PROCEEDINGS
OF THE
FIFTH SYMPOSIUM
ON THE
GEOLOGY OF THE BAHAMAS

Edited by

Roger J. Bain

Production Editor

Donald T. Gerace

Bahamian Field Station
San Salvador, Bahamas
1991

Printed in USA by Don Heuer

ISBN 0-935909-37-0

PERITIDAL SEDIMENTATION IN A SANDY LAGOON: STANIARD CREEK, ANDROS ISLAND, BAHAMAS

Tracy A. Love and Mark R. Boardman
Department of Geology
Miami University
Oxford, Ohio 45056

ABSTRACT

Staniard Creek is a 1x4 km low-energy "lagoon" located on the windward margin of Andros Island and protected by a Holocene barrier island. The southern half is presently a sandy intertidal environment which grades to the north into a subtidal environment up to 3 m. Analysis of twenty-four sediment cores (0.87-1.85 m long) included megascopic core descriptions, texture, mud fraction mineralogy and identification of the constituent components. Twelve southern cores revealed a shallowing upward sequence which consists of three distinct units: 1) a basal gray muddy subtidal unit followed by 2) a gray sandy intertidal unit and capped by 3) a tan sandy intertidal unit. Nine northern cores reveal two units: a muddy basal unit followed by a gray sandy unit. Three cores were taken from a transitional area between the subtidal and intertidal environments and contain the same gray sandy unit but are capped by a tan-gray sand.

Cluster analysis on 78 samples and 10 variables reveals four distinct facies: 1) aggregate-aragonite rich "grainstone", 2) foraminifera-rich "grainstone", 3) foraminifera-poor "pack/wackestone" and 4) the foraminifera-poor "grainstone". The foraminifera-poor "pack/wackestone" corresponds to the basal muddy subtidal unit. The foraminifera-rich "grainstone" includes both the gray sandy intertidal unit and the capping tan sandy unit while the aggregate-aragonite rich "grainstone" is restricted to the upper 20-40 cm of three cores in the sand flat. The foraminifera-poor "grainstone" facies is not laterally persistent and therefore is not considered a major contributor of the vertical sequence.

The initial environment of Staniard Creek was intertidal, indicated by basal peat from several cores. As sea level rose, the platform was flooded and the foraminifera-poor "pack/wackestone" (lagoonal subtidal unit) accumulated in pockets in the lee of the barrier island. The slow rise in sea level allowed sediments to accumulate in the lower intertidal zone where sufficient oxygen circulated through the pore spaces and allowed the grains to retain their tan color. As sea level continued to rise, sediments were submerged into a marine phreatic state where reducing conditions caused a color change in the grains from tan to gray. The sediments continued to accumulate in this way outpacing and building up to sea level creating the southern sand flat. A bedrock gradient in which the northern portion is one meter deeper than the south resulted in the northern half remaining subtidal. The aggregate/aragonite-rich " grainstone" facies found in the sand flat is caused by an abundance of aggregates formed *in situ*. The sand flat is rarely flooded, therefore evaporation and subsequent precipitation of aragonite caused surficial sediments in the sand flat to be cemented together and have high concentrations of aragonite.

Nine radiocarbon dates of bulk sediment and basal peat from two southern cores indicate the sequence is in stratigraphic order and began approximately 4700 ybp. Rates of sediment accumulation range between 58.5 cm/1000 yrs and 157 cm/1000 yrs.

INTRODUCTION

High and low-energy lagoons are common to modern carbonate settings and there should be abundant counterparts in the geologic record. Their recognition in the rock and sediment record is important not only because of volumetric concerns, but also because they can provide information useful in interpreting the surrounding lithologies and depositional environments. In general, a lagoon may be considered as a shallow body of water, partially or completely isolated from open oceanic conditions by a barrier system (for example, a reef, sill, or island; Reijers and Hsu, 1986). The depositional environment is controlled by chemical (salinity), physical (water temperature, depth, energy

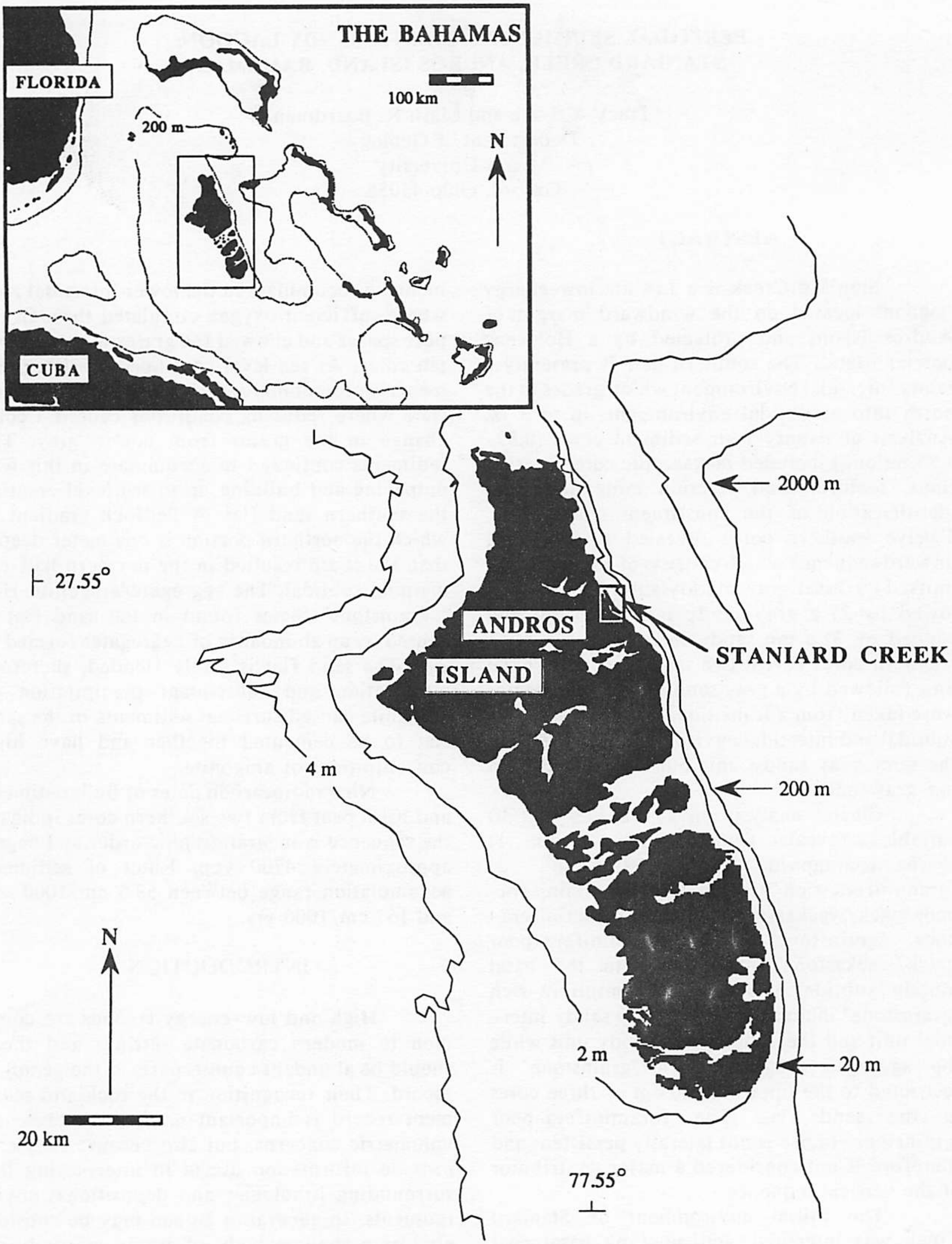

Figure 1. Location of Staniard Creek on Andros Island Bahamas.

conditions, antecedent topography) and biological (benthic communities) parameters (Till, 1970; Colby and Boardman, 1989; Tucker and Wright, 1990).

Lagoons are diverse; yet the term "lagoon" has become synonymous with the very protected, low-energy, muddy type (e.g. Florida Bay, Bimini Lagoon, Bight of Abaco). Sediments from the muddy lagoon are well preserved, and are the focus of many studies (Enos, 1977; Till, 1970; Boardman, 1976; Wanless, 1990), however, few studies have concentrated on the sandy lagoon (high or low-energy) and understanding its mode of deposition.

Lagoon Sequences and Recognition Criteria

The ideal shallowing upward sequence is comprised of four zones: a basal transgressive unit, a subtidal unit, an intertidal unit and the supratidal unit which may be missing (James, 1984; Laporte, 1967). A deepening upward sequence would consist of a basal lag followed by an intertidal unit and capped with a subtidal unit (Fischer, 1965). In both cases, the intertidal zone appears to be the most recognizable because it contains features such as algal mats, laminoid fenestrae, cryptalgal laminations and desiccation polygons that are not found in other zones and that are typically preserved in muddy environments (James, 1984). For example, Fischer (1965) interpreted the Lofer cyclothems as a deepening upward sequence because he was able to identify as intertidal environment based on algal mats and shrinkage structures of muddy sediments. This allowed the identification and interpretation of the overlying unit as subtidal which contained a richer biota and oncolites instead of stromatolitic algal mats.

Likewise, in the Purbeckian carbonates of the Swiss and French Jura mountains, Strasser (1988) identified six types of small scale shallowing upward sequences. One sequence (type A) was "more or less restricted lagoonal sediments" that had a shallowing upwards tendency. This is indicated by birdseyes and desiccation fissures caused by exposure in the upper intertidal to supratidal zones of the lagoon. Similar features are found in his type D sequence representing a tidal flat environment comprised of mudstones and wackestones. Abundant birdseyes, algal laminations, mudcracks and desiccation polygons are all common features.

The identification and interpretation of shallow marine sequences are important; however, incorrect or incomplete interpretations will be made unless recognition criteria are available for all the associated facies, not just for intertidal muddy sediments. Therefore, one question is obvious: how are shallowing upward (deepening upward) sequences recognized in the sandy lagoonal environment if there are virtually no criteria to distinguish one sediment package from another? The purpose of this paper is twofold. First, it describes the facies and discusses the history of sedimentation in Staniard Creek because Staniard is an example of a low-energy sandy lagoon. Second, it provides a modern analog of a sandy sedimentary sequence which is difficult to interpret because unique, diagnostic criteria are absent.

STUDY AREA DESCRIPTION

Andros Island

Andros island is the largest island in the Bahamas (Fig. 1A) and is comprised of oolite sand and dune deposits, peloidal grainstones and reefal boundstones (Gebelein, 1974; Boardman, *et al*, in press). It also has little relief except for Morgan's Bluff located on the northeastern corner of the island which is over 20 m. Temperature of the surface waters range between 22°C in February to 31°C in August (Gebelein, 1974). Winds are from the east travelling between 5-10 knots and the tidal range is a little less than 0.75 m. Salinity on the Great Bahama Bank (leeward or west of Andros) fluctuates seasonally where lower salinities occur during the winter months (Gebelein, 1974). On the windward side (east) of Andros, salinities are normal marine.

Staniard Creek

Staniard Creek is a 1 x 4 km low energy "lagoon" located on the windward east margin of Andros Island, and is protected by a Holocene barrier island (Figs. 1, 2A). The southern half is an intertidal sand flat, and contains a small ebb-tidal delta. It changes gradually to the north into a subtidal environment containing tidal channels as well as a flood and ebb tidal delta. Small Pleistocene islands are found to the west; while mangrove thickets bound the east and west (Fig. 2A). Staniard Creek has two primary depocenters, one in the north and one in the south that are separated by a plateau that is 1-2 m

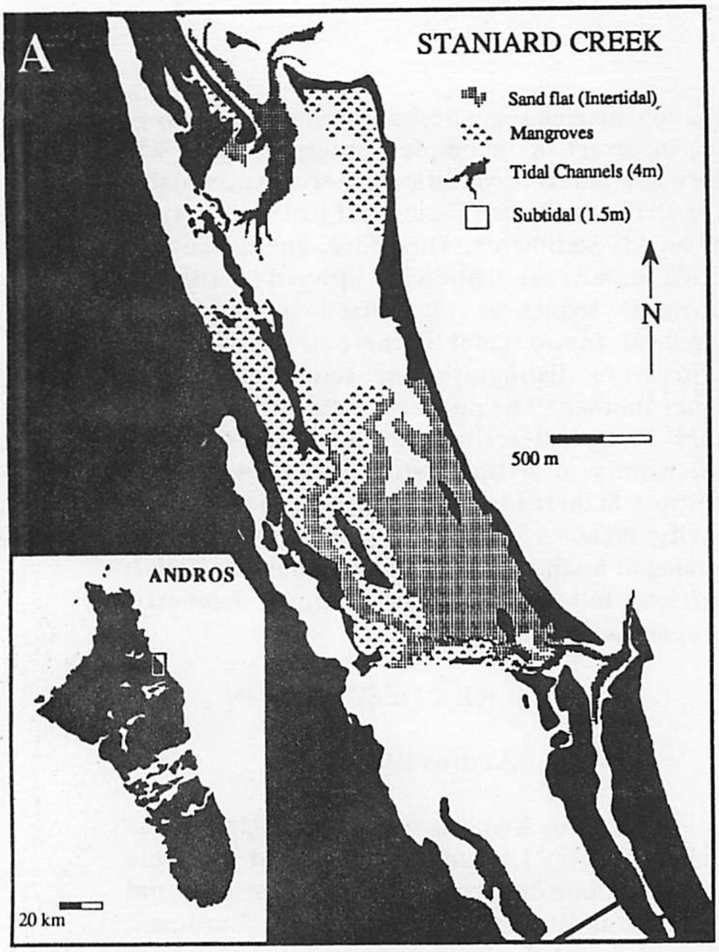

Figure 2A. Benthic description of Staniard Creek.

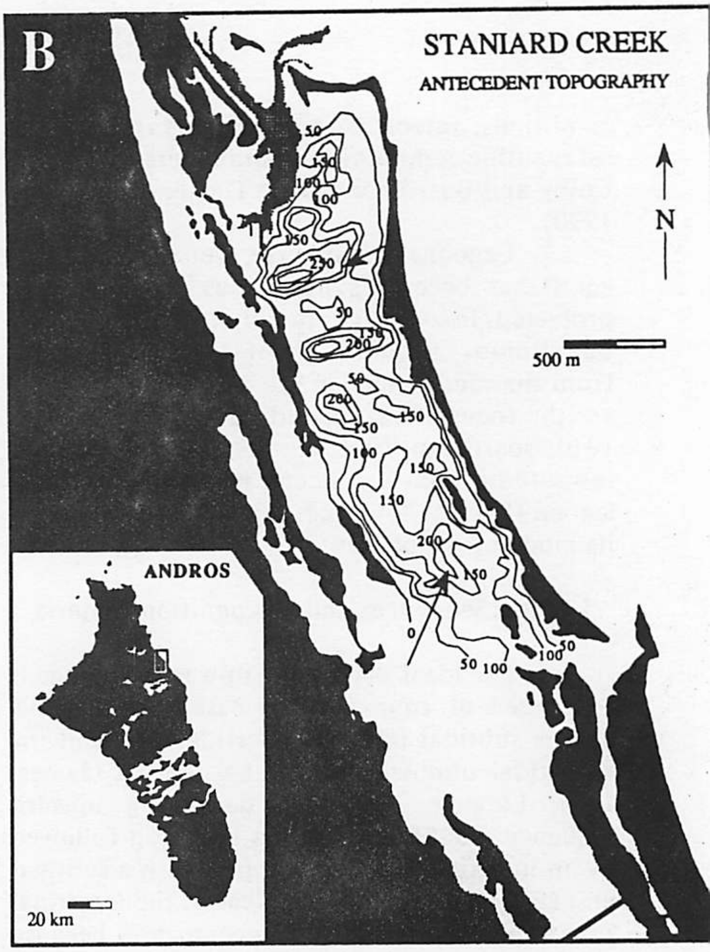

Figure 2B. Antecedent topography of Staniard Creek. Contour interval = 0.5 m. Note that there are two major depocenters (shown by the black arrows) separated by a plateau containing several smaller basins. Note also that there is a slight bedrock gradient in the lagoon where the basins in the northern half are deeper than the southern basin by approximately 1 meter.

higher (Fig.2B). It also contains several smaller or secondary depocenters that are located in the middle of the lagoon (Fig.2B). The southern basin is shallower than the northern basin by one meter indicating the presence of a slight gradient. Sediment thicknesses range from 0 m (on the sides of the lagoon) to over 2 m in the northwestern and southwestern portions of the lagoon (Fig. 2C). Water depths range from 0 m (on the banks of the barrier island and the western islands) to over 3 m in the tidal channels.

The southern intertidal section has a thin (≈1 cm)tan algal mat covering tan sand;however, behind the western islands in the south, the algal mat covers a very dark gray almost black sand. There is no vegetation cover in the sand flat except for mangroves to the west. A transitional area is located between the southern intertidal sand flat and the northern subtidal region. This transitional area is characterized by the same algal mat covering the south; however, the surficial sediment is a mixture of gray and tan sand. Portions of the northern subtidal section are very shallow (≈ 0.5 m in some areas during high tide). The sediments throughout the north are mounded (up to 40 cm),and also have a thin tan to gray algal mat cover which is very prominent in areas directly adjacent the barrier island. There is very little vegetation (excluding mangroves) in the northern section. *Thalassia* and *Batophora* are sparse (147 blades/m^2 and 93 plants/m^2 respectively) in the transitional area but increase in abundance (640 blades/m^2 and 623 plants/m^2 respectively) in areas directly adjacent or close (e.g. along transect 4; Fig. 2D) to the tidal channel. The tips of the *Thalassia* blades are burned due to periodic emergence. Calcareous green algae (*Halimeda*, *Penicillus*, *Rhipocephalus* and *Udotea*) are also very sparse in the interior of the lagoon (0, 17.6, 0, and 0 plants/m^2 respectively), however, they too become more abundant in the northern tidal

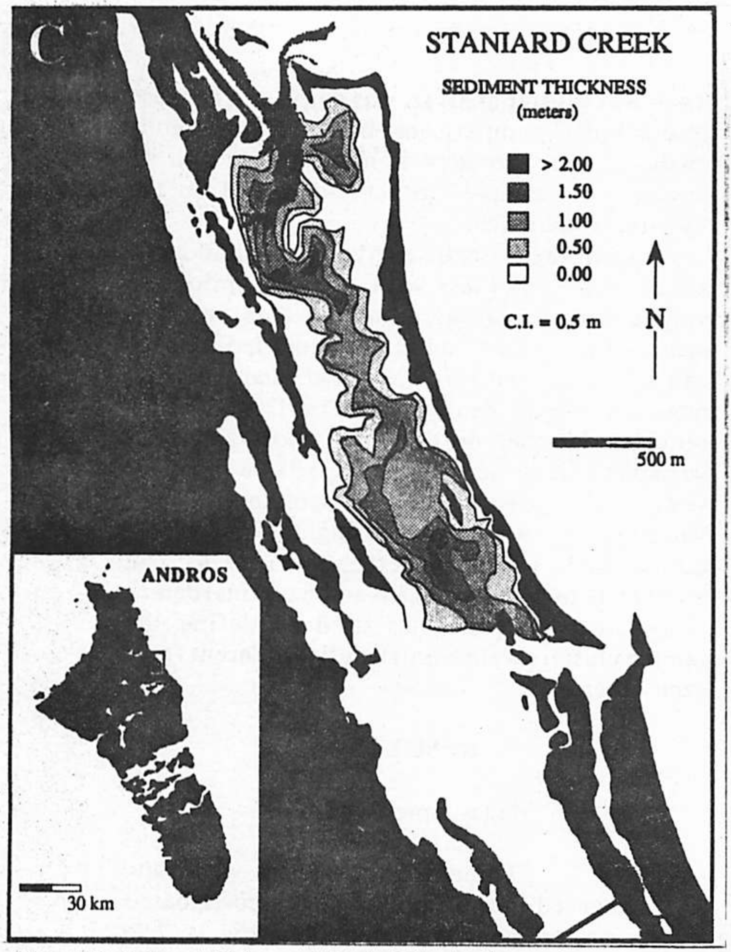

Figure 2C. Sediment thickness of Staniard Creek. Contour interval = 0.5 m.

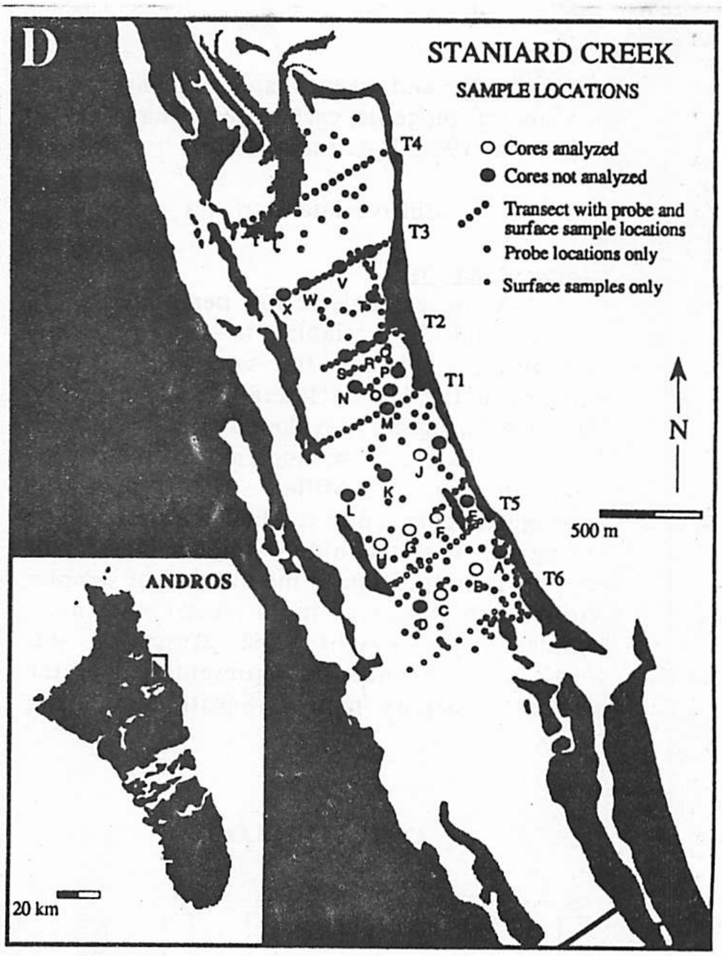

Figure 2D. Sample locations. Large open circles represent cores that have been sampled and analyzed. Large closed circles are cores that have been described megascopically only. Small closed circles represent probe locations and small open circles represent surface samples only. T1-T6 are transects taken from northeast to northwest at a 240 degree bearing.

channel at the mouth of the lagoon. The southern tidal channel was not examined.

METHODS

Field

Twenty-four sediment cores and 78 surface samples (Fig. 2D) were collected in seven transects throughout Staniard Creek. Of the seven transects, four were in the north where a vegetation census was conducted. Sediment thicknesses were determined using a probe rod.

Laboratory

Each core was cut and described megascopically. To date, only six cores, taken from the southern portion of the lagoon have been sampled and analyzed for extensive analyses. One half of each core was sampled at 10 cm intervals for a total of 78 samples used in sedimentary analyses. All samples were soaked in a 50% Clorox™ solution to remove the organics which may bind sediments then rinsed three times in pH 9 water to remove the Clorox™. Standard wet sieving procedures were employed at one phi intervals between 4 mm and 0.625 mm to evaluate the texture of the sediments. Pipette analysis on the mud produced $\leq 62\mu m$, $\leq 16\mu m$ and $\leq 4\mu m$ size fractions.

Sediment composition was determined by identifying at least 300 grains in the 1-2 mm size fraction from each of the 78 samples. This size fraction was chosen because it contained at least 300 recognizable grains. Size fractions less than 1-2 mm also have 300 grains, but in Staniard Creek they are usually too abraded to identify. Size fractions greater than 1-2 mm have recognizable grains but frequently, there is less than 300 gains.

Mud fraction mineralogy was determined by X-ray diffraction on a Phillips XRG-3000 x-ray diffractometer using Cu-Kα radiation. The % aragonite was determined using the peak areas of aragonite and calcite and compared to a mixture of biogenic carbonates (Chave, 1954; Neumann, 1965; Boardman, 1976).

Multivariate Statistics

Cluster Analysis.

A cluster analysis was performed on 78 samples and 10 variables to determine any relationships between the samples and their location in the lagoon laterally and vertically. The CLAP program (developed by J.J. Sepkoski, Jr. and J. Sharry, 1976; modified for the microcomputer by A. Miller, 1988) uses the unweighted pair group method with arithmetic averaging. This technique weights clusters of samples in proportion to the number of samples within each cluster giving a cluster with more samples more weight. The effect of this weighing is an unbiased representation of the original similarity matrix (Sneath and Sokal, 1973).

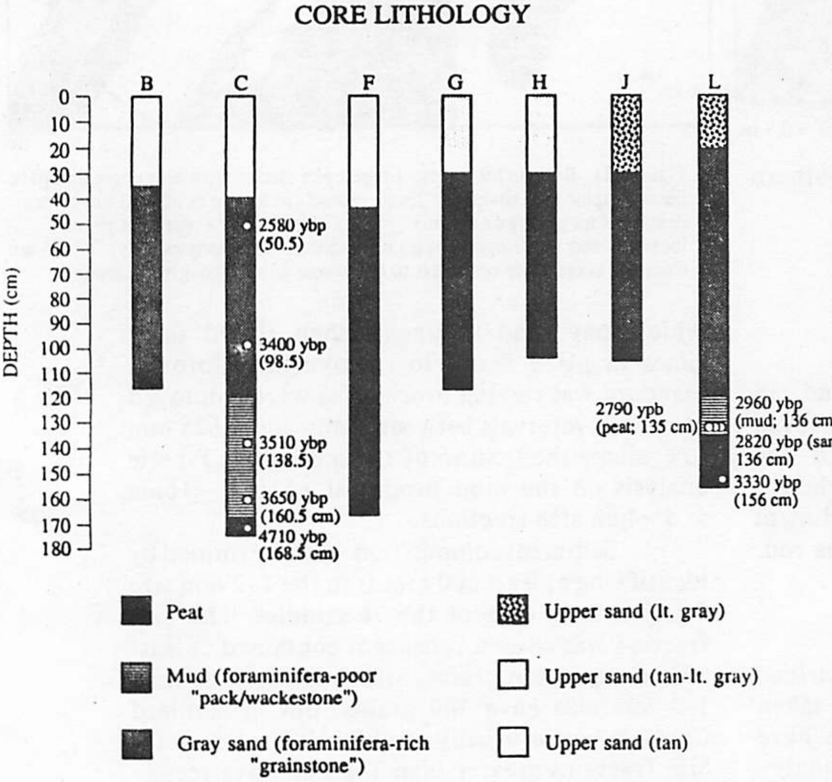

Figure 3. Lithology of seven southern cores. All cores except core L were sampled and analyzed. The upper sand unit is found only in the southern sand flat area. It varies in color becoming more gray toward the northern subtidal portion.

Two-way cluster analysis was employed because it combines comparisons by Q and R-mode analyses and provides a means in which to separate the samples into facies based on the variable abundance.

For the Q-mode analysis, raw abundances of the variables with the exception of aragonite and mud were converted to percentages. Aragonite and mud are recorded as percentages, and therefore did not need any adjustments. R-mode analysis was performed on a reduced data set of the eight most abundant variables which accounted for ≥98 % of every sample. Comparisons on the samples (Q) and variables (R) were made using the quantified Czekanowski's coefficient (Sepkoski, 1974). The Student T-test (independent comparisons) determined that the variables used to define the sample clusters were significantly different from each other.

RESULTS

Megascopic Results

Three distinct units were observed in the Staniard Creek cores based on sediment type and color (Fig.3). The basal unit is a gray mud overlying peat layers or bed-rock fragments. Mud that is directly over the peat is sometimes stained brown and frequently has peat strands scattered throughout. The mud grades upward into a muddy sand. Overlying the mud and the muddy sand is a medium-grained, gray sand unit. It is abundant in foraminifera, gastropods (*Cerithid*, *Bulla* and *Batalaria*) and bivalves (*Codakia*). The sequence is capped by a medium-grained tan sand unit which differs from the underlying gray sand only in color.

Cluster Analysis Results

Four groups were identified in the Staniard Creek cores based on cluster analysis (Fig.4) and are considered sedimentary facies. The groups identified are 1) the foraminifera-poor "pack/wackestone", 2) the foraminifera-rich "grainstone", 3) the aggregate-aragonite "grainstone", and 4) the

Table 1. **Staniard Creek : means and standard deviations of variables for each of the four facies**

FACIES	Foraminifera-rich "grainstone"		Aggregate/ Aragonite-rich "grainstone"		Foraminifera-poor-"pack/ wackestone"		Foraminifera-poor "grainstone"	
Variables	mean	std. dev	mean	std. dev	mean	std. dev	mean	std. dev
Foraminifera	42.2	6.9	27.6	10.4	13.3	1.3	19.7	18.5
Gastropods	16.4	7.4	10.5	7.7	15.3	5.4	22.0	11.3
Bivalves	7.3	2.3	5.7	1.8	14.3	4.6	17.1	8.7
Halimeda	10.4	5.2	11.4	3.7	13.2	6.6	13.0	8.4
Aggregates	8.2	4.0	17.1	7.3	4.0	1.9	8.6	7.3
Abraded Grains	4.3	2.4	7.6	2.1	4.3	2.0	4.5	0.5
Mollusc Fragments	6.4	2.5	4.4	2.1	9.4	2.7	9.3	4.4
% Mud	7.2	4.9	11.3	11.3	6.7	3.3	51.3	25.0
% Aragonite < 62 um	55.3	9.2	68.0	5.4	54.0	3.6	24.3	18.6
% Aragonite < 4 um	41.1	11.6	62.0	8.2	36.1	9.2	53.2	1.6

foraminifera-poor "grainstone" which can be compared on a gross scale with the units identified from megascopic descriptions. The foraminifera-poor "pack/wackestone" facies corresponds to the basal gray muddy sand unit, the foraminifera-rich "grainstone" facies to the fine-grained gray sand as well as the fine-grained tan sand while the aggregate-aragonite "grainstone" facies represents an overprinting on portions of the tan sand unit. The foraminifera-poor "grainstone" facies is not laterally persistent occurring only in one core, therefore, it is not considered as a major contributor of the vertical sequence. The textural names assigned to the three clusters were based on each clusters relative abundance of the variables (Table. 1). Quotation marks are used for textural names because they were defined for lithified sediments. The Student T-test confirmed that the variables used to define the clusters are significantly different from each other.

Facies Description and Distribution

Basal unit/Foraminifera-poor "pack/wackestone" facies.

The majority of the samples in this group are comprised of samples from the bottom of core C (Fig. 4), the only core of those analyzed by the cluster analysis to have a muddy base. Basal samples from other cores are also included in this facies, but they are not muddy. This facies occurs in very few places in the lagoon and there is no geographical preference for its accumulation (C, D, L and W; Fig. 2B). Based on the four cores, three of which are the longest in the data set, and the deepest probe depths, the foraminifera-poor "pack/wackestone" faces is found where the depth to bedrock is the greatest (Fig. 2C).

There is approximately 85% mud at the base of the facies decreasing to 30 % at the top (Fig. 5). The sand-sized particles are comprised of gastropods (28%), bivalves (22%), foraminifera (15%), *Halimeda* (9%) and aggregates (8%). Aragonite is the most dominant mineral in Staniard Creek muds and averages 54% for both the silt-sized and clay-sized fractions in this facies (Table 1). At the base of the facies, aragonite ranges between 25 and 30% of the mud but increases to 70% at the top of this basal facies.

There are no features such as mudcracks which are indicative of intertidal conditions or fenestrae, indicative of supratidal and occasionally subtidal conditions. Sedimentary laminations, another indicator of the intertidal or supratidal zone, are also lacking perhaps due to the homogenization of the sediments (Shinn, 1983).

Tan and Gray sandy units/Foraminifera-rich "grainstone" facies.

Unlike the muddy unit, the foraminifera-rich "grainstone" facies occurs everywhere in Staniard Creek. It dominates the lagoon both vertically and laterally. This dominance is illustrated through cluster analysis where approximately 2/3 of all the samples are grouped in this facies (Fig. 4). Its thickness ranges between 1 m and 1.5 m. The sediments are gray, medium sized (0.33 mm) and poorly

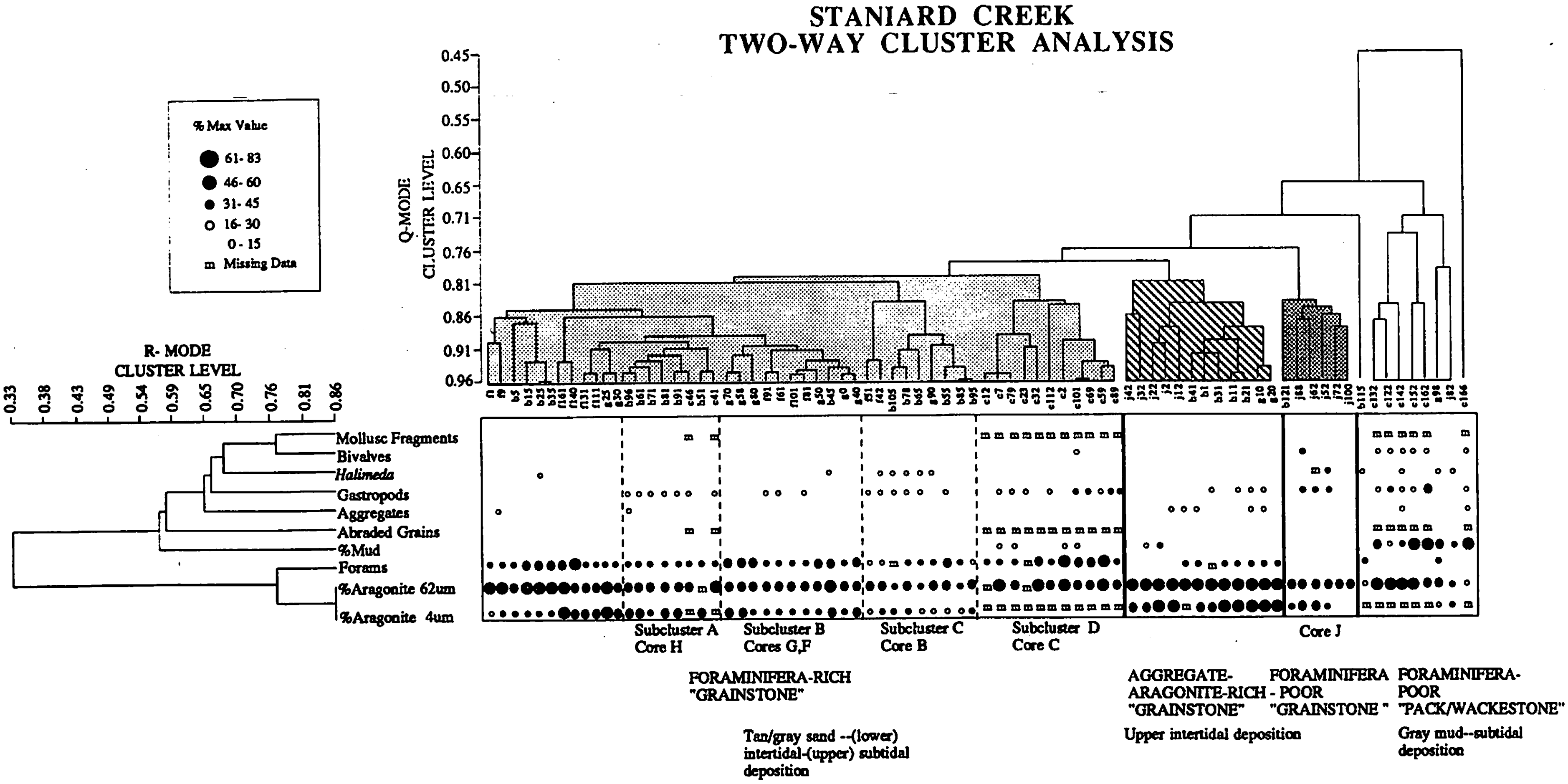

Figure 4. Two-way cluster analysis of Staniard Creek southern core samples. Sample names (Q-mode) are the core and depth of sample in cm. Subclusters are dominated primarily by samples of one core indicating although there are no statistical differences between the samples, there are lateral changes between the cores.

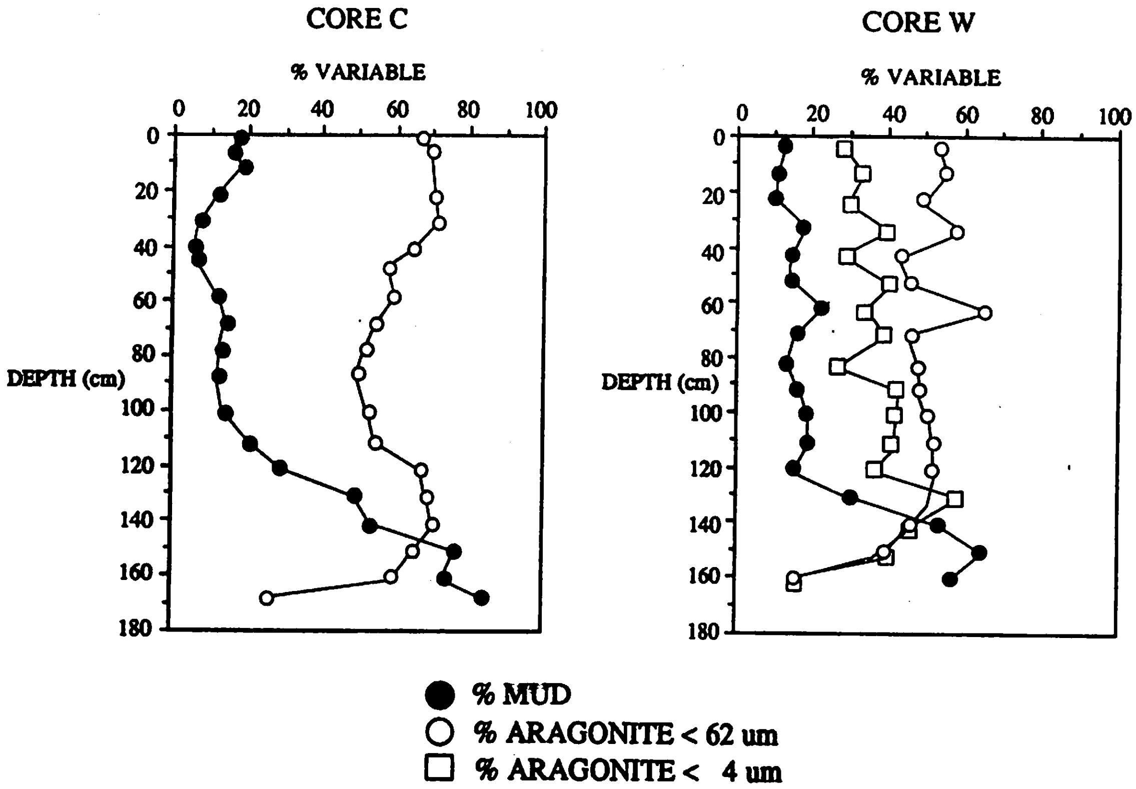

Figure 5. Abundance of selected variables from a southern core (C) and a northern core (W). Note that in both cores, the concentration of aragonite is very low at depths between 160 and 170 cm. Also note that as the depth decreases, the aragonite increases sharply.

sorted (mean Φ = 1.62). The skeletal components of this facies are dominated by foraminifera (avg. = 43%; Table 1). There is very little mud (generally <10%). The mineralogy of the mud however is very similar to the muddy basal unit and differs slightly by a small decrease of aragonite in the clay sized fraction. The foraminifera-rich "grainstone" facies shows no obvious features characteristic of individual depositional environments.

Aggregate-Aragonite-rich "grainstone" facies.

This facies is found only in the southern intertidal sand flat. Cluster analysis shows that it is comprised of samples found in the upper 30-40 cm of the sediment in three cores. The sediments are tan to light gray, fine to medium grained (0.22 mm) and very poorly sorted (mean Φ = 2.19). Although foraminifera are abundant in this facies, their abundance is significantly lower (avg.= 27%; Table 1) than the underlying sandy unit. The aggregate abundance doubled from 8% to 17% and the aragonite concentration in the mud has increased to 63%.

This facies is the only one to show any features characteristic of its depositional environment. The tan or light gray color is indicative of oxidizing conditions in the upper intertidal zones as is an algal mat cover. The algal cover extends over the entire southern sand flat and into shallow portions of the northern subtidal area.

Foraminifera-poor "grainstone" facies.

This facies occurs at the base of two cores (B and J), but is most prominent in core J (Fig. 4). It has gray medium grained sediments (0.24 mm) and is poorly sorted (mean Φ = 1.26). It differs from the foraminifera-poor "pack/wackestone" facies only by the lack of mud (7% vs 51%). In all other respects, there is no statistical difference between the two facies. Because it occurs very sporadically in the lagoon and cannot be associated with a megascopic unit, it has not been considered an integral part of the vertical sequence.

DISCUSSION

History of Sedimentation

Peat/Soil Deposition.

The presence of basal peat over bedrock in six cores (C, D, F, G, L, W; Fig. 2D) shows that the initial environment of Staniard Creek was intertidal (Fig. 6A). The peat accumulated only in pockets where it was preserved from erosion by waves and currents (Wanless, 1974). Peat from core C contained boehmite, a mineral

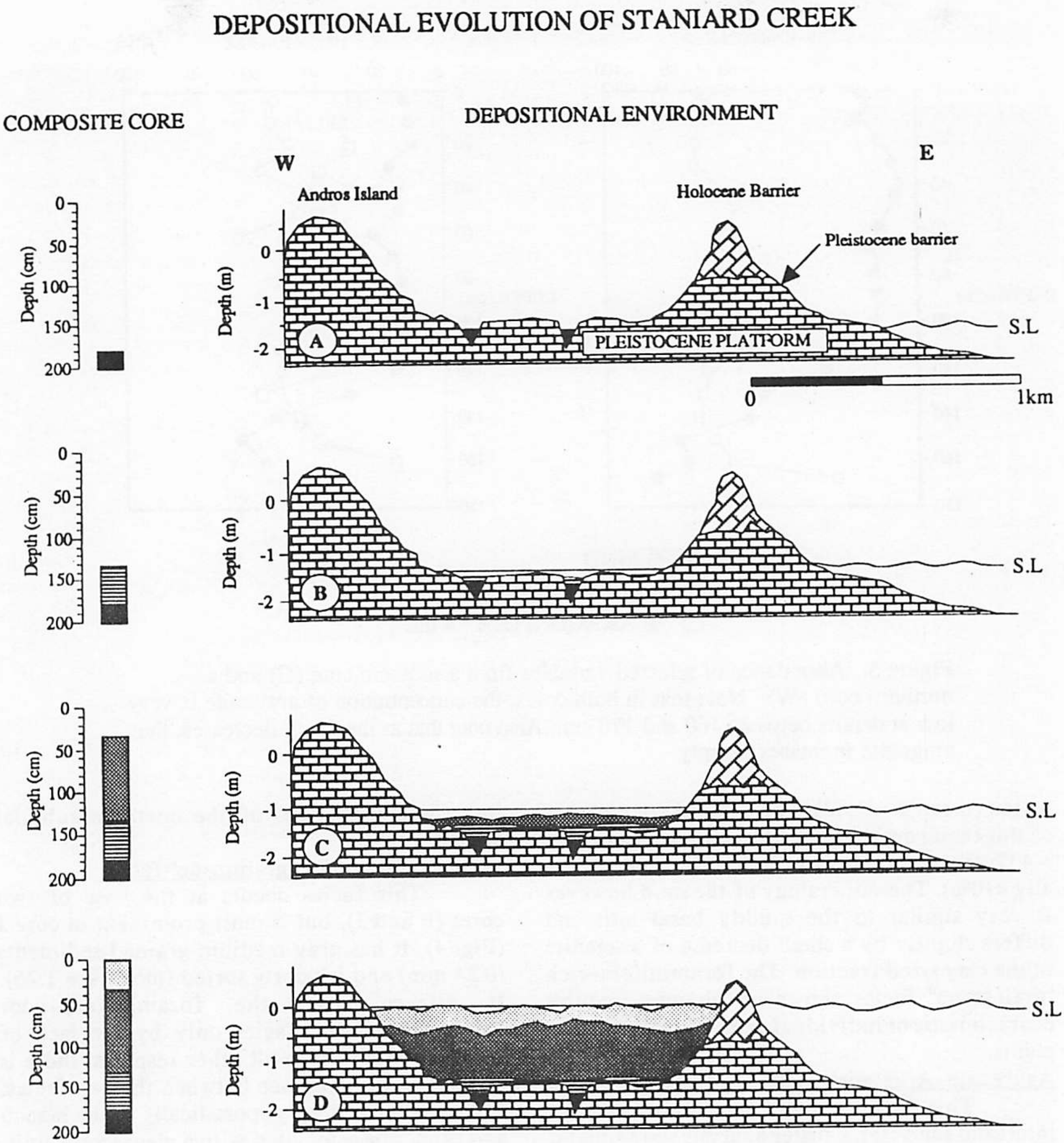

Figure 6. The depositional evolution of Staniard Creek. A) 4700 ybp (4710 - 3330). Sea level is approximately 1.7 m below present and peat is accumulating in localized pockets. B) 3700 ybp. A slowly rising sea level floods the platform and is approximately 1.50 m below present. Mud (foraminifera-poor "pack/wackestone" facies) begins to accumulate in the subtidal environment and is deposited in localized pockets containing peat. C) 3500 ybp. Sea level continues to rise slowly and is approximately 1.20 m below present. The gray portion of the foraminifera-rich "grainstone" is being deposited in the lower intertidal environment. D) 1800 ybp. Sea level is now approximately 0.4 m below present. The tan portion of the foraminifera-rich "grainstone" is accumulating in the upper intertidal environment. Prolonged exposure causes precipitation of aragonite which cements the sediments in portions of the lagoon. The result is an abundance of aggregates and high concentrations of aragonite in the sand flat.

usually found in highly weathered, leached soil (Bear, 1964). Its presence suggests subaerial soil formation prior to sedimentation (Ahmad and Jones, 1966; Isophording, 1974). Radiocarbon dates of basal peat in cores C 4710 ybp (at 168.5 cm) and L 3330 ybp (at 156 cm) indicate the approximate time of submergence by sea level.

Subtidal Early Marine Mud Deposition (foraminifera-poor "pack/wackestone").

In Staniard Creek, mud is always found with peat. The presence of a thick (40-60 cm) muddy unit only found overlying peat suggests that during the Holocene sea level rise mud accumulation was not a widespread occurrence but restricted to localized pockets and preserved with peat (Fig. 6B). Radiocarbon dates of bulk sediment (sand and mud) taken from the early marine mud in cores C and L were plotted against a Bahamas sea-level curve (Boardman, *et al*, 1989; Fig.7). The points lie beneath the best fit line and indicate that the muddy facies was deposited in a shallow (0.5 m) subtidal environment approximately 3700 ybp.

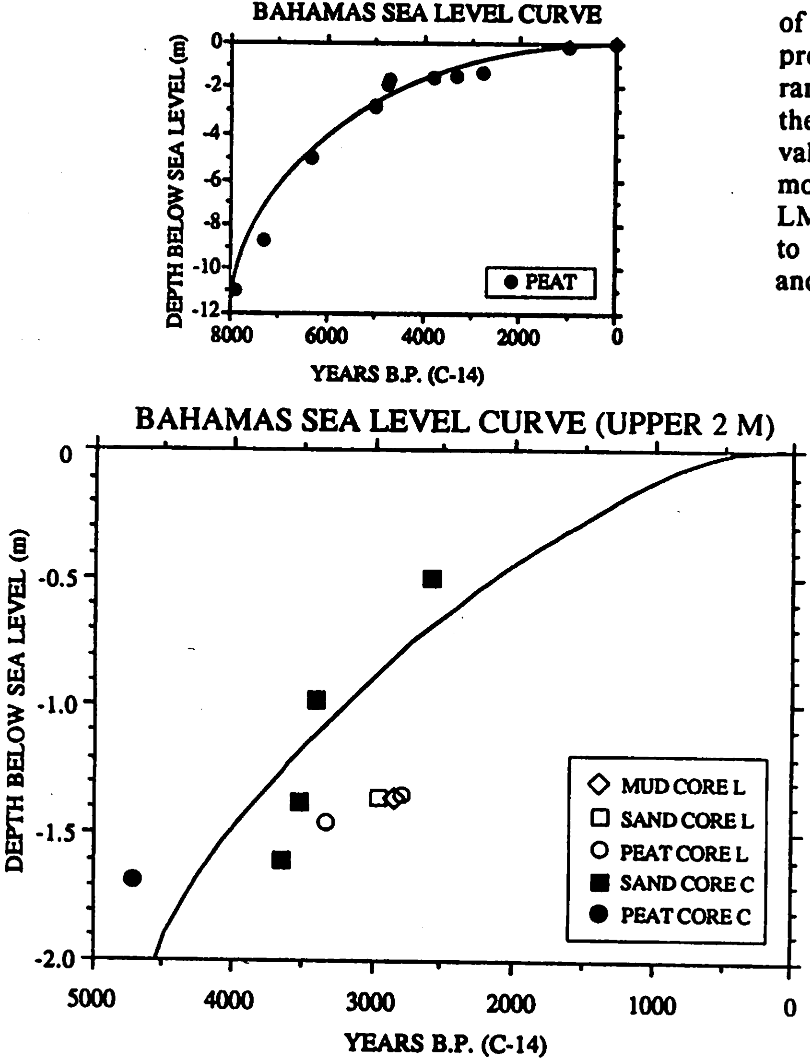

Figure 7. Bahamas Sea level curve based on Boardman et al (1987). Peat samples from Andros Island, Bight of Abaco and San Salvador were taken from bedrock.

The mineralogy of the mud in core C and preliminary results from a northern core (W) suggest that at the onset of mud accumulation, there was inorganic precipitation or erosion of the underlying Pleistocene limestone. Aragonite concentrations in the mud fraction of these basal samples are very low for basal samples from both cores (25% and 15% for C and W respectively) leaving high-magnesium (HMC) and low-magnesium calcite (LMC) to make up the remainder of the mud. Because the radiocarbon dates are reasonable for this depth and facies, it is unlikely that significant quantities of Pleistocene calcite are in the mud. If Pleistocene calcite were present in appreciable amounts, the C-14 date would be older. The only other source of calcite are foraminifera which were very low in abundance during this time (17% at the base of core W and 0% at the base of core C); thus, the origin of the carbonate is more likely to be a result of precipitation. The mole % $MgCO_3$ in the mud ranges between 8 and 9% depending on whether the mud is silt or clay sized (Fig. 8A, B). These values may be a mixture between forams (13.5 mole % $MgCO_3$) despite their low abundance and LMC (4 mole % $MgCO_3$). As sea-level continued to rise, the lagoon was flooded with sea-water and the change in the mud origin is reflected in the sharp increase in the aragonite concentration (Fig.5) and the mole % $MgCO_3$ to 15.0. A rate of sediment accumulation for the foraminifera-poor "pack/wackestone" is 157 cm/1000 yrs.

Lower Intertidal/Upper Subtidal Sand Deposition (foraminifera-rich "grainstone")

Radiocarbon dates of bulk sand from two southern cores were plotted against the Bahamas sealevel curve and indicate that the southern half of Staniard Creek was intertidal during the deposition of the foraminifera-rich "grainstone" facies (Fig. 6C). Samples from the northern cores have not yet been dated. Because the foraminifera-rich "grainstone" facies dominates the lagoon both vertically and laterally, the conclusion is that Staniard Creek was intertidal to shallow subtidal keeping up with sea-level rise throughout most of its development. Rates of

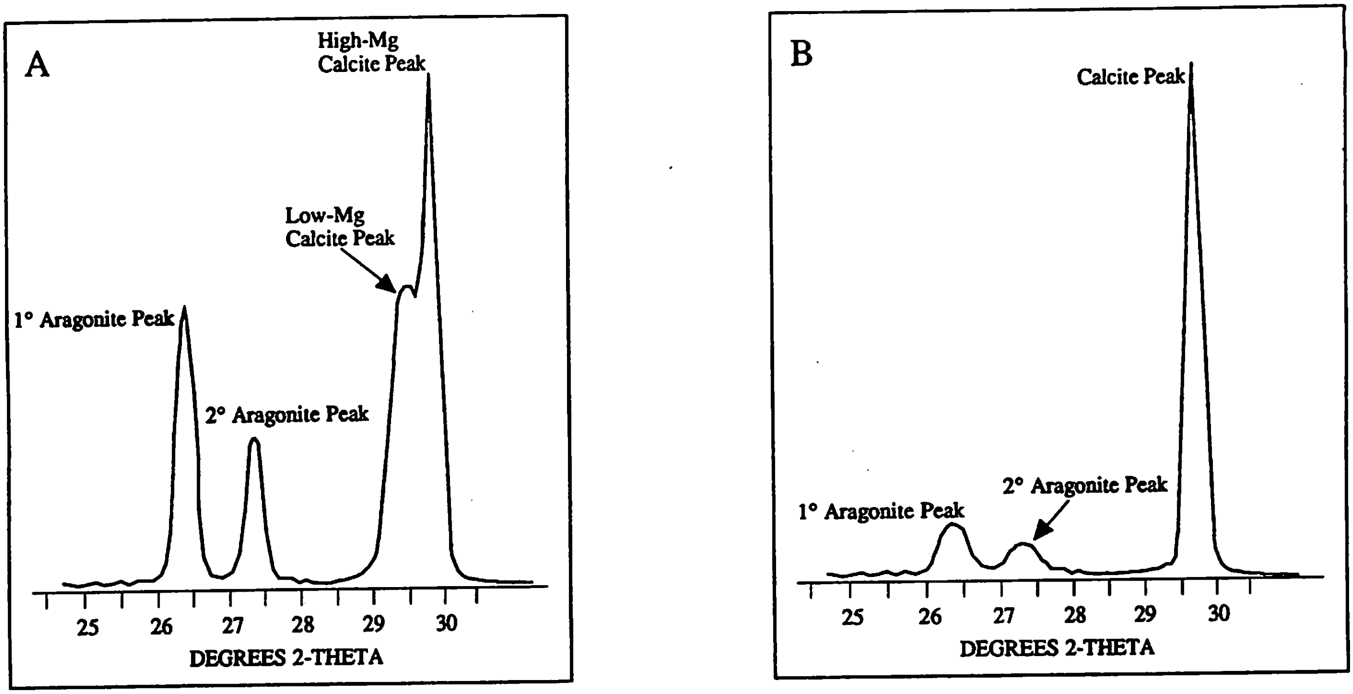

Figure 8 A). X-ray diffraction pattern of a typical sample from Staniard Creek. The average mole % MgCO3 is 13.9. B). X-ray diffraction pattern of a sample from core W taken at 163 cm. The average mole % MgCO3 for this sample is 8.75 and the aragonite concentrations are very low (avg = 15.00%). It is obvious that the chemistry of the depositional environment at the onset of sedimentation was different from any other time in the lagoon's history.

sedimentation for the foraminifera-rich "grainstone" facies is 58.5 cm/1000 yrs. The last rate is obviously extremely high (higher than the rate of rise of sea level which is 60 cm/1000 yrs; Boardman *et al*, 1987) and may result from mixing older sand with younger sand. This is an indication of the necessity for many C-14 dates to be chosen carefully.

Cluster analysis indicates that the upper tan sand and the underlying gray sand are not different. The cluster diagram (Fig. 4) shows the upper 30-40 cm of cores containing only tan sand (B,C,G,F; Fig. 2D) clustered with those samples containing gray sand. In other words, there is no statistical difference between the two types of sand, and perhaps they were deposited as one unit. One possibility is that sufficient oxygen circulating through the pore spaces allowed the sediments to maintain their original tan color. As sea-level continued to rise, the pore spaces in the underlying sediments became saturated with marine water which enhanced reducing conditions and turned the tan sediments gray. Because there is a bedrock gradient in Staniard Creek in which the northern section is slightly deeper than the south, the southern half was able to build up to and keep up with sea-level while the northern half remained in the upper subtidal zone or "gave up". As a result, the foraminifera-rich "grainstone" in the northern half of the lagoon always remained gray. This explanation does not however explain why the gray sands do not have as high an abundance of aggregates and as high a concentration of aragonite.

Mineralogy of mud-size fractions is very important in evaluating facies because it gives information about skeletal breakdown and its distribution and (Enos, 1977; Boardman, 1978; Andersen, 1988). Studies have shown that calcareous green algae such as *Halimeda, Penicillus, Rhipocephalus* and *Udotea* all contribute significantly to aragonite mud (Stockman, *et al*, 1967; Neumann and Land, 1975). *Halimeda* contains the most calcium carbonate (97%) based on the percentage of dry weight of the entire plant, while *Penicillus* and *Rhipocephalus* contain 60% and *Udotea* 37% (Bohm, 1973; Wray, 1977). Additional studies have shown that epibionts on *Thalassia* (largely comprised of HMC) also contribute to carbonate mud production (Land, 1970; Patriquin, 1972) and can produce more material than calcareous green algae (Nelson and Ginsburg, 1986). Table 1 shows the aragonite concentration of the silt-sized fraction in the foraminifera-rich "grainstone" facies averages 55% while the clay sized fraction is 41%. Although the breakdown of foraminifera is not well documented, their abundance in the sand fraction (43%) suggests that these high-magnesium calcite producers are able to break down into the mud-sized fractions thus decreasing the aragonite concentration.

Foraminifera are a large part of the sand fraction and their distribution may be related to seagrass density. Studies have shown foraminiferal diversity and density to be related to seagrass density (Brazier, 1975). Brazier (1975) cites an example from Abu Dhabi lagoon (Murray, 1970), where seagrass colonization enhanced foraminiferal diversity and standing crop of forams. In Buccoo Reef, Tobago, destruction of seagrass by storms decreased the diversity and standing crop (Brazier, 1975). In Staniard Creek, foraminiferal abundance is also related to seagrass density (Fig. 9); however, the relationship is not directly proportional which suggests there are additional parameters that affect the abundance of seagrass. Figure 9 shows the % forams increase as seagrass increases, but there is significant scatter in the data (r^2=0.4). In the transitional area (along transect 1; Fig. 2D), where *Thalassia* is sparse, foraminifera are abundant (48%). They are also abundant (43%) in areas where there is no seagrass cover (the sand flat). However, where *Thalassia* is more abundant, (along transect 4 and close to the northern tidal channel; Fig. 2D) foraminifera are most abundant (71%). Because foraminifera are able to proliferate in the absence of seagrass, perhaps these epibionts may be able to graze on an algal mat cover and do not need seagrass as a substrate.

Upper Intertidal Sand Deposition (Aggregate-Aragonite-rich "grainstone").

The increase in aragonite could be the result of precipitation coupled with a decrease in the foraminifera population. Because the sediments have built up to sea-level, the sand flat is now subject to prolonged exposure. Evaporation of sea-water supersaturated with respect to aragonite has probably led to precipitation. The latter explanation is more viable because the increase in aragonite concentration is seen in all the samples taken from cores in the sand flat.

Portions of the sand flat also have high percentages of aggregates. Because aggregates are usually found in areas of mobile sand (Imbrie and Purdy, 1962; Purdy, 1963; Windland and Matthews, 1974) their presence in the upper facies and surface samples of the sand flat suggest they have been transported from subtidal regions, possibly in front of the barrier island to the intertidal portions of the lagoon by storms or some other medium. The idea however does not explain why the northern subtidal portion of the lagoon has significantly fewer aggregates. An alternative explanation is that the aggregates in the sand flat are formed *in situ*. During prolonged exposure sufficient aragonite may precipitate to bind sand particles together. Where there are abundant aggregates, there is a high concentration of aragonite (Fig. 10), however, the converse is not true. Aggregates are abundant in only in the southwestern portion of the lagoon around cores G and H. Elsewhere in the sand flat, aggregates are low and are similar to concentrations in the northern subtidal area.

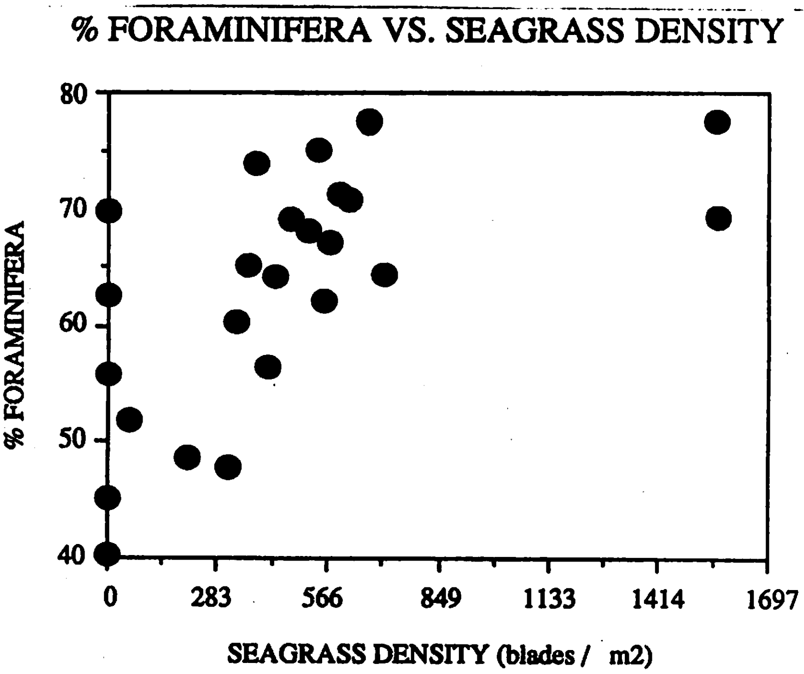

Figure 9. % foraminifera vs. seagrass density. As seagrass density increases slightly, the abundance of foraminfera also increases indicating there is a relationship between the two variables. There is significant scatter in the data; r-squared = 0.4, incating that the relationship is not one to one and that there are other parameters controlling the abundance of foraminfera. Seagrass density was measured by counting the number of blades in a circular plastic ring which had an area of 0.071 meter-squared.

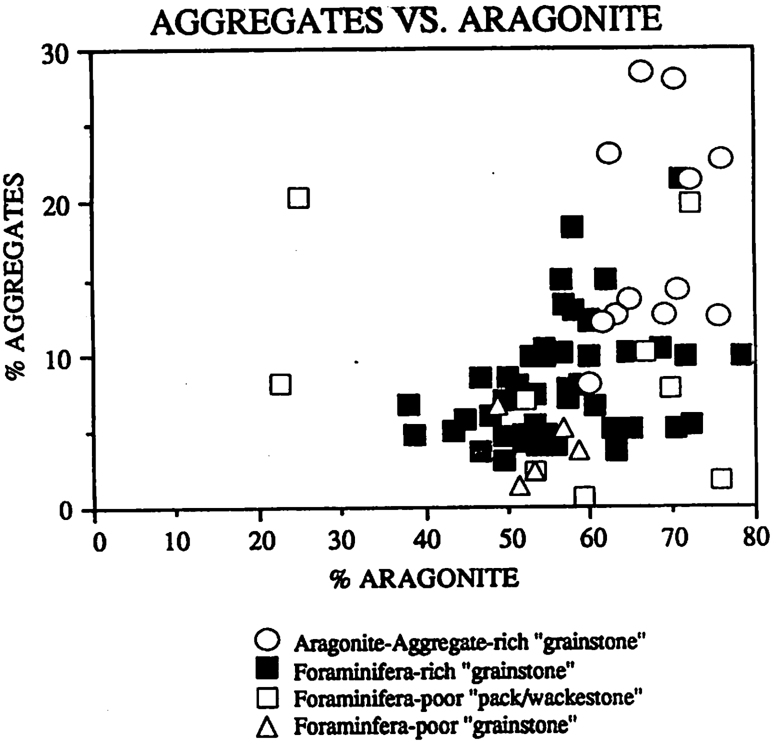

Figure 10. Graph of relationship between % aggregates and % aragonite from the four cluster facies. Note that as % aragonite increases, the % aggregates also increase. The more aggregates there are, the higher the aragonite concentration. The converse is not true because there is overlap between the facies where a significant proportion of aggregates are not present in highly concentrated areas of aragonite.

Rates of Deposition

Sediment accumulation rates and times for deposition were determined from radiocarbon dates on bulk sediment from core C and from a sand/mud couplet from core L. The mud dates probably give the most accurate values for *in situ* accumulation because age reversals are common in the sand size fraction where old sand can be permanently mixed in with younger sand (Colby and Boardman, 1989). Only the sand fractions in the facies of core C were dated and as a result, the rates of deposition for the foraminifera-rich "grainstone" are suspect.

The rates were calculated by dividing the difference between two dates by the thickness of the interval. A peat date from the base of core C (4710) indicates the sequence in Staniard Creek was deposited in approximately 4700 years. The rate of deposition for the foraminifera-poor "pack/wackestone" is 157 cm/1000 yrs and the rate of deposition for the foraminifera-rich "grainstone" facies in core C is 58.5 cm/1000 which is rate sufficient to "keep up" with sea level (Fig. 6). Because the gray, intertidal sandy facies was not dated in core L, a reasonable rate for the foraminifera-poor "pack/wackestone" was not calculated.

Recognizing Intertidal Units in Sandy Sediments

Depositional environments are very difficult to determine from sandy sediments when there are few diagnostic criteria. Features characteristic of a muddy intertidal zone such as desiccation polygons and birdseyes are not present in sand. Algal mats and diagnostic sedimentary laminations are infrequently preserved because of bioturbation (Shinn, 1983) or the lack of textural contrasts. The intertidal zone in Staniard Creek was identified by using radiocarbon dates and a sea-level curve. The dark gray sediments were used to indicate the subtidal environment, but it is possible that the gray sand are altered tan sediments.

Recognizing Shallowing Upward Sequences in Sandy Sediments

The difficulty of identifying sandy depositional environments is reflected in the misinterpretation of sequences without a clear indication between subtidal and intertidal units since they can be virtually indistinguishable (Shinn, 1983). An example of the misinterpretation of a sandy sequence in which there were no diagnostic criteria for intertidal sands is from Graham's Harbor, San Salvador. Colby and Boardman (1989) claim that the sequence found in Graham's Harbor lagoon is a shallowing upward sequence. Their data however contradict their interpretation. The sequence neither shallowed upward nor deepened upward.

The Graham's Harbor sequence is comprised of basal peat representing intertidal conditions followed by three sand facies none of which are intertidal. Colby and Boardman (1989) explain the lack of intertidal sands in the sequence by saying the lagoon has not had sufficient time to build up to sea-level. Nine radiocarbon couplet dates of sand and mud taken from varying depths in three cores from Graham's Harbor are plotted against the Bahamas sea-level curve (Fig. 11). All the points fall beneath the sea level curve indicating that Graham's Harbor was subtidal throughout its entire evolution. Also the surface of deposition at each core site never shallows up; it remains at approximately the same depth.

Graham's Harbor started with basal peat and was followed by a wackestone deposited in

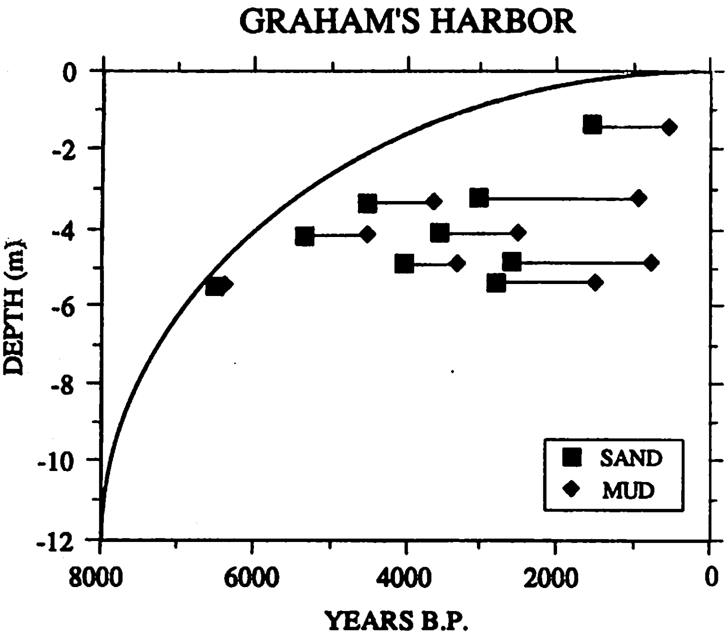

Figure 11. Radiocarbon dates of sand mud couplets taken from three cores at varying depths in Graham's Harbor are plotted against the Bahamas sea-level curve. Note that all the points plot below the best fit sea-level curve indicating subtidal conditions throughout Graham Harbor's evolution. Note also, there is little evidence to indicate a shallowing upward tendency.

low-energy silled conditions. It was followed by grainstone facies of aggregates and abraded grains. The lack of mud and higher percentages in the aggregates and abraded grains facies indicated higher energy conditions. Colby and Boardman (1989) then reviewed Strasser's (1988) type-A sequence. Strasser (1988) had a basal peloidal grainstone interpreted as washover deposits. The grainstones were followed by wackestones deposited in a quiet lagoonal setting which passed upward into high-energy ooid sands. Based on those similarities, Colby and Boardman (1989) interpreted their sediment package as shallowing upward; however, they neglected the fact that Strasser had interpreted his sequence based on the presence of birdseyes and desiccation fissures (features characteristic of an intertidal environment) which resulted from exposure of the lagoonal sediments. Even though it has been shown that features characteristic of intertidal environments are rarely preserved in modern settings, Colby and Boardman (1989) used another method, radiocarbon dates and the Bahamas sea-level curve, but still there is no conclusive evidence to warrant their interpretation of a shallowing upward sequence in Graham's Harbor.

Another example of misinterpretation of a sandy sequence is from Snow Bay, San Salvador. Andersen (1988) claimed that Snow Bay has shallowing upward regressive deposits, however, his interpretation is also not well supported by the data. In addition, he compares the Snow Bay sequence to James' (1984) hypothetical high-energy shallowing upward model which is doubtful.

The Snow Bay sequence is comprised of three facies which are represented by two cores: a basal transgressive sand of abraded grain "grapestone" overlain by regressive deposits of *Halimeda*-rich "pack/wackestone" and abraded grain "grainstone". Radiocarbon dates of samples from the two cores were plotted against the Bahamas sea-level curve and show that the *Halimeda*-rich "pack/wackestone" is not conclusively shallowing upward. The facies in core 5 deepens upward while shallowing upward in core 2 (Fig. 12). Although the *Halimeda*-rich "pack/wackestone" and the abraded grain "grainstone" facies show a shallowing upward tendency in core 2, the depth of the sample relative to the sea-level curve is ≤0.5 m in each case.This is not enough to conclude a shallowing upward sequence because sea-level fluctuates within 0.5 m and cannot be measured to that degree of accuracy.

SUMMARY

Facies

Four facies are recognized in Staniard Creek based on sedimentological and multivariate statistical analyses. The foraminifera-poor "pack/wackestone" facies deposited subtidally is found in localized depressions throughout the lagoon. The foraminifera-rich "grainstone" facies dominates the lagoon laterally and vertically. It accumulated in a shallow subtidal to lower intertidal environment. The aggregate/aragonite-rich "grainstone" facies capping the sequence and found only in the southern intertidal sand flat was deposited in the upper-intertidal environment. It is the only facies in the sequence to have features indicating its depositional environment. An algal mat cover over these sediments extends throughout the sand flat and into portions of the northern subtidal area. The foraminifera-poor "grainstone" is found at the base of two cores and is not considered a major contributor to the vertical sequence.

Depositional History

The initial environment of Staniard Creek was intertidal and is indicated by the presence of basal peat in several cores. Peat in core C contained boehmite suggesting subaerial exposure and soil formation prior to sedimentation. Radiocarbon dates of peat and bulk sediments indicate that carbonate deposition began at the latest 3330 ybp. Before the foraminifera-poor "pack/wackestone" facies was deposited, there was inorganic precipitation of mud. This is indicated by low concentrations of aragonite and high-magnesium calcite. When sea-level rise began to flood the platform during the Holocene, the foraminifera-poor "pack/wackestone" facies was deposited in localized depressions containing peat and was preserved. The foraminifera-rich "grainstone" facies accumulated in the lower intertidal environment where enough oxygen was present in the sediment pores for the grains to retain their tan color. As sea-level continued to rise slowly, the sediment pores became saturated and reducing conditions turned the sediments from tan to gray. Due to a change in the gradient the southern half of Staniard Creek was able to build up to sea level while the northern half remained subtidal. Evaporation of the sand flat resulted in the precipitation of aragonite and the increase in its concentration. The increase in aggregates in portions of the sand flat are attributed to the precipitation of aragonite and subsequent cementation of sand grains.

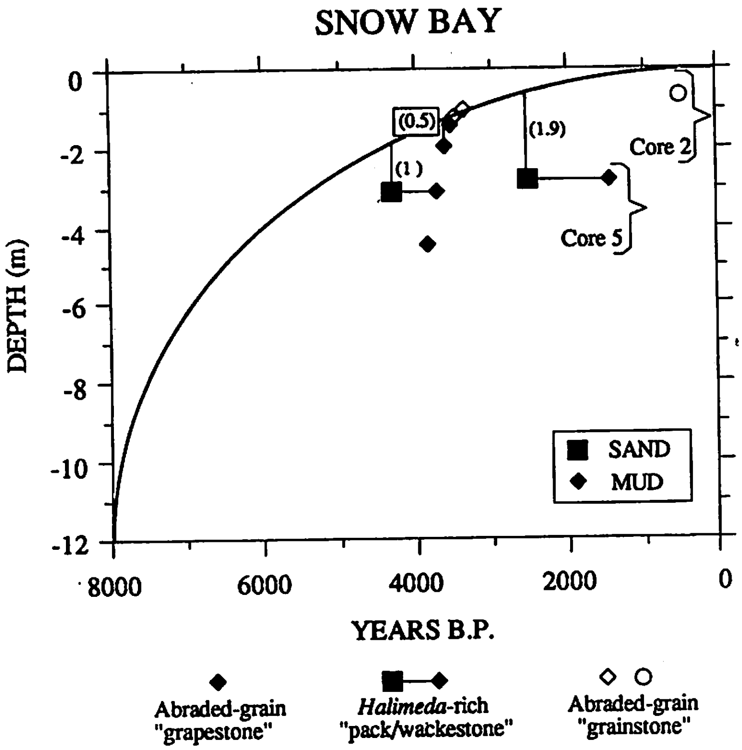

Figure 12. Radiocarbon dates of the three major facies in Snow Bay taken from two cores. The shallowing upward interpretation given to the *Halimeda*-rich "pack/wackestone" and abraded-grain "grainstone" are not supported by the radiocarbon dates and the Bahamas sea-level curve. In core 5, the *Halimeda*-rich "pack/wackestone" is deepening upwards by almost 1 meter (1.9 m - 1.0 m = 0.9 m deeper up core). In core 2, the same facies has a shallowing upward tendency, however, it shallows up by ≤ 0.5 m which is within the tidal range. The sea-level curve has an error of at least 0.5 m, therfore, the observation of slight shallowing upward tendecies in some sediments is not enough to warrant a conclusion applied to the entire lagoon.

ACKNOWLEDGMENTS

The authors would like to thank the staff at Forfar Field Station on Andros Island for their cooperation and generous help. Thanks go to Larry Evans who collected the twelve southern cores. Thanks also go to Dr. Sam Valastro and the staff at the Radiocarbon Lab, University of Texas at Austin for the C-14 dating. This project was partially funded by the annual summer workshop, *Modern Carbonate Deposition*, directed by Mark R. Boardman, and grants in aid from AAPG and British Petroleum (to T. Love).

REFERENCES CITED

Ahmad, N. and Jones, R., 1966, Genesis, mineralogy and related properties of West Indian soils: Soil Sci. Soc., America Prog, v. 30, no. 6, p.719-722.

Andersen, C. B. and Boardman, M. R., 1988, The depositional evolution of a high-energy lagoon, Snow Bay, San Salvador, Bahamas, (unpublished master's thesis): Oxford, Ohio, Miami University, pp.

Bear, F. R., ed., 1964, Chemistry of soil: Reinhold Publishing Corp., New York, p. 112.

Boardman, M. R., 1976, Lime mud and deposition in a tropical island lagoon, Bight of Abaco, Bahamas (unpublished master's thesis): University of North Carolina, Chapel Hill, North Carolina.

Boardman, M. R., Evans, L. A. and Andersen, C. B., 1986a, Sedimentary gradients of Holocene Bahamian lagoons: controlled by sills and sea-level (abst.): Society of Economic Paleontologists and Mineralogists Annual Midyear Meeting,v.3,p.12.

Boardman, M. R., Neumann, C.A. and Rasmussen, K. A., 1989, Holocene sea-level in the Bahamas: In Mylroie, J.E., ed., Proceedings of the 4th Symposium on Geology of the Bahamas, Bahamian Field Station, San Salvador, Bahamas, p.45-52.

Boardman, M. R., and Carney, C., 1991, Lime mud accumulation in ooid tidal channels, Bahamas: in press, Journal of Sedimentary Petrology.

Bohm, E. L., 1973, Studies on the mineral content of calcareous algae: Bulletin of Marine Sciences, v.23, p. 177-190.

Brazier, M. D., 1975, An outline history of seagrass communities, Paleontology, v.18, p. 681-702.

Chave, K. E., 1954, Aspects of the biochemistry of magnesium 1. Calcareous marine organisms: Journal of Geology, v.62, p.266-285.

Cloud, P. E., Jr., 1962, Environment of calcium carbonate deposition west of Andros Island: U.S. Geological Survey Professional Papers,350, p. 1-138.

Colby, N. D. and Boardman, M. R., 1989, The depositional evolution of a windward, highenergy lagoon, Graham's Harbor, San Salvador, Bahamas: Journal of Sedimentary Petrology, v. 59, p. 819-834.

Enos, P,1977, Holocene sediment accumulations of the South Florida shelf environment: in Enos, P. and Perkins, K. D. (eds.), Quaternary sedimentation in South Florida: Geological Society of America Memoir 147, p.49-115.

Enos, P., 1983, Shelf environments: in Scolle, P. A.; Bebout, D. G.; and Moore, C. H., eds., Carbonate depositional environments: American Association of Petroleum Geologists, Memoir. 33, p. 268-295.

Fischer, A. G., 1964, The Lofer cycothems of the Alpine Triassic: in Merriam, D.F. ed., Symposium on cyclic sedimentation: State Geol. Survey Kansas Bull., 169, v. 1, p. 107-149.

Gebelein, C. D., 1974, Guidebook for modem Bahamian platform environments, prepared for a field trip of the Geological Society of America annual meeting, p.9-15.

Imbrie, J. and Purdy, E. G., 1962, Classification of modern Bahamian carbonate sediments: in Ham, W. E., ed., Classification of Carbonated Rocks: American Association of Petroleum Geologists Memoir, v. 1, p.252-272.

Isophording, W. C., 1974, A mode for limestone weathering and soil development in tropical climates: Geological Society of America, Abstracts with Prog. V. (6)7, p. 805-806.

James, N. P., 1984, Shallowing upward sequences in carbonates: in Walker, R.6. ed, Facies Models: Geoscience Canada Reprint Series 1, p.213- 228.

Land, L. S.,1970, Carbonate mud: production by epibiont growth on *Thalassia testudinum*: Journal of Sedimentary Petrology, v.40, p. 1361-1363.

Laporte, L., 1967, Carbonate deposition near mean sea-level and resultant facies mosaic: Manlius Formation (lower Devonian) of New York State, American Association of Petroleum Geologists, Bulletin, v. 51. p. 73-101.

Miller, A. I, 1988, Spatial resolution in subfossil molluscan remains: Implications for paleobiological analyses: Paleobiology, v. 14, p.91-103.

Murray, J. W., 1970, The foraminifera of the hypersaline Abu Dhabi lagoon, Persian Gulf: Lethaia, v.3, p.51-68.

Nelson J. E. Jr. and Ginsburg, R. N., Calcium carbonate production by epibionts on *Thalassia* in Florida Bay: Journal of Sedimentary Petrology, v.56, p. 622-628.

Neumann, A. C., 1965, Processes of recent carbonate sedimentation in Harrington Sound, Bermuda: Bulletin Marine Science, v. 15, p.987-1035.

Neumann, A. C. and Land, L.S., 1975, Lime mud deposition and calcareous algae in the Bight of Abaco, Bahamas: A Budget: Journal of Sedimentary Petrology, v.45, p.763-786.

Patriquin, D. G., 1972, Carbonate mud production by epibionts on *Thalassia*: An estimate based on leaf growth rate data: Journal of Sedimentary Petrology, v.42, p. 687-689.

Pratt, B. R. and James, N. P., 1986, The St. George Group (Lower Ordovician) of western Newfoundland: tidal flat model for carbonate sedimentation in shallow epeiric seas: Sedimentology, v. 33, p. 313-343.

Purdy, E. G., 1963, Recent calcium carbonate facies of the Great Bahama Bank: Journal of Geology, v. 71, p. 334-355.

Reijers, T. J. A., and Hsu, K. J., eds., 1986, Manual of carbonate sedimentology: A lexicorgraphical approach: Academic Press Inc. Orlando, Florida, p. 132-133.

Seposki, J. J. Jr., 1974, Quantified coefficients of association and measurement of similarity: Mathematical Geology, v. 6, p. 135-152.

Schlager, W., 1981, The paradox of drowned reefs and carbonate platforms: Geological Society of America Bulletin, v. 92, p. 197-211.

Scoffin, T. P., 1970, The trapping and binding of subtidal carbonate sediments by marine vegetation in Bimini Lagoon, Bahamas: Journal of Sedimentary Petrology, v. 40, p. 249-273.

Shinn, E. A., 1983, Tidal flat environments: in Scolle, P.A.; Bebout, D.G.; and Moore, C.H., eds, Carbonate depositional environments: American Association of Petroleum Geologists, Mem. 33, p. 186.

Sneath, P. H. A. and Sokal, R. R., 1973, Numerical Taxonomy: The principles and practice of numerical classification: San Francisco: W.H. Freeman.

Stockman, K. W., Ginsburg, R. N., and Shinn, E. A., 1967, The production of lime mud by algae in South Florida: Journal of Sedimentary Petrology, v. 37, p. 633-648.

Strasser, A., 1988, Shallowing-upward sequences in Purbeckian peritidal carbonates (lowermost Cretaceous, Swiss and French Jura Mountains): Sedimentology, v. 35, p. 369-383.

Till, R., 1970, The relationship between environment and sediment composition (geochemistry and petrology) in Bimini Lagoon, Bahamas: Journal of Sedimentary Petrology, v. 40, p. 367-385.

Tucker, M. E. and Wright, V. P., 1990, Carbonate sedimentology: Blackwell Scientific Publications, Cambridge, Massachusetts, p. 96-113.

Wanless, H. R. and Tedesco, L. P., 1990, Depositional and early diagenetic controls on fabrics and porosity of carbonate mud banks: Carbonate Microfabrics Symposium and Workshop, Sept. 30-Oct.3, Texas A&M University, p. 19.

Windland, H. D. and Matthews, R. K., 1974, Origin and significant of grapestone, Bahama Islands: Journal of Sedimentary Petrology, v. 44, p. 921-927.

Wray, J. L., 1977, Calcareous algae: Elsevier/North-Holland Inc. New York, p.80.