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Cover Photo: Outcrop showing Pleistocene soil profile,
caliche crust, and rhizocretions,
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Photo taken by Daniel R. Suchy.

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AN OFFSHORE TRANSGRESSIVE SEDIMENTARY SEQUENCE AND ITS IMPLICATIONS FOR A LATE HOLOCENE RISE OF SEA LEVEL

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ABSTRACT

In a small embayment on the southwest coast of San Salvador a transgressive carbonate rock, peat, and sediment sequence lies just offshore. The basal carbonate sediment contains a fossil assemblage typical of a saline lake fauna commonly found in many of the island lakes, followed by a 20-cm thick fibrous-to-rooty mangrove peat, and capped by a limestone unit. The sequence is now 0.5 - 1.5 m below sea level and the peat thins as water depth increases, eventually pinching out.

The peat consists of twigs, roots, rootlets, and leaves of *Rhizophora mangle* (red mangrove), one of several salt-tolerant mangrove species that surround many of the island's lakes. Chemical analysis reveals it to be high in sulfur which is indicative of marine influence, with organic sulfur being the dominant sulfur species. The iron content, and therefore pyrite, was very low and the ash content was low, both of which are atypical of mangrove peat. A palynologic analysis of the top and bottom of the peat and the top few centimeters of the carbonate sediment was performed. The dominant palynomorph species were *Rhizophora* and *Laguncularia* (white mangrove). The presence of fresh-water pollen was not significant.

Mass spectrometry Carbon-14 dates of the top and bottom of the peat gave an age of approximately 1600 years B.P. The age and depth of submergence of the peat are consistent with work on mangrove peat in southwest Florida. The sea-level curve supports a slowly rising sea level for the past 4500 years.

INTRODUCTION

Eustatic sea-level rise over the past 5000 years has received considerable attention in the literature. Young sediments are widespread along shorelines, easily accessible for study, and the results of these studies are likely to have a direct impact on where man chooses to live. Approximately 60% of the total human population lives in coastal and low-lying areas that are directly affected by changes in sea level.

Three schools of thought feature prominently in studies of the status of sea level for the past 5000 years. One states that sea level was 3-5 m higher 5000 years ago and rapidly fell to its present level where it has remained. Another states that sea level reached its present level 5000-3000 years ago and has fluctuated slightly with small-scale climatic changes. The third states that sea level has been rising continuously over 5000 years, but at a steadily decreasing rate. A 3-5-m higher sea level largely has been disproved, as much of the data were obtained from sediments that have been shown to be artifacts of human activity or storm surges. Most published sea-level curves showing fluctuations with climate are statistically insignificant when standard errors are included. Therefore, this study supports the third school - a slowly rising sea level whose rate has steadily slowed over the last 5000 years.

The Bahamas sits on a tectonically stable platform undergoing only 1-2 m of subsidence per hundred thousand years (Mullins and Lynts, 1977), therefore, it is well suited to the study of Holocene eustatic sea-level rise. Mangrove peat is an excellent indicator of sea level due to the affinity of mangroves for marine-influenced terrestrial environments. However, mangroves will grow in fresh-water conditions although their growth will be stunted, which may lead to erroneous interpretations of past sea level. A palynologic study should be included in studying mangrove peat for the purposes of interpreting sea level in order to prevent misinterpretations of environment. A transgressive peat deposit containing fresh-water species can appear to be entirely mangrove peat due to root penetration of mangrove species. But a peat accumulating under saline conditions with no fresh-water influx will lack significant amounts of all fresh-water species because most pollen grains are not carried by the wind for very long distances. (Conifer pollen are the exception, having air-filled bladders which allow them to be carried for many miles.)

Although pyrite and organic sulfur are more commonly found in brackish-marine sediments and rocks, they can be introduced into a fresh-water peat layer in a transgressive sequence as mangrove peat and other marine sediments are deposited on top. For this reason, trends in iron and sulfur contents of transgressive sediments usually are not observed (Kuehn, 1980). However, San Salvador is somewhat unique in that there is no local iron source, therefore, the distribution of sulfur forms in the sediments may be affected.

EXPERIMENTAL

Field Collection

Peat and marl samples were collected at Three Dog archeological site located along an embayment on the southwest shore of San Salvador near Sugarloaf Settlement (Figure 1). The embayment is about 400 m across and the sediments dip toward the center. The beach also slopes more steeply in the center and the water is deeper. The thickest peat (~ 20 cm) is found near a containment wall on the north side of the embayment under about 0.5 m of water. Its perimeter follows the contour of the beach where it becomes thinner and pinches out about halfway around the embayment under 1.5 m of water. The peat is only exposed laterally for about 1-2 m before carbonate rock conceals it.

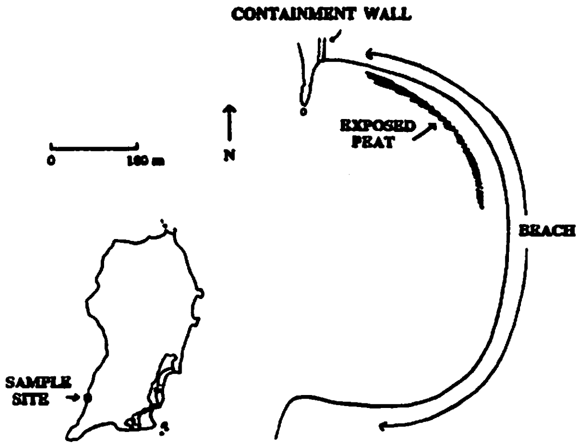

Figure 1. Sample collection site on San Salvador, Bahamas.

A channel sample of exposed peat was taken near the containment wall. A 30 x 15 cm section was cut and extracted with a shovel. It was split vertically into three sections, one for carbon-14 dating, one for chemical analysis, and one for palynologic analysis. Each of these sections was split into a top and bottom section. The 4-cm underlying marl that was extracted with the peat also was retained for palynologic analysis. Water depth, date, and time were recorded and later compared to tide data. In the laboratory all samples were frozen, in order to prevent desiccation and decomposition, until ready for processing.

Laboratory Analysis

The peat was examined megascopically, noting color, dominant plant parts, and cohesiveness. Then, the first channel sample was subsampled and the top half of the top section and the bottom half of the bottom section were sent to The University of California's Lawrence Livermore Laboratories for mass spectrometry carbon-14 analysis. The second and third samples were sectioned similarly. One was sent to the Coal Characterization Laboratory at Western Kentucky University for total sulfur, sulfur forms, iron, moisture, and ash analyses, and the other was used for palynologic analysis. The unused sections were reserved for additional analyses, should the results suggest that a more detailed study of vertical variability be needed.

The samples for palynologic analysis were processed with KOH for 5 minutes, centrifuged, rinsed, and treated with HCl to remove the carbonate sediments that appeared to have avalanched into holes left by roots. Extensive HCl treatment was needed on the marl sample. Typically, acetylation with acetic anhydride and sulfuric acid is the final chemical step performed on Holocene-age pollen. Acetylation destroys the interior protoplasm and renders the pollen more translucent, however, the pollen in the residues already were the proper color and translucency, so no further chemical treatment was performed. The residues were sieved through a 230 μm screen to concentrate the pollen further, centrifuged in 50 ml polyethylene test tubes, and inverted for several minutes to drain the excess water. A glycerin jelly mounting medium was added to the residues. Residues and microscope slides were set on a warming tray at 60° C for 30 minutes. One to two drops of pollen residue were extracted and placed on each slide and a cover slip was placed on top. Six slides were made for each of the three samples. They were allowed to cure on the warming tray for 24 hours.

A transmitted-light microscope equipped with 10x, 20x, and 40x objectives was used to identify pollen. The 10x objective was used for locating grains quickly during the processing of the peat in order to determine processing times. The 20x objective was used for scanning and identifying pollen. The 40x objective was useful in the identification of folded, contorted, or partial pollen grains. The Fleet method of point counting (Fleet, 1926) was employed. This method is designed for the quantitative determination of the relative abundances of constituents in a grain mount (in this case pollen grains). All pollen grains on the slide were counted and percents of the total were calculated. Because pollen grains were not randomly distributed on the prepared slides, this method was determined to be the most satisfactory for obtaining reliable percents of each pollen type.

The total minimum number of pollen grains to be counted per sample was determined from the following equation from Galehouse (1971):

$$E_{95.4} = 2 \quad \frac{P(100-P)}{N} \tag{1}$$

where E = probable error in percent
N = total number of grains counted
P = percent of a pollen species

At the 95% confidence level a pollen species abundance greater than 4% would be statistically significant with a total minimum grain count of 96. Because mangrove peat usually does not yield large amounts of pollen, an initial total count of 100 was chosen. The total would have been raised to 200 if many species were identified, for a minimum statistical significance of 2%. If the minimum total was not reached on one slide, additional slides of the same sample were counted, until the total sum reached or exceeded the minimum total after a completed slide.

Slides of the marl sample contained very few pollen grains with only two major species represented, therefore only 50 grains were counted, yielding significance of a species at 8%.

RESULTS AND DISCUSSION

Megascopic Observations

The peat contains roots, twigs, leaves, and occasional logs of *Rhizophora*. Some of the roots are noticeably fresher and likely represent the last stand of red mangrove before the peat-forming environment was destroyed by transgression. The peat is reddish in color and quite fibrous in texture. Occasional stringers of carbonate sediment fill in old root sites.

Palynologic Analysis

The pollen types identified and their relative abundances in the peat and marl are reported in Table 1. *Rhizophora* sp., *Laguncularia* sp., and *Avicennia* sp. are the only pollen found in significant amounts. *Rhizophora* dominates the pollen assemblage in the peat, although *Laguncularia* increases in the bottom section. There is no significant difference between *Rhizophora* and *Laguncularia* concentrations in the marl. *Avicennia* appears to be constant throughout the peat, but drops out in the marl.

Riegel (1965) interpreted the environment of deposition of mangroves from the palynologic analysis of peat from southwest

Table 1. Results of Palynologic Analysis of Peat and Marl Samples

	Peat				Marl	
	Top		Bottom			
Pollen Types	Total	%	Total	%	Total	%
Rhizophora sp.	78	75.7±8.4	59	58.4±9.8	28	54.9±13.9
Laguncularia sp.	17	16.5±7.3	34	33.7±9.4	21	41.2±13.8
Avicennia sp.	6	5.8±4.6	6	5.9±4.7	0	0.0
Compositae	1	1.0±2.0	1	1.0±2.0	1	2.0±3.9
Unknown	1	1.0±2.0	1	1.0±2.0	1	2.0±3.9
TOTAL	103	100.0	101	100.0	51	100.1

Florida. He assigned a *Rhizophora-Laguncularia-Avicennia* pollen assemblage to a coastal mangrove-fringe environment. This was substantiated by Kuehn (1980) who studied cores of peat taken up to 2 km offshore of southwest Florida, now buried under 0.5 - 1.5 m of marl. Both studies showed *Avicennia* to prefer high salinity typical of more inland supratidal conditions, *Rhizophora* normal marine salinity typical of coastal intertidal conditions, and *Laguncularia* brackish to normal marine salinity where it also may flourish near tidally dominated streams. The interpretation of salinity requirements of *Rhizophora* and *Avicennia* on San Salvador by Godfrey and others (1994) is consistent with the studies from southwest Florida.

The depositional environment of this peat sample is interpreted as a coastal lake. Although a modern analog is lacking on the island, the faunal assemblage found throughout the underlying marl is identical to others found in many of the island's saline lakes and has been interpreted as an inland lake fauna (Teeter, 1994). The symmetry of the embayment from which the peat was sampled also suggests a submerged lake (Figure 1). The width of the embayment decreases in a seaward direction, and rocks on the north end project into the ocean, narrowing the opening even more. Carbon-14 dates of the peat would put the time of submergence at about 1600 years B.P., the time when the seaward margin of the lake would have been breached by rising sea level.

There are problems with a lake interpretation, however. Most of the organic material accumulating today in inland lakes is algal in origin. Also, on average these lakes have a higher than normal marine salinity and generally are not suitable for the growth of *Laguncularia*. But, circulation of water in this coastal lake could have been high if it was connected indirectly to the ocean. The ocean affects all inland lakes on the island through infiltration of the carbonate bedrock and, in some cases, by flow through underground conduit systems (Edwards et al., 1990). In the latter situation the lake levels rise and fall with the tides and, if the conduits are large and numerous, normal marine salinity may prevail. A lake of normal marine salinity could support a large population of *Laguncularia* that is suggested by the pollen data. Many existing lakes - No Name, Pain, Moon Rock, Wild Dilly, and Oyster - contain blueholes and have normal marine salinities, but the faunal assemblage is more typical of an open marine environment, rather than a lake (Edwards et al., 1990). The ancient lake in this study may be more similar to Clear, Little Fortune Hill, and Peter Cooke's Ponds which have normal marine salinities and contain typical inland lake fauna, however mangrove peat is not forming in them.

An additional problem concerns the lack of faunal remains in the peat that would suggest the continuance of a lake environment once peat began accumulating. This could be explained by a change in water chemistry of the lake at the onset of peat formation. The accumulation of peat requires an environment where organic material is not likely to be decomposed readily. When organic material is abundant, oxygen supply is quickly depleted by aerobic bacteria which break down the organics. An oxygen-poor lake not only would prevent the rapid breakdown of organics, but it also would kill the faunal population.

Finally, the carbonate rock on top of the peat is problematic. It lacks the fenestral porosity typical of beachrock and has been interpreted as subtidal in origin (Bain, 1993). The question that arises, then, is "where is the intertidal beachrock that one would expect to find in a transgressive sequence?" Further research of this embayment may reveal that the lake was much larger and that the peat may extend inland, buried by beach sand and underlying beachrock. If the complete lateral extent of the peat were known and if cores of the entire peat thickness were taken along a land-to-sea transect, the pollen may reveal more conclusively the environment of deposition. A lake peat probably would contain similar distributions of pollen to those reported in Table 1, with a possible increase of *Avicennia* near the lake margins where higher salinity from evaporation may prevail. If the lake was breached prior to peat formation, the pollen then should show a tidally dominated distribution of mangrove species similar to the study of Godfrey and others (1994).

Chemical Analysis

Results of chemical analyses performed on the peat are reported in Table 2. The moisture content is typical of mangrove peats studied in southwest Florida, however, the remaining results showed some dissimilarities. Ash contents of most southwest Florida mangrove peats exceed 30% (dry basis), and values as high as 75% have been reported (Kuehn, 1980). However, San Salvador has no indigenous source of silica and iron, therefore their contributions as oxides in ash would be

Table 2. Sulfur, Iron, Moisture, and Ash Data for the Peat in Percent

	Sulfur											
	Pyritic		Sulfate		Organic		Total		Ash		Elemental Iron	Moisture
	Wet*	Dry**	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry		
Top of Peat	0.04	0.08	0.25	0.55	1.11	2.45	1.40	3.09	9.86	21.78	0.13	54.72
Bottom of Peat	0.19	0.37	0.50	0.96	1.13	2.17	1.82	3.50	11.64	22.37	0.31	47.97

* Wet refers to as-received basis. Air dry loss moisture was 0.00, therefore the as-received and as-determined values are identical.

** Dry refers to dry basis. Values are recalculated to 100% after removing the moisture contribution. Sulfur in organic sediments routinely is reported on a dry basis.

very low compared to southwest Florida peats. Elemental iron contents of some Florida mangrove peats range between 1.5 - 6% (Kuehn, 1980), but are much lower in this peat (.13 -.31%). The iron content was expected to be low, yet the presence of iron-containing laterite soils on the island suggest a potential terrigenous source.

The pyritic sulfur content of the peat also was much lower than expected. With little or no local source of iron, the formation of pyrite would require the extraction of iron from sea water. But, the average dissolved iron content of sea water is 0.01 ppm, less than 0.01% of the total dissolved solids in the ocean (Boggs, 1987). Although both iron and pyrite contents in the peat increase with depth, only a fraction of the iron was tied up by pyrite (mass Fe = 0.47 x mass FeS_2). The fraction is higher in the basal peat (56% compared to 29%, dry basis), suggesting some possible secondary pyrite formation. Since secondary pyrite enrichment is not uncommon in peat under salt-water conditions (Smith, 1968; Kuehn, 1980), the pyrite content often increases with depth.

Organic sulfur is the dominant sulfur species in the peat, followed by sulfate sulfur. This is consistent with other studies of mangrove peat (Casagrande et al., 1977; Given; 1971). The lower organic sulfur content in the basal peat corresponds to an increase in pyritic sulfur, yet one probably is not a direct response to the other. When pH is greater than 7, as is the case with ocean water, even under peat-forming conditions, bacterial sulfate reduction produces HS^- instead of H_2S. In the presence of iron, HS^- will readily react to form secondary pyrite (Drever, 1988). Organic sulfur, as defined, is bonded to organic matter and is not reactive in the presence of iron. Elemental sulfur (S^2) can form pyrite, however its equilibrium stability field lies above a pH of 13 (Fetter, 1993). The stability field, however, is extended by the presence of microbial oxidation of organic matter which can contribute to the formation of elemental sulfur. Routine sulfur-forms analyses do not distinguish between organic and elemental sulfur.

Age Determinations

The top and bottom of the peat dated at 1660 ± 50 and 1610 ±50 years B.P., respectively. Although the top appears to be older than the bottom, the 50-year standard error at the 67% confidence level makes the differences in age nonsignificant. At the 95% confidence level, or two standard errors, the peat ranges in age between 1760 and 1510 years B.P.

These dates and other dates from southwest Florida peat are included in a regional graph of Holocene sea-level rise in Figure 2A. The data suggest a rising sea level since 4500 years B.P. for this area, but the rate of rise has been steadily decreasing. Figure 2B contains the same data plotted on a log scale and the results of a linear regression analysis of the data. The percent of sea-level change (y axis) that statistically can be explained by the long term climatic change over this time (x axis) is 83.8. Although this leaves nearly 16% unexplained, an attempt to relate that 16% to fluctuations of sea level due to smaller superimposed climate changes is not statistically acceptable. A very large part of the 16% left unexplained by time arises from the standard error obtained in dating a sample. At the 95% confidence level the standard error of a dated sample easily can be 16% of the date or higher, especially for young samples. Therefore, Late Holocene climatic changes that may have resulted in small fluctuations of sea level cannot be documented statistically at the present time.

Sampling error is another major factor that can affect the accuracy and precision of local or regional sea-level-rise curves. Compaction of sediments, inaccurate water-depth determinations due to tides and relationship of sediments to original sea level, and incorrect mapping are just a few of the error possibilities. New techniques in determining accurate sea-level readings are being developed, including GPS systems, satellite altimeters, and the development of a Global Sea-Level Observing System, and these may reduce sampling error significantly. However, errors associated with carbon-14 dating, although they have been reduced considerably with mass spectrometry, cannot be eliminated entirely. Carbon-14 in the atmosphere has fluctuated throughout the Holocene (e.g., the DeVries effect); samples younger than 150 years cannot be distinguished from modern samples due to the effects of man in the burning of fossil fuels (Suess

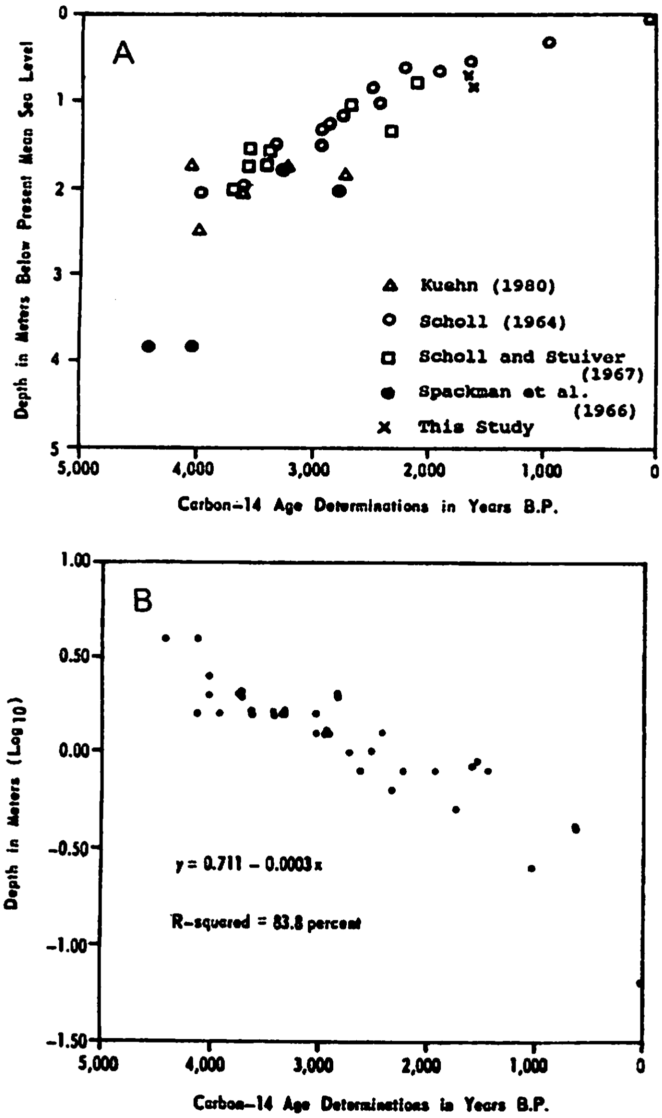

Figure 2. Eustatic Sea-level-rise curve for Southwest Florida and San Salvador, Bahamas since 4500 Years B.P., (A) Arithmetic scale. (B) Log scale.

effect) and the detonation of atomic devices (Libby effect); and organisms may not use carbon in the same ratios as they occur on the earth's surface and/or may recycle "dead" carbon. The daily monitoring of sea level within this century and into the future should produce very accurate and precise data, and fluctuations that might be recorded may be statistically valid. Although evidence from sediments, fossils, and chemical analyses suggest episodes of Holocene climatic fluctuations, the data used to generate sea-level curves do not support it.

CONCLUSIONS

A peat sample collected just off the southwest shore of San Salvador is composed of *Rhizophora* plant parts throughout its thickness. The underlying faunal assemblage and the morphology of the embayment suggest that a lake once occupied this site. The actual lake may have been much larger than the present embayment. The pollen content of the peat and underlying marl suggests that a *Rhizophora-Laguncularia* plant community dominated. The growth requirements of Laguncularia suggest that the lake was of normal salinity, which implies either a plentiful supply of fresh-water or connection to the ocean through underground conduits.

Whether the lake was breached by a rising sea level before, during, or after peat deposition is not certain. A palynologic study of a lateral seaward transect of cores of peat should be studied.

The sulfur content of the peat is high but lower than comparable mangrove peats in southwest Florida. The relative abundances and distribution of sulfur species in this peat are consistent with results of other studies, except for pyrite, which is very low due to the lack of a terrigenous source of iron. The ash content also is very low for mangrove peat.

Carbon-14 dates from the peat, plotted with dates from southwest Florida peats, show that sea level has been rising throughout the Late Holocene in this region, but the rate has been slowing. Smaller fluctuations in sea level, as a result of climatic pulses, are not supported by these data. Although considerable evidence exists in the literature to support smaller sea-level fluctuations, standard errors in carbon-14 dating and sampling errors prevent their statistical verification.

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