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# THE DEPOSITIONAL EVOLUTION OF SNOW BAY, SAN SALVADOR

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## ABSTRACT

Snow Bay, located on the southeast windward margin of San Salvador, is a 1x2km inner shelf lagoon rimmed by a barrier reef and cays. The lateral and vertical Holocene facies mosaic of Snow Bay records the banktop response of a high-energy lagoon to the Holocene sea-level rise. Cluster analysis of surface and subsurface sediments reveals four distinct marine facies - an abraded grain "grainstone", and abraded grain "grapestone", a foraminiferal "packstone", and a *Halimeda*-rich "packstone/wackestone". Although the facies are distinct, enough overlap exists to consider the sedimentary gradients gradational. The most important variables for determining sedimentary gradients are mud, mud fraction mineralogy, sorting, *Halimeda*, aggregates, and abraded grains.

The four facies are recognized in sediment cores and are combined to form a composite high-energy shallowing-upwards sequence. The sequence is composed of a basal transgressive abraded grain "grapestone" containing intraclasts overlain by a fining-upwards (shallowing-upwards) subtidal *Halimeda*-rich "packstone/wackestone" and foraminiferal "packstone". The regressive intertidal/subtidal abraded grain "grainstone" of the ebb-tidal delta abruptly overlies the *Halimeda*-rich "packstone/wackestone" of the *Thalassia* meadow.

The high-energy sequence in Snow Bay records the banktop response to a sea-level rise. Radiocarbon dating of peat deposited in poorly drained topographic lows and sediment within cores link the banktop response to sea-level rise. Rapid transgression and deepening of the lagoon produced the abraded grain "grapestone" facies. The mobile sand sheet of Snow Bay is a relict of this transgression. With continued sea-level rise, stabilization of the sandy lagoon substrate by benthic flora produced the shallowing-upwards *Halimeda*-rich "packstone/wackestone". During the relative stillstand of the last 1500 years, the ebb-tidal delta abraded "grainstone" prograded over the *Thalassia* meadow forming a regressional cap of redeposited sand.

## INTRODUCTION

Changes of depositional style as a result of sea-level rise are an important feature of carbonate platform growth. Sediments characteristically build up to sea-level during transgressions because sedimentation rates are generally much greater than the rate of subsidence and/or sea-level rise (Schlager, 1981). The resulting sediment accumulation often forms a shallowing-upwards sequence (James, 1984) which is a special type of punctuated aggradational cycle produced by a base-level fluctuation (Goodwin and Anderson, 1985).

Shallowing-upwards sequences are classified as low-energy and high-energy sequences (James, 1984), and are distinguished by intertidal environment. Low-energy lagoonal sequences are capped by tidal flats, and often the shallow subtidal sediments contain stromatolites (James, 1984). High-energy sequences are capped by beaches, which often lack distinctive characteristics and are difficult to recognize in the rock record (Inden and Moore, 1983; James, 1984).

Facies models of carbonate platforms have concentrated on low-energy facies relationships. As a result, more emphasis is placed on models of low-energy banktop responses to sea-level rise (tidal flats and muddy lagoons) than high-energy banktop responses (beaches and sandy lagoons; Enos, 1983; Wilson and Jordan, 1983; James, 1984; Read, 1985). This is not surprising for two reasons. First, our understanding of cyclic carbonate facies models comes from half a dozen modern examples (James, 1984), of which the most herald-

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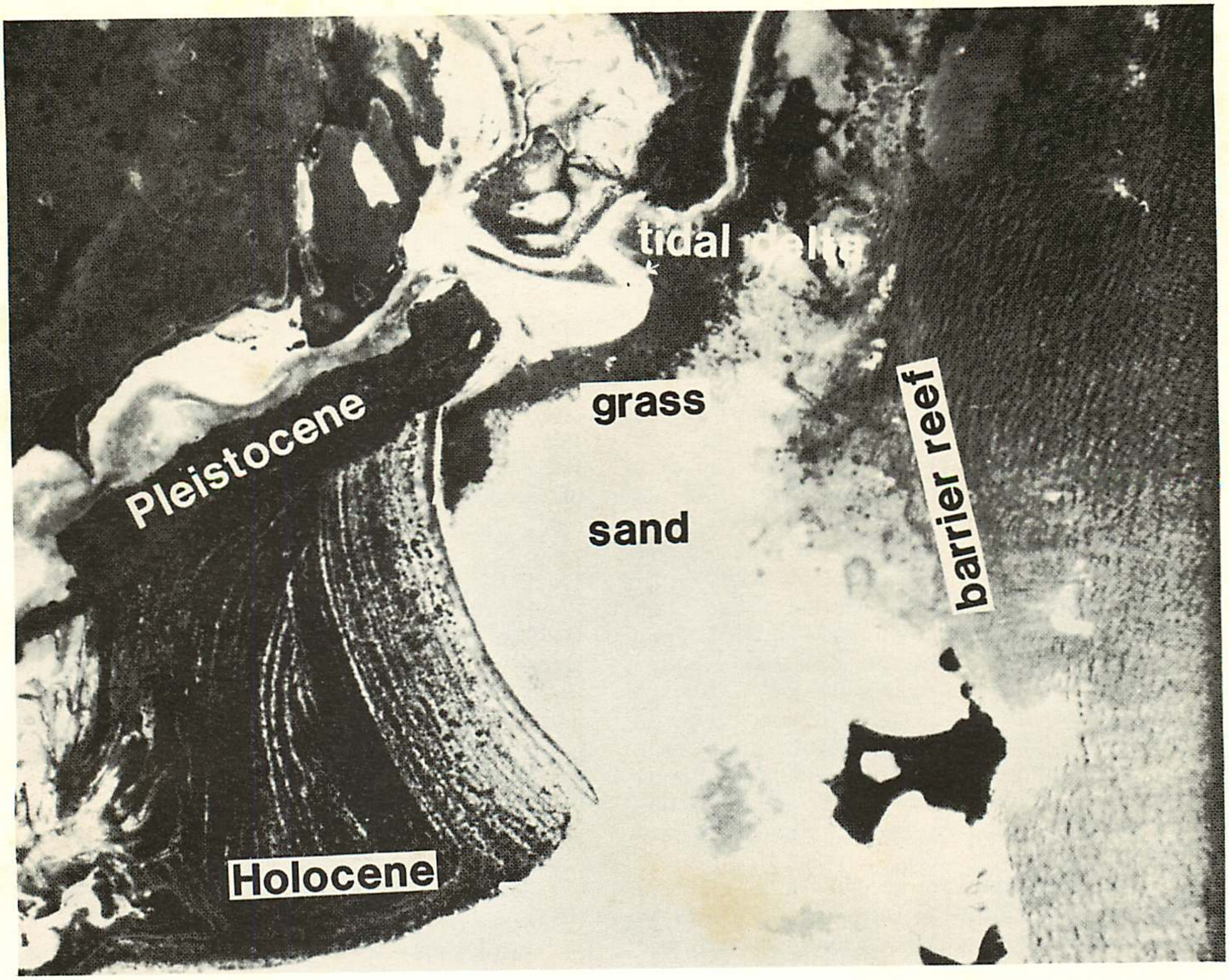

*Fig. 1. Air photo of Snow Bay, San Salvador showing the major subtidal depositional environments. The lagoon is rimmed by a barrier reef and cays to the east of the photo. Note the prograding beach ridges of Sandy Hook on the north.*

ed are tidal flat studies (e.g., Shinn, Lloyd and Ginsburg, 1969; Logan, Davies, Read, and Cebulski, 1970; Purser, 1973; Hardie, 1977). Second, high-energy facies associations appear to be rare in the geologic record, probably as a result of poor recognition criteria (Inden and Moore, 1983).

Few modern analogues of the high-energy shallowing-upward model exist, and geologists encounter difficulty when trying to interpret ancient carbonate packstone and grainstone facies associated with a high-energy environment (Inden and Moore, 1983; McKee and Ward, 1983). Since no single criterion is diagnostic for an environment as diverse as lagoons, lateral and vertical sequence transitions are the most reliable guide (Enos, 1983).

Lagoons are the carbonate "factories" of platforms (Neumann and Land, 1975; James, 1984), and the sediments form a vertical sequence which records the flooding history of the platform (Boardman, 1976; Boardman, Evans, and Andersen, 1986; Andersen and Boardman, 1987; Rasmussen and Neumann, 1988). A variety of factors control the depositional evolution of modern lagoons including benthic flora, water depth, and antecedent topography.

Few studies have concentrated on lateral and vertical sedimentary gradients in modern windward high-energy lagoons (e.g., the Florida reef tract and northeast of Abaco Island; Ginsburg, 1956; Swinchatt, 1965; Locker, 1981). In contrast, other studies have primarily concentrated on the relationship of benthic communities and their sediment record (Taylor and Lewis, 1970; Miller, 1988). Only a few studies have examined the origin and time frame for the development of high-energy environments (Enos, 1977; Hine, 1977; Locker, 1981; Harris, 1984).

The objective of this study is to examine the lateral (Andersen and Boardman, 1987) and vertical sedimentary gradients in order to understand the relationships and controls of high-energy lagoonal sedimentary characteristics. The relationship between the response to sea-level rise and the time frame for the development of the high-energy shallowing-upward sequence is of special interest.

## METHODS

### Field Work

Snow Bay is a 1x2km high-energy inner shelf lagoon located on the southeastern corner of San Salvador, Bahamas. The lagoon is rimmed by a barrier reef and small cays (Fig. 1). Water depth and a general description of flora, fauna, and sedimentary structures were recorded for two of the northern transects (sites 1 to 8, and 15 to 24). In addition, four beach samples were collected for comparison to the subtidal samples.

Six sediment core sites were chosen based on sediment thickness and environment (Fig. 2). One core is from the center of the tidal delta, two cores are from the tidal delta edge, and three cores are from the *Thalassia* meadow. The core sites form a transect which crosses the thickest accumulation of sediment. All cores were brought back to the lab and described megascopically. Four cores were sampled at 10cm intervals for an additional 67 samples.

### Sample Analysis

Textual analysis. All sediment samples were prepared for textural analysis by soaking in a 25% Clorox solution followed by three rinses of pH 9 water. Textural data were collected using standard wet sieving at one phi intervals and pipette techniques for <63$\mu$m, <16$\mu$m, and <4$\mu$m. The method of moments was used to determine sorting (Folk, 1966; Lewis, 1984).

Mineralogical analysis. The aragonite:calcite ratio of the mud fraction (<63$\mu$m) was calculated from x-ray diffraction data using the peak area method (Chave, 1954). Position of the 104 peak of calcite determined whether the calcite composition was of the high- or low-magnesium variety (Goldsmith, Graf and Joensuu, 1955).

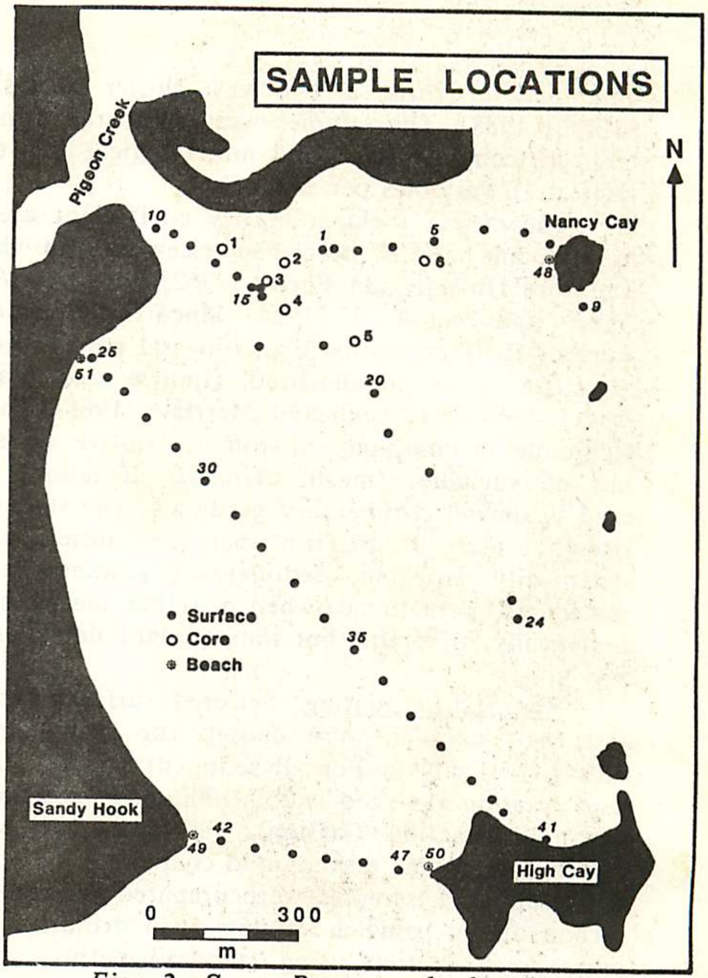

*Fig. 2. Snow Bay sample locations. Filled circles represent surface samples. Open circles represent cores. Circled stars represent beach samples.*

Compositional analysis. Composition was determined by identifying approximately 300 grains per sample of the coarse sand fraction 1-2mm). The coarse sand fraction was chosen to maximize the ease of identification (minimize the amount of grains of unidentifiable origin). Also, *Halimeda* is concentrated in the coarse sand fraction, so it could be used as an environmental indicator (Basan, 1973; Mallik, 1976).

Petrographic analysis. Composition of intraclasts and eolian rocks were determined using standard petrographic techniques. Cement types of the intraclasts, eolian rocks, and aggregates were confirmed using SEM in combination with EDX analysis.

Statistical analysis. Relationships between surface and core samples were determined by cluster analysis. The program CLAP (written by Sepkoski and Sharry, 1976; modified by Arnold Miller, 1987) provided Q-mode and R-mode analysis of the data using the UPGMA method of clustering. The Q-mode and R-mode analyses were combined to form a two-way cluster analysis (Miller, 1988). The samples were compared using textural, compositional, and mineralogical data (a total of 10 variables per sample).

The cosine theta similarity coefficient used in this analysis is described elsewhere in the literature (Imbrie and Purdy, 1962; Purdy, 1963; Imbrie and Van Andel, 1964). Since the variables were of different units (e.g., phi and percentage) the data were standardized (Imbrie and Van Andel, 1964; Harbaugh and Merriam, 1968). This technique in combination with descriptive statistics of variables (mean, standard deviation) is used to define sedimentary gradients. The student t-test is used to confirm that the clusters are statistically different. Sedimentary gradients are considered gradational when variable means are statistically different, but the standard deviations overlap.

Radiocarbon dating. Selected surface, core, and rock samples were chosen for radiometric carbon-14 analysis. For all sediment samples, the sand fraction analyzed is 250-1000$\mu$m. In addition, the mud fraction (<63$\mu$m) was dated for two samples to provide a sand-mud couplet.

Bulk rock samples were prepared for radiocarbon dating using a stainless steel drillbit. The rocks were studied using standard petrographic techniques, and all contained less than 10% cement. The minor amount of cement is not considered to significantly affect the rock ages since carbonate eolianites lithify soon after deposition (McKee and Ward, 1983; Carew and Mylroie, 1985; Boardman and others, 1987).

## RESULTS

### Environments of Deposition

The bathymetry of the lagoon slopes seaward to a maximum depth of 3.3m (Fig. 3). The northern and southern ends of the lagoon are slightly shallower than the center of the lagoon, but a pronounced sill was not found. Snow Bay has excellent exchange with the open Atlantic and maintains normal salinity. The coast is dominated by beaches and fits the criteria for a microtidal, wave-dominated coast (Davis and Hayes, 1984).

Transects across the lagoon distinguish three major subtidal environments (Fig. 1). An ebb-tidal delta located in the northwestern corner of the lagoon forms a 2m thick lobe of sand prograding into the *Thalassia* meadow. A 200-400m wide *Thalassia* meadow rims the tidal delta, and forms a 2m thick sediment package deposited in a topographic low. The rest of the lagoon is dominated by a mobile sand sheet (equivalent to a platform interior sand blanket; Illing, 1957; Ball, 1967) less than 50cm thick. Patch reefs dot the mobile sand sheet between the cays. A fourth major subtidal environment, the barrier reef, is considered a separate sedimentary system beyond the scope of this study.

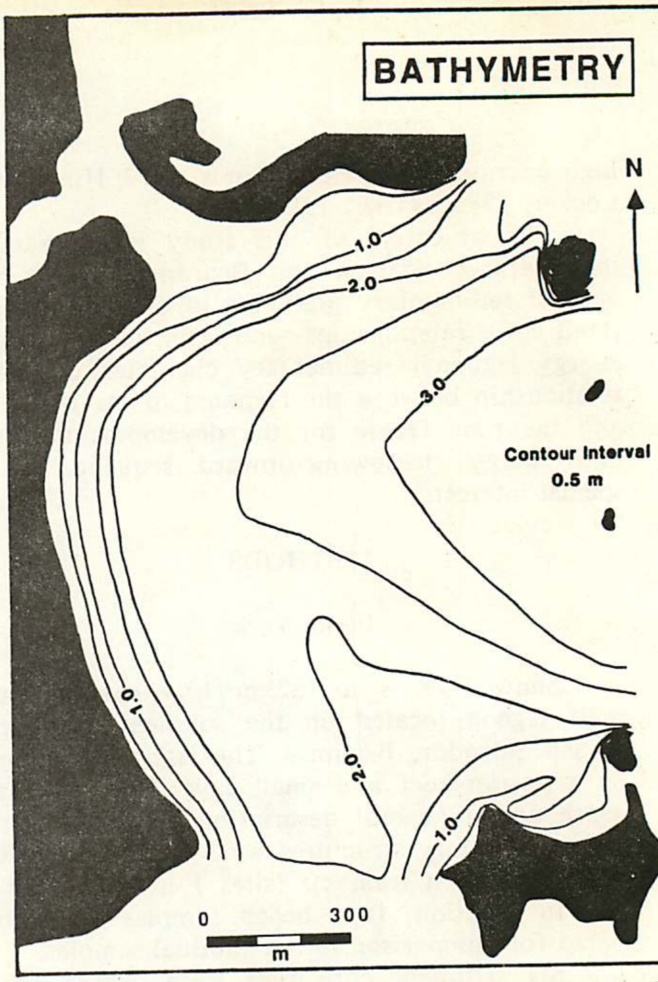

*Fig. 3. Snow Bay is slightly shallower to the north and south, but a pronounced sill which would restrict circulation with the open ocean does not exist.*

Two-way cluster analysis of surface and core samples distinguishes four sediment facies based on composition, texture, and mud fraction mineralogy (Fig. 4). Facies names are based on variable means (Table 1). T-test statistics indicate that the means of the most abundant variables for each facies are distinct, even though overlap occurs between the sediment facies. The four sediment facies are: 1. abraded grain "grainstone", 2. abraded grain "grapestone", 3. foraminiferal "grainstone/packstone", and 4. *Halimeda*-rich "pack

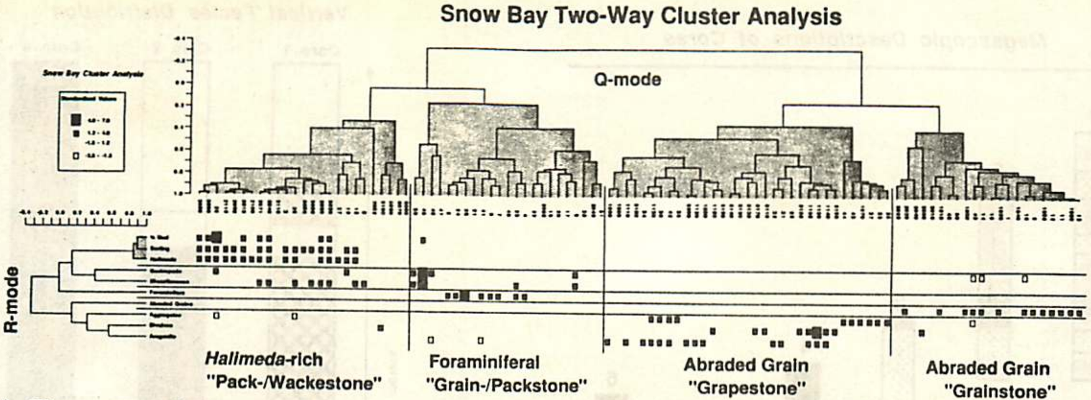

*Fig. 4. Two-way cluster analysis of Snow Bay surface and core samples using ten variables. Filled squares depict variables well above the standardized mean and open squares depict variables well below the standardized mean. No square indicates variables near the mean.*

**Snow Bay Cluster Analysis**
**Variable Means of Cluster Facies**

| | Cluster A | Cluster B | Cluster C | Cluster D |
|---|---|---|---|---|
| | N=22 | N=33 | N=23 | N=25 |
| % Mud | **0.89 ± 0. 89** | **3.03 ± 2.02** | **6.40 ± 6.96** | **23.01 ± 12.87** |
| Sorting (ø) | 0.92 ± 0.20 | 1.34 ± 0.28 | 1.56 ± 0.43 | 2.71 ± 0.49 |
| *Halimeda* | 6.50 ± 4.35 | 8.43 ± 4.11 | 19.83 ± 9.64 | **48.11 ± 16.74** |
| Bivalves | 5.07 ± 3.72 | 12.03 ± 8.50 | 5.28 ± 3.33 | 6.10 ± 4.07 |
| Gastropods | 5.28 ± 2.40 | 6.55 ± 1.91 | 8.69 ± 5.20 | 5.75 ± 2.30 |
| Foraminifera | 12.04 ± 5.76 | 9.45 ± 3.34 | **28.43 ± 14.76** | 12.65 ± 3.76 |
| Aggregates | 13.31 ± 5.05 | **28.08 ± 8.76** | 12.49 ± 6.75 | 11.08 ± 6.00 |
| Abraded Grains | **53.51 ± 11.69** | **30.83 ± 9.78** | 17.22 ± 11.32 | 9.39 ± 6.10 |
| Miscellaneous | 3.98 ± 2.59 | 4.08 ± 1.68 | 7.39 ± 3.81 | 6.80 ± 3.55 |
| Aragonite | 55.72 ± 6.76 | 66.05 ± 8.13 | 47.70 ± 5.95 | 50.83 ± 3.03 |
| Water Depth (cm) | 49.33±44.85 | 199.58±32.92 | 192.30±87.41 | 161.57±74.90 |
| | Abraded Grain "Grainstone" | Abraded Grain "Grapestone" | Foraminiferal "Grain-/Packstone" | Halimeda-rich "Pack-/Wackestone" |

*Table 1. Variable means of two-way cluster analysis sediment facies. Bold face indicates variables used for facies name designation.*

stone/wackestone". Of these facies, all four are important surficially, but the foraminiferal "grainstone/packstone" is only a minor component of the vertical sequence.

## Vertical Sedimentary Gradients

Megascopic descriptions of the six sediment cores from the ebb-tidal delta and *Thalassia* meadow show that the vertical sequence is composed of "grainstone", "packstone", and "wackestone" sediments (Fig. 5).

The analysis of cores 1, 2, and 5 show that the four sedimentary facies which form the lateral sedimentary gradients are also present in the vertical sedimentary sequence (Fig. 6). The vertical sedimentary sequences from all cores are combined to form a composite sequence.

Ebb-tidal delta cores. The sediments underlying the ebb-tidal delta are comprised of a lower abraded grain "grapestone" facies which is overlain by the abraded grain "grainstone" facies (core 1). There is a distinct upward increase in abraded grains and sorting; however the mud content is consistently low (Fig. 7).

The abraded grain "grapestone" of the ebb-tidal delta contains three intervals of intraclasts (Fig. 5). The intraclasts, which range in size from 0.5-3.0cm, are composed of moderate to poorly sorted, well-rounded micritized grains and cortoids cemented by isopachous rims of aragonite needles.

At the ebb-tidal delta edge, 60cm of abraded grain "grainstone" overlies sediments of the *Thalassia* meadow (core 2). A thin foraminiferal "grainstone" forms a transition between the two sediment types. The abrupt transition between sediments of the *Thalassia* meadow and the ebb-tidal delta is recognized by abrupt changes in texture and composition (Fig. 8).

Thalassia Meadow Cores. The sediments underlying the *Thalassia* meadow are composed of a basal abraded grain "grapestone" facies which is overlain by the *Halimeda*-rich "packstone/wackestone" facies (core 5). The upper part of the

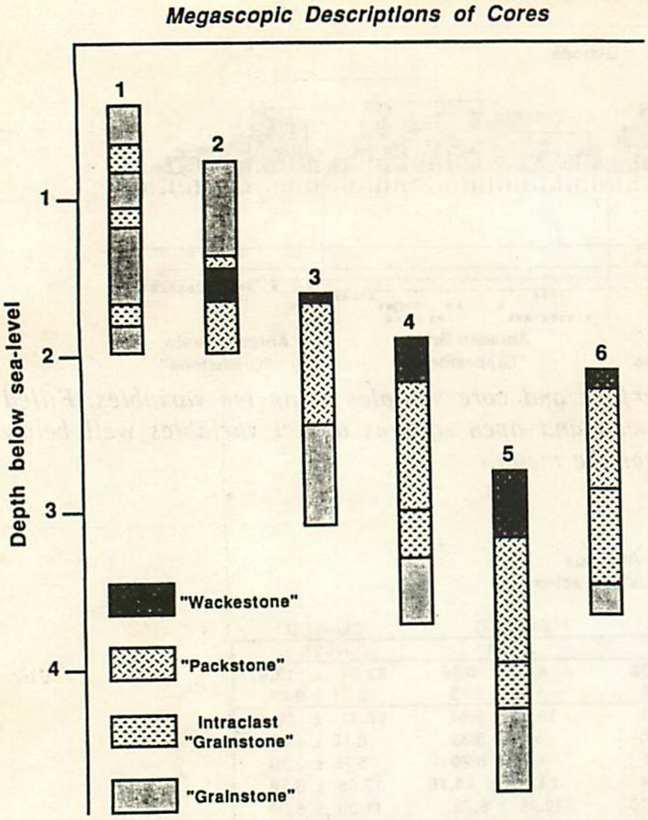

*Fig. 5. Megascopic core descriptions. Textural terminology from Dunham (1962). Intraclastic "grainstone" contains intraclasts ranging in size from 1-10cm.*

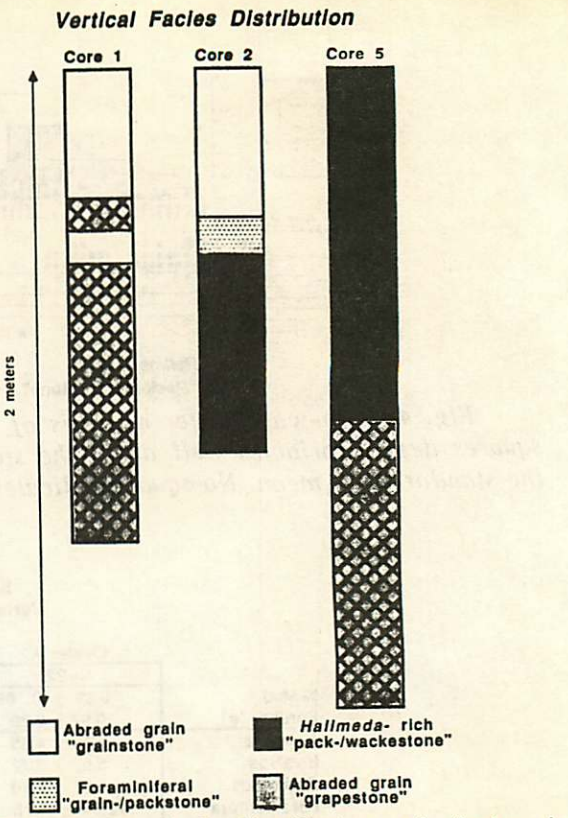

*Fig. 6. Vertical distribution of facies in cores 1, 2, and 5. Core 1 is from the center of the ebb-tidal delta, core 2 is from the seaward edge of the ebb-tidal delta, and core 5 is from the* Thalassia *meadow.*

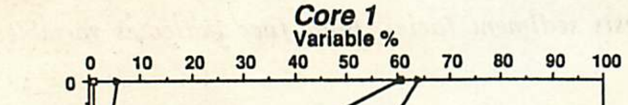

*Fig. 7. The low proportion of mud and* Halimeda *in core 1 suggest a lack of substrate modification by benthic flora. AGGr = abraded grain "grainstone" and AGGp = abraded grain "grapestone".*

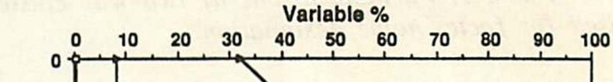

*Fig. 8. The abrupt change in texture and composition at 60cm in core 2 reflects progradation of the tidal delta over the* Thalassia *meadow. AGGr = abraded grain "grainstone", FGr/P = foraminiferal "grainstone/packstone", and HP/W =* Halimeda-*rich "packstone/wackestone".*

abraded grain "grapestone" from the *Thalassia* sequence also contains intraclasts of the same type as the tidal delta (see previous section).

The *Halimeda*-rich "packstone/wackestone" fines upwards and becomes more poorly sorted (Fig. 9). Compositionally *Halimeda* increases upwards while aggregates and abraded grains decrease. Also, the mud fraction mineralogy changes upwards from aragonite-dominated to approximately equal amounts of aragonite and high-magnesium calcite.

## Radiometric Dating

Radiometric dating using carbon-14 was performed on selected surface, core, and rock samples and a peat sample (Table 2).

Surficially, carbon-14 dating of the abraded grain "grapestone" yields an age of 3090 y.b.p. for this sediment. A single peat sample was recovered *in situ* from the Pigeon Creek tidal channel where tidal currents have eroded the overlying sediments. Carbon-14 dating yields and age of 6280 y.b.p. for this peat.

Carbon-14 dates for cores were obtained for the abraded grain "grainstone" of the ebb-tidal delta sequence and the abraded grain "grainstone" and *Halimeda*-rich "packstone/wackestone" of the *Thalassia* sequence. The ebb-tidal abraded grain "grainstone" overlying the *Thalassia* sequence yields ages of 3350 y.b.p. 30cm below the surface and 3470 y.b.p. 50cm below the surface.

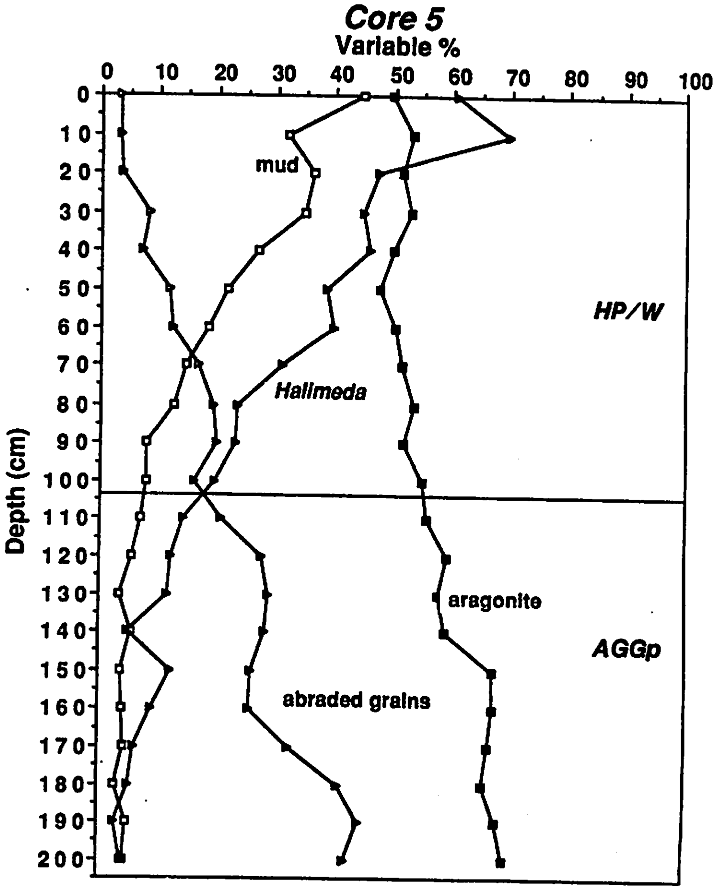

*Fig. 9. The textural and compositional trends in core 5 reflect the effect of substrate modification by benthic flora. HP/W =* Halimeda*-rich "packstone/wackestone" and AGGp = abraded grain "grapestone".*

**SNOW BAY RADIOCARBON DATES**

Core Samples

| Core | Sample Type | Sample Depth | Water Depth | Total Depth | Age |
|---|---|---|---|---|---|
| 2 | sand | 30 cm | 70 cm | 100 cm | 3350±60 |
| 2 | sand | 50 cm | 70 cm | 120 cm | 3470±90 |
| 2 | mud | 66 cm | 70 cm | 136 cm | 490±70 |
| 2 | sand | 70 cm | 70 cm | 140 cm | 3510±320 |
| 2 | sand | 120 cm | 70 cm | 190 cm | 3630±120 |
| 5 | mud | 34 cm | 250 cm | 284 cm | 1410±470 |
| 5 | sand | 34 cm | 250 cm | 284 cm | 2540±140 |
| 5 | mud | 63 cm | 250 cm | 313 cm | 3690±240 |
| 5 | sand | 63 cm | 250 cm | 313 cm | 4280±240 |
| 5 | sand | 196 cm | 250 cm | 446 cm | 3850±190 |

Surface Samples

| Sample Type | Sample Depth | Water Depth | Total Depth | Age |
|---|---|---|---|---|
| peat | surface | 500 cm | 500 cm | 6280±740 |
| sand | surface | 190 cm | 190 cm | 3090±80 |

Rock Samples

| Sample Type | Sample Location | Age |
|---|---|---|
| bulk rock | western most sand ridge of Sandy Hook | 3650±60 |
| bulk rock | SE corner, Sandy Hook | 1990±70 |
| bulk rock | eolianite, Nancy Cay | 4220±80 |
| bulk rock | eolianite, Snow Bay Ridge | 3700±70 |

*Table 2. Radiocarbon dates from the Snow Bay area of San Salvador.*

A carbon-14 date from the abraded grain "grapestone" near the base of core 5 yields an age of 3850 y.b.p., which is nearly the same age as the surficial abraded grain "grapestone".

Radiocarbon dating of sand-mud couplets from the *Halimeda*-rich "packstone/wackestone" show large discrepancies in sand and mud ages. Mud dates range from 600 to 3140 years younger than the sand dates. The discrepancy between the ages increases upwards with the largest difference being at the tope of the *Thalassia* sequence in core 2 where ebb-tidal delta sands directly overlie *Halimeda*-rich "packstone/wackestone" (Table 2).

## DISCUSSION

Examination of the vertical sedimentary gradients reveals the influence of benthic flora, water depth, and antecedent topography on facies relationships in high-energy carbonate environments. The lateral facies distribution (Andersen and Boardman, 1987) and the vertical sedimentary sequence provides a record of banktop responses to the Holocene sea-level rise.

### Vertical Facies Distribution

The depositional sequence in Snow Bay includes a pulse of transgressive sand (abraded grain "grapestone") overlain by shallowing-upward regressive deposits. The regressive deposits include subtidal muddy sands (*Halimeda*-rich "packstone/wackestone") and upper regressive sands (abraded grain "grainstone"). The foraminiferal "grainstone/packstone" is a minor constituent of the vertical sequence.

Basal transgressive sand. The basal sediments from cores in the *Thalassia* meadow and ebb-tidal delta are comprised of the abraded grain "grapestone" facies which is up to one meter thick (cores 1 and 5, Fig. 6). The abraded grain "grapestone" facies represents a subtidal sand and/or beach deposited during the initial strandline migration.

The upper 50cm of abraded grain "grapestone" contains 1-10cm intraclasts in cores 1, 4, 5, and 6. The grains comprising the intraclasts are not aggregates, but are similar to the abraded grain "grainstone" of the beach and ebb-tidal delta. The sand matrix surrounding the intraclasts contains a proportion of aggregates similar to the lower 50cm of the basal abraded grain "grapestone" (20-25%).

Typically, transgressive beach deposits are not preserved; rather, erosion of a beach deposit leaves behind a winnowed surface capped by a thin lag of coarse intraclasts of fossil debris (Adams, 1983; Inden and Moore, 1983). The composition of the intraclasts suggests they represent beachrock lag from the erosion of the beach during strandline migration. Although the intraclasts fit the criteria for being beachrock fragments (Stoddart and Cann, 1965; Scoffin, 1970b; Alexandersson, 1972; Beier, 1985), these same criteria can be applied to non-beach, submarine cementation (Shinn, 1969). Cores from Joulter's ooid shoal show dramatic increases in aggregates where submarine crusts occur (Harris, 1979). The increased abundance of intraclasts from the Snow Bay cores are not associated with an increased abundance of aggregates. This distinction further suggest beachrock origin rather than a submarine crust. Therefore, we interpret the sediment to represent a reworked beach (abraded grain "grainstone") and beachrock deposit. As sea-level rose, this sediment became subtidal and was cemented by aragonite forming an abraded grain "grapestone".

Radiometric dates from the surficial abraded grain "grapestone" and from the basal abraded grain "grapestone" (bottom of core 5) yield ages of 3090 y.b.p. and 3850 y.b.p. respectively. The closeness of the two ages suggests two possibilities. First, that the abraded grain "grapestone" is a transgressive lag deposit, a "relict" foreshore deposit from 3000 to 4000 y.b.p. Alternatively, the mobile sand sheet is receiving significant quantities of "old" sand from the present day erosion of dunes (Boardman et al, 1987), which is being cemented subtidally. Nearby dunes such as Nancy Cay (C-14 age=4220 y.b.p.) and Snow Bay Ridge (C-14 age=3700 y.b.p.) show appreciable erosion.

Subtidal muddy sands. Cores from the *Thalassia* meadow contain a fining-upwards *Halimeda*-rich "packstone/wackestone" facies which represents gradual substrate modification by benthic flora. Substrate modification by benthic flora results in changes in texture, composition, and mud fraction mineralogy (cores 2 and 5, Fig. 6; Andersen and Boardman, 1987). An interesting feature of the vertical sequence is the general absence of the transitional environment (foraminiferal "grainstone/packstone") between the basal transgressive sand and the subtidal muddy sands.

The source of sand in *Thalassia* meadows is thought to be produced and deposited *in situ* (Scoffin and Tudhope, 1984; Boscence, 1986). In the *Thalassia* meadow of Snow Bay the coarse sand fraction is angular which indicates that transport and mechanical abrasion of the coarse sand is minimal. While minimal transport is recognized for the coarse sand fraction, significant transport is recognized for the medium sand fraction. Analysis of the medium sand fraction (0.5 to 1.0mm) of core 2 shows an average of 29% more abraded grains per sample than in the coarse sand fraction.

Radiometric dating of medium sand and the mud fraction from the same sample (a sand-mud couplet) shows that there is a difference in ages. The discrepancy between the medium sand and mud ages increases upwards, with the sand always being older than the mud (Boardman and others, in prep.). Therefore, a significant portion of the medium sand fraction is "old sand which has been redeposited, i.e., there is an additional (allocthonous) source of sand (Boardman and others, 1987); Boardman and others, in prep.). This may indicate that only the coarser sand fractions contain abundant sand which has been produced *in situ*. The significantly higher proportion of abraded grains in the medium sand fraction further supports this hypothesis. The abundance of "old" sand is also evidence of the bankward transport of sand characteristic of windward-oriented high-energy lagoons (Halley and others, 1983).

Upper regressive sand. Only cores from the ebb-tidal delta contain an abraded grain "grainstone" facies (cores 1 and 2, Fig. 6). In the center of the ebb-tidal delta, this facies overlies the abraded grain "grapestone" (core 1, Fig. 6); whereas at the seaward edge of the ebb-tidal delta, the abraded grain "grainstone" abruptly overlies the *Halimeda*-rich "packstone/wackestone" with a thin foraminiferal "grainstone" between the two facies (core 2, Fig. 6).

The upward transition to the abraded grain "grainstone" represents the formation or progradation of the ebb tidal delta. In the Florida Reef Tract, ebb-tidal deltas only form where shoals at the shelf margin damp large oceanic waves (Enos, 1977). Although subtidal shoals do not exist in Snow Bay, the growth of the barrier reef to sea-level should have the same dampening effect on wave energy.

The C-14 ages of the abraded grain "grainstone" (3350 and 3470 y.b.p.) suggest that the ebb-tidal delta is old (>3000 y.b.p.). However, a radiometric date of mud within the *Halimeda*-rich "packstone/wackestone" sediment just below the ebb-tidal delta sediments is 490 y.b.p. and suggests progradation of the delta within the last 500 years. The medium sand fraction of the same sample from the *Halimeda*-rich "packstone/wackestone" yields an age of 3510 y.b.p. which is similar to the ebb-tidal delta sediments. The similarity of the medium sand ages suggests that the ebb tidal delta sands are comprised primarily of redeposited "old" sand (Boardman and others, in prep.).

Composite high-energy shallowing-upwards sequence. The shallowing-upward sequence is an important concept in carbonate geology, but few modern analogues for the high-energy shallowing-upward sequence exist. The composite vertical sequence from Snow Bay is a high-energy shallowing-upward sequence (Fig. 10) and provides a modern analogue to ancient high-energy deposits.

Goodwin and Anderson (1985) propose that in all sedimentary environments, sediments accumulate episodically as thin (1-5m) shallowing-upward cycles separated by sharply defined non-depositional surfaces. These shallowing-upward cycles are called punctuated aggradational cycles (PAC). Each individual PAC is characterized by gradational internal facies boundaries similar to those recognized in cores from Snow Bay. In the special case of shallow marine carbonate sequences, PAC's form as a direct response to sea-level fluctuations and have exposure surface boundaries, such as the Pleistocene exposure underlying the Snow Bay sediments.

James' (1984) model of a high-energy shallowing-upward carbonate sequence is a special case of the PAC hypothesis. James proposes four distinctive sedimentary units: a thin basal transgressive grainstone, a subtidal fossiliferous mudstone, intertidal grainstones of the lower and upper foreshore, and a supratidal exposure surface. The composite high-energy vertical sedimentary sequence observed in Snow Bay is remarkably similar to this model (Fig. 10). The 2-3 meter thick high-energy sequence from Snow Bay is characterized by:

1. An intertidal basal transgressive sand (~90cm thick); the abraded grain "grapestone" facies which contains intraclasts,
2. subtidal muddy sands (~100cm); the fining-upwards *Halimeda*-rich "packstone/wackestone" facies,
3. subtidal/intertidal regressive tidal delta sands (~50cm); the abraded grain "grainstone" facies.

The transitional environment (foraminiferal "grainstone/packstone") is a minor component of the

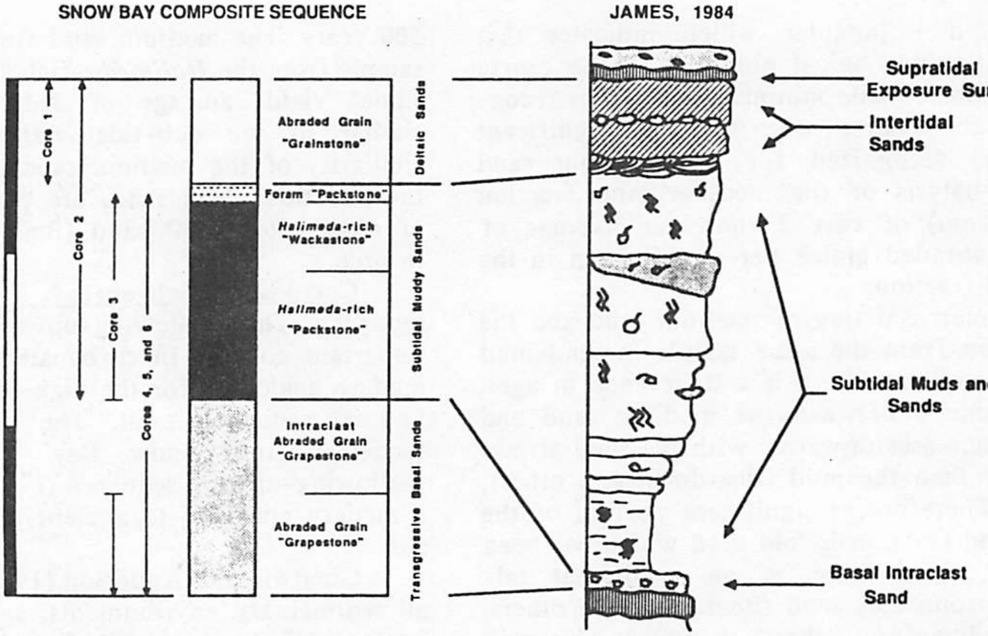

*Fig. 10. Comparison of the composite high-energy shallowing-upwards sequence for Snow Bay to the model proposed by James (1984).*

vertical sequence.

The two primary differences between James' model and the cores from Snow Bay are the substitution of tidal delta sands for beach sands and the incomplete nature (in each core) of the Snow Bay shallowing-upward sequence.

The composite Snow Bay high-energy shallowing-upward sequence supports the PAC hypothesis and provides a modern example for James' (1984) model. While a sedimentary sequence containing *Thalassia* can be properly applied only to late Cretaceous and younger rocks (Brasier, 1975), the principles of the high-energy shallowing-upward sequence as a punctuated aggradational cycle should be applicable to Paleozoic and early to mid-Mesozoic rocks. Algae, bryozoans, and crinoids have acted as sediment traps and baffles in the past (Harris and Martin, 1979; McKinney, McKinney, and Listokin, 1987; Carbonate Seminar, 1987); so similar high-energy sequences should have formed in topographic lows of ocean-facing environments in the past.

## The Depositional Evolution of Snow Bay

The previously described lateral and vertical sedimentary gradients of Snow Bay record the banktop response to a sea-level rise. The depositional package contains both eolian and marine facies which accumulated within the last 6300 years (Andersen and Boardman, 1988).

A peat deposit in a topographic low five meters below sea level records banktop flooding 6300 years ago (Fig. 11). The peat formed in a low, poorly drained area and overlies a hard, well-cemented surface which we presume is the Pleistocene contact.

The rest of the Pleistocene surface in Snow Bay is covered by a poorly sorted transgressive sand which includes intraclasts of probable beachrock origin. This transgressive sand, similar to the basal unit in the high-energy shallowing-upward sequence described in James (1984), records strandline movement across the bank as sea-level rose. A large amount of sand was produced during the initial transgression, and redeposition of this sand is an important feature of the evolution of Snow Bay and other high-energy lagoons (Trumbel and Neumann, 1986; Boardman and others, 1987; Boardman and others, in prep.).

Temporally associated with this transgressive sand is eolian dune formation (Carew and Mylroie, 1985; Boardman and others, 1987; Andersen and Boardman, 1988). Dunes up to twenty meters high form the cays and cliffs along the eastern margin of San Salvador. Well preserved eolian cross bedding which dips below sea level and C-14 ages from 5400 to 3700 y.b.p. indicate the dunes formed rapidly during initial banktop flooding. Erosion of these dunes provided additional sand to the strandline (Fig. 11).

Stabilization of the sandy lagoon floor by

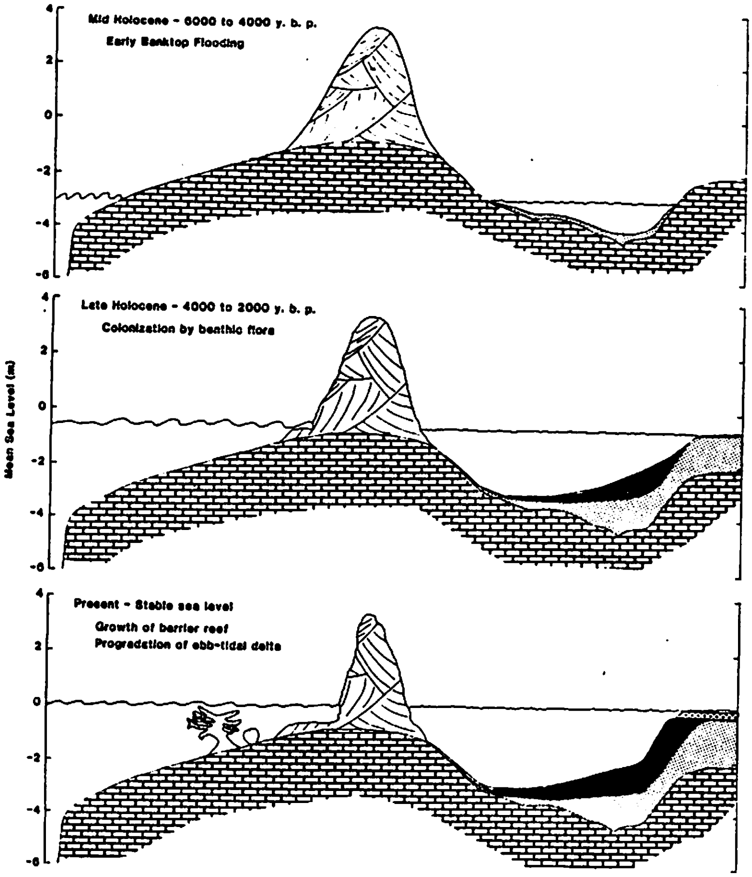

*Fig. 11. The depositional evolution of Snow Bay. Mid Holocene - initial banktop flooding and temporal dune formation on Pleistocene bedrock (limestone pattern). Late Holocene-strandline migration forms the abraded grain "grapestone" (light stipple). As sea-level rose, this sediment was colonized by benthic flora forming the* Halimeda-*rich "packstone/wackestone" (black). In the last 1500 years, growth of a barrier reef allowed coastal beach ridges and the ebb-tidal delta to prograde into Snow Bay forming the abraded grain "grainstone" (heavy stipple).*

benthic algae, most notably *Halimeda*, coincided with the continued rise of sea-level. *Thalassia* was able to colonize areas with sufficient sediment thickness (at least 7cm, Scoffin, 1970a) and sufficient sediment stability (Moore, 1963). Substrate modification by benthic flora caused gradational changes in the sediment characteristics.

Regressive deposition of sand along the strandline began when sea-level reached near present level (Fig. 11). The style of deposition changed from dune formation to prograding beach ridges (Boardman and others, 1987; in prep.). Air photos and geologic surveys clearly indicate that Sandy Hook is a recently prograded beach ridge system.

In their stratigraphy of San Salvador, Carew and Mylroie (1985) place Sandy Hook in the youngest member (Hanna Bay Member) of the Holocene Rice Bay Formation. They proposed that the Hanna Bay Member was deposited in equilibrium with present sea level sometime after 5000 years ago. Sea-level in the Bahamas has been within 70cm of present for at least 1400 years (Winter, 1987; Donn and Boardman, 1988; Boardman, Neumann, and Rasmussen, 1988); yet whole rock C-14 ages of the oldest and youngest sand ridges of Sandy Hook are 3650 and 1990 y.b.p. respectively (Table 2). Therefore, either 1. the sand ridges were formed when sea level was between 1.2 and 0.5m below present (i.e. Carew and Mylroie, 1985, are wrong), or 2. the sand comprising the ridges is older (>1400 y.b.p.) than the progradation of Sandy Hook. We favor the second alternative for two reasons. First, the very friable nature of the Sandy Hook sand ridges suggests a shorter time for cementation than the better cemented rocks of the nearby North Point Member (High Cay, Nancy Cay, Snow Bay Ridge) which range in age from 3700-4200 y.b.p. (Table 2). Second, C-14 dates of sand-mud couplets suggest a source of "old" sand which could easily contribute to the formation of Sandy Hook and "contaminate" the C-14 ages of the Sandy Hook sand ridges.

The ebb-tidal delta, formed at the mouth of the Pigeon Creek tidal channel, is a prominent feature of Snow Bay. The ebb-tidal delta may have formed any time since the area was flooded (-2m at 4500 y.b.p.). Our data however, suggest that the tidal delta formed recently from "old" sand. The form of the ebb-tidal delta requires that sand dispersal by ebb currents dominate over dispersal by wave energy. The growth of reefs to sea-level may have reduced wave energy enough to allow the dominance of ebb-tidal currents, in a manner similar to that described by Enos (1977). Today the line of barrier reefs and cays substantially reduces wave energy entering the lagoon. The high, ocean-facing cliffs of the North Point Member cays suggest they are absorbing wave energy in addition to supplying sand to the strand line.

### Time Frame for Sequence Development

Ancient shallowing-upward sequences developed in 10,000 to 250,000 years (Goodwin and Anderson, 1985; Hardie, 1985; Heckel, 1985; Grotzinger, 1986). However, this time frame includes time of subaerial exposure, so the actual time for sediment accumulation is unknown. Studies of modern carbonates indicate that sediment accumulation occurs rapidly. Six to eight meters of oolitic sediment formed in 1500 years on Lily Bank (Hine, 1977), and the four meter thick ooid shoal of Joulter's Cay formed in less than 5000 years (Harris, 1984). The sediment package of Snow Bay, a modern example of a high-energy shallowing-upward sequence, formed in less than 6300 years.

## CONCLUSIONS

The composite vertical sequence of Snow Bay is remarkably similar to the high-energy shallowing-upward sequence proposed by James (1984). The sedimentary sequence includes a transgressive basal sand of possible lower foreshore/beach origin, fining-upwards subtidal muddy sands representing substrate modification by benthic flora, and regressive intertidal/subtidal ebb-tidal deltaic sands. The sequence contains an abundance of "old" sand transported bankward into the *Thalassia* meadow, ebb-tidal delta, and prograding beach ridges.

The lateral and vertical facies mosaic of southeastern San Salvador records the banktop response to the Holocene sea-level rise. The complete depositional package accumulated in the last 6300 years and contains both eolian and marine facies. The summary of events which formed the Snow Bay sedimentary sequence are:

1. The initial banktop flooding 6300 y.b.p. resulting in peat formation in topographic lows five meters below present sea level.
2. The deposition of a transgressive abraded grain "grapestone" as the strandline migrated across the banktop in response to continued sea-level rise. Eolianite deposition is closely associated with early strandline migration.
3. Colonization and stabilization of the sandy lagoon floor first by benthic algae, then by seagrasses. These benthic flora trap and bind increasingly muddier sediments and form the *Halimeda*-rich "packstone/wackestone".
4. Recent (since 1400 y.b.p.) progradation of Sandy Hook and formation of the ebb-tidal delta. Ebb-tidal formation is probably due to growth of the barrier reef to sea level.
5. Progradation of the ebb-tidal delta over the *Thalassia* meadow.

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