: TERMS AND ANALYTICAL PROCEDURES

The American Society for Testing and Materials (ASTM, 1969) sets standards for the composition of organic-rich sediments: by definition, peat contains less than 25% dry weight inorganic material (ash); clayey peat (or sandy peat) has 25% to 50% ash, and peaty clay (or peaty sand) has greater than 50% ash, dry weight. Less than 10% mineral matter is 'low-ash' peat, and 10% to 25% mineral matter is 'high ash'. Fresh peat is frequently 90% water by weight (Cameron et al., 1989). Peat is defined according to ash content using the Organic Sediments Research Centre, University of South Carolina, standard (Andrejko et al., 1983). By this standard, peat is defined as Low (<5 wt%), Medium (5-15 wt%) and High Ash (15-25 wt%). Above 25 wt% is carbonaceous sediment.

Peat may form in virtually any humid climate, if the groundwater table remains for a sufficiently long time at a level such that the organic material near the surface remains waterlogged, and yet the growing surface is not drowned, or buried by inorganic sediments. That part of the peat which is commonly above the groundwater table, aerated and permeable, is termed the acrotelm, while the denser, less permeable, waterlogged part is the catotelm (Moore, 1989). Peat deposits can be classified according to their source of water, the nature of the drainage patterns, and the underlying topography on which they accumulate. The term mire is a general one used in Europe to refer to any non-saline peat-forming wetland system (Moore, 1989). This usage has now been expanded into the concept of a mire complex in acknowledgment of the heterogeneity and evolutionary potential of wetland systems. In the present study, the marginal mangrove swamp, a saline wetland, would strictly speaking be excluded from the definition of mire. It is, however, a fundamental element in the evolution of many tropical mire complexes, and thus encourages the expansion of the definition.

Rheotrophic (Moore, 1989) or minerotrophic (Cameron et al., 1989) mires are fed by both rainwater and groundwater. Ombrotrophic (or ombrogenous -Stach et al., 1982) mires receive water only as rainfall. In both types of mires, the water table can be either above or below the peat surface. Rheotrophic mires tend to be nutrient-rich (eutrophic) due to the influx of groundwater. They may have complex internal drainage systems, a diverse and luxuriant flora, and significant inorganic sedimentation. Ombrotrophic mires tend to be nutrient-poor (oligotrophic), the flora relatively poorer in species and stunted in its growth, and the resulting peat low in mineral matter (ash).

The terms 'bog', 'moor', 'marsh' and 'swamp' are all applied to peat-forming wetlands, with varying degrees of consistency. To most authors, raised bogs or 'high moors' are ombrotrophic
mires, with perched water tables fed by rainfall, which form in closed depressions that result from a variety of geomorphological processes. They are commonly lens-shaped, with domed or convex surfaces (hence 'raised'), and the relative impermeability of the catotelm results in a domed water table, and drainage away from the centre, which tends to be particularly nutrient-poor. Near the margins, where the peat is thinner, the substrate may provide plant nutrients, and the vegetation become progressively more luxuriant. Vegetation ranges from moss (*Sphagnum*) and stunted trees in higher latitudes, to dense forests in the tropics. Raised bogs may contain areas of swamp or marsh (Cameron et al., 1989).

Types of mires (from Moore, 1989):

'Bog' is land that is wet, soft and spongy, and underlain by peat. Bogs may occur within marshes and swamps (Cameron et al., 1989).

'Marsh' is relatively open, saturated or shallow-water wetland dominated by herbaceous vegetation - sedges, rushes, grasses. It is normally rheotrophic.

'Swamp' is shallow-water wetland dominated by trees. It too is normally rheotrophic.

Stach et al. (1982) tend to use the terms ‘reed-swamp’, ‘forest-swamp’ and ‘moss-swamp’ for some of the above terms, and many authors use generic identifiers (Mangrove swamp) on the assumption that the context will clarify the hydrologic nature of the site. In the case of rheotrophic peats, they may be freshwater (telmatic or limnic), or experience brackish or marine influences, with profound effects on the biology and chemistry of the deposit.

Tissue preservation (degree of humification) is described in field observations, and in the written descriptions in this report using a modified von Post Humification Scale adapted to tropical peats by Esterie (1990). There are 5 field categories, described by Esterle (1990) as follows:

**Coarse Hemic:** Abundant coarse fibrous particles with particulate matrix and occasional large root or wood fragments.

**Hemic:** Dominant fine particulate matrix with minor amounts of coarse fibrous particles and common large root and wood fragments.

**Fine Hemic:** Dominant fine particulate matrix with minor amounts of coarse fibrous particles and fewer large root and wood fragments than hemic peat.

**Sapric:** Primarily fine particulate matrix material with occasional large roots or wood fragments and few coarse fibrous particles.

In this study, reference is made to the field categories and the vonPost system, alongside particle-size distributions determined by wet sieving, because peat workers are familiar with this index of
tissue preservation (von Post, 1922). A scale of ten is used to grade the peat by degree of
decomposition in the von Post system:

H1: Completely unhumified and muck-free peat; upon pressing in the hand, gives off only
colourless, clear water.

H2: Almost completely unhumified and muck-free peat; upon pressing, gives off almost clear but
yellow-brown water.

H3: Little humified and little muck-containing peat; upon pressing, gives off distinctly turbid
water, no peat substances pass between the fingers and the residue is not mushy.

H4: Poorly humified or some muck-containing peat; upon pressing, gives off strongly turbid
water. The residue is somewhat mushy.

H5: Peat partially humified or with considerable muck content. The plant remains are
recognizable but not distinct. Upon pressing, some of the substance passes between the
fingers together with mucky water. The residue in the hand is strongly mushy.

H6: Peat partially humified or with considerable muck content. The plant remains are not distinct.
Upon pressing, at the most, one third of the peat passes between the fingers together with
mucky water. The residue in the hand is strongly mushy, but the plant residue stands out
more distinctly than in the unpressed peat.

H7: Peat quite well humified or with considerable muck content, in which much of the plant
remains can still be seen. Upon pressing about half of the peat passes between the
fingers. If water separates it is soupy and very dark in colour.

H8: Peat well humified or with considerable muck content. The plant remains are not
recognizable. Upon pressing about two thirds of the peat passes between the fingers. If
it gives off water at all, it is soupy and very dark in colour. The remains consist mainly
of more resistant root fibres, etc.

H9: Peat very well humified or muck-like, in which hardly any plant remains are apparent. Upon
pressing, nearly all of the peat passes between the fingers like a homogenous mush.

H10: Peat completely humified or muck-like, in which no plant remains are apparent. Upon
pressing all of the peat passes between the fingers.

The traditional use of field-determined peat types has been used only sparingly in the study of these
tropical peats, as recent work (Esterle, 1990) suggests low correspondence between the traditional
field classifications and the actual particle-size distribution as determined by point counting or
sieving methods.
Degree of humification of the peat was established by particle-size distribution of each sample. Degree of humification of the peats is based on the relative proportions of coarse, medium and fine constituents as determined using a wet-sieving procedure modified from Staneck and Silc (1977), according to the following scheme (Esterle et al, 1987):

Coarse  >25% >2.0 mm  <30% <0.25 mm (= fibric to coarse hemic)
Medium  <25% >2.0 mm  <30% <0.25 mm (= hemic)
Fine    <25% >2.0 mm  >30% <0.25 mm (= hemic to fine hemic)

The results of sieving are recorded as percentages of total by dry weight, as the methods of measuring volume are less accurate, and do not lend themselves well to woody or fibric peats. Mineral matter was separated-out by flotation, and the results of sieving with 2.0 mm and 0.25 mm sieves were dried in a 50°C oven to constant weight.

Peat Classification is based on the identification of macroscopic plant parts and palynomorphs in the peat, compared to plant and pollen associations identified in the surface samples, and uses botanical (e.g. Rhizophora peat, sedge peat) nomenclature.

Mineral matter content (wt % ash) of 137 samples was determined by weight loss on ignition in a muffle furnace at 550°C (ASTM-D 2974: Jarret, 1983). Moisture content of wet peat, drained of superficial water, was measured by air drying at 50°C (wt % moisture lost), and is used in plots as an approximation of the density of the peat.

Total sulphur content (dry weight percent) of 203 samples (dried at 50°C, crushed to 100 mesh) was determined using a Leco® SC-132 Sulphur Analyzer (see Tabatabai, 1992, p.313 for a description of this instrument). Procedures for the determination of sulphur forms have been discussed by Lowe (1986, 1992) and Lowe and Bustin (1985) and are summarized here. Sulphate sulphur was determined by extraction with a 0.1 M CaCl₂ solution followed by sulphate determination by HI reduction and Bi-colorimetric determination of H₂S (Kowalenko and Lowe, 1972). Pyritic sulphur was determined by Zn-HCl reduction of the whole peat followed by H₂S determination, using the methods outlined by Williams and Steinberg (1959). Elemental sulphur was determined by soxhlet extraction with chloroform for three hours followed by Zn-HCl reduction and colorimetric determination of H₂S. The total organic sulphur was determined by difference between total sulphur and the sum of elemental sulphur, sulphate sulphur and pyritic sulphur.
For determination of carbon-bonded sulphur and organic sulphate sulphur (C-O-S form of sulphur) the entire peat was reduced by HI and H₂S was determined by colorimetry. HI reduction reduces elemental sulphur, sulphate sulphur, organic sulphate sulphur and pyritic sulphur to H₂S (Freney, 1961). Organic sulphate sulphur was estimated by subtracting elemental sulphur, sulphate sulphur and pyritic sulphur from the HI reducible sulphur. Carbon-bonded sulphur was estimated by the difference between total sulphur and HI reduced sulphur. If any acid soluble sulphides are present, they are removed by Zn-HCl reduction and thus lumped with pyritic sulphur.

Pollen slides were prepared from surface litter and shallow peat samples, and from 2 cores, one in the central part of the deposit and the second near the eastern margin. Pollen was prepared and concentrated using standard acetolysis techniques from the fine fraction of the peat (< 0.25 mm). The use of HF was avoided to enable phytoliths to be counted. Samples were first separated into coarse, medium and fine fractions using a wet-sieving procedure modified from Staneck and Silc (1977). Pollen profiles were prepared for each phasic community. To establish the pollen 'fingerprint' for each phasic community, a count of 1000 grains, where possible, was made from surface litter and surface peat samples (3 sites produced less than 750 grains each from multiple slides). The results were combined, and the percentage of the total count plotted for the most numerous palynomorphs. Although it would be preferable to compare counts from numerous similar sites to better represent each phasic community, it was felt that including the upper 25 cm of the peat gave considerable range to the sample, and given the sampling interval in the cores (25 or 30 cm) finer discrimination was not necessary. No attempt is made to relate the pollen found in the peat to the actual species which dominate each community - the problems associated with proportional representativeness of dominant plants in pollen profiles are well known. Rather it was hoped that an easily recognizable 'fingerprint' would emerge which could then be related to pollen recovered from cores.

Counts of 200 grains for each 25-30 cm increment of two cores were used to construct the pollen stratigraphy of the central and eastern sections of the deposit (Appendix D). The pollen diagrams of the two cores were constructed using selected palynomorphs or combinations of palynomorphs which are considered to be valid markers, as determined from the surface samples, and which best define transitions in vegetation. In both surface and core samples, the following grains were omitted from the counts: all single-celled fungal spores, all fungal hyphae, all
fragments less than 2/3 complete, and any ambiguous grain. In identifying palynomorphs, botanical names are used wherever possible, and pollen and spore genera where necessary.
REFERENCES


Access to the central areas of the Changuinola mire is extremely difficult, and necessitated the use of multiple remote sensing techniques. Digital satellite imagery from both Landsat and SPOT® satellites was utilized in this study. Landsat imagery of western Panama is available from the image archives of the US Geological Survey.Eros Data Centre. The image used in this study was acquired in January 1979 by the Landsat 3 satellite.

SPOT satellite imagery was acquired and interpreted by the author specifically for this study. The image, which has a ground resolution of 20 m, was obtained by the SPOT 3 satellite on January 7, 1994. The images published herein were generated from 3-band multispectral (Green, Red and Near-infrared) digital data using E. R. Mapper® image analysis software. Digital manipulations were performed to enhance contrasts in reflectivity of vegetation types, and to highlight the presence of standing water. The digital data, and a large number of interpreted images are on file at the University of British Columbia. and images are available to interested parties on diskette as .TIF files.

Low level, oblique normal colour and colour infrared photographs were taken by the author and used in the mapping of vegetation zones and drainage channels. Colour infrared is particularly useful in assessing the health of vegetation and thus is useful in monitoring the extent of saline intrusion into freshwater wetlands. High altitude air photograph stereo pairs are available for part of the deposit from the Instituto Geografico ‘Tommy Guardia’, Panama City, and were used to map detailed vegetation zones.
APPENDIX I  LEVELLING SURVEYS

A total of 9 km of survey lines were run by the author and Ing. Eduardo Reyes of the Instituto de Recursos Hidraulicos y Electrificacion. Accuracy is considered to be within 10 cm elevation in the marginal areas of the peat deposit, and 20 cm in the central regions. The use of the theodolite became problematic in areas where the peat surface was submerged, extremely soft, and irregular, as is the case in much of the central region. In such areas, the tripod was placed on 10 cm wooden pads which supported it at what was deemed the peat ‘surface’. The deepest standing water encountered by this method was 40 cm, near Lake 10. It was not possible to traverse the section between Lake 10 and Ed 3. Thus this part of the transect is represented by a straight line on all cross sections. The SE ends of the levelling lines were tied to benchmarks along the Almirante - Changuinola railway. The NW end was tied to sea level using tidal data from the Instituto Geografico ‘Tommy Guardia’, Panama City. The survey data and field notes are extensive and thus have not been included in the text. They are, however, archived at The University of British Columbia and will be made available to interested parties on request.

Site locations not surveyed were determined by Magellan® Model 5000 Pro GPS receiver. Attempts to use GPS for elevation control were abandoned due to the accuracy limits, about 15 m, of single-receiver GPS data. All positions recorded in Appendix A are thus limited to at best 15m accuracy, and in some cases may be as much as 50 m out. This inaccuracy can be due to the geometry of the satellites at the time of acquisition, but is more frequently the result of the interference of overhead foliage. At the time of writing, the use of GPS in surveying is considered impractical in treed areas.