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DEPOSITIONAL EVOLUTION OF A WINDWARD, HIGH-ENERGY CARBONATE LAGOON, SAN SALVADOR, BAHAMAS

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ABSTRACT

Graham's Harbor is a windward, 2x3km high-energy lagoon located at the northeast end of San Salvador. It is open to the west and rimmed to the north and east by cays and a barrier reef. Cluster analysis reveals four marine facies in Graham's Harbor: 1) abraded grain "grapestone"; 2) abraded grain "grainstone"; 3) *Halimeda* and foram-rich "packstone"; and 4) grapestone/bioclast "wacke-/packstone". These facies are distinct both laterally and vertically within the lagoon.

Studies of sediment cores reveal a coarsening upwards sedimentary sequence. This sequence differs from previous models for lagoonal deposition. Sediment probes indicate that a pronounced sill exists in Graham's Harbor. The presence of this sill has been recorded in the vertical sedimentary sequence during the Holocene sea-level rise. A muddy facies (grapestone/bioclast "wacke-/packstone") is overlain by a grainy facies (abraded grain "grapestone"). In protected, seagrass stabilized areas of the lagoon, the latter facies is overlain by a slightly muddier facies (*Halimeda* and foram-rich "packstone").

The sedimentary sequence in Graham's Harbor records the banktop response to the Holocene sea-level rise. Deposition within the silled basin allowed the accumulation of lower energy, muddy sediments followed by less muddy, higher energy sediments as sea level rose and breached the sill. Radiocarbon dates of peat and sediment from cores indicate that the sequence in Graham's Harbor was deposited at rates of 30-80 cm/1000 years. The entire sequence formed in less than 7000 years.

INTRODUCTION

Vertical and lateral facies changes in limestones are related to sea-level, energy, and production rates. Sea-level rise often results in a shallowing-upwards sequence (James, 1984) since sedimentation rates generally outpace sea-level rise and/or rates of subsidence (Schlager, 1981).

Models developed to explain carbonate deposition are based primarily on the rock record and concentrate on the formation of tidal flat and low-energy lagoonal sediments (Goodwin and Anderson, 1985; Pratt and James, 1986; Wright, 1986). James (1984) has developed a hypothetical model for carbonate deposition in a high-energy environment. Few modern analogues to this model exist, however. In addition, many of the studies of high-energy lagoons have focused on benthic communities and their relationship to the sediment record (Ginsburg and Lowenstam, 1957; Taylor and Lewis,1970; Miller, 1988). Few studies have focused on lateral and vertical facies relationships in high-energy lagoons (Ginsburg, 1956; Swinchatt, 1965; Locker, 1981; Andersen, 1988).

The purpose of this study is to examine vertical and lateral facies relationships in a high-energy lagoon in order to better understand the depositional processes and controls acting on this type of environment. Establishing a timeframe for deposition of the vertical sequence during a sea-level rise is also a primary focus of the study.

METHODS

Field

Graham's Harbor is a 2x3km high-energy lagoon located at the northeast end of San Salvador, Bahamas. It is open to the west and rimmed to the north and east by cays, eolian dunes, and a barrier reef (Fig. 1). Fourteen cores and 48 surface samples have been collected in several transects across the lagoon. Water depths, sediment thicknesses, bedforms, and floral and faunal variability have been recorded.

Laboratory

All cores were described megascopically and

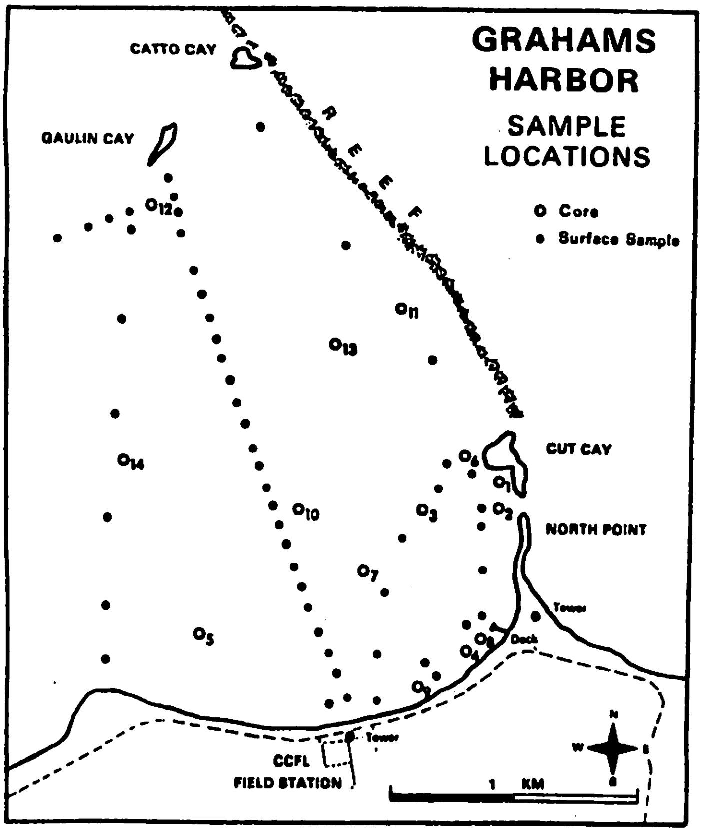

Fig. 1: Graham's Harbor sample locations. Open circles represent core locations, closed circles represent surface samples.

three cores were sampled at 10 or 20 cm intervals. Of the surface samples, 36 were chosen in order to cover the widest geographic area of the lagoon. All of these samples were analyzed with respect to texture, composition, and mud fraction mineralogy.

Texture

Standard wet sieve analysis was used on samples at one phi intervals. Pipette analysis was performed on the <63μm, <16μm, and <4μm mud fractions. All samples were rinsed in a 50% Clorox solution prior to sieving to remove organics. The method of moments was used to determine sorting (Folk, 1966; Lewis, 1984).

Composition

At least 300 grains from the 1-2mm size fraction were counted from each sample. This size fraction was chosen because it provided the greatest number of readily identifiable grains.

Mud Fraction Mineralogy

The ratio of aragonite to calcite was determined from x-ray diffraction data using the peak area method (Chave, 1954). The type of calcite (high or low magnesium) was determined using the position of the 104 peak of calcite (Goldsmith, Graf, and Joensuu, 1955).

Statistical Analysis

Cluster analysis was used to recognize the relationships between samples. The program CLAP (written by Sepkoski and Sharry, 1976; modified by A. Miller, 1987) was used to accomplish both Q-mode and R-mode analyses. The UPGMA method of clustering was used on standardized data (Imbrie and Van Andel, 1964; Harbaugh and Mirriam, 1968). The cosine theta similarity coefficient was used in combination with a total of 10 compositional, textural, and mineralogic variables per sample. A combination of Q-mode and R-mode analyses provided a two-way cluster analysis (Miller, 1988), from which the various facies are derived.

Radiometric Dating

Selected core, surface, and rock samples were chosen for carbon-14 dating. The sand (125-1000μm) and mud (<63μm) fractions were separated from three samples (sand-mud clouplets) and dated. A total of 15 samples were analyzed.

RESULTS

Depositional Environments

Graham's Harbor deepens towards the center to a maximum depth of 6m and shallows to the north, east, and south (Fig. 2). It remains open to the west, allowing excellent exchange with the Atlantic Ocean. The coast is dominated by beaches, with beachrock exposed in many areas.

Sediment thickness also increases towards the center of the lagoon, reaching a thickness of at least 4m (Fig. 3). By combining sediment thickness with bathymetry, a map of antecedent (Pleistocene) topography was developed (Fig. 4). This shows that Graham's Harbor was a silled, bowl-shaped basin with a maximum depth of about 10m below present sea level before Holocene sedimentation began.

Facies

Four marine facies are found in Graham's Harbor: 1) abraded grain "grapestone"; 2) abraded grain "grainstone"; 3) *Halimeda* and foram-rich

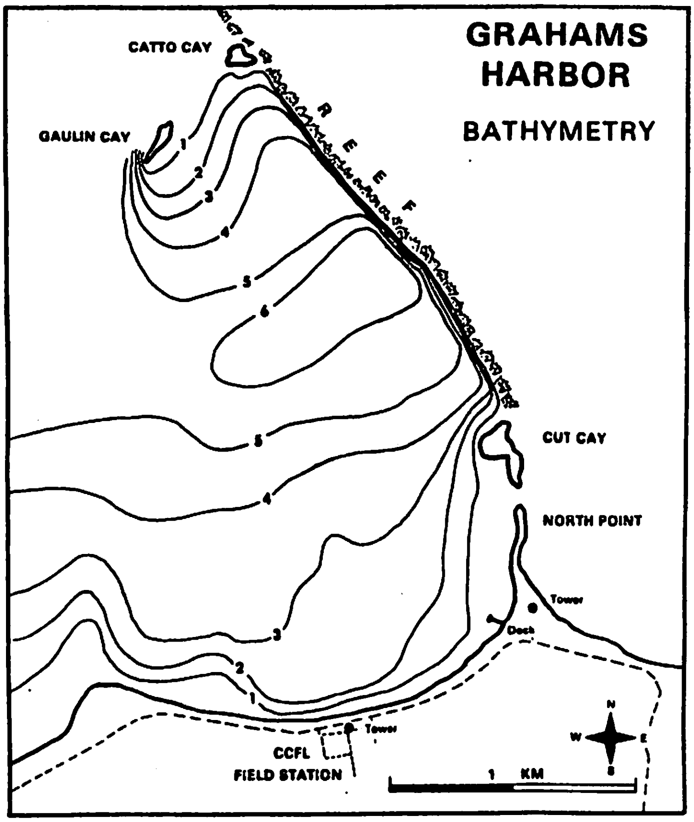

Fig. 2: Graham's Harbor bathymetry. The lagoon is deepest in the center. It is open to the west but rimmed on the north and east by a barrier reef and cays.

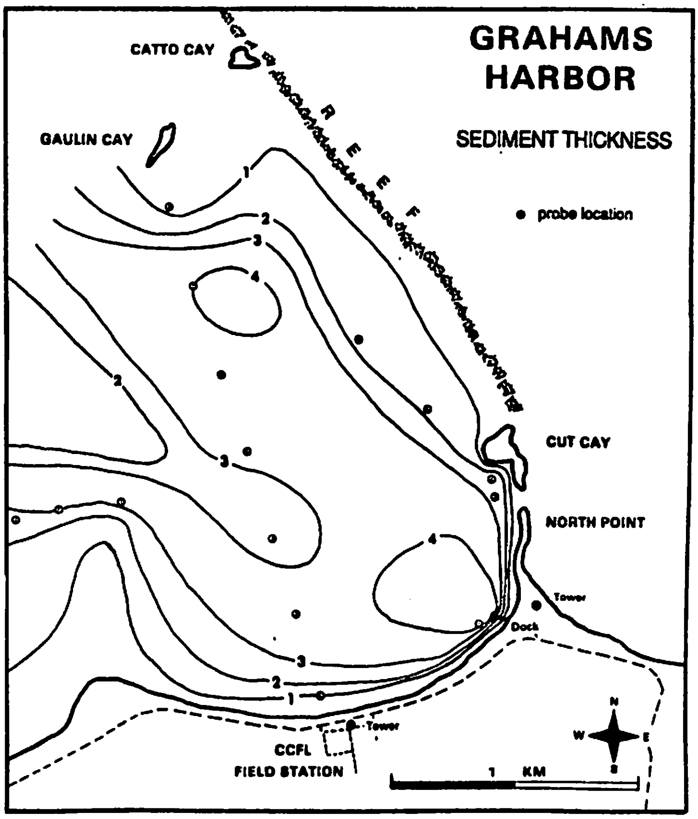

Fig. 3: Sediment thickness in Graham's harbor. Thickness increases toward the center of the lagoon. Contour intervals are in meters.

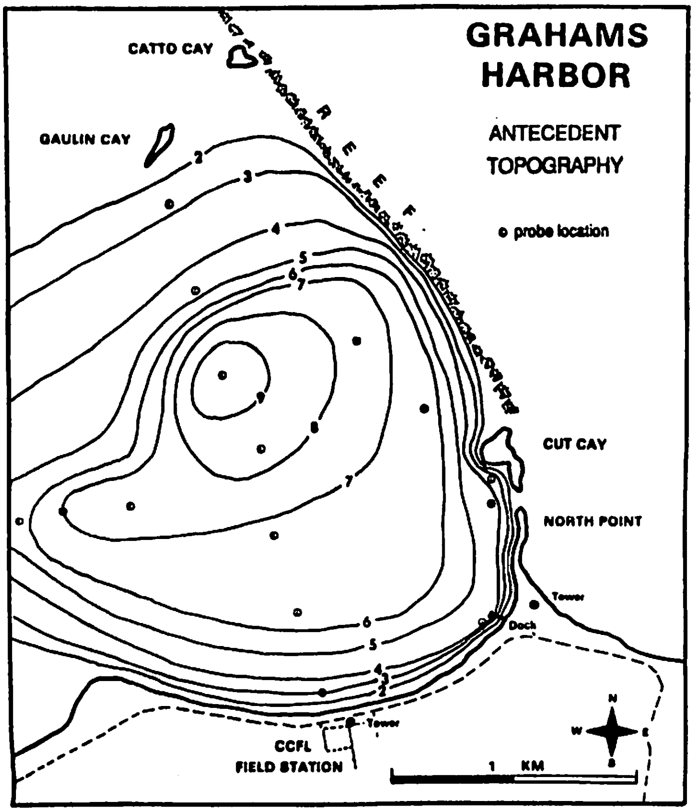

Fig. 4: Antecedent (Pleistocene) topography. Graham's Harbor was a silled basin at the time of the Holocene sea-level rise.

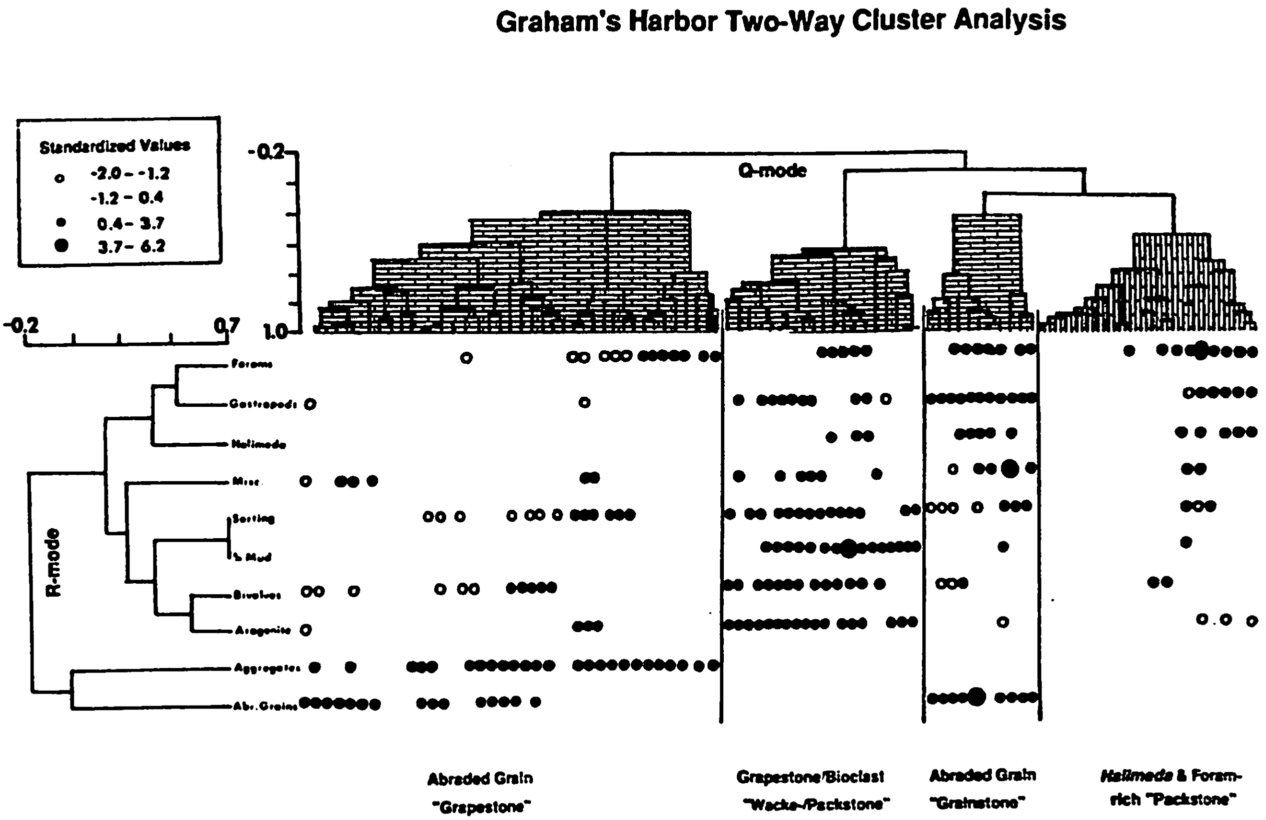

Fig. 5: Two-way cluster analysis of Graham's Harbor core and surface samples. Negative values represent variables below the mean, positive values represent variables above the mean.

"packstone"; and 4) grapestone/bioclast "wacke-/packstone". These facies are recognized by cluster analysis (Fig. 5) which groups core and surface samples together based on 10 sedimentary characteristics (Table 1). Facies are named on the basis of the most abundant allochems within each cluster group. A corresponding environment of deposition is then assigned to each facies. All cores facies were combined to form a composite vertical sequence for Graham's Harbor.

Lateral Gradients

All of the facies are found surficially in Graham's Harbor except the grapestone/bioclast "wacke-/packstone". The abraded grain "grapestone" covers much of the lagoon in areas of periodically shifting sand. The abraded grain "grainstone" is found in a high-energy zone near the barrier reef and south of Gaulin and Catto Cays. The *Halimeda* and foram-rich "packstone" is located behind North Point, in a relatively low-energy, seagrass stabilized area (Fig. 6).

Vertical Gradients

The grapestone/bioclast "wacke-/packstone" forms the basal portion of 2 of the 3 cores analyzed (Fig. 7). This facies contains the highest percent mud of the four facies as well as a high proportion of grapestone. Where this facies is present, it is abruptly overlain by the abraded grain "grapestone", a much coarser facies. The *Halimeda* and foram-rich "packstone" is found overlying the abraded grain "grapestone" and also directly overlying peat (core 1). This facies is bioclast-rich and slightly muddier than the previous facies. The vertical extent of the abraded grain "grainstone" is not yet established, but it has been found in the upper portion of core 11. This facies contains very little mud and a high proportion of abraded grains.

The mud fraction mineralogy of cores 4 and 7 changes from aragonite dominated to roughly equal proportions of aragonite and high magnesium calcite. Core 1 mud contains co-equal proportions of aragonite and high magnesium calcite throughout.

Radiometric Dating

Carbon-14 dating was performed on selected core, surface, and rock samples (Table 2).

Samples were taken from cores 1, 7, and 8

Graham's Harbor Facies

Variable Means and Standard Deviations

	Abraded Grain Grapestone	Grapestone/Bioclast Wacke/Packstone	Abraded Grain Grainstone	Halimeda & Foram-rich "packstone"
Halimeda	3.1 ± 1.9	11.2 ± 9.6	14.9 ± 8.7	33.3 ± 11.8
Bivalves	10.2 ± 5.4	22.64 ± 5.0	7.9 ± 2.5	14.6 ± 5.5
Gastropods	2.0 ± 0.9	4.8 ± 2.7	5.1 ± 1.5	3.9 ± 1.9
Forams	10.4 ± 6.5	18.9 ± 7.3	16.8 ± 5.5	22.4 ± 7.8
Aggregates	52.1 ± 14.0	25.2 ± 13.6	16.3 ± 13.0	8.7 ± 5.7
Miscellaneous	4.1 ± 2.6	8.1 ± 3.0	6.8 ± 6.2	5.8 ± 2.2
Abraded Grains	18.1 ± 11.7	9.3 ± 7.9	32.2 ± 9.0	11.2 ± 4.4
Mud	6.6 ± 4.6	32.6 ± 15.8	7.7 ± 9.7	14.7 ± 5.4
Aragonite	52.9 ± 5.9	67.6 ± 4.9	46.9 ± 4.7	48.4 ± 2.9
Sorting	1.7 ± 0.5	2.2 ± 0.3	1.59 ± 0.5	1.9 ± 0.1

Table 1: Variable means and standard deviations of sedimentary facies recognized by cluster analysis.

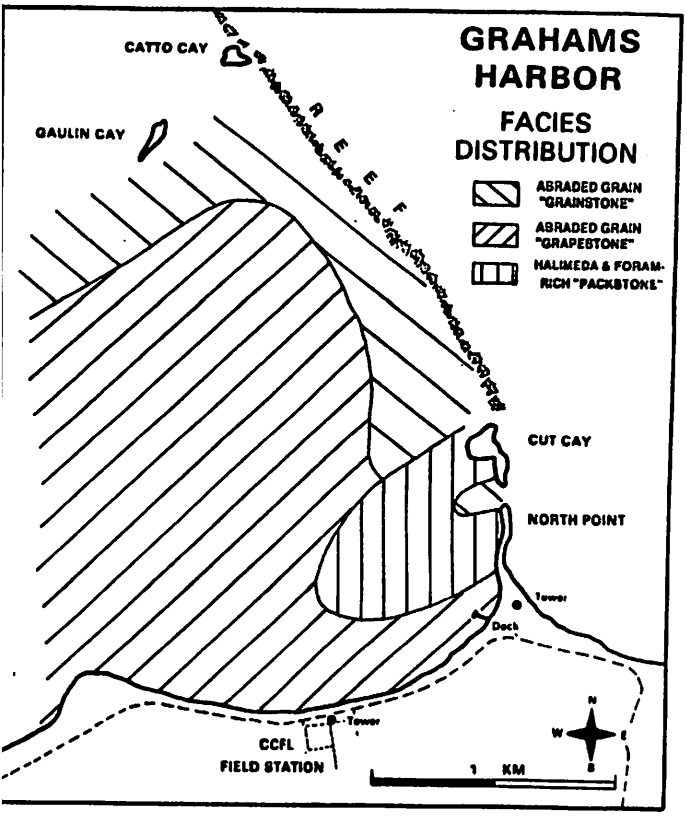

Fig. 6: Lateral facies distribution in Graham's Harbor.

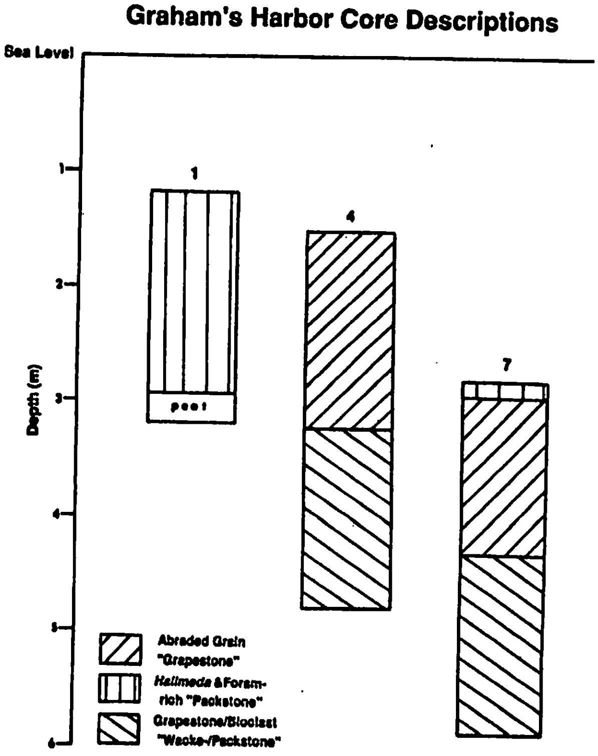

Fig. 7: Vertical distribution of facies in cores 1, 4, and 7. Cores are drawn relative to mean sea-level.

GRAHAM'S HARBOR RADIOCARBON DATES

Core Samples

Core	Sample Type	Sample Depth	Water Depth	Total Depth (cm)	Age
1	peat	198	120	318	4960 ± 70
1	shell	170	120	290	4700 ± 90
7	sand	20	300	320	3080 ± 70
7	mud	20	300	320	960 ± 90
7	sand	110	300	410	3550 ± 80
7	mud	110	300	410	2550 ± 90
7	sand	284	300	584	6480 ± 100
7	mud	284	300	606	6500 ± 100
7	shell	306	300	584	4640 ± 140
8	peat	406	120	526	7080 ± 90

Rock Samples

Sample Type	Sample Location	Age
Bulk Rock	North Point, 2m above sea level from calved off face of eolianite	5360 ± 110
Bulk Rock	(same as above)	5435 ± 125
Bulk Rock	North Point, near top of dune, +4.2m m.s.l.	5670 ± 160
Bulk Rock	North Point, near center of dune, +2.2m m.s.l.	6000 ± 100
Bulk Rock	North Point, near bottom of dune, approx. +1m m.s.l.	6190 ± 150

Table 2: Radiocarbon dates from core, rock, and surface samples in Graham's Harbor.

for radiocarbon dating. Peat samples were collected from the base of cores 1 and 8. These samples yielded ages of 4960±70 and 7080±90 ybp, respectively. A shell sample was taken at the sand/peat interface of core 1, which yielded an age of 4700±90 ybp.

Sand-mud couplets were collected from the abraded grain "grapestone" facies of core 7. Radiocarbon dates of these samples shows a wide discrepancy between sand and mud ages upward in the core. Sand and mud ages are very close in the lowest part of the core, but diverge toward the top. The largest difference is near the top of the core, where the *Halimeda* and foram-rich "packstone" overlies the abraded grain "grapestone" facies (Table 2).

DISCUSSION

Facies in Graham's Harbor

The source of sediment in Graham's Harbor is the lagoonal "carbonate factory" (Neumann and Land, 1975; James, 1984)). This in-situ accumulation of sand sized skeletal material from breakdown of molluscs, bivalves, and reef material and mud from calcareous algae and epibionts on seagrass provides the bulk of the sediment in the lagoon. Studies have shown that the production by green algae alone is more than enough to fill most lagoons and that a large percentage is probably transported off-platform (Neumann and Land, 1975). Radiocarbon dates from sand-mud couplets in sediment cores also suggests another source of sand in the lagoon. While mud dates get progressively younger upwards in the cores, the sand remains old (Table 2). This suggests that erosion of older North Point dune sand, dated at between 6200 and 5300 ybp, has contributed a large proportion of the sand sized material in Graham's Harbor. Other studies on San Salvador have yielded similar results (Boardman et al, 1987; Boardman et al, in prep.)

Lateral Distribution of Facies

The principal controls on lateral facies distribution in Graham's Harbor are wave energy and substrate modification by benthic flora. In most of the lagoon today, the substrate is open to wave energy, is not stabilized by benthic flora, and abraded grain "grapestone" is the dominant facies. Higher wave energy and lack of stabilization allows winnowing of mud and abrasion of grains. Presence of grapestone also indicates periodic shifting of sand followed by periods of stabilization and cementation (Illing, 1954, Winland and Mathews, 1974). Similar sediments are found under similar conditions today on northern Great Bahama Bank (Imbrie and Purdy, 1962; Trumbel, 1986), Bight of Abaco (Neumann et al, 1975; Boardman, 1976; Locker, 1981), and Snow Bay (Andersen and Boardman, 1987).

In protected (lower wave energy) areas of the lagoon that have been stabilized by seagrass, *Halimeda* and foram-rich "packstone" is found. North Point sand dunes provide protection from the dominant easterly waves in Graham's Harbor. The dunes refract and dampen much of the wave energy. The North Point dunes are 10m high, 15m wide, and extend about 500m to the north. A barrier reef extends from the northwest tip of Cut Cay to Catto Cay, the northern portion of the study area, and absorbs much of the wave energy entering the lagoon. In addition, seagrass baffles wave energy and provides a substrate for encrusting forams and other epibionts (Scoffin, 1970; Scoffin and Tudhope, 1985; Boscence, 1986).

Areas of greatest wave energy are found next to the barrier reef and south of Gaulin and Catto Cays, which receive uninterrupted wave energy from the west. Abraded grain "grainstone" rims the lagoon in these areas. Abundant east-west trending blowouts adjacent to the reef, the high percentage of abraded grains, and the low mud content attest to the heavy wave and current activity.

Vertical Gradients

Vertical facies gradients in Graham's Harbor are controlled by energy and substrate modification, as well as the presence of a sill. The presence of a sill strongly influenced the basal portion of the vertical sequence (Fig. 8) in Graham's Harbor by restricting wave energy and allowing a very muddy sediment to accumulate. Grapestone/bioclast "wacke-/packstone" forms the basal component of cores which penetrate the deeper portions of the lagoon (Fig. 8), representing deposition within a silled, semi-enclosed basin. Cores taken on the higher portions of the Pleistocene bedrock do not contain this facies.

Abraded grain "grapestone" abruptly overlies the grapestone/bioclast "wacke-/packstone" facies, indicating a rapid change in deposition. The low mud content and abundance of abraded grains in

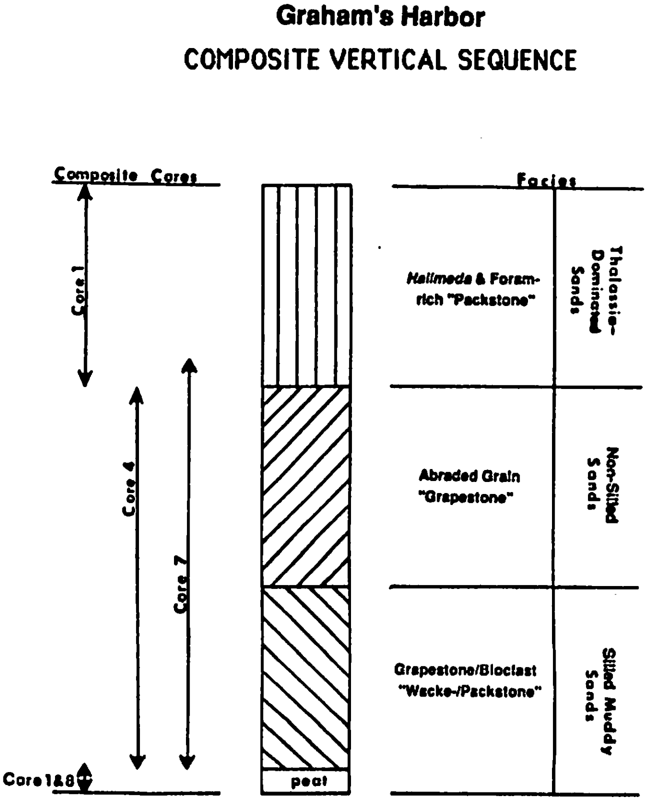

Fig. 8: Composite vertical sequence in Graham's Harbor. Composite cores represent cores used to develop each part of the vertical sequence.

this facies suggest a greater degree of agitation and winnowing by waves and currents. This facies signifies deposition after the sill had been breached by rising sea level under higher-energy, less restricted conditions.

The vertical sequence is capped by *Halimeda* and foram-rich "packstone", which comprises all of core 1 and the upper 15cm of core 7. This facies accumulated in the sheltered environment behind North Point only after seagrass was able to colonize and provide a substrate for epibionts and a stabilized environment for *Halimeda.* It therefore indicates a protected, bottom-stabilized environment. Radiocarbon dates from peat and shells at the base of core 1 indicate that this facies began forming in some areas less than 5000 years ago. The abraded grain "grainstone" forms in a zone near the barrier reef and south of the cays. This facies may represent an alternate, high-energy cap to the vertical sequence in Graham's Harbor.

The vertical sequence in Graham's Harbor is also characterized by a distinct mineralogic signature. The mud fraction mineralogy changes from about 70% aragonite to roughly equal proportions of aragonite and high-magnesium calcite upward in the core. This is due to the colonization by seagrass in the upper part of the cores and the associated production of high-magnesium calcite from epibionts. This mineralogic signature can be a more reliable indicator of seagrass stabilization than percent mud (Andersen et al, 1988).

History of Deposition

The depositional history of Graham's Harbor began about 7000 years ago with the Holocene sea level rise and flooding of the platform. Peat formation began and was preserved in low-lying, protected areas of the silled basin. Radiocarbon dates of peat are 7080±90 ybp and 4960±70 ybp, indicating that peat formation continued in Graham's Harbor as sea level rose. As sea level continued to rise, subtidal muds (grapestone/bioclast "wacke-/packstone") were deposited above the peat in the lowest lying areas of the silled basin. As the sill was breached, higher energy conditions prevailed, less mud was deposited, and these muds were covered by subtidal sands (abraded grain "grapestone"). This facies overlies the grapestone/bioclast "wacke-/packstone" wherever it is found in the lagoon. Protected areas behind the North Point dunes allowed colonization by *Thalassia* and accumulation of a somewhat muddier sediment (*Halimeda* and foram-rich "packstone"). Alternately, heavy wave and current activity in a zone near the barrier reef allowed a high-energy, sandy sediment to accumulate (abraded grain "grainstone"). Fig. 9 illustrates the depositional evolution of Graham's Harbor. Radiocarbon dates of mud indicate the sequence was deposited at rates of 30-80 cm/1000 years.

Vertical Sequence

The vertical sedimentary sequence in Graham's Harbor coarsens upwards from subtidal muds to subtidal sands and muddy sands. This sequence differs from models proposed by James (1984), Fischer (1964), and Boardman (1976) for lagoonal deposition. The sequence described here illustrates a previously undescribed set of conditions: deposition in a semi-enclosed, silled basin followed by higher-energy, open marine deposition. Standard sedimentological analysis combined with multivariate statistical techniques have permitted the recognition of this sequence.

CONCLUSIONS

Four marine facies are found in Graham's Harbor: 1) abraded grain "grapestone"; 2) abraded grain "grainstone"; 3) *Halimeda* and foram-rich "packstone"; and 4) grapestone/bioclast "wacke-/packstone". These facies are distinct both laterally and vertically in the lagoon. Very little overlap occurs. Standard sedimentological analysis combined with multivariate statistical techniques have permitted recognition of these facies.

Abraded grain "grapestone" blankets most of the lagoon today, because the substrate is open to wave energy and is not stabilized by benthic flora. *Halimeda* and foram-rich "packstone" is found today in protected (lower wave energy) areas of the lagoon that have been stabilized by seagrass. Rimming the lagoon on the east and north is the abraded grain "grainstone" facies. This facies accumulates along the barrier reef and next to the northern cays, areas which receive the greatest wave energy.

The vertical sequence in Graham's Harbor begins with the grapestone/bioclast "wacke-/packstone", which forms the basal component. This facies represents deposition within a low energy, silled, semi-enclosed basin. Abraded grain "grapestone" overlies the grapestone/bioclast "wacke-/packstone" facies. This facies results from high-energy, less restricted conditions after the sill

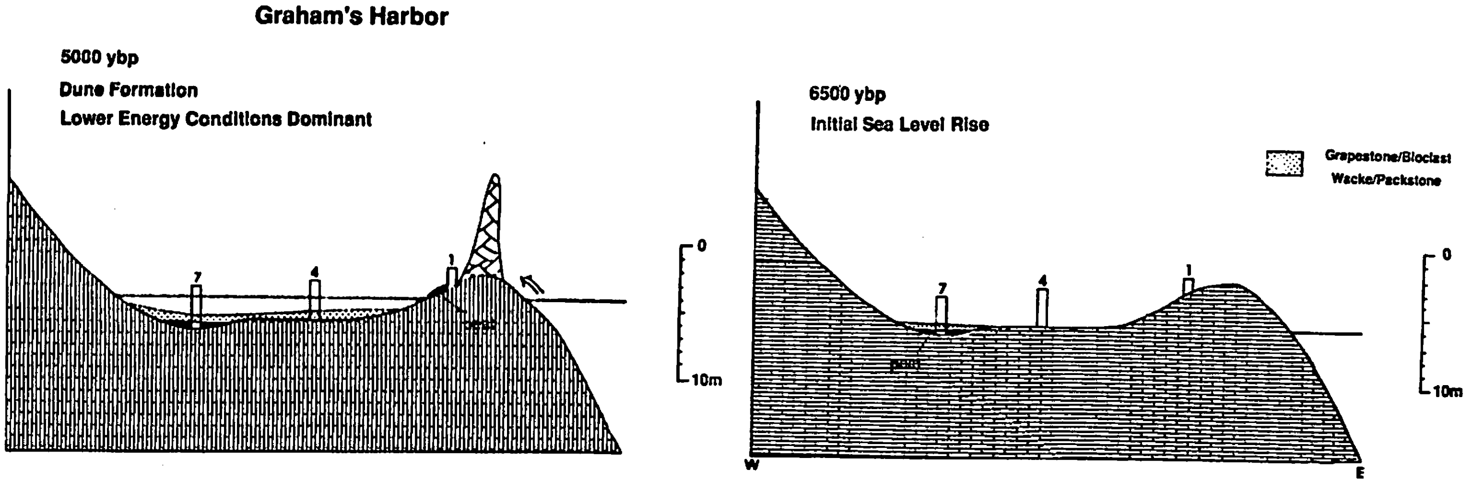

Fig. 9a: Depositional evolution of Graham's Harbor from 6500-5000 ybp. Sequence illustrates the response of the lagoon to a progressive sea-level rise.

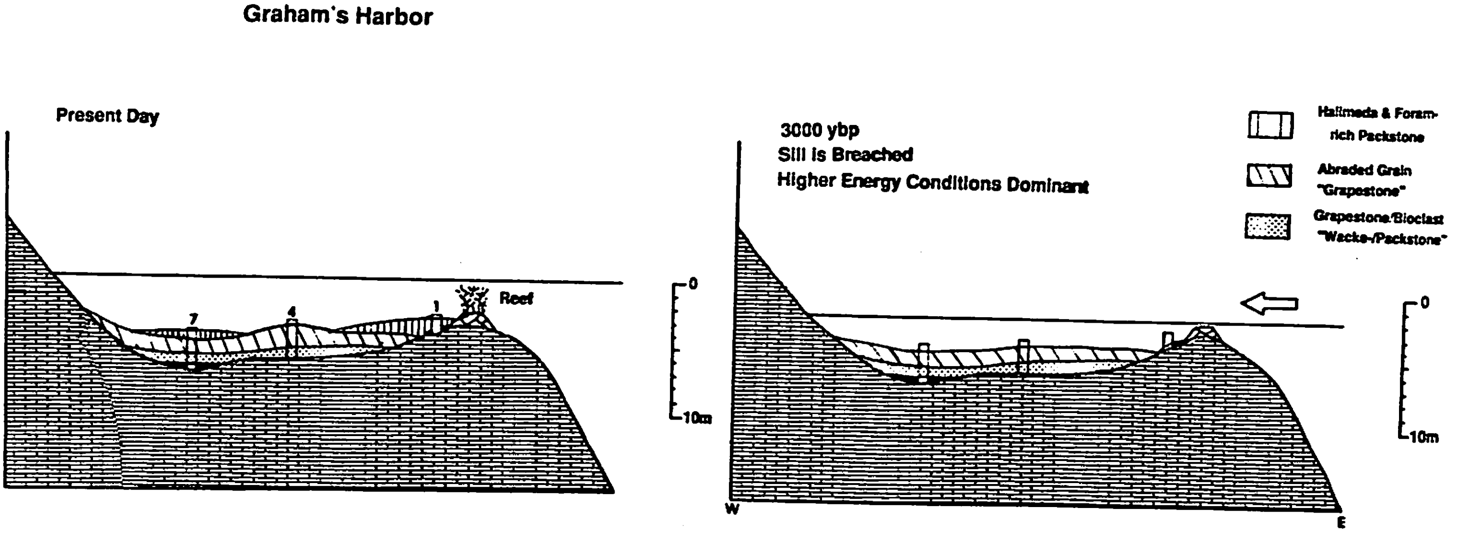

Fig. 9b: Depositional evolution of Graham's Harbor from 5000 ybp-present.

has been breached by rising sea level. The vertical sequence is capped by *Halimeda* and foram-rich "packstone", produced in a protected, bottom-stabilized environment.

The depositional history of Graham's Harbor began about 7000 years ago with platform flooding accompanying Holocene sea level rise. Peat accumulated in low-lying, poorly drained areas. Subtidal muds were then deposited within the silled basin as sea level continued to rise. These muds were covered by subtidal sands and muddy sands as the sill was breached, higher energy conditions prevailed, and less mud was deposited. Radiocarbon dates of the mud fraction indicate the sequence was deposited at rates of 30-80 cm/1000 years. Radiocarbon dates of the sand sized fraction from cores indicates that erosion of old (6200-5300 ybp) North Point sands has contributed much of the sand in the lagoon. The vertical sequence in Graham's Harbor coarsens upwards from subtidal muds to subtidal sands and muddy sands. This sequence is a significant departure from other models for lagoonal deposition.

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