VIRGIN ISLANDS RESOURCE MANAGEMENT COOPERATIVE

BIOSPHERE RESERVE
RESEARCH REPORT NO. 23

MAN'S LONG-TERM IMPACT ON SEDIMENTATION: EVIDENCE FROM SALT POND DEPOSITS

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U.S. MAN AND THE BIOSPHERE PROGRAM

Virgin Islands National Park

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The Virgin Islands Resource Management Cooperative (VIRMC) was formed in 1982. Signatories to the Memorandum of Understanding are: Virgin Islands National Park, the Department of Planning and Natural Resources of the U.S. Virgin Islands Government (Division of Fish and Wildlife and Division of Natural Resources Management), University of the Virgin Islands, West Indies Laboratory, Island Resources Foundation, Eastern Caribbean Natural Area Management Program, U.S. Geological Survey, U.S. Fish and Wildlife Service, Southern Forest Experiment Station, University of Puerto Rico (Sea Grant Program and the Center for Energy and Environment Research), Caribbean Fishery Management Council, the Ministry of Natural Resources and Labor of the British Virgin Islands Government, and the British Virgin Islands National Parks Trust.

The objectives of the cooperative are:

1. To establish a Virgin Islands Resource Management Cooperative for the purpose of providing coordinated research, extension, and educational support of programs to achieve full benefits of island forests, wildlife, water resources, the marine environment, and historic areas and their associated resources for their cultural, social, commercial, economic, and recreational utilization and enjoyment.

2. To provide for the direction and management of the Cooperative by forming an Executive Committee, comprised of one representative from each of the organizations who are parties to this agreement, which will a) elect annually a Chairman from the membership of the Executive Committee to serve for a term of one year, b) appoint an Executive Officer to a staff position to coordinate the work of the cooperative, c) appoint technical committees and project leaders, d) provide for the orderly process of development and implementation of policy, and e) foster cooperative activities and relationships among participating parties and with other agencies and institutions.

3. To coordinate and facilitate financial and other support for research on environmentally acceptable uses of forests, wildlife, the marine environment and historic areas, and their associated resources in order to provide for their better management.

4. To provide for the collective utilization of the unique attributes and resources (personnel, facilities, equipment, and other support services) of the parties as they may relate to objectives pursued under this agreement.

5. To plan for appropriate dissemination, publication, and application of research and information.

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NATIONAL PARK SERVICE

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ABSTRACT

Coastal ecosystems of the Virgin Islands Biosphere Reserve, St. John, are subject to stress of sedimentation from watershed erosion, both natural and man-induced. A pilot study was initiated at Mandal Pond and Reef Bay mahgrove swamp on the southern coast of St. John to determine sedimentation rates and to discover if the rates have changed in response to man's historical activity in the watershed. The results reveal the deposits are ordered in time, display horizons and preserve components produced in the pond/swamp or derived from the watershed. Radiocarbon ages of intertidal peat indicate that both sites have submerged at a uniform rate of 0.08 cm/yr. Submergence exceeds sediment infilling at Mandal Pond whereas infilling exceeds submergence at Reef Bay. Consequently, the swamp size at Reef Bay and water depth decrease with time, depositional units change and watershed-derived alluvium encroaches on the swamp. Despite man's activity, no massive effect of sedimentation on the swamp is observed. Man's effects are relatively small in comparison to the long-term natural evolution of the system.

ACKNOWLEDGEMENTS

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INTRODUCTION

Coastal ecosystems on Caribbean oceanic islands are subject to stress of sedimentation produced by watershed erosion. Part of the sediment is a natural input whereas another part can be caused by man's varied use of the land dating back 270 years to deforestation and sugar agriculture. As tropical forests were destroyed, soil erosion likely set in, soil composition changed, stream loads increased and sedimentation in coastal sinks likely accelerated. The present status of the coastal ecosystems therefore, can be partly a product of past mismanagement as well as present-day use. The effects of man are superimposed on the natural processes. The central problem poses three key questions for management: (1) What is the status of present-day sedimentation rates in relation to natural or "baseline" rates prior to man's intervention? (2) Are the present rates increasing or decreasing in comparison to the recent past? (3) If recent trends continue, what future sedimentation rates are predicted?

Much research has been done on erosion rates and sediment yield induced by deforestation, farming and mining, for example Gilbert (1917), Douglas (1967) and Meade and Trimble (1974). Very little has been done however, to measure changes in the rate that sediment goes into storage in coastal sinks. Most erosion or yield rates are determined from measurements of stream sediment loads at time scales of years or a decade, for example, Lugo et al. (1980). A few data come from weirs or reservoirs, before and after a change of land-use (Wolman, 1967; McCall et al. 1984). Much less is known about rates of erosion and sedimentation at time scales of decades and centuries, a scale at which much human activity prevails. The gap in knowledge is widened by the fact that most erosion and sedimentation rates are determined for continental areas whereas few data are available for oceanic islands. This gap is amplified by recent findings of Milliman and Meade (1983). On a world-wide basis, oceanic islands, for example in the western Pacific, have higher rates of sediment yield than elsewhere, 1,000 tons/km^2/yr, a rate 2.5 times greater than the Asia mainland. This is attributed to steep slopes, heavy rainfall and intense human activity.

Although the island of St. John has an undeveloped appearance today, its past contained a cultural landscape. Like other islands in the region there are mountainside terraces, plantation ruins, an old road network, impoverished soils and secondary or introduced vegetation (Lugo et al. 1983). Watersheds are dissected into narrow guts and steep stream banks. It remains to determine where the eroded sediment goes. Does it go into storage in stream valleys and coastal sinks? As the coastal systems evolve by sediment infilling and streams dominate, flowing into the sea, are coral reefs threatened by sedimentation?

SITE DESCRIPTION

The study sites are located in coastal environments that are likely sinks for sediment supplied from their watersheds, a mangrove swamp and a salt pond. The sites lie on the south coast of St. John (Figure 1) where annual average rainfall on the watersheds ranges 114 to 140 cm (Bowden, 1970). The watershed of Reef Bay mangrove swamp covers 5.63 km^2 and the average slope is 19%. The main valley is filled with alluvium and vegetated in lowlands with dry evergreen thicket and in uplands with gallery and basin moist forest. Higher slopes are covered by dry evergreen woodland (Woodbury and Weaver, 1984). The watershed of Mandal Pond covers 1.33 km^2 and has an average slope of 40% (Hubbard et al. 1985). Dry evergreen woodland is the dominant vegetation. Choice of the Reef Bay site provides an example of watershed having a history of substantial human activity. Changes of land use are marked and these are well documented by Tyson (1984;1985). In contrast, the Mandal Pond watershed and vicinity is relatively free of historical human activity (Tyson, 1986). Therefore, natural conditions likely prevailed while settlement proceeded elsewhere on St. John.

The environment of deposition in the Reef Bay mangrove swamp and vicinity consists of four zones that vary with distance seaward from the river valley and with decreasing elevation: (1) An alluvial lowland of dry evergreen thicket. (2) A zone of *Laguncularia racemosa* (white mangrove) 75 to 100 m wide and a canopy height of 7 to 9 m with numerous dead and dying trees. (3) Farther seaward, a zone 60 to 80 m wide and 30 to 50 cm below zone two, is *Avicennia germinans* (black mangrove) with heights less than three meters. The "scrubbiness" of this zone and the open areas of dead trees indicate this zone lacks vitality. Scrubbiness is characteristic of mangroves subject to high soil salinity (Cintron et al. 1978). (4) Behind the barrier along the seaward swamp edge is a fringe of *Rhizophora mangle* (red mangrove) in a band 5 to 8 m wide at elevations of 20 to 40 cm below zone two. The trees are mainly less than 2 m high.

Water in the mangrove swamp is stagnant and circulation is restricted by the numerous dead trees. During rainy periods the swamp receives intermittent inflow mainly from a stream along the northwest side and secondarily from an intermittent stream that enters on the east side. Swamp water discharges across the barrier through a channel 110 m long and 8 to 20 m wide (Figure 1). During normal conditions the entrance is blocked by littoral sand and therefore, fine fluvial sediment is likely retained in the swamp. Because the channel is straight for a considerable distance and its sand bed attains depths of 1.5 to 2.0 m below sea level, it is likely a man-made cut. Examination of aerial photography dated 1947, reveals that the swamp once contained a small pond in eastern reaches. Additionally, a U.S. Coast and Geodetic Survey Chart dated 1919, reveals the swamp contained a small lagoon connected to Reef Bay, in western reaches. The swamp and enclosed pond or lagoon reportedly were

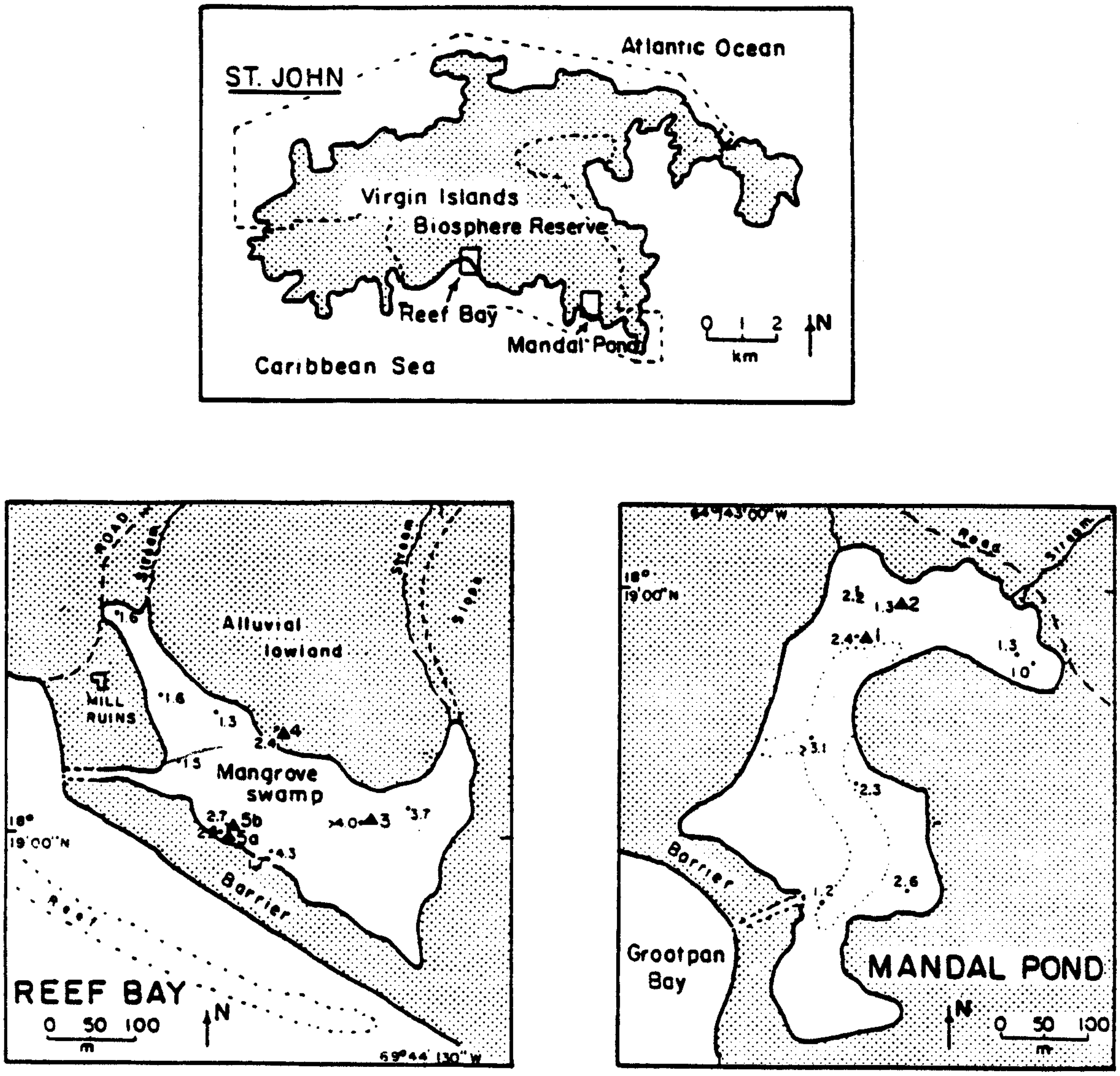

Figure 1. Location of study sites and configuration of Reef Bay mangrove swamp and Mandal Pond. Dots are probe sites and sediment thickness in meters. Triangles are core locations.

used as places to dump sugar factory wastes. Edges of the swamp are inhabited by numerous land crabs, Cardisoma guanhumi. By burrowing into the near-surface sediments 30 to 35 cm, the crabs mix the upper 30 to 70 cm of sediment and thus can destroy sediment stratification and the recent geologic record.

Mandal Pond occupies a drowned stream valley of Cob Gut. This is evidenced by alluvium that underpins the filling of pond deposits. Additionally, reentrant "arms" of the pond lead into small tributary streams. The drowned appearance of the shoreline is interrupted by a very small delta protruding pondward at the entrance to Cob Gut. On its seaward side the pond is enclosed by a sand and cobble barrier about 1.8 to 2.5 m high. The barrier is dissected in its central part by a channel 84 m long, 7 m wide and 0.3 to 1.2 m deep. This channel is likely an artificial cut and its course is displayed in a 1947 aerial photograph as well as on a 1919 U.S. Coast and Geodetic Survey Chart. Although the channel is choked with mangroves it likely allows discharge of overflow flood water into Grootpan Bay. In contrast, seawater likely enters the pond from the ocean through the channel during infrequent periods of high waves and storm surge. During normal conditions the pond is essentially a closed system and provides a good trap for sedimentary materials.

Water depths in the pond after rainy periods range 0.6 to 1.3 m. In aerial photographs dated 1965 however, the pond floor displays a white tone. This is indicative of salt efflorescence and hence, subaerial exposure during drought periods. When the pond is full, local wind waves can stir up fine "soupy" bottom sediment and render the water turbid. Therefore, near-surface sediment is subject to physical mixing. Bioturbation of the sediment however, is limited by the scarcity of macrofauna. The pond fauna consists of numerous microfauna less than 2 mm size, mainly gastropods, of the species Assiminea succinea or Littoridine sphinctostoma. Since the shores are steeply sloping, mangroves are limited to a narrow irregular fringe along the pond edge.

Both sites are subject to infrequent disturbances as droughts and hurricanes. Droughts can last 2 to more than 20 years or 66% of the time according to the Palmer Drought Severity Index (Bowden, 1970). Drought weakens the protective vegetal soil cover and provides favorable conditions for fires. Droughts are often terminated by rainstorms or hurricane floods which are conducive to rapid soil erosion and sediment discharge. Landfall hurricanes on St. John have an estimated recurrence interval of five per century (Mills et al. 1964). Most sediment in fluvial systems is transported during short periods of infrequent storms. Consequently, flood deposits are likely to have sharp lithologic changes.

OBJECTIVES

This study aims to determine if the sediment deposits of the mangrove swamp and salt pond contain an interpretable record of long-term changes in response to natural processes and human disturbance in the watershed. This broad objective resolves into four sub-objectives: (1) to determine if the record of sediment accumulation is ordered in time, forms horizons and is sufficiently complete for stratigraphic and geochronologic analyses; (2) to determine what constituents are preserved in the deposits that bear a relation to watershed source; (3) to date horizons that exhibit a significant vertical change in composition or lithology and to determine the rate of sedimentation between dated horizons; (4) to document the sedimentation impacts on the salt pond and mangrove systems.

RATIONALE AND APPROACH

An initial premise for study is that the mangrove swamp and salt pond systems are essentially closed systems and sinks for sediment supplied from their watersheds. This is likely because they are near, or slightly below, the fluvial base level and they lie behind barriers protected from wave action. Additionally, submergence by the relative rise of sea level in the past several thousand years enables sediment to accumulate and be preserved. Data on submergence is provided in a subsequent section. Therefore, depositional processes in the sinks should produce an accumulation of sediment that is ordered in time. Further, the deposits should naturally archive the time history of sediment input that varies with climate, streamflow, vegetal cover, and watershed land use. Changes in accumulation rate of watershed-derived sediment in the sink are likely proportional to changes in the watershed sediment input. The resulting changes in the deposits therefore, can be keyed to prospective causes in the watershed. In some instances these are known from historical information or can be determined from pollen analyses. Instead of comparing volume or mass of sediment in the sink with that of source in a mass balance context, this study deals with changes in rates of sedimentation. Therefore, it is an inverse solution to detecting historical changes in the watershed. The approach focuses on long-term changes recorded in cores at time-scales of centuries to a few millennia. It provides a means to explore whether present rates are unique or continuous with the past, unidirectional or cyclic. The approach is a potential research strategy that can strengthen watershed management and development of a Biosphere Reserve on St. John.

Success of the approach depends on several initial assumptions. It assumes direct delivery of sediment from the source to the sink without extensive storage or secondary erosion from stream valleys. Further, it assumes that watershed-derived sediment in the sink can be differentiated from sediment produced in the sink. It assumes that sedimentary

components are preserved in the deposits and that they are free of post-depositional redistribution and extensive mixing. The validity, or fallacy, of these assumptions is indicated by results of this study.

Pollen grains from terrestrial plants are particularly useful for stratigraphic and geochronologic studies. They enter coastal sinks from the atmosphere and are transported like fine sediment, eventually deposited, buried and preserved in sediment deposits. Once diagnostic pollen assemblages or species ratios are determined, the vertical change of pollen composition in the deposits can be linked to changes in the history of a watershed vegetation, which is associated with changes of land use. If the time of the land use change is known from historical information, then pollen horizons provide a means to date the deposits. Once dates are assigned to pollen horizons, or acquired by radiometric dating, then sedimentation rates can be determined between dated horizons. The relative concentration of pollen per unit volume between dated horizons indicates the relative rate of sedimentation, assuming constant input of major marker pollen. Because the range of radiometric isotope analyses is limited, pollen analyses is the chief means of dating deposits in the time span of about 80 to 400 years before the present (B.P.).

The geochronologic and stratigraphic approach employing pollen analyses has been successful for detecting effects of land use on small lakes, for example, Davis (1976) and Haworth et al. (1984), and in estuaries, Brush (1984); Brush and Davis (1984). Application to other coastal systems and to subtropical environments remains to be explored.

METHODS

Field Methods

The thickness of soft or loose sediment above a firm base or layer in the deposits was determined by manual probing with a 4.3 m length steel rod. Depths of refusal to penetration and thickness of interlayers along transects or at points were noted and recorded.

Borings were made at selected stations with a Davis peat sampler. This is essentially a small piston corer that takes 30 cm long sections in a 3.8 cm diameter core barrel. By adding extensions, relatively undisturbed replicate cores (2 to 4) were obtained to 2.6 m depth.

Short cores were obtained by driving a 7.6 cm diameter PVC pipe into the sediment to depths of 53 cm. Replicate cores were cut lengthwise, photographed, X-rayed for structure and subsampled at 1 to 3.8 cm intervals for analyses of water content, grain size and coarse fraction. Other subsamples were frozen for geochemical and radiometric analyses.

Stations were positioned by pacing, ranging and compass bearings using topographic maps and aerial photographs for base reference.

Laboratory Methods

In the laboratory, water content was determined gravimetrically by weight loss on drying following procedures of Dawson (1959).

Davis cores were examined under a binocular microscope noting the gross lithology, color, relative firmness, minor structures and composition including organic and carbonate content. Subsamples were washed over a 63µ size sieve to separate sand and mud. The fine fraction was further analyzed for silt and clay content by pipette following Folk (1961). The coarse fraction was analyzed for composition of components by a frequency count of at least 200 grains under a binocular microscope.

The chronology of the lower core section was determined by assaying horizons for radiocarbon activity. The radiocarbon ages reported here were made by Geochron Labs and Beta Analytic using the CO_2 method. The material reportedly was pretreated by first removing rootlets and concentrated by dispersion in a large volume of water whereby the clays and organic matter were eluted away from any sand and silt by decantation. The clayey organic fraction was then dispersed in dilute HCl to remove carbonates, filtered, washed, rinsed to neutrality, dried and roasted in oxygen to recover carbon dioxide from the organic matter. All counting was normal and sample size was adequate. In collecting samples for radiocarbon analysis, efforts were made to avoid contamination following handling procedures of Polach and Golson (1966). To minimize errors due to compaction, samples were initially obtained near the top of an alluvium base. Subsequent samples were obtained to avoid sediment disturbance, physical mixing and root contamination. All ages are calculated using a half-life value for C-14 of 55% and stated in years before the present, 1950 A.D. (B.P.).

The ^{137}Cs activity of near-surface sediment was determined by gamma ray counting using a lithium-drifted germunium detector and multichannel analyzer. The ^{137}Cs radio-isotope is a product of nuclear weapon testing and fallout activity. The sediment chronology is derived from activity peaks in vertical profiles assuming the first appearance of ^{137}Cs coincides with 1950 and peak activity represents 1963, the year of peak nuclear testing.

Pollen was extracted at the Johns Hopkins University following basic procedures of Fraegri and Iversen (1969). In brief, this involves first weighing a 1.5 ml subsample wet and dry and then treating it with dilute hydrochloric and hydrofluoric acid. The samples were then acetylyzed using a mixture of sulfuric acid and acetic anhydride. Following extraction the entire residue of the sediment used was stored in 25 ml of tertiary butyl alcohol. Aliquots of the stored residue (0.1 ml) were

mounted in silicone oil on microscope slides. The slides were examined for pollen at 400 x magnification with counts of 150 or more. Values for total pollen are expressed as concentration, number per gram dry sediment and individual types as percentage of total pollen. Average rates of sedimentation in cm/yr were obtained by dividing the length of the core between the dated horizons by the number of years between the horizons. Mass rates of sediment accumulation, $g/cm^2/yr$, were calculated by dividing cumulative dry weight of sediment between the dated horizons by the number of years. Additionally, pollen concentrations in the sediments were used to calculate sedimentation rates for individual increments of the core. The average sedimentation rate was adjusted according to the concentration of the pollen in the sediment, by assuming that the average pollen concentration in the cores is proportional to the long-term average sedimentation rate. Therefore, changes in sedimentation rate for a single increment, x, can be estimated by dividing the average pollen concentration, $\bar{P}$, by the pollen concentration in a single increment, Pi, and multiplying by the average sedimentation rate (obtained from radiocarbon dates), $\bar{Ms}$, as follows:

$$X = \frac{\bar{P}}{Pi} \cdot \bar{Ms}$$

RESULTS

Thickness

The thickness of soft deposits lying above a firm base, which is usually alluvium, is illustrated in Figure 1. Thickness in central reaches of Reef Bay swamp is greater than 4.0 m and landward of the barrier it attains 4.3 m. Thickness decreases landward toward the west stream entrance. Near station 5 interlayers of shell and sandy gravel are encountered between 1.6 and 2.7 m depth. In Mandal Pond the fill of soft sediment ranges from more than 3.1 m thick in central reaches to 1.0 m and 1.2 m in landward and seaward zones. Cores from station 1 and 2 reveal that the firm base is alluvium.

Depositional Units

By examining the gross lithology of cores that penetrate the deposits beneath the Reef Bay mangrove swamp, four units are recognized:

1. Alluvium, the deepest and most landward unit consists of poorly sorted gravelly clay or mixtures of sand and clay with angular rock and quartz fragments. A few fragments are iron-stained or weathered. The sediment is non-calcareous and structureless except for root structures that depart a mottled appearance of dark grey in a matrix of light grey.

2. Lagoonal, the central unit in lower core sections consists of dark grey silty clay with abundant organic debris. Shell layers are pronounced and fossil fauna is abundant. The shells consist of oyster, clam, mussels and lagoonal foraminifera including species of <u>Streblus</u> and <u>Nonionella</u>.

3. Mangrove peat, an intermediate unit at mid-depth, is the most widespread unit. It is dark brown or reddish brown and spongy in consistency. Fauna is scarce except for a few arenaceous foraminifera. Organic debris, roots and leaves dominate. Since living red mangroves normally inhabit the lower intertidal zone, this peat is a good reference of former sea level positions.

4. Swamp clay, the topmost unit is inhabited by white mangrove. It consists of dark grey silty clay with one to five percent organic debris. A few arenaceous foraminifera are present. The clay is very firm and structureless except for light grey color mottles. This sediment is likely deposited in ponded water following periods of high stream inflow.

Stratigraphic Relations

When the buried depositional units are compared from core to core in a section with distance seaward from the alluvial lowland, vertical and lateral relationships are displayed as shown in Figure 2. The most significant features are: (1) Along the seaward edge of the alluvial lowland, core 4, alluvium overlies mangrove peat in a seaward prograding relationship. (2) Buried mangrove peat in core 4 between 1 and 2 m depth overlies alluvium in a transgressive relationship, a trend indicating that peat extended farther landward in the past. (3) In central reaches, core 3, lagoonal deposits are replaced upward by mangrove peat and then by mangrove swamp clay. This change denotes shoaling conditions.

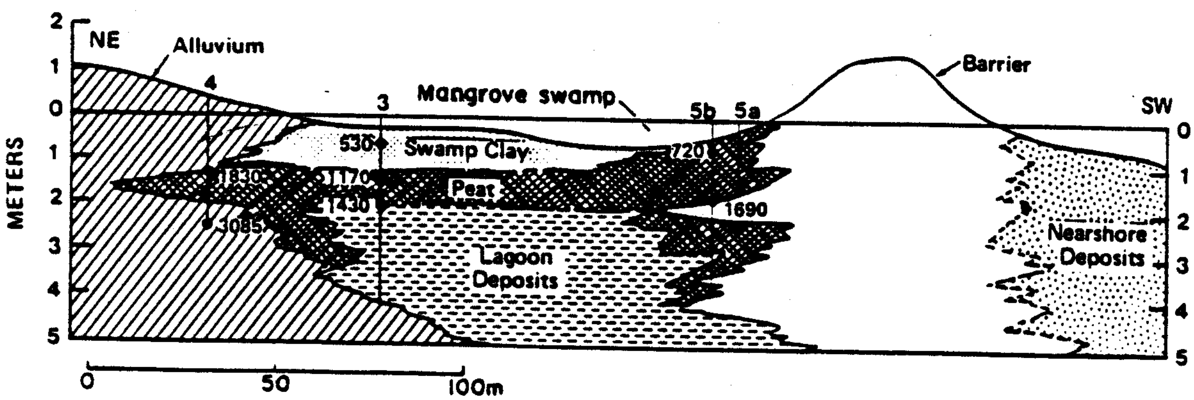

Figure 2. Stratigraphic section through Reef Bay deposits showing major depositional units, relationships, and radiocarbon age.

(4) Along the landward edge of the barrier, cores 5a, 5b, mangrove peat overlaps barrier sediment near the surface whereas barrier sediment underlies peat at depth. The overall relation is a slight onlap of lagoonal deposits over barrier sediment. At intermediate depths tongues of barrier sediment locally protrude into lagoon deposits in a relation indicative of storm washovers.

Submergence

Changes in the elevation of sea level relative to the land over hundreds to several thousand years may be inferred from radiocarbon dates of the peat. This assumes that formation of the peat has occurred in the intertidal zone and that mean range of the tide has been the same during the time span under consideration. Prior study of the Mangrove Lagoon, St. Thomas, by Nichols et al. (1977), shows that the elevation of red mangrove is close to (±8cm) mean low water referred to local tidal datum, a site where the mean range is 27 cm. Although part of the mangrove peat may have developed in ponds isolated from the tide, which are subject to seasonal changes of pond level produced by precipitation and drought, over the long term the peat level is likely linked to sea level rise. The data obtained from radiocarbon age determinations of peat and organic debris contained in near-basal strata, which is relatively free of compaction effects, is illustrated in Figure 3. Depths are corrected to approximate mean low water level. Table 1 lists the age and depth of samples analyzed. The data are relatively consistent in indicating a continuous rise of sea level since 3,300 years B.P. at a rate of 0.08 cm/yr.

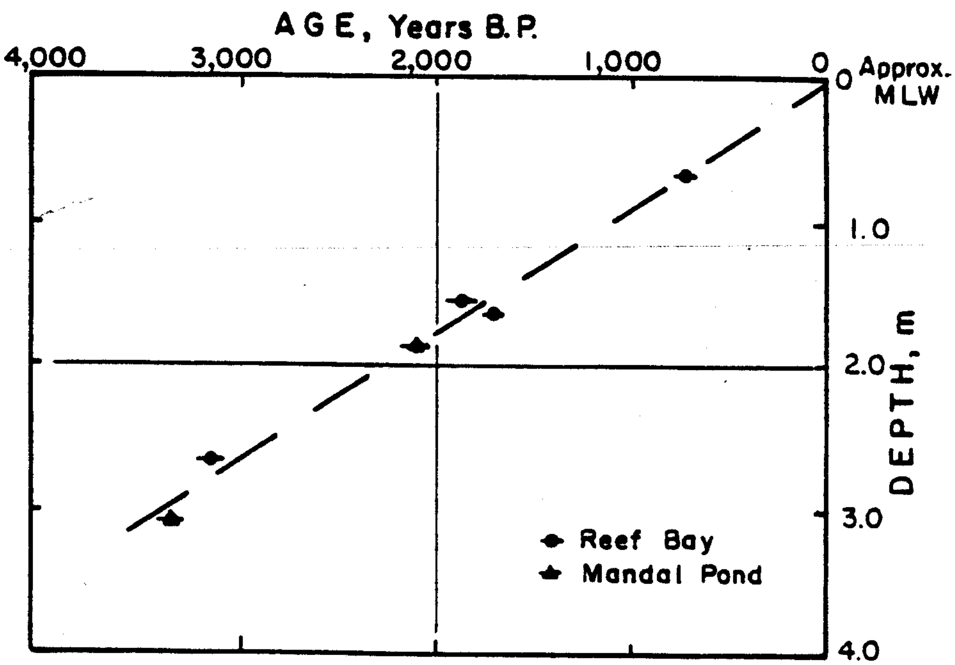

Figure 3. Radiocarbon age and depth below approximate mean low water of samples from Reef Bay, dots; and Mandal Pond, triangles.

Table 1. Age and Depth of Samples Dated by Radiocarbon Analyses

Sample Field	Lab Number	Midpoint Depth Below Sediment Surface, m	Midpoint Depth Below Approximate Low Water, m	Character of Material	Age Years B.P.
1b	Beta-19521	0.35	0.99	Organic fragments in silty clay	560 ± 90
1b	Beta-18849	0.53	1.17	Organic debris in silty clay	880 ± 120
1	Geochron-GX12606	2.39	3.03	Organic peat debris in clay	3,300 ± 165
2	Beta-18848	1.24	1.88	Organic fragments in sandy clay	2,090 ± 110
3b	Beta-19522	0.36	0.66	Peaty clay	530 ± 60
3	Beta-18847	1.09	1.39	Peat	1,170 ± 100
3	Geochron-GX12607	1.73	2.03	Peaty clay	1,430 ± 80
4	Geochron-GX12608	1.74	1.54	Peat	1,830 ± 140
4	Geochron-GX12609	2.82	2.62	Organic fragments in clayey gravel	3,085 ± 135
5b	Beta-19524	0.50	0.72	Peat	720 ± 60
5a	Beta-19523	1.45	1.67	Peat	1,690 ± 90

Sedimentation Rates

Radiocarbon dates also provide valuable information on the rate of sedimentation assuming sediment accretion is vertical. Because the sediment is dominately fine-grained and subject to compaction with time as accretion proceeds, the sediment volume deposited between dated horizons is converted into weight per unit area. This avoids the uncertainties of compaction inherent in the use of thickness (cm/yr) as an expression of rate of sedimentation. The conversion starts with the average water content on a dry weight basis between the dated core horizons. Then the porosity is determined and in turn the percentage volume of solid grains assuming a grain density of 2.65 g/cm^3 for sand, silt and clay, and 1.3 g/cm^3 for peat. Subsequently, the product of the percentage volume of solid grains and the grain density times the sedimentation rate in cm/yr, yields the sedimentation rate in $g/cm^2/yr$.

The sedimentation rate derived for Mandal Pond averages 0.042 $g/cm^2/yr$ whereas for central reaches of Reef Bay swamp (cores 3 and 4) it averages 0.082 $g/cm^2/yr$, two times greater (Table 2). Relatively young material from the upper part of Mandal Pond core 1 has about the same sedimentation rate as older material from the lower part of the core. However, in relatively young material from cores 3 and 4 in Reef Bay swamp, the rates are faster than for older material in lower parts of the cores, a fivefold increase in core 4. The young material in core 4 however, does not allow determination of an age younger than 1830 years B.P. because it is mixed by land crabs and lacks organic matter. Radioactivity of ^{137}Cs for surface material is relatively low, 0.1817 pci/g, indicating an age older than 35 years.

Sediment Characteristics

The results of textural and compositional analyses for core 1, Mandal Pond, are shown in Figure 4. Sand, silt and clay percentages vary within narrow limits, mainly 8%, 23% and 69% respectively. Water content diminishes from a peak of 92% in "soupy" surface sediments to 41% in relatively firm sediment at 65 cm. Organic content is relatively low, less than 2% dry weight, except of thin layers and laminae at 0-2, 40-41, 51-57 and 111-121 cm depth that are enriched 5% or more. Most of the enriched layers are in the form of algal deposits whereas elsewhere detrital fragments of leaves, twigs and seeds are common. Algal laminae are prominent and interlayered with carbonate sand layers in bands 1 mm to 2 cm thick between 200 and 260 cm depth.

The coarse fractions, i.e. sand fractions more than 62µ, consist of calcium carbonate particles, quartz and feldspar, organic detritus and shells or tests of microfossils including ostracods, foraminifera, diatoms and gastropods. Although the coarse fractions generally make up less than 10% of the total sample by weight, they are a useful indicator of changes in pond conditions or sediment input. Carbonate particles make up higher percentages of the coarse fractions in the upper 60 cm and lower 90 to 260 cm of core 1. The distribution of carbonate percentage displays a peak at the 25 cm depth, an estimated date of 1600 A.D.

Table 2. Sedimentation rates for cores from Mandal Pond and Reef Bay mangrove swamp based on radiocarbon age determinations. Average is integrated average from zero age to oldest age.

Core Number	Depth Interval, cm	Age Span, yrs	Sedimentation Rate, cm/yr	Sedimentation Rate, $g/cm^2/yr$
1b MP	0 - 35	560	0.063	0.032
1b MP	35 - 53	320	0.056	0.027
1 MP	53 - 239	2,420	0.077	0.037
1 Average	0 - 239	3,300	0.072	0.042
2 MP	0 - 124	2,090	0.059	0.030
3b RB	0 - 36	530	0.068	0.056
3 RB	36 - 109	640	0.114	0.069
3 RB	109 - 173	260	0.246	0.048
3 Average	0 - 173	1,430	0.119	0.064
4 RB	0 - 174	1,830	0.092	0.173
4 RB	174 - 282	1,255	0.088	0.032
4 Average	0 - 282	3,085	0.091	0.101
5b RB	0 - 50	720	0.069	0.016
5a RB	50 - 145	970	0.098	0.014
5a Average	0 - 145	1,690	0.086	0.011

MP is Mandal Pond; RB is Reef Bay mangrove swamp.

(Figure 4) whereas in more recent time percentages are less. The carbonate is likely produced by precipitation in the pond or in near-surface sediment during periods of drought and high evaporation.

Microfossils are dominated by ostracods throughout core 1. Percentages are more than 20% in silty clay zones in lower parts of the core, for example at 148 cm, 185 cm and 215 cm. Foraminifera tests are abundant in lower parts of the core, 145-250 cm depth, but absent or scarce in upper parts above 145 cm. In contrast, gastropods, mainly species of Assiminea succinea or Littoridina sphinctostoma, make up about 0.5 to 1 percent of the coarse fraction in the upper 90 cm or last 1,400 years. At the 35 to 42 cm depth they form a distinct horizon with percentages of 1 to 6%.

Coarse fraction composition in cores from Reef Bay is characterized by large percentages of organic debris and less than one percent carbonate. Quartz, feldspar and rock particles make up 2 to 11 percent of the particles. The upper one meter of sediment is devoid of microfossils except for a few arenaceous foraminifera. Below one meter, in a zone including the lower lagoon deposits, shell, ostracods and calcareous foraminifera are present in addition to traces of coral debris.

Pollen grains in core 1, Mandal Pond, are preserved in the sediment and they are relatively abundant and diverse. Fifty-one different types are tentatively differentiated and classified according to morphological characteristics. Pollen descriptions by assigned artificial names are given in Appendix I. A minimal number of only four types irregularly increases upward in the core from 16.5 cm reaching 15 in surface sediment. Between 24 cm and 50 cm depth, or 1600 to 1150 A.D., five to twelve types occur. The trends in the upper 50 cm of core 5 from Reef Bay, are similar to these in core 2 from Mandal Pond.

The abundance of pollen grains in core 1 ranges 5,200 to 29,000 grains per gram of sediment per square centimeter (Figure 4). The concentrations are minimal at the 16.5 to 17.0 cm depth, an estimated time 1720 A.D. The abundance irregularly increases upward in the core reaching a peak at 3 to 3.5 cm depth or about 1930 A.D. (Table 3). Pollen abundance in core 5, from Reef Bay, is similar to core 1 except the upward increasing concentrations begin at the 50-51 cm depth (Table 4).

An extremely abundant, small (12 to 16 microns) smooth spheroidal pollen grain with no apertures occurs in sections of the core from Mandal Pond, but was virtually absent from Reef Bay. This taxon may belong to members of Cupressaceae which includes the genus Juniperus. An abundance of this component is found in core 1 between the 15.5 and 40.5 cm depth. The most abundant pollen type with the widest stratigraphic range is a tricolporate pollen grain in the J-group, which may include the genus Rhizophora (red mangrove). Pollen type D-4

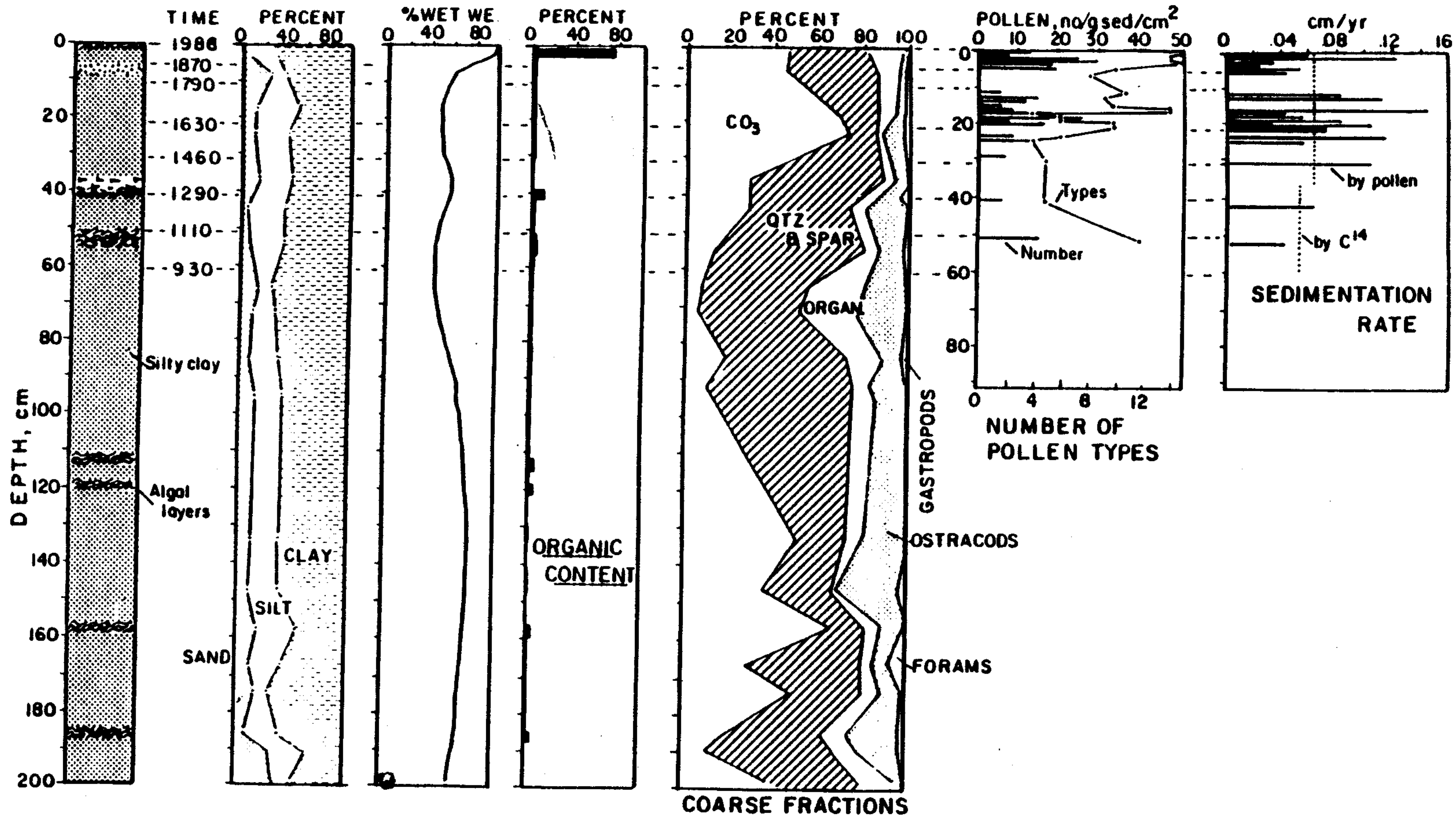

Figure 4. Changes of core lithology, estimated chronology based on ^{14}C dates, composition of coarse fractions, pollen abundance and number of pollen types as well as sedimentation rates based on relative pollen concentration, dots, and radiocarbon dates, dashed. Core 1 from Mandal Pond, May, 1986.

Table 3. Pollen data from Core 1, Mandal Pond, in terms of abundance, average and adjusted sedimentation rate. Average sedimentation rates based on ^{14}C dates at 35 cm (560±90yrBP) and 52 cm (880±120yrBP).

Depth cm	Dry (bulk) density g sed/cc	Pollen accumulation no/sq cm²	Pollen accumulation no/g sed/sq cm²	Average sedimentation rate cm/yr	Adjusted sedimentation rate cm/yr
Top	0.502	6167	12285	0.06	0.06
1.5-2.5	0.438	3167	7230	0.06	0.12
2.5-3.0	0.457	11667	25529	0.06	0.03
3.0-3.5	0.511	15000	29354	0.06	0.02
3.5-4.0	0.452	8000	17699	0.06	0.05
4.0-4.5	0.473	9333	19732	0.06	0.04
11.0-11.5	---	5000	---	0.06	0.08
11.5-12.0	0.487	3333	6845	0.06	0.11
15.0-15.5	0.511	2667	5218	0.06	0.14
15.5-16.0	0.557	8667	15559	0.06	0.04
16.0-16.5	0.546	7000	12820	0.06	0.05
16.5-17.0	0.449	2333	5197	0.06	0.16
17.0-17.5	0.521	3333	6398	0.06	0.11
17.5-18.0	0.607	5000	8237	0.06	0.08
18.0-18.5	0.405	8000	19753	0.06	0.05
18.5-19.0	0.461	12333	26753	0.06	0.03
19.0-19.5	0.535	4000	7477	0.06	0.10
19.5-20.0	0.354	5667	16008	0.06	0.07
23.0-23.5	0.359	3333	9285	0.06	0.11
23.5-24.0	0.551	7000	12704	0.06	0.05
29.5-30.0	0.550	4000	7273	0.06	0.10
40.5-41.0	0.577	4000	6932	0.05	0.06
50.5-51.0	0.414	6000	14492	0.05	0.04

Table 4: Pollen data from Core 5, Reef Bay, in terms of abundance, average and adjusted sedimentation rate

Depth cm	Dry (bulk) density g sed/cc	Pollen accumulation no/sq cm	Pollen accumulation no/g sed/sq cm	Average sedimentation rate cm/yr	Adjusted sedimentation rate cm/yr
0-1	0.4731	6333	13387	0.07	0.05
1-2	0.4465	5833	13064	0.07	0.05
2-3	0.5135	5000	9737	0.07	0.06
3-4	0.3129	4750	15180	0.07	0.06
20-21	0.3625	3833	10575	0.07	0.08
40-41	0.3225	3000	9302	0.07	0.10
50-51	0.3192	2167	6788	0.07	0.14

which resembles the grass Sparganium (burreed) is common in sediments from Reef Bay, but is found only rarely in Mandal Pond sediments. H-4, which resembles pollen of Quercus (oak) is common in Mandal Bay, but not in Reef Bay, core 5.

Rates of sedimentation based on the concentration of pollen between radiocarbon dated horizons and the surface are shown in Figure 4, Tables 3 and 4. Whereas the average rates are 0.06, 0.05 and 0.07 cm/yr in Mandal Pond, core 1, the adjusted rates are highly variable ranging from 0.02 to 0.16 cm/yr in the upper part of the core, and from 0.03 to 0.24 cm/yr in the section of the core from 200 to 300 cm. In core 1, Mandal Pond, the most prominent feature is a peak, 0.16 cm/yr, at the 16.5-17.0 cm depth, or an estimated age of about 1720 A.D. Near-surface sedimentation rates are similar to those at depths of 11 to 15 cm as well as those at 16.5-17.5 cm, and 19-19.5, 29.5-30 cm.

The average rate is 0.07 cm/yr in core 5 from Reef Bay, with adjusted rates ranging from .05 to .14 cm/yr. Rates in Reef Bay decreased in recent years relative to Mandal Pond.

INTERPRETATION

The results show that deposits accumulating in the coastal sinks meet most of the requirements for stratigraphic and geochronologic analyses. Many of the assumptions noted in the approach hold. That the record of sediment accumulation is ordered in time is revealed by the radiocarbon age versus depth plot whereby points follow a linear trend. This trend not only holds for near-basal material from core to core (Figure 3) but for material from mid-depths in individual cores except for peat deposits of core 3, 1.5 to 2.0 m depth. This peat is subject to compaction because of its high initial water content. Therefore, peat of a certain age lies below the depth at which it was originally produced. The cores do not exhibit discontinuous contacts between layers or depositional units indicating hiatuses. Instead, most contacts are gradational and surface sediments are continuous with deposits of the recent past.

Although the deposits lack distinct stratification and appear homogenous, except for banding in the lower part of core 1, analyses reveal that horizons are present. They are evident in some of the X-ray radiographs as subtle changes of tone which reflect changes of sediment density associated with variations of sediment compaction, texture and composition. Some horizons consist of an abundance of gastropods; others consist of organic layers, changes in the ratio of carbonate to quartz and feldspar grains and vertical changes in the abundance and composition of pollen types. Sediment mixing therefore, must proceed within narrow vertical intervals, except for the upper part of Reef Bay core 4 which is heavily bioturbated by land crabs.

Preservation of sedimentary components in the deposits is relatively good. Although pond-produced algal layers diminish just below the surface in core 1, peat is preserved in layers 1 to 2 m thick in cores from Reef Bay. Carbonate grains are preserved throughout cores 1 and 2 despite the anoxic and reduced state of the sediment indicated by the black and dark grey color. The vertical variations of percentage carbonate grains likely result from variations in dilution of carbonate by input of terrigenous clay and in supply of carbonate by precipitation from pond water or sediment pore water. Precipitation can be induced by excess evaporation during drought. Alternately, precipitation can be caused by contact of calcium-rich fresh water with saline pond water during fresh water inflow. Post-depositional carbonate dissolution is likely limited because ostracod valves occur throughout pond cores 1 and 2. Pollen grains are not only preserved in the deposits but bear a relation to watershed sources. Many types of pollen, other than mangrove types produced in or around the swamp and pond, occur in the deposits. Of note is the increase of diversity since about 1600 A.D., the variable number of types during the "sugar era", and the marked increase of diversity since about 1850 A.D. which is evidence of additional species introduction.

Clay is the chief sediment supplied from the watershed. Sand and gravel layers indicative of intense stream flooding caused by hurricanes are limited to the lower part of core 1, below 214 cm. Although the watershed source of the clay has not been confirmed by mineralogic analyses, supply from marine areas is unlikely since marine clay sources are unknown and the systems are largely isolated from the sea. Clay content increases upward in core 1 about 17 cm depth, or since 1690 A.D., a trend paralleling higher coarse fraction percentages of quartz and feldspar. Some of the feldspar grains are angular and weathered indicating a watershed source. In Reef Bay core 3, clay content is high, 68-78%, in near-surface sediment about 90 cm depth. Watershed influence in recent years is also evidenced by stratigraphic relationships in cores 3 and 4 whereby alluvium overlies peat and progrades seaward over swamp clay. These deposits however, include accumulation during both pre-settlement and post-settlement periods.

The long-term change in thickness of the deposits, core lithology, sediment composition, stratigraphic relations and in radiocarbon chronology are part of the natural evolution of the system. However, the rate and degree of evolution vary with location. Both Mandal Pond and Reef Bay mangrove swamp occupy valleys excavated by ancestral streams when sea level was lower prior to 3,000 years B.P. The streams likely flowed through valleys to a shoreline located farther seaward than at present. By 3,000 years B.P., the global sea level rise inundated the valleys forming a narrow estuary at Mandal and an embayment at Reef Bay. Longshore drift of material across entrances to these systems formed spits or barriers, thus partly isolating them from the sea. At Mandal a pond formed though it must have had intermittent exchange with the sea to allow introduction of marine microfauna. At Reef Bay a lagoon formed with an open connection to the sea allowing lagoon fauna and occasional introduction of reef debris.

Continued rise of sea level after 3,000 years B.P. flooded and enlarged both systems. At Mandal Pond the enlargement is maintained today since the rate of sea level rise proceeds faster than the rate of sediment infilling. If the pace of infilling and sea level rise continue, the pond may be expected to increase its present water depths and continue its natural condition. In contrast, enlargement of Reef Bay lagoon was arrested about 2,000 years B.P. by growth of mangroves and lateral infilling. The infilling consisted mainly of mangrove peat which likely segmented the lagoon into ponds and thus reduced tidal exchange and promoted barrier growth further isolating the system. By about 1000 years B.P. isolation from the sea was nearly complete and vertical sedimentation reached an elevation that converted the red mangrove habitat to a black and white mangrove habitat. Peat development was replaced by silt and clay from the watershed and alluvium prograded into the swamp further reducing the swamp size, drainage and capacity to absorb and store sediment. Owing to the erratic nature of flood discharges near base level, the depocenter or focus of sedimentation within the system has likely shifted with time and location. Low zones behind the barrier and eastern reaches must receive some accumulation while western reaches, which are very shallow, likely by-pass part of the clayey sediment load into Reef Bay during high freshwater discharge. In summary, the long-term pace of infilling in landward zones of Reef Bay swamp in the last 2,000 years has slightly exceeded the pace of sea level rise. Today the swamp is at the brink of extinction. It is no wonder that the swamp is stagnant and mangrove stands are dying or dead.

The influence of human activities on sedimentation rates in the upper part of cores from Reef Bay is slight compared to the long-term natural variations over 3,000 years. Although rates at Reef Bay are one and one-half to two times greater than at Mandal Pond, the ratio of pond sink area to watershed area is much smaller (0.01) compared to Mandal Pond (0.07). Therefore, the relative storage capacity of Reef Bay swamp is less per unit area of watershed than Mandal Pond. The most marked increase in sedimentation rates is noted in the upper part of core 4 but short-term changes cannot be separated from the long-term trends at present. Core 5 reveals little change in sedimentation rate over the last 350 years. It is evident however, that release of upland sediment during the sugar era did not eliminate the mangrove swamp though it may have accelerated sedimentation in some sectors.

A speculation is that sediment released by sugar agriculture may have been partly stabilized in terraces near its source. Another part may be stored in the stream valley behind plantation impoundments, boundary line walls or in alluvial bars. That is, the main "wave" of sugar era sediment may be stored in the valley for decades or a century, until the next large hurricane capable of eroding it again and transporting it into the coastal sink. This threat is especially critical because the mangrove swamp is nearly filled with sediment and offers little buffering capacity against massive flood inputs. Thus, despite man's concern the system appears doomed as a long-continued natural mangrove swamp. With its demise will come a further contraction in the remaining coastal resources of the Biosphere Reserve. Only a major effort can hope to arrest the decline and, in turn, conserve nearshore coral reefs.

MANAGEMENT STRATEGIES

Since one of the aims of developing a Biosphere Reserve on St. John is to provide a scientific basis for managing the Reserve, several strategies are offered to illustrate prospective application of results. It is assumed that maintaining the integrity of St. John's nearshore coral reefs is of priority importance.

1. Manage from an evolutionary baseline. Despite man's historical use of the watershed at Reef Bay (Tyson, 1986) and possible "mismanagement", the findings indicate no massive sedimentation effect. From the perspective of a century and millennium time scale, man's activity in the watershed and resultant change in coastal systems are part of a long-term evolutionary process. Therefore, the Biosphere Reserve needs to be managed essentially as a "natural area" rather than managed "back" toward pristine conditions. Human management efforts can relieve stress temporarily on coastal ecosystems and postpone damage to coral reefs, but evolution of the systems is likely, to continue so long as rate of sedimentation exceeds the global rise of sea level. The following strategies therefore are offered to slow the pace of natural processes rather than to interrupt or reverse their direction.

2. Manage to improve entrance exchange. Although both systems have former man-made channels to the sea, these are clogged by mangroves, and littoral drift. As a result, swamp water is stagnant and pond, water "dead" especially during periods of drought and low water. Subaerial exposure and hypersalinity place an added stress on the swamp system, one that has already lost its vitality at Reef Bay. Any measure that would open the existing channels and create a "valve" to control exchange with the sea during extreme conditions would be of benefit. The valve is needed not only to reduce subaerial exposure during drought but to retain fine sediment during floods by "ponding" water and sediment and thus mitigate the threat of sedimentation on coral reefs. A small effort could produce a large improvement and help postpone the long-term consequences.

3. Manage to stabilize bottom sediments. Although Mandal Pond has a capacity to absorb more watershed sediment, shoaling water depth allows wind waves to resuspend clayey bottom sediment and render the water turbid. Contact sports such as water skiing would amplify turbidity. Turbidity reduces light penetration as well as growth of benthic algal that stabilize the bottom sediments. Resuspension can be minimized by any measure that will calm the water for longer periods, and reduce wave fetch. Benthic algal growth can be encouraged by improving light penetration.

4. Manage to control sediment input at its source. Since the Reef Bay swamp has little capacity to absorb and store sediment, it is important to minimize man-produced sediment sources, i.e. to stabilize sediment near its source in the watershed, in stream beds,

on exposed banks and alluvial slopes. Former impoundments and retaining walls that are eroded through, or back-filled to capacity, should be renovated. Vegetation types with good stabilizing capability should be encouraged. Techniques are provided by Black, Crow and Eidsness, CH_2M (1979).

CONCLUSIONS

1. The record of sedimentation in the coastal sinks studied is ordered in time and displays horizons defined mainly by vertical changes in the composition of components.

2. Constituents of the sediment are relatively well-preserved. Watershed-derived sediment is distinguished by the type of pollen grains, the clay content, quartz and feldspar grains, and stratigraphic relationship between alluvium and coastal deposits.

3. The sedimentary record of Mandal Pond archives a time-history of submergence by global sea level rise and infilling for 3,300 years. Submergence exceeds infilling and the pond may be expected to persist. Composition of the deposits changes with respect to percentages of clay, carbonate and organic content in response to changes of watershed and pond-produced sediment input. These changes are likely caused by alternate wet and dry periods varying irregularly over time spans of 20 to 500 years.

4. Surface sediments of the pond are not unique but exhibit characteristics similar to those deposited over the last 100 years. Sedimentation rates for the last 300 years are relatively low and vary within narrow limits, a feature consistent with the history of little human activity in the watershed.

5. The sedimentary record of Reef Bay mangrove swamp reveals a history whereby sediment infilling rates exceed submergence. Consequently, depositional units change with shoaling and contraction in size of the system over the last 3,000 years. They proceed from old alluvium to lagoon deposits, to peat, swamp clay and young alluvium.

6. Near-surface deposits on the landward edge of the swamp are changing from swamp clay to alluvium as sedimentation rates in the last 1,800 years accelerated fivefold. Despite man's substantial historical activity in the watershed, no massive effect of sedimentation on the swamp is observed. Man's effects are small in view of the long-term natural evolution.

7. If recent sedimentation rates continue or increase, the swamp is doomed as a natural mangrove swamp. With its loss of storage capacity comes a threat to nearshore reefs. Human efforts can only postpone the long-term consequences.

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APPENDIX I

KEY TO POLLEN TYPES, ST. JOHN

A: Spores with trilete marks

A-1: spherical; punctate to verrucate; 23 microns
A-2: Lycopodium
A-3: punctate; with spines; 70 microns
A-4: smooth; 60 microns

B: Spores of pollen without apertures; spherical

B-1: smooth with a central indentation; 14-16 microns
B-2: punctate; 14-16 microns
B-3: large, regularly spaced spines; 14-16 microns
B-4: smooth; 46 microns
B-5: verrucate; 35 microns

C: Monolete spores or monocolpate pollen

C-1: thick, smooth exine; 37 microns
C-2: smooth; furrow with a well-developed margo; 74x23 microns
C-3: irregularly spaced short spines; 60 microns
C-4: punctate; 14 microns
C-5: reticulate; 32 microns

D: Monoporate pollen

D-1: pore not well defined; Cyperaceae type; 27 microns
D-2: well defined pore; no annulus; 16 microns
D-3: pore with well defined annulus; Gramineae type; 48 microns
D-4: Sparganium type

E: Diporate pollen

E-1: smooth; 14 microns

F: Triporate pollen

F-1: smooth to striate and regulate; shape and pore structure resembles Betula; 16 microns
F-2: non-aspidate pore; well developed annulus; resembles Celtis; 16 microns
F-3: Corylus type

APPENDIX I (continued)

G. Multiporate pollen

G-1: pores with annuli located along the equator; 21 microns
G-2: 3 to 5 pores; smooth; resembles Carva; 45 microns
G-3: many discrete pores; without annuli; smooth; resembles Caryophyllaceae; 57 microns
G-4: many pores; striate; 14 microns
G-5: 3 to 4 to 5 pores; regulate; resembles Ulmus
G-6: 4 to 5 pores; resembles Alnus, but without arcs; 12 microns

H: Tricolpate pollen

H-1: smooth; 16 microns
H-2: striate; 18 microns
H-3: finely reticulate; 16 microns
H-4: verrucate; resembles Quercus; 20 to 40 microns H-4-a: same as above but with possible pore; resembles Fagus
H-5: gemmate; resembles Ilex
H-6: coarsely reticulate; 40x18 microns
H-7: distinct spines irregularly and sparsely distributed; 23 microns
H-8: Acer type
H-9: thick, smooth exine; 37 microns
H-10: smooth; 45 microns

I: Four-furrowed pollen

I-1: punctate; resembles Fraxinus; 30 microns
I-2: striate; 23 microns

J: Tricolporate pollen

J-1: smooth; pores of varying size; 16-20 microns
J-1-a: same as above but sparsely punctate
J-2: smooth to punctate; "Rhizophora" type; 23 microns
J-3: reticulate to striate; 23 microns
J-4: Anacardiaceae type
J-5: short furrows with annular pores; punctate; Tilia and/or Nyssa type
J-6: punctate; beaded-type ornamentation; long thin furrow with very small pore; 30 microns

K: Six furrows and pores

K-1: smooth; 16-20 microns

Acacia

Typha

Ambrosia type